Short-term Tests For Evaluating The Machinability Of Free-cutting Steel.

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Short-term tests for evaluating the machinability of free-cutting steel

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Lehigh University, 1987

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SHORT-TERM TESTS FOR EVALUATING THE MACHINABILITY OF FREE-CUTTING STEEL

by

Osama Khaled Eyada

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Presented to the Graduate Committee
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ABSTRACT

Machinability tests that closely simulate production conditions, such as automatic screw/bar machine tests, are commonly regarded as the most reliable ones and are usually utilized for evaluating free-cutting steel machinability. They are, however, of the long-term type and, in turn, can not be engaged in the steel mill production lines for checking daily machinability level. The majority of the short-term tests developed were aimed at replacing the long-term ones. Also, their results have not correlated well with those of the screw machine tests. From a disscusion with Bethlehem Steel Corporation, Homer Research Laboratories, it was, initially, decided to develop a short-term test that would correlate well with the results of the Bethlehem's test, an automatic screw machine test, and could be utilized in the steel mill production lines for daily machinability assurance. However, examination of the machinability dilemma, in terms of the many definitions and descriptions, various predictive models, and developed tests indicated that machinability should stand for machining efficiency and should be viewed as a probabilistic input/output system. Based on this approach, three short-term tests, a Power Hacksaw Test (PHT), an End Milling-Slotting Test (EMST), and a Cutting Forces Test (CFT), were developed to test different aspects in the machinability space of the free-cutting steel with the least possible sources of error. The tests were also designed to provide capability for assuring the machinability level in the production lines. Fifteen work materials, basically different designs of two grades; 1213 and 12L14, were utilized for this investigation. The results indicated that the three short-term tests have high repeatability, high sensitivity to variations in machinability, and correlated well with the results of the long-term test as well as among themselves. They also indicated that the ranking of the work materials is independent of cutting conditions, and that the feed force is the most sensitive resultant force component in differentiating between the work materials. Finally, a quality control procedure was developed for the Power Hacksaw Test.

Chapter 1: INTRODUCTION

In the area of metal cutting operations, a subset of the general field of manufacturing processes, machinability is usually regarded as one of the most important concepts. Yet scientists and investigators do not agree on how it should be defined and/or measured.

Machinability is sometimes considered as the ease with which materials are cut using appropriate cutting tools, and at other times as the material resistance to machining. Either way, terms such as ease, resistance and appropriate are themselves subject to individuals' definitions. For example, what is appropriate for a certain machining operation is not appropriate for another. Ease and/or resistance can be expressed in terms of obtained part qualities and/or material effects on tools. In addition, machinability data are usually given in the form of a single index where a standard material is assigned 100 per cent and the others are ranked relatively [1]. Questions regarding how machinability should be defined and tested, whether machinability results should be provided in absolute or relative values, etc. are discussed in Sections 2.1 to 2.4.

With the increasing trend towards the application of automation in manufacturing, the machinability of work materials is becoming increasingly important. The consistency of work materials, cutting tools and cutting fluids are vital factors to the reliability of modern manufacturing systems (i.e., Flexible Manufacturing Systems). The high demand for consistency in the input factors of metal cutting operations intensifies pressure on the manufacturers of work materials, cutting tools and cutting fluids. This dissertation is thus concerned with one materials manufacturer, Bethlehem Steel Corp. - Homer Research Laboratories (HRL), whose problem is not only how to design new materials that would provide better physical properties and/or machinability, but also how to control improved machinability in production (i.e., within and among batches).

The machinability evaluation system of HRL (described in more detail in Section 2.3) includes a production performance test (PPT) for evaluating free-cutting steel machinability [2]. It is a long-term test in which the production of a certain part is simulated on an automatic screw/bar machine of the multiple spindle type. Another long-term test, the Taylor test [3], is often excercised before the PPT where the time to catastrophic tool failure and the cutting forces are determined for a series of speeds. However, HRL had concluded that the Taylor test does not screen among the materials, and that no correlation exists between the two tests' results ([2] & [3]). As a result, HRL was confronted with the following:

(1) Because of economical considerations, the PPT is limited in applications to those newly designed materials with the highest expected potential.

(2) Since the PPT is a very long-term test (five weeks are usually needed to evaluate one material), it can not be engaged as a quality control tool in their production lines for checking

daily machinability level.

(3) There are several publications that present a summary of various short-term tests ([4] to [11]), and it is questionable whether these or other tests would provide a high correlation with the PPT results.

In addition, HRL was an active member on the committee that led to the publication of a standard method for evaluating the steel machinability on an automatic screw/bar machine [12]. The test procedure was examined by several researchers [13], and some of the problems were identified. For example, modifications to the single-spindle machine indicators are required to allow for comparisons with the multiple-spindle types. Recommendations, if any, on this method were then required.

The main requests of HRL were thus:

(1) To find/develop a short-term test that correlates well with the PPT and can be utilized in production lines for daily machinability evaluation.

(2) To provide recommendations on their machinability evaluation system with an emphasis on the Automatic Screw/Bar Machine Test [12], a standardized PPT.

There are certain requirements that must be first fulfilled by any test in order to be considered as having the potential for satisfying the first request. Based upon these requirements, given in Chapter 3, none of the published machinability testing procedures qualified. At the same time, examination of the PPT procedure and results pointed to possible flaws in the HRL machinability evaluation system. For example, it is questionable how two materials' results differ by only five pieces per hour (383 & 388 pcs/hr), given that there are so many input factors that can sometimes be beyond control in such a long-term test (i.e., cutting fluid variations).

The main objectives were, therefore, to develop three short-term tests that would;

(1) test different aspects in the machinability space of the free-cutting steel with the least possible sources of error,

(2) screen among the materials under investigation with high sensitivity and repeatability (fifteen materials were utilized which are basically different designs of two grades 1213 & 12L14, described in detail in Section 3.1),

(3) provide reasonable correlation with the PPT results, and

(4) be capable of evaluating the machinability level in daily production.

The three developed tests are named; the Power Hacksaw Test (PHT), End Milling-Slotting Test (EMST), and the Cutting Forces Test (CFT). Questions regarding why these three tests, why fifteen materials, etc. are explained in Chapter 3 along with the testing methodology utilized. Chapters 4, 5, and 6 cover the three tests respectively in terms of objectives, setups, results, and conclusions. In Chapter 7, a cross correlation analysis between the tests' results and HRL data, and recommendations on HRL machinability system are given. Finally, a summary of the conclusions and possible future work are provided in Chapter 8.

Chapter 2: MACHINABILITY

Machinability is an important and complex concept which has acquired a variety of connotations that can be unclear or confusing to the uninitiated. The difficulty is not only how it should be defined, but also how it should be measured accurately.

The machinability dilemma, in terms of the many definitions and descriptions, various predictive models and developed tests, and its current data disadvantages, is viewed in the first three sections. A new approach for defining and describing the term machinability along with a proposal for improved machinability data is given in section 2.4. In section 2.5, the HRL machinability evaluation system is briefly described with an emphasis on the PPT. Finally, the argument of quality testing and the reasons behind the high demand for short-term tests are discussed in section 2.6.

2.1 Machinability - Definition and Description

As early as 1924, the term machinability was defined by Kessner [14] as a material property that represents its resistance to machining by cutting tools which depends on a combined effect of two other properties, hardness and plasticity. Kessner also stated that information on machining qualities cannot be obtained from a hardness test. Since then, the term has conveyed several meanings and has been defined in various ways. Some authors had two definitions for it ([7] & [8]), while others had changed their definition over time ([4] & [21]).

Henkin and Datsko [15] reported that in 1928, the term was used by Hebert [16] to refer to the Taylor speed-life relationship. In this same year, 1928, Boston [4] considered machinability to be like hardness in that it is not clearly defined but could be expressed in different and independent ways to denote a metal-structure resistance to a cutting tool action. He also mentioned that it may refer to the relative machining qualities of several materials obtained under the same cutting conditions or to those of a certain material under various cutting conditions. Although he had pointed to the possibility of having materials regarded machinable by one process while not by another, a year later [5], he concluded (based upon the obtained results of four different machinability tests applied on eighteen ferrous metals and twenty-one nonferrous metals) that the four tests' results were similar and independent of hardness. However, his work was indirectly criticized in the written disscussion by B.H. Blood [5, pp. 698-700], who pointed out that no one tool geometry nor one cutting speed exists for the practical or optimum machining of this range of metals. In 1939, Cook and Davis [17] used the term ease instead of resistance and demonstrated that the machinability of a material is dependent on the employed test. They thus advised that caution should be exercised in interpreting machinability results. In 1949, Boulger, Shaw and Johnson [18] defined machinability from a metallurgical point of view to be a complex material property that controls the facility with which it is machined. A year later, Boulger [19] quoted A.B. Kinzel, who defined machinability as the ability of a workpiece to go through a machine shop without causing problems to the machinist. Meanwhile, Field and Zlatin [20] had chosen to restrict its definition to tool life, surface finish and consumed power in machining metals.

In 1951, Boston [21] changed his earlier definition (given above) to the machining response of a metal which involves the cutting tool performance that is usually assisted by a cutting fluid. He also stated that good machinability can be indicated by one or more of the following factors; tool life, surface finish, chip breakability, consumed power, dimensional accuracy, metal removal per tool grind, etc.

In 1958, Boulger [22] defined the term as the material effects on machining operations. Five years later, Murphy and Aylward [2] mentioned that machinability is often employed to designate the machining performance of a material, yet they simply defined it as the capability of being machined by an appropriate cutting tool. In 1965, Brown and Tao [23] stated that the term does not have a precise definition, but it may relate to chip-formation type, consumed power, produced surface finish or tool life. In 1968, Davies [6] stressed that machinability can only be defined in terms of specific criteria that are chosen because of their relevance to cutting operations normally applied on the material, and that a more fundamental approach was not practical at that time.

In 1973, Chisholm, Mills and Redford [7] suggested that neither cutting energy nor machined surface quality should figure in the meaning of machinability, and that the term should only refer to the way a material wears away a cutting tool during machining. They even went further to suggest a new name for this material property, "wearproducibility". They also mentioned that machinability is a function of the test itself and not of other material properties. The same year, Redford and Mills [8] mentioned that the most acceptable definition was in terms of machining parameters, where a material would have a good machinability if it satisfied certain conditions; low tool wear rate, good surface finish, low power requirements, and high metal removal rates.

In 1975, after Cook [24] had looked up the meanings of machinability, machinable and machine in a dictionary, he concluded that they are of little value to a manufacturing engineer. He also mentioned that the problem of defining machinability lies in the fact that it has different meanings for different situations. At this same time, Tipnis and Joseph [25, p. 11] stated the following:

> The machinability response of a given workpiece material depends on many metallurgical factors and on the machining operation being performed including the specific machine tool, cutting tool, cutting fluid and operating conditions of speed, feed and depth of cut. Since the machinability response is known to be different for different operations and operating conditions, machinability should probably be viewed as an interaction rather than a property.

They also mentioned that there is no universally acceptable definition for machinability. Two years later, Tipnis [26] stressed that machinability is not a property like tensile strength or yield strength and that it stands for the outcome of a machining operation under specific conditions. In 1980, Naylor [27] considered machinability as an interaction between work material, cutting tool, cutting fluid and machine tool. In 1982, Redford and Mills [11] mentioned that because of the high energy cost, cutting efficiency could now be a reasonable measure of machinability, but again they suggested that the term should be restricted to the material effects on cutting tools.

Examination of the above references indicates that machinability;

(1) has no standard definition

(2) is not a property of materials

(3) should be viewed as an interaction

(4) depends on several input factors

(5) can be indicated by several criterion.

In addition, some definitions overlook some users' interests while others oversimplify the term until it is no longer a technical (quantitative) definition. All users' points of view should, therefore, figure in the definition of machinability without any simplification. Any attempt to restrict its meaning to some users and/or oversimplify it would only add confusion to an already existing problem.

2.2 Machinability - Prediction and Testing

Machinability Prediction

The main objective of Taylor's pioneering work was to provide the machinist with answers to three questions: which tool, speed and feed should be applied in a given metal cutting situation [28]. His other objectives included the determination of facts or laws that govern the art of metal cutting and the establishment of simple mathematical models for daily usage. Since then, several mathematical models (theoretical and empirical) have been developed to aid involved disciplines (metallurgists, designers, manufacturing engineers, etc.) in predicting the outcome of a given machining condition.

A single theoretical model that describes the metal cutting process even in its simplest case (turning with a single-point tool) does not exist ([29] to [31]). The majority of established theories are restricted to orthogonal cutting while the rest are based on unrealistic assumptions, such as a zero nose radius. Further, most theories require some kind of machining or testing to obtain values for the input factors, and the only way to branch between orthogonal or oblique cutting and actual machining is through empirical models.

The literature contains many empirical models for predicting tool life, cutting temperature, surface finish, chip breakability, etc. based on cutting condition, chemical composition, microstructure, physical (mechanical, thermal, and/or electrical) properties, or a combination of these.

The first empirical model is the Taylor speed-life relationship ($VT^n = C$). It is based on the assumption that the logarithmic transfer of the power relationship, between the tool life and the cutting speed, is linear. If the model parameters are determined over that speed range in which the assumption is valid, it can be used in predicting the tool life for a given speed or visa versa. However, the estimated constants can be invalid when predicting the machining outcome of a different batch of the same work material. This is due to possible variations among batches. Further, any extrapolation outside the testing domain (cutting conditions under which the model parameters were determined) could be invalid, because the linearity assumption may no longer be true. Another important factor to the accuracy of any predictive model, and one that is rarely reported, is the variances of the estimated parameters. These are a reflection of the data variability and should be considered before any predictive model is utilized.

Since the cutting speed is the main contributing factor to the tool wear, it would, therefore, pay to machine at a low speed and high feed rather than the other way around for obtaining the same removal rate. As a result, the modified Taylor equation (speed-feed-life power relationship; $VT^n f^m = C$) was introduced to accommodate both speed and feed effects ([10] & [21]). Other investigators ([32] to [35]) preferred the general or extended Taylor equation (speed-feed-depth of cut-life power relationship: $VT^nf^md^l= C$). Whether the logarithmic transfer of these assumed power relationships would stabilize the tool life variance ([36] & [37]), or whether a first logarithmic order, second logarithmic order or a nonlinear model is more appropriate ([35], [38] & [39]), would all depend on the data obtained [40]. Therefore, a standard tool life model based on cutting conditions does not exist. The model type is dictated by the experimental results, and the obtained constants are limited to the used batches, testing domain and employed setup.

Although a material microstructure depends on its chemical composition, machinability prediction through chemical composition would only be valid when all other factors that can influence the structure are held constant. Any small variations in bar size, final rolling temperature, cooling rate, heat treatment, etc. could lead to a variation in microstructure and, thus, unknown machinability rating. Nonetheless, such early studies (given in references [11] & [22]) pointed to the importance of controlling the range of each element. It has been shown that small variations in chemical composition can have significant effects on machinability which could, thus, vary between the high and low ends of each element [22]. This has led to the high demand for narrower chemical composition range.

Despite the numerous studies that have addressed the microstructure of materials, there are no predictive models based on microstructure analysis, but rather general trends to microstructure effects on machinability ([2], [3], [11], [22] & [41] to [48]). This is due to the possibility of having two microstructures that can have no significant differences in their structural properties, but yet provide different machining performances [42].

The utilization of physical properties for machinability prediction is another approach that has led to various predictive models. Based on the room-temperature properties of twenty different steels, Janitzky [49] developed a model to predict the speed for a 60 - minute tool life through hardness and area reduction ($V_{60} = D / (H_B \cdot A_r)$, where D is a constant dependent on the size of cut). He also pointed out the importance of the yield-tensile ratio for steels. Henkin and Datsko [15] applied the dimensional analysis technique to derive a relationship for calculating the speed for a given tool life. The utilized materials ranged from steel to leaded red brass. Although they stated that no one tool geometry is the optimum for all materials, they still used one tool geometry. Their final model shows this machinability indicator to be a function of hardness, area reduction and thermal conductivity ($V_{60} = 1150\, k\, (1 - (A_r/100))^{.5} / H_B$, where k is the thermal conductivity). With the exception of thermal conductivity, the above two models are similar in that hardness and area reduction are the required mechanical properties for estimation. For the plain carbon and alloy steels, Takeyama and others [33] developed relationships for the rough estimation of the speed for a 60 - minute tool life through hardness.

However, in the developing stage of the Henkin and Datsko model, they found the yield-tensile ratio to be insignificant and to have no general validity. This is supported by the results obtained for the work materials under investigation, see Appendix-B, where there is no correlation between the production rate and this ratio. They also discovered that room-temperature properties do not provide good correlation with machinability as indicated by the speed for a 60-minute tool life. The elevated temperature properties, determined at the average cutting-zone temperature that was implicitly assumed to be the same for all materials, were hence utilized and gave better correlation. This is partially in agreement with Boulger's comment [19] that tensile tests are made on specimens taken parallel to the rolling direction and at room temperature, while cutting metals is done in the transverse or thickness direction and at elevated temperatures and faster strain rates. For this reason, Boulger stated that reliable machinability indicators cannot be obtained from hardness and tensile tests. He also mentioned that the most misleading generality is that small differences in hardness can be correlated with machinability. Examination of the hardness and machinability data given in reference [1] confirms that machinability is independent of hardness for at least this group of materials. Yet hardness is used as a rough measure of machinability. For each group of materials, hardness should be within a certain range to achieve good machining [9], but within this range, machinability is independent of hardness. Finally, the above three models were developed to predict machinability in terms of the speed for a 60-minute tool life, while Boston [30] found that the ranking of materials based on the speed for a 60 -minute tool life is different than that for a 20 - minute tool life.

Because of the amount of heat generated during metal cutting, thermal properties have been used as basis for prediction. For the rough estimation of the practical cutting speed, especially for newly designed materials, Ewell [51] recommended a new machinability index based on the work material thermal conductivity, density and specific heat. The index is based on two coefficients; the thermal dispersion and absorption. The thermal dispersion coefficient, conductivity per density, is for external type operations, such as face milling. The thermal absorption coefficient, conductivity times specific heat, is for internal type operations, such as drilling. The higher the coefficients' values, the higher the estimated machining speed. He, however, stated that these coefficients are not the complete answer nor equal to empirical data. They reflect rough estimates based on thermal properties that could be used in conjunction with other factors (i.e., mechanical properties) especially in designing new materials.

Others [52] investigated the affects of tool material thermal conductivity on cutting forces and crater wear, where the lower the tool thermal conductivity, the better the machinability. Due to the difficulties and costs associated with the measurements of thermal conductivity, the electrical resistivity which correlates well with it was used by Lorenz [53]. The higher the electrical resistivity, the lower the machinability, as indicated by the permissible speed. Lorenz's objective was to investigate whether electrical resistivity, thermoelectric potential or their combined results would yield a non-destructive test method for assessing batch to batch variations in the machinability of a free-machining brass (58 % Cu, 3 % Pb - type) and free-cutting Al-Cu alloy (type 2011). Some success was achieved only for the free-machining brass. He mentioned that this approach is in its infancy and that when tool performances on various commercially manufactured batches are available, the desired correlation may result. Whether thermal or electrical properties are the answer or not, the cost of equipment and staff required to accurately measure these properties should be weighed carefully.

Due to cutting temperature influence on tool wear, it has received considerable attention in terms of its measurement, prediction and relationship with tool life or wear. Although there are several techniques for measuring cutting temperature (given in [54]), the most commonly used method is the tool-work thermocouple in which the tool-work interface is the hot-junction. This provides a good measure of the average cutting temperature when all other junctions in the system are secured, and the produced 'emf' is accurately calibrated. Levy and Thompson [55] investigated the presence of a general predictive model based on cutting conditions. They assumed a speed-feed-temperature power relationship and used previously published data obtained by the thermocouple technique on steel to determine the model parameters. Due to differences among other cutting conditions in the data sources (i.e., tool geometry), the constants varied from one set of data to another. They concluded that a higher order equation which would consider all pertinent variables is required in order for a predictive model to have any general validity. Cook [32] utilized the dimensional analysis technique and empirical data to develop a temperature predictive model. The model shows the temperature to be a function of speed (V), feed (f), specific cutting energy (u), volumetric specific heat (density times specific heat, v_{sh}) and thermal conductivity (k); $(\theta = (.4\,u / v_{sh})(V\,f / k)^{1/3})$. He, however, stated that his model provides a crude approximation and mentioned other work that may provide better estimation, but with a higher degree of computational difficulty.

Others ([10], [34] & [56] to [58]) related tool life or wear to cutting temperature or to the initial cutting temperature. An assumed speed-temperature power relationship was combined with Taylor's model to predict tool life through cutting temperature (reported in [10]). Based on the obtained parameters, it was concluded that small changes in temperature would have large effects on tool life. However, the influence of temperature on tool life or wear is usually neglected at low cutting speeds or below critical temperature values ([57] & [58]). Further, the chance of BUE formation increases at low cutting conditions and, thus, lowers the cutting temperature reliability. For this reason, Levy and Thompson [55] did not include the low cutting speed data in their analysis.

Other predictive models include surface finish, chip breakability, etc. prediction. Bhattacharyya and others [59] developed a surface roughness regression model based on machining data of plain carbon steel. The surface roughness was dependent on feed, tool nose radius, work material hardness, complimentary angle of SCEA and speed, while the model parameters were dependent on the feed and speed range. However, system rigidity and BUE formation are also major factors to the obtained surface finish. Schmidt, Ham and Wilson [61] concluded that variable surface finishes would result when the same tool is used on different lathes. Further, others (reported in [6]) found the surface finish to be dependent on the tool position with respect to the workpiece, where the best finish in machining free cutting brass was achieved when the tool was slightly below the workpiece center-line. Based on a computer simulation of chip formation, Spaans and Goedemondt [60] concluded that either the chip fracture strain or its reciprocal can be used as a powerful criterion for chip breakability and, thus, machinability. Although ease of chip disposal or breakability is important, especially for automated manufacturing systems, a good chip-breaker design [62] and/or slight modification to the cutting condition [6] make this machinability criterion least important.

From the above, the following conclusions can be drawn:

(1) A single theoretical model that describes the metal cutting process even in its simplest case (turning with a single-point tool) does not exist. Existing theories are restricted to orthogonal or oblique cutting.

(2) A standard model for tool life or cutting temperature prediction through cutting conditions does not exist. The model type is dictated by the experimental results, and the obtained constants are limited to a work material batch, tool material batch, cutting fluid batch (if used), testing domain and a given setup.

(3) A valid predictive model based on the analysis of chemical composition and/or microstructure does not exist. Their effects on machinability can be only assessed in terms of general trends.

(4) Although room-temperature mechanical properties are usually available for each work material batch, machinability evaluation through hardness and tensile tests' results is not reliable. Mechanical properties are only useful for product design. Neither hardness nor tensile strength is a rough measure of machinability.

(5) There is not enough evidence that room-temperature thermal or electrical properties can be used as a basis for machinability evaluation. Even so, the cost of measuring these properties should be considered versus other inexpensive alternatives (i.e., the Power Hacksaw Test).

(6) Machinability evaluation, through current theories or empirical models, provides, if anything, a crude estimation of a single aspect of machinability. These rough estimates should not be used in a decision making process unless the cost of being in error is considered. There are two types of

errors that are costly to determine, the probability of predicting good machinability when it is bad, and visa versa.

In summary, a commonly accepted theoretical or empirical model that can be safely used in predicting the machinability of a work material does not exist. Further, the statement of Tipnis and Joseph [25, p. 12] that "a predictive theory for machinability has not yet evolved", Ham's comment [63] that existing theoretical and empirical relations are inherently difficult to apply to actual production operations, and Boulger's conclusion [22] that machinability is best evaluated by machining studies are, to date, still valid.

Machinability Testing

Over seven hundred references were retrieved when Reiter [10] searched the Metals Abstracts for machinability tests conducted within a ten-year period. He concluded that due to the complexities of the machining process and the wide variety of methods used for testing, there is no universally acceptable test for machinability. This was supported by a similar search conducted by the author which retrieved one hundred and forty references from English publications spanning the years 1979 to 1984. The majority of machinability tests described in these publications are appropriate for the investigation of work materials, cutting tools or cutting fluids.

Some authors viewed the tests in terms of two criteria; machining or non-machining and absolute or ranking [11]. Non-machining tests represent chemical composition, microstructure and physical properties analysis. They are assumed to provide input data to empirical models for the objective of predicting machinability. As mentioned earlier, this machinability evaluation approach is the least reliable one, since it provides crude estimations, if any at all. This does not mean that the investigation of chemical composition and/or microstructure effects on physical properties and/or machinability is not important. The absolute tests are those aimed at the machinability evaluation of two or more tool-work combinations over a range of cutting conditions. The ranking tests are the ones that investigate these combinations at a given set of conditions.

Others described the tests in terms of output criteria, such as tool life, cutting temperature, etc. [9]. However, a universally acceptable system for classifying these tests does not exist. Further, there are no standard cut-off values (based on consumed material and/or time) to identify whether a test is of the long-, medium-, or short-term type.

Based on the above mentioned approaches and others, several attempts were made by the author to classify the machinability tests. Unfortunately, an acceptable system was not found. If the procedure of a ranking test is applied to more than one set of conditions, it would fall under the absolute type. Similarly, if the absolute test procedure is applied to a single set of conditions, it would fall under the ranking type. Two tests can have identical testing procedures but one measures tool life while the other measures surface finish. A testing procedure could hence be classified under many output criteria.

Other classification factors included the objective of testing, workpiece geometry and operation type. Tests that investigate a new work material design ought to be different than those that check the incoming raw materials, or than those that determine the machinability level in production lines. However, with a slight modification to the testing procedure of a given test (i.e., the Power Hacksaw Test), it can serve more than one objective. Although some tests are suitable for a very wide range of workpiece geometries and others are only applicable in a narrow range, an overlapping could occur. A system based on operation types such as turning and drilling does not reflect the employed machine (i.e., conventional or non-conventional lathe) nor setup requirements, including the degree of workpiece preparation. The last attempt was to utilize different combinations from the above mentioned factors. However, it was soon discovered that this would be a substantial task which would require more than one investigator's effort. It was, therefore, decided to view the tests in terms of what had been done on lathe, milling, drilling, etc. machines (i.e., according to the machine type). The tests reported below are by no means the complete list. Nevertheless, they reflect the many approaches that were used in testing for machinability. Since the majority of these tests can be used to investigate work materials, cutting tools, or cutting fluids performances, the cited tests are not limited to those that investigated the machinability of work materials.

(A) Lathe Machine Tests

Among metal cutting operations, turning with a single-point tool is the simplest case. As a result, the majority of machinability tests were developed on a lathe machine. Information obtained from this simple case is usually assumed applicable to other operations (i.e., drilling and milling). However, this assumption is questionable. In drilling, the chip has to find its way out through the drill flute and against the gravity force. In milling, the cutting is of the interrupted (discontinuous) type and, thus, thermal factors (or cycling) could play a paramount role [64]. Therefore, any information obtained from the following tests should be restricted to turning operations. Any generalization of their results to other operations is invalid.

(A.1) Taylor Type Tests

Tests that compare tool wear data or determine the speed for a given tool life are related to the pioneering research of F.W. Taylor that was done on a lathe [65]. The comparison of tool wear data is usually limited to plots showing the obtained tool wear versus cutting time under a given set of conditions. Tool wear (TW) is usually indicated by the mean flank wear land when it is regularly worn, the maximum width of the flank wear land when it is irregularly worn, and/or the depth of crater wear. Other indicators could include tool nose wear, surface roughness (especially for finish turning), etc.

The determination of the speed for a given tool life requires obtaining tool wear data at different cutting speeds and using Taylor's formula ($v T^n = C$; where v is the cutting speed in meters/ minute, T is the tool life in minutes, and n & C are constants). Tool life end-point is of two types; catastrophic failure, usually limited to HSS tool materials, and non-catastrophic (or predetermined) failure, for all tool materials. The predetermined tool life failure requires establishing a threshold value (TWo) for the tool wear indicator under measurement. Figure 2.1 shows typical tool wear curves at different cutting speeds. The logarithmic transfer of Taylor's model is usually linear within a certain range of speeds. Figure 2.2 shows the speed-life (v-T) curve when plotted on double logarithmic paper.

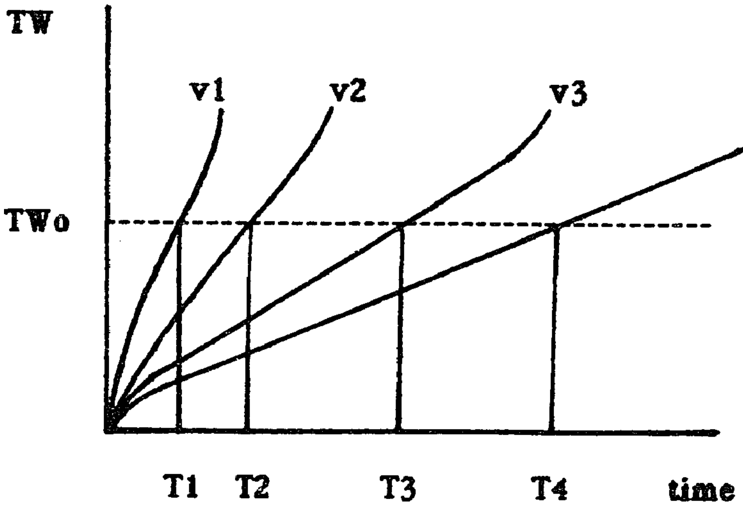


Fig. 2.1 Typical Tool Wear Curves at Different Cutting Speeds

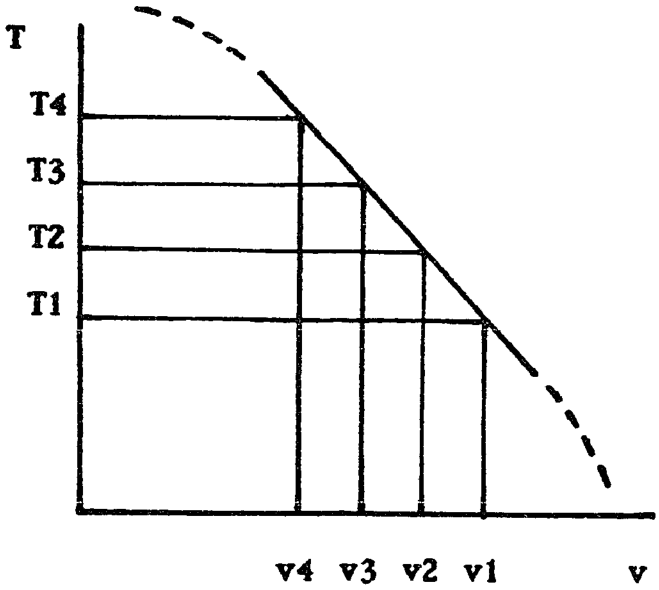


Fig. 2.2 Typical Logarithmic Plot of a Speed-Life Curve

The first problem in utilizing the Taylor test is the selection of a range for cutting speeds. Since extrapolation outside this range is invalid, the desired speed for a given tool life must fall within this range. The second problem is the number of data points required to establish each tool wear curve, unless catastrophic tool life failure is used. This number would depend on the desired accuracy in determining the intersection points between the threshold value and the tool wear curves. Each intersection point can be considered as a sample of size one (i.e., no replications). The third problem is the linearity assumption. Three or more data sets would, hence, be needed to assure that the v-T curve is at least linear within the testing domain. If all the above is overcome, the desired speed for a given tool life can be estimated from the graph or through the calculation of Taylor's constants based on regression analysis. If regression analysis is used, a confidence interval that would reflect the data variability can be found. Unfortunately, neither the variances of the estimated constants nor confidence intervals are given in most publications. Further, replications would be necessary when the gradual wear zone of the tool wear curve is not clearly established (i.e., for small tool life values).

The Taylor test can be used for two broad objectives; comparison of work materials, cutting tools or cutting fluids, and determination of practical cutting data. Either way, testing would be expensive and time consuming and, hence, it is usually regarded as a long-term test. In addition, any slight deviation in the testing procedure from one investigator to another would prevent any comparison to be made between the obtained results. Also, the obtained results of one researcher would be limited to the used batches. For example, if the machinability of two work materials was investigated using, say, one batch of a certain HSS tool grade, one cannot assume that other batches of the same tool material would yield the same results. From the above, it is not surprising that as early as 1950, Boston [50] started the standardization attempts. In 1977, the International Standardization Organization (ISO) published a standard tool-life testing procedure that was approved by the member bodies of all countries except Austria and Japan [66]. The main objective of the ISO procedure is to obtain comparable results among different sources and with the least possible dispersion. The procedure was used before its publication by Akhtar, Redford and Mills [67] on 14 casts of low carbon free machining steel. Based on the observation that the width of the flank wear land prior to the catastrophic failure of an M2 HSS tool decreases with increase in cutting speed or flank wear rate, they established a short-time method. Simply stated, catastrophic tool life failure is predicted through the measurement of a portion of the gradual tool wear zone.

Although the ISO test is the only internationally accepted testing procedure, it is not widely used. This is, perhaps, due to several reasons: (a) it is a very long-term test, (b) it limits the testing variables flexibility in order to achieve comparable results, and (c) it does not consider the feed effects on tool wear or life. Furthermore, a variable speed drive system is usually required.

Several short-term tests were, hence, developed to reduce the cost (in terms of consumed material and/or time) of the Taylor test. These are:

(1) Facing Tests

Facing tests can be classified into two groups; conventional and non-conventional. The conventional facing tests are those that utilize a regular facing operation [23] in which the tool starts cutting from an outer diameter (O.D.) and feeds inwards to an inner one (I.D.). The majority of facing tests are, however, of the non-conventional type, where facing starts from an I.D. and feeds outwards ([68] to [72]). This is to allow the same HSS tool (or tool holder) to be used for both face and longitudinal cutting so that valid comparisons can be made. Either way, the underlying assumption is that information obtained from a facing cut can be related to an equivalent longitudinal cut. The Taylor's constants were obtained from a single facing pass, using a HSS tool material and the catastrophic tool life failure as a criterion [69], and from several facing passes (i.e., multi-pass facing tests), using different tool materials and tool life criteria ([23] & [70] to [72]). However, only those tool life criteria that are based on flank wear were used.

Since tool life is highly dependent on cutting speed, the resulting tool wear in a given facing pass (with disregard to the type of facing) would be more dependent on the work material characteristics near the O.D. than near the I.D. Lorenz and Gibson [72] claimed that for the non-conventional facing tests, the flank wear is affected only by the tool travel between a critical I.D. and the O.D. For the conventional facing tests, Brown and Tao [23] claimed that the initial 35 % of the distance traveled by the tool from the O.D. to the I.D. accounts for 85 % of the tool life. Therefore, the assumption that variations in work material properties across the bar are insiginificant seems valid, especially for a non-cold-drawn, but homogenuous work material.

Although these tests may not consume a great amount of material, the testing time can be as long as that of the Taylor test depending on the tool life criterion, desired cutting conditions and workpiece geometry. The minimum O.D. that can be used depends on the available spindle speed and facing type. For example, when a carbide tool is used in a non-conventional facing test, the I.D. must be large enough to provide a clearance for the tool holder. Also, the lost time in facing below the critical I.D. should be considered versus the amount of time required to drill and perhaps bore the I.D. to a critical size. Therefore, the facing tests are not as flexible as the Taylor test with regard to workpiece geometry, and cold-drawn bars cannot be tested using these tests.

Most investigators who used a facing test claimed its general validity as a replacement to the Taylor test. This was based on some results and simple mathematical relationships that related the Taylor's constants (or other models' constants) obtained from facing cuts with those of normal turning, through workpiece geometry and cutting conditions. However, these mathematical proofs ignore many aspects of the metal cutting process. In conventional turning, steady or even semi-steady state conditions are achieved as soon as the tool starts cutting. These are in terms of cutting temperature, forces and stresses, acting tool wear mechanism or mechanisms, presence or absence of BUE formation (including type [73] and stability), etc. Although Sun [74] concluded that the adjustment to equilibrium conditions when face cutting should be quite rapid, in a work by Redford [34], the steady state temperature was reached after 25 seconds of conventional turning. It is then questionable how rapid the adjustment is, given that the speed is continuously increasing or decreasing. Therefore, none of the facing tests is a replacement to the Taylor test. Further, they are limited to some workpiece geometries, non-cold-drawn bars, and neither surface roughness nor crater wear, which is usually temperature dependent, can be used. Nevertheless, they can be utilized as short-term tests within a certain testing domain given that they have a good correlation with Taylor's results of this domain.

(2) Taper and Variable Rate Turning Tests

In order to overcome some of the facing tests disadvantages, Heginbotham and Pandey [75] developed a taper turning test that employs the same principle of the non-conventional facing tests, linear increase in cutting speed with time. Although the test requires preparing a tapered workpiece, it has the advantage over the facing tests in that through the proper choice of the taper angle, it is possible to control the required taper turning time between two desired cutting speed limits. Also, possible variations in work material properties across the taper are far less than that when facing between the outer and inner diameters. But, again, cold-drawn bars cannot be tested, and for small bar diameters, there will be a limitation on the taper angle range.

Other facing tests disadvantages that were also overcome include the assurance of the acting tool wear mechanism and the stability of a BUE type. A tool material that possesses a good crater wear resistance, but a reasonable flank wear rate was selected through pilot tests for the investigated work material. For each feed value, a cutting speed range in which a BUE type is constant was established. This was achieved through the analysis of the chip microsections (a quick tool withdraw device was used). In addition, special considerations were taken to achieve two identical replications on roughly the same diameters and lengths of traverse.

They determined Taylor's constants from taper turning at two different spindle speeds, but at the same taper angle (i.e., constant gradual speed increase). Their results indicated that pre-worn tools should be used to reduce the effects of the non-constant tool wear rate, which occur during the tool wear break-in period, on the obtained results. Based on their analysis of the results, they claimed that the taper turning characteristics seem to correspond with those of the steady state turning. Yet, they also mentioned that a further work is being carried on to investigate when the rate of increase in cutting speed will produce inaccurate results due to temperature lag or lead. Instead, they developed the Variable Rate Test [76] to eliminate the need for preparing the tapered workpiece and the possibility of radial variations in work material properties. The test utilizes the same principle, turning at gradual increase in speed, but requires a special drive system. The system must provide an accurate gradual increase in speed as soon as the cutting starts.

They estimated the consumed material and testing time for the conventional, taper and variable rate turning tests. The ratios are roughly 4 : 2 : 1 respectively, where their conventional testing required 270 lb (122.5 kg) and 3 hours and 23 minutes. These estimates are actually a good indication to the advantages of conventional turning over their developed tests. That is, in conventional turning; (1) there are not limitations for workpiece geometry, (2) a special drive system which can be a source of error is not needed, (3) the influence of temperature lag or lead, which is to date still unanswered, does not exist, (4) pilot tests that assure the type of tool wear mechanism and/or the stability of a BUE type are not needed, (5) any tool life criteria can be used, including surface roughness, and (6) the establishment of a threshold value at which the tools should be broken-in is not required. It might be noted here that perhaps current microprocessors which can aquire data in nano-seconds could be utilized to collect temperature and force measurements so that questions regarding temperature lag or lead, etc. can be answered.

Therefore, it can be concluded that these tests which employ a gradual increase/decrease in cutting speed have several disadvantages and limitations. Such tests are not, by any means, a replacement to the Taylor test. They cannot even be used as short-term tests without establishing a valid correlation with the Taylor test results of a given testing domain. In such an application, a conventional facing test could be very practical.

(3) Step Turning Tests

Because of the shortcomings in the above mentioned tests, step turning tests were developed. The basic idea is to represent the range of a gradual speed increase by discrete speeds. Poduraev and Yaroslavtsev [77] used two steps (i.e., information obtained from machining at two speeds would represent a range of those gradual speed increases), while Kiang and Barrow [78] proposed to increase the number of steps. Either way, Taylor's constants are determined from machining at two different speed ranges (i.e., two tests).

In Kiang and Barrow's experimental work, five steps were used to cover each speed range. Although the higher the number of steps, the better the approximation, it is not wise to engage and disengage the tool some 20 or 30 times within, say, 10 minutes of cutting. At each step, the cutting time should be long enough so that most of the time interval would represent a steady-state condition. They used a 2 minute time interval, and it was sufficient for their tool-work combinations as indicated by some temperature tests. The selected cutting speeds were high enough to avoid any BUE effects. The obtained results indicated that pre-worn tools must be used. Actually, all the above mentioned short-term tests should employ pre-worn tools. They are based on two assumptions; (1) flank wear versus time is in the gradual wear zone (i.e., constant tool wear rate), and (2) log T versus log v is linear. Any violation to these assumptions would produce inaccurate results. Again, only tool life criteria that are based on flank wear can be used. An infinite variable speed drive system would be needed to reduce the degree of computational calculations. They recommended the use of their test only in cases in which conventional tests are impossible (i.e., as a replacement). The test seems to have a great potential for checking incoming raw materials, once a correlation is established with a conventional turning test.

(4) Other Short-Term Taylor Type Tests

1- Sliding Wear Tests

The sliding wear tests provide sliding wear rates under conditions slightly similar to those in metal cutting [41]. The tool, in the form of a cylindrical specimen, is fed along a rotating workpiece, held in a lathe, with the desired feed and approach angle. Since tool wear depends on other tool geometry, the obtained rates are only a crude approximation to possible general trends.

2- Micro Wear Tests

These tests can be used to determine Taylor's constants from information on the flank wear rate at various cutting speeds [79]. However, special precautions are needed in preparing the tools so that micro flank wear increments can be measured within short durations. Furthermore, pre-worn tools must be utilized.

3- Softened (Degraded) Tool Tests

The basic idea of these tests revolves around hardness reduction of HSS tool materials so that high wear rates on the flank or face of the tool can be reached in short periods of time [80]. However, the choice of the hardness level to which the tool should be degraded and the maintenance of this level among tool replicates require special considerations. For example, any chance for tool failure due to deformation must be avoided.

4- Radioactive Tracer Tests

Radioactive elements are added to the composition of tool materials so that the tool flank and/or crater wear can be determined from the workpiece and/or chip radioactive contents ([81] to [83]). These tests are subject to several criticisms that are given in [84].

5- Shortened Conventional Tests

As soon as the gradual wear zone of a tool wear curve is established, linear regression analysis techniques are utilized to extrapolate tool wear values for a given tool life threshold value. This approach was used by Thomas and Lambert [85] and was based on the assumption that the linear part of the tool wear curve would remain linear for longer cutting periods. Unless this assumption is validated for a desired testing domain, the obtained results would have a 0.5 probability of being right. At low cutting speeds, there is a chance for an inflection to occur in the gradual wear rate zone (i.e., the zone is divided into two wear rates). This was observed by Kahng and Patterson [86] at low cutting speeds and feeds. At high cutting speeds, this linear zone can be very short and sometimes difficult to distinguish.

It might be noted here that the work of Thomas and Lambert was aimed at comparing two short-term tests (facing and taper turning) with a conventional turning test. Their shortened conventional test was extracted from the conventional one. They recommended a statistical procedure for the comparison, but it is similar to that used by Heginbotham and Pandey [75]. Either way, it is a questionable approach because it implies that the conventional test is a probabilistic case while the others are of the deterministic type. Assumed confidence limit lines were drawn parallel to the conventional turning v-T line. If the v-T line of a short-term test (without its own limits) was within these assumed confidence limit lines, the test was considered as accurate as the conventional one. Yet the v-T lines of the three tests had different slopes. If a regular regression analysis is used, the confidence limits will be in the form of curves. It is not known why they assumed the confidence limits to be lines, given that it is not a quality control procedure where lines are applicable. A better approach is to test the hypothesis of equal slopes given that the tests have equal variances.

6- Extrapolated Cutting Conditions Tests

These tests are similar to the previous ones in that extrapolation beyond the testing domain is utilized. The v-T curve is first determined at severe (heavy) cutting conditions, usually in terms of the speed, and then the desired speed for a longer tool life or visa versa is extrapolated. This implies that the v-T curve is assumed linear over the entire v-T space, which is not the general case but rather the exception. Further, tool wear mechanism or mechanisms are dependent on cutting conditions, especially the speed.

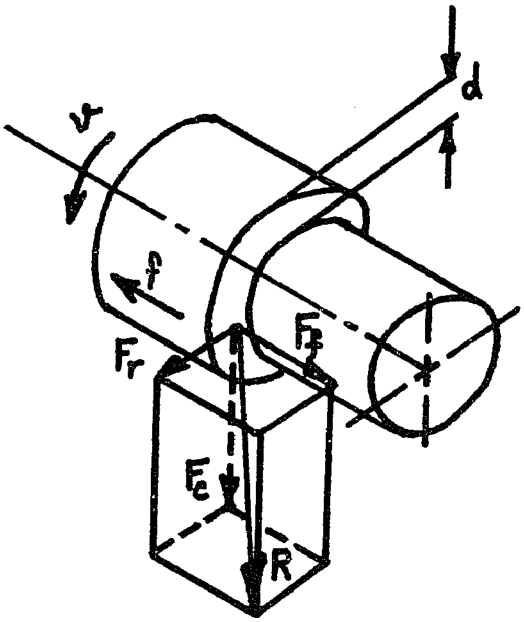
Another type of test that could fall under this group is the use of unconventional tool geometry to accelerate tool wear. For example, Wager and Barash [87] utilized a negative rake angle for an HSS tool material.

It might be mentioned here that some of the above mentioned tests are sometimes called accelerated (instead of short-term) tests. This can be a source of confusion. The tool wear can be accelerated by many methods, but not all of them are of the short-term type. For example, when dry cutting is utilized to avoid cutting fluid variations, the tool wear is accelerated. However, the degree of acceleration is not usually high to be considered as of the short-term type.

In conclusion, none of the above mentioned short-term tests is a replacement to the Taylor test. The Taylor procedure is based on certain assumptions (i.e., the v-T curve is linear) that must first be validated for the desired testing domain. Further, the acting tool wear mechanism(s) can only be investigated at conventional turning conditions. Without these validations, any short-term test would only provide a likely general trend that may or may not be true. Otherwise stated, they should not be used in isolation but rather in conjunction with Taylor's results of a given testing domain.

(A.2) Cutting Forces Tests

Cutting forces are measured in almost every machining study. In addition to their importance for the design of machine tools, cutting tools and fixtures, as well as for calculating many cutting parameters (i.e., required power, coefficient of friction and specific cutting energy), they can be used either directly or indirectly for machinability evaluation. Figures 2.3 and 2.4 show the resistance forces that must be overcome by the cutting tool during normal turning and orthogonal cutting respectively. In normal turning, the resultant force (R) is resolved into three components; cutting force (Fc), feed force (Ff) and radial force (Fr). In orthogonal cutting, it is resolved into two components; cutting force (Fc) and thrust force (Ft). Normally, Fc is the largest component and Fr is the smallest one. However, in some cases, Ff can be the largest component depending on tool-work combination, tool geometry and cutting conditions.



$$R^2 = Fc^2 + Ff^2 + Fr^2$$

$$Pm = Fc.v + Ff.v_f + Fr.v_r$$

$$MRR = v . f . d$$

$$Us = Pm / MRR = Fc / f.d$$

Fig. 2.3 Typical Normal Turning Forces

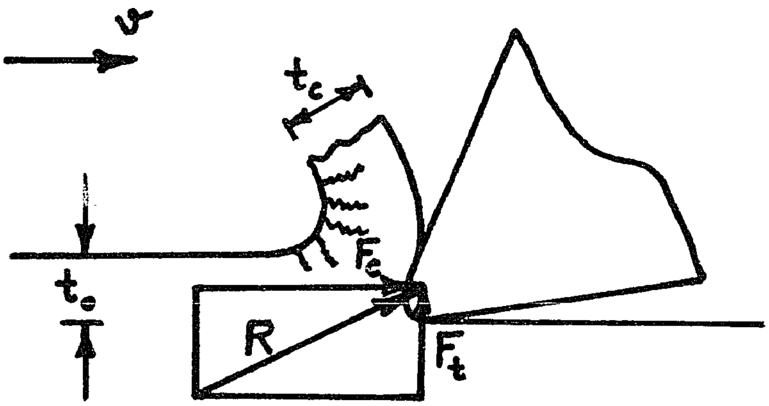


Fig. 2.4 Typical Orthogonal Cutting Forces

It might be noted here that the power consumed in machining depends only on the cutting force and cutting speed (i.e., Pm = Fc.v). That is, there is not any tool travel in the radial or thrust directions (i.e., $v_r = 0$, and $v_t = 0$). Also, the power required to accomplish the feed motion is very small (the speed of the tool travel in the feed direction is very small in comparison to the cutting speed), and can be safely disregarded. The metal removal rate (MRR) is the product of speed, feed and depth of cut. The specific cutting energy (Us) is the ratio of consumed machining power to metal removal rate, or the cutting force per cross-sectional area of the uncut chip. Both metal removal rate and required power are proportional to cutting speed, while the specific cutting energy is independent of speed. When orthognal cutting, the coefficient of friction can be determined from the measurements of cutting and thrust forces.

Fersing and Smith [88] indicated that the feed force increases faster than the cutting force with tool wear. This was also observed by De Filippi [89]. And in a work by Colwell, Mazur and DeVries [90], the feed force was a better indicator of the beginning of the accelerated tool wear region than the cutting force. Otherwise stated, the feed force is more sensitive to variations in the machining process than the cutting force. Perhaps due to that and the small magnitude of the radial force, the majority of cutting forces tests are based on the feed force.

Cutting forces tests can be classified into two main groups; conventional and non-conventional. The first group would include all of these tests that directly utilize the cutting forces measured on a conventional set-up in their analyses. The second group would include those tests that require an unconventional set-up and utilize either directly or indirectly the measured forces in their analyses (i.e., turning at constant feed force tests).

(1) Conventional Cutting Forces Tests

Fersing and Smith [88] employed the feed force in their study on tool life and wear of cutting tools. Mayer and Stauffer [91] utilized the resultant force and its three components (where the measurements were taken at the start and end of a given tool life criterion) along with measurements of surface roughness, in their analysis of different tool geometries. Measurements at the start or end of a tool life usually mean that a new (reground) or worn tool is used and cutting proceeds only for the few seconds required to record the force measurements. However, the above studies overlook a simple fact. Despite the high rigidity and sensitivity of current dynamometers, they are less rigid than a standard tool post. Their utilization in any setup decreases the system rigidity, and, thus, the results obtained on tool life and wear, surface roughness, etc. are less reliable. A better approach is the one used by Schmidt, Ham and Wilson [61] where the tool forces were measured in separate tests than those that were aimed at other indicators (i.e., tool wear and surface roughness).

Loria and Walker [92] investigated whether force and temperature measurements can be a rapid guide to tool life evaluation and, thus, machinability. Four cast irons that were previously tested by a tool life test were utilized for a force and temperature test. The amount of metal removed for a certain flank wear value was the indicator in the tool life test. Both cutting and feed forces as well as the average cutting temperature obtained by the thermocouple technique were the indicators in the force and temperature test. Based on their results, they concluded that the four indicators give same ranking. Boulger [18] applied the constant feed force test (described in detail on page 48) on these same materials. Although he obtained similar ranking, he concluded that the ranking of the materials by the different indicators differ quantitatively. For example, cutting temperature measurements showed the smallest spread while tool life values gave the largest range. However, these results were determined under non-conventional face cutting (i.e., non-constant cutting speed). Further, there are no indications to the number of replications, and a sample size of four materials is too small for a valid correlation. Nevertheless, examination of these results indicates that the ranking of the four cast irons based on the feed force differed quantitatively from that of the cutting force, but was in agreement with that based on the tool life indicator. Perhaps this is an indication of the better accuracy of the feed force over that of the cutting force in ranking materials.

Because of the small magnitude of the radial force, Murphy and Aylward [2] omitted it from their analysis. For different feeds, the cutting and feed forces were measured at the beginning of the tool life. They mentioned that from the plot of cutting or feed force versus feed, an indicator based on the feed which produced a desired cutting/ feed force value, or visa versa (cutting/feed force obtained at a certain feed) can be used in machinability evaluation. The higher the feed value for a desired force level or the lower the force value for a given feed, the better the machinability. Without any justification, the feed which produced a desired feed force value was chosen as an indicator to the machinability of steel in their comparison with commercial performance ratings (i.e., PPT results). Examination of their results indicates that the feed force data show better spread among the materials than those of the cutting force. Perhaps because of that, they selected that indicator. Based on their results, they concluded that the cutting forces test does not correlate well with the PPT. This same conclusion was reached by Troup [93] using a similar procedure. Troup also utilized what he called a modified force test, where a form tool was used instead of a single-point turning tool. Although his setup was on a screw machine, it can be done on a lathe. The indicator of the modified force test was the consumed machining power calculated from the cutting force measurements. Again, the results did not correlate well with commercial ratings. It might be mentioned here that a direct method of measuring the required power is with the aid of a wattmeter. Further, the underlying objective of the above investigators' work was to prove that results obtained from Taylor or cutting forces tests do not correlate well with commercial performance ratings.

De Filippi [89] proposed two testing procedures that depend on feed force measurements. When testing for the machinability level among batches of same material, he suggested keeping the cutting conditions constant and to use the percent increase in the feed force within two minutes of cutting as an indicator. However, the cutting speed must be selected so that this increase is at least 30 %. He stated that when the increases are somewhat below 30 %, the method is no longer reliable. He ran preliminary tests on various batches of three materials to determine the particular cutting speed that would provide at least 30 % feed force increases for each material batch. Even with that condition, the correlations obtained between this method's results and the speed for a 30 - minute tool life existed only for two materials and were as follows: - 0.63 and - 0.64. In addition to determining the mean values of the machinability level among batches, one should check whether their corresponding variances are constant or not. The machinability level can vary from one batch to another in terms of its mean and/or variance value. For evaluating the machinability of different materials, he proposed to use the speed that provides exactly 30 % increase in the feed force as an indicator. However, in this case, trial and error attempts would be required. No experimental results to the latter procedure's validity were given.

Shaw, Smith, Loewen, and Cook [94] investigated the influence of lead on forces and temperature. The tool-face friction force, specific cutting energy, and the tool-face temperature (obtained from high speed flash pictures) were the indicators. Although their results were determined under orthogonal cutting and had not been correlated with normal turning, the problem of sources of errors was addressed. For example, before utilizing the re-sharpened HSS tools, they were tested to insure they give results close to the mean of the batch. They also advised to use pre-worn tools to avoid possible errors during the tool break-in period, and to start recording once the forces and temperature reach the equilibrium/steady-state condition. A cut of half inch (12.5 mm) was enough in their work. Based on additional results, they concluded that tool life prediction can not be estimated directly from the above mentioned indicators.

Other investigators ([47] & [95]) limited their comparisons of work materials to plots showing the tool forces obtained versus speed. In one study [47], the cutting and feed forces first decreased and then increased as the speed increased. In another study [95], the cutting force continued decreasing while the feed and radial forces first increased and then decreased as the speed increased. Therefore, a general trend to the effect of speed on cutting forces does not exist.

(2) Non-conventional Cutting Forces Tests

Non-conventional cutting forces tests are those that require a special setup to provide a constant feed force or to measure tool forces under gradual speed increase. Machining at constant feed force (load or pressure) is one of the most important concepts in the machinability evaluation of work materials. When machining at constant feed force, the work material becomes the dominant factor to the outcome of the cutting process. This is in terms of the amount of metal removed per unit of time ([96] & [97]), resulted feed rate ([18] & [92]), etc. The notion is, for example, that the heavier the feed rate obtained, the better the machinability.

Boulger, Shaw and Johnson [18], in their study on the machinability of free-cutting steels, used the number of spindle revolutions per 2-inch (50.8 mm) cut as an equivalent to the obtained feed rate when machining at constant pressure. A machinability index, defined as the ratio of the average results obtained for a standard reference material to that of a given steel, was then calculated for each material tested. The HSS tools utilized were ground to a certain geometry (both back rake and side cutting edge angles were equal to zero) because it was easy to reproduce and gave a satisfactory useful life. Also, some of their preliminary results pointed to the insignificance of the back rake angle on materials ranking. The tools were honed and broken-in before being utilized, to achieve uniform performance and to avoid erratic readings in the first few cuts. After each tool had been used in cutting around 4 ft (1.22 m) of steel, it was lightly reground with precautions taken to avoid overheating. Using one tool, a group of materials was tested in a series, sequence of tests, that also included three tests on the standard material. The order of testing varied from one series to another to compensate for tool wear, and each material was included in six series (i.e., six replications) in order to minimize possible variations among tools. The tests were either conventional turning or facing depending on the materials' diameters. This was perhaps to achieve a good utilization of the work materials. The conventional turning tests were first employed. The facing tests were then applied on the remainder from the first tests. The depth of cut utilized in the facing tests was larger than that of the conventional tests. No explanation was given on why the depth of cut was different among the two types of operations. Further, for some of the results reported, the type of operation was clearly stated. The other results were given without any indication to the operation type nor to the degree of mix between these two operations' results.

Their results indicated that high speeds and heavy loads caused large changes in chip and cutting temperature during testing. The spread among the materials was best at low speeds. The machinability indicies were independent of both hardness and pressure. Some of their results correlated well with data based on the speed for a 60 - minute tool life, while others gave a poor correlation with those based on the commercial performance ratings. They claimed that some of the lots (batches) were not sufficiently uniform (i.e., variations within batches were high). It might be noted here that any machinability index should not be based on mean values only. Some consideration should be given to their variances which are a reflection of the data variability.

Others [98] developed a short-term test that depends on cutting force measurements while turning at increasing speed. Briefly, when the cutting force had reached a certain constant value upon tool contact, it activated a gradual speed increase circuit. Both cutting force and angular speed (RPM) were recorded versus time. When the cutting force doubled that intial constant value, the cutting was stopped. This was an indication to total tool failure. Preliminary tests were run on a stainless steel material using a selected tool geometry (zero back rake angle) on an HSS tool material. Among the three indicators (time and distance traveled to tool failure, and cutting speed calculated from the angular failure speed) that were subject to investigation, the cutting speed at tool failure gave the least dispersion and was independent of the initial cutting speed. Other preliminary results indicated that the dispersion of the results was independent of feed, but increased with a larger depth of cut. The speed at tool failure increased with an increase in the rate of the gradual speed increase, and decreased with an increase in workpiece diameter. This was thought to arise from thermal effects. Although other tool geometries were investigated, they gave irregular force increase at tool failure. The results obtained with that particular tool geometry correlated well with those based on the speed for a 60 - minute tool life.

In conclusion, none of the above mentioned cutting forces tests has shown excellent correlation with commercial ratings. Even so, they cannot be used in isolation as indicators to the machining quality. The feed force seems more sensitive than the cutting force to variations during machining and among materials. The main drawback to the non-conventional cutting forces tests is the very special setup required. Such setups are not even available in most laboratories. It might be mentioned here that one of the short term tests developed in this study, called the Cutting Forces Test (CFT), is a conventional cutting forces test. The test was primarily developed to justify the mentioned conclusions that cutting forces tests do not correlate well with the PPT (or commercial performance ratings). It also addressed the sensitivity of the resultant force components (cutting, feed and radial foeces) in differentiating among the machinability of different work materials. The results indicate that the feed force is the most sensitive component to variations among the machinability of work materials. This is followed by the radial force. The cutting force component is the least reliable indicator to the machinability of work materials. In addition, the feed force results correlate well with the PPT results, contrary to the above reported conclusions.

(A-3) Cutting Temperature Tests

The mechanical energy required for metal cutting is converted into heat as the tool shears its way through the workpiece. The main heat sources are the shear and tool-chip interface zones. Since the cutting tool edge is buried in the workpiece, controlling the cutting temperature through cutting fluid application has little success. The majority of the heat generated is dissipated into the chips. The remainder is dispersed into the cutting tool and workpiece.

Because of the strong relationship between tool wear mechanisms, especially the thermally activated ones (e.g., mass diffusion), and the tool-chip interface temperature, many attempts have been made to measure it. Unfortunately, all direct methods, such as radiation pyrometers, temperature sensitive paints, or embedded thermocouples, measure the average temperature rise in the vicinity of the interface rather than the actual temperature at the interface ([10] & [34]). For this reason, the tool-work thermocouple technique, which is the easiest to employ and measures the average cutting temperature, is the commonly used direct method.

As mentioned earlier, on page 44, Loria and Walker [92] utilized a force and temperature test to evaluate the reliability of different machinability indicators on four cast irons. The main drawback to their work is that their results were determined under non-conventional face cutting (i.e., variable cutting speed). The cutting temperature is directly dependent on the cutting speed. Further, the conversion process of mechanical energy into heat requires time. In a work by Redford [34], the steady state temperature was reached after 25 seconds of cutting. In another work by Mills and Akhtar [41], 20 seconds of cutting was required to reach the steady-state condition.

Kane and Groover [99] investigated whether the cutting temperature is a more consistent and reliable measure of the machinability of steel than tool wear or surface roughness. Nine grades of steel that ranged from easy-to-machine to difficult-to-machine were utilized in their study. Among the three machinability indicators, rankings based on cutting temperature results were the least influenced by changes in cutting conditions. Their results were compared against commercial ranking as well as ranking based on ratings from the ASME manual on cutting of metals [100]. Unexpectedly, the industrial ratings have shown a poor correlation (0.34) with the ASME ratings. Meanwhile, ratings based on cutting temperature have correlated well, 0.86, with both commercial and ASME ratings. They were also in better agreement with these ranking sources than those based on tool wear and surface roughness. The only drawback to Kane and Groover's work is the time required to accurately calibrate each combination of tool and work material.

Redford [34] investigated the reliability of the cutting forces and temperature as indicators for on-line tool wear assessment. Preliminary tests were run to ensure that there was no BUE formation. The cutting forces showed more scatter, particularly at larger flank wear lands, than the cutting temperature. The rate of temperature change with flank wear changes was independent of cutting conditions, speed, feed and depth of cut.

The utilization of the cutting temperature alone as an indicator to the machinability of work materials or as a simple sensor for adaptive controls can be misleading ([94] & [101]). The presence of BUE during cutting lowers the cutting temperature reliability. Nevertheless, the average cutting temperature measured by the thermocouple technique can be a reliable indicator to the machinability of work materials if, and only if, the following considerations are met;

(1) all junctions in the system except the tool-work interface are

secured,

(2) each combination of tool and work material is accurately calibrated,

(3) cutting is performed in the absence of BUE,

(4) cutting is continued until the steady-state temperature is reached, and

(5) a valid correlation between the cutting temperature and, say, commercial ranking is first established for the desired testing domain (extrapolation outside this domain should be avoided).

One of the questions that was raised during the initial stage of this study was: why cutting forces, which are the main sources of the heat generated, do not correlate well with commercial ratings while the cutting temperature does? Perhaps this can be attributed to the high scatter in the cutting forces readings. This was indirectly indicated in Redford's work [34] where cutting forces readings gave more scatter than cutting temperature readings when the tool was worn. If this scatter is the only reason for not having a correlation between the cutting forces and commercial ratings, it can be overcome by a good experimental design. Several advantages can be realized; (1) the setup of cutting forces tests is easier than that of the cutting temperature ones, and (2) the machining time required for the cutting forces to reach the steady-state condition is less than that needed for the cutting temperature. That is, the conversion of mechanical energy into heat which raises the cutting temperature takes time.

(A-4) Other Lathe Machine Tests

Other lathe machine tests would include those of the orthogonal-cutting type, double tool, and go no-go feed ones. The literature contains many orthogonal-cutting type tests ([22], [45], [52], [54], [87], [94], & [102] to [104]). There are advantages as well as disadvantages to orthogonal cutting. The advantages can be summarized in that orthogonal cutting provides a better control over the input factors than normal machining. The mechanics of the metal cutting process is simpler. Some indicators can be only estimated with orthogonal cutting, such as the coefficient of friction. The main disadvantage is that the results obtained are limited to this testing domain, which is rarely found in manufacturing shops. Conclusions drawn should not be generalized unless a correlation between orthogonal and actual machining is first established. Normally, to achieve orthogonality on a lathe machine, some workpiece preparations or certain workpiece geometries would be required.

Double tool tests are based on the same principles of the tool-chip thermocouple technique [106]. Two cutting tools of different compositions, connected to an electro-motive-force (emf) measuring device, simultaneously, machine the work material. The cutting speed is increased until an e.m.f. of 8.5 mV which corresponds to some initial calibration is recorded. The idea of this type of testing was originally suggested by Reichel in the 1930's [105]. The main drawback to these tests is that they are based on the wrong hypothesis of identical temperature in the two cutting zones [89].

The machinability group of LaSalle Steel Company developed a test which can be called a go no-go feed test ([107] to [109]). In order to save material while testing for the machinability level in daily production, they recommended to use the test as an integral part of preparing a tension test specimen. The test requires establishing two threshhold-feed values for each material. The go feed value is the one at which the tool does not fail catastrophically. The no-go feed value is the one at which catastrophic tool failure occurs. For example, for a given material lot, the go and no-go feed values were 0.0024 ipr (0.0610 mm/r) and 0.0025 ipr (0.0635 mm/r) respectively. These values were determined by machining on a CNC machine and under constant cutting conditions, while incrementing the feed value by a 0.0001 ipr (0.00254 mm/r) from one cut to another. For 31 heats, a 0.735 correlation value was found between the maximum go feed and the twenty minute tool life (V20). However, there are some conflicting issues. The go no-go feed values should have confidence intervals that reflect variations between lots. Further, the go feed value was considered the desired norm although it was determined from past lots. The machinability of various batches of a material can be assumed to have a normal distribution with two parameters, mean and variance Also, variations from one lot to another can be in terms of means (machinability levels) and/or variances (homogeneities). The true mean and variance of a material (norms) should be the ones for which the material was originally designed. Any quality control test should, then, be capable of identifying any mean and/or variance deviation from these norms. Also, the cost of using a CNC machine should be weighed versus the other alternatives, such as the Power Hacksaw Test.

Finally, the concept of the cutting rate-tool life function was developed on a lathe machine equipped with a circular saw attachment [38]. Briefly, the function would provide a tradeoff between the metal removal rate and tool life, if, and only if, either the material removal rate, tool life or both are at least second order or nonlinear functions in the log transformed cutting variable space.

From the above mentioned lathe machine tests, the following conclusions can be drawn:

(1) None of the short-term Taylor-type tests is a replacement for the Taylor test. The Taylor procedure is based on certain assumptions that must first be validated for the desired testing domain.

(2) The ISO test, which is a standardized Taylor test, is the only internationally accepted testing procedure. Still, it is not widely used and considered a long-term test.

(3) None of the cutting forces tests examined has shown good correlation with commercial ratings. Even so, they cannot be used in isolation as indicators to the machining quality.

(4) The cutting temperature, measured by the thermocouple technique, has shown good correlation with commercial ratings. However, the testing procedure requirements, especially the calibration process, could disqualify it from being a short-term machinability assurance method.

(B) Drilling Machine Tests

Drilling machine tests can be classified into two main groups, conventional and non-conventional. The conventional type would include those tests that drill under constant feed rate. The non-conventional tests, usually called penetration tests, are the ones that require drilling under constant feed force (or load). The majority of the drilling machine tests are of the non-conventional (penetration) type.

(B-1) Non-conventional (Penetration) Drilling Machine Tests

Non-conventional drilling tests can be dated as far back as 1900 when Keep introduced a penetration test [115]. Kessner [14] used the drilling depth obtained by 100 revolutions of the tool as an indicator to the machinability of brass. He claimed that the test can detect the hard spots in a material. One of the four tests that were applied by Boston [5] on eighteen ferrous metals and twenty-one non-ferrous metals was a penetration test. His drilling indicator was the same as of Kessner. He used one drill on all metals in order to avoid the difficulties encountered in regrinding a drill with exact angles. After all tests were completed, he ran many duplicate tests to check the influence of the dulling of the drill on the results. Cook and Davis [17], in their study on the machinability of free-turning brass, employed a different indicator. They fixed the drilling time to 15 seconds. The ratio of the hole depth obtained to that obtained on a standard material was the machinability indicator. However, in selecting the time interval, they advised that the drill should penetrate to a depth of at least one inch (25.4 mm) into the standard material. They also used one drill on all materials, but frequent tests were run on the standard material to check the influence of the dulling of the drill on the results. Crampton [110], in his study on the machinability of copper alloys, used the time required to penetrate 1 inch (25.4 mm) as an indicator. He also measured the torque while drilling under constant feed force. His torque results indicated that the rate of torque increase varied inversely with the time required for penetration. He, thus, advised that the results obtained from short-term tests, such as the penetration test, should be interpreted and applied with judgement since they may not tell the complete story about machinability.

Schmidt, Gilbert and Boston [111] revised the penetration test in order to overcome the regrinding problems. They used a special single-point tool that could be reground accurately. The tool bit was rotated in a spindle under constant load while cutting a stationary tubular test bar. They mentioned that their setup is similar, but simpler, than the one used by Herbert in 1914 to measure tool wear. However, they concluded that the revised penetration test had several possibilities of error. For example, they questioned whether the feed remained positive during testing. It might be mentioned here that the main objective of their paper was to compare the horsepower obtained by a calorimetric method with that determined from measurements of torque and thrust under conventional (constant feed rate) drilling.

In Dagnell's penetration tests ([112] & [113]), a special flat drill was used to drill in a pre-drilled (tubular) specimen. This was to eliminate the chisel edge effects. The hole depth was divided into equal distances, and air was blown in from below to remove the chips. The time required to drill each unit length, a reflection of the penetration speed (or feed rate), was recorded. The feed rate (inverse of time per unit length) decreased as the drill wear increased. Wear diagrams were constructed from the plot of time per unit length versus unit length number. These so called wear diagrams were, then, used as indicators to the machinability of some ferrous and non-ferrous metals. The ranking of the materials was independent of cutting speed, and the data scatter was less for small drill diameters. The results were compared with other results determined from turning and milling tests. The turning test indicator was the speed for a 30 - minute tool life, and the milling test indicator was the volume of material removed for a given flank wear value. He claimed that the drilling test had shown the greatest selectivity.

Lindgren [114] investigated Dagnell's test. Measurements of force and torque were taken on Dagnell's setup. Based on the results obtained, several revisions were required. For example, the method of applying the constant feed force had to be changed. Other setup alterations included the use of a cutting fluid, instead of air, to obtain less scatter in the results. Even so, he mentioned that accurate knowledge of the magnitudes of the feed force and cutting speed and knowing that their variations remain within reasonable limits is a must. For example, if large variations were observed for a test run, this test point was rejected. Other modifications included the machinability indicator. A machinability number was evaluated by first plotting the inverse of feed versus drilling time on a log-log paper. From the plot, the inversed feed for a given drilling time, which could correspond to a certain material removal rate (or tool life criterion), was considered the indicator. Lindgren claimed that after all these modifications, the testing procedure can now be applied for the investigation of work materials and tool materials. However, he also stated that the main drawback is the low obtainable feed rate. When the feed force was increased to increase the feed rate, the drill gave torsional vibrations. A year later [115], he used a spade drill and claimed that the test can, also, be used for the investigation of cutting fluids. However, the usage of tool wear while drilling under constant feed force as an indicator is questionable. For example, how would one assure that the wear mechanism under such a testing condition would be the same in actual machining ? In summary, the main drawback to the non-conventional (penetration) drilling machine tests is the special setup required to provide a constant feed force in drilling.

(B-2) Conventional Drilling Machine Tests

In conventional drilling operations, the criteria commonly used for machinability evaluation are the number of drilled holes to total failure of the drill tip, drill wearland, and the resultant drill thrust and torque. Other indicators include the surface roughness, reduction of hole diameter, and burr height ([116] & [117]).

De Chiffre [116] developed a testing procedure for evaluating the overall performance of cutting fluids. Four subsequential operations; drilling, boring, reaming and tapping, that form a machining cycle were utilized. The number of drilled holes to total drill failure was the drilling indicator. The reduction in hole diameter was the indicator for both boring and reaming operations. A go no-go gauge was utilized for the tapping process. Measurements of thrust and torque, and the resultant surface roughness were also taken during testing. From the results obtained, he concluded that the ranking of cutting fluids is strongly dependent on the type of operation as well as the performance indicator. Others [36], in their evaluation of the stability of the coefficient of variation, utilized the number of drilled holes obtained for a given drill wearland value as a tool life indicator. Siemonsen [117] investigated the machinability of extruded aluminum alloys under deep-hole drilling. The chip size was the primary indicator. Second indicators included the hole size, burr height and surface finish. Response surface contours were developed for these indicators.

In conclusion, conventional drilling machine tests are of the long-term type. Although non-conventional drilling machine tests (penetration tests) are of the short-term type, they require a special setup to provide a constant feed force (load) in drilling. Even so, they should not be used in isolation as indicators of the machining quality of work materials. A valid correlation between their results and actual machining results of a desired testing domain is a must.

(C) Milling Machine Tests

Milling methods are of two basic types, peripheral (slab) and face milling. In slab milling, the periphery of the cutter is used to generate surfaces parallel to the cutter axis. In face milling, the face and the periphery of the cutter are used to generate surfaces at right angles to the cutter axis. End mills have an end face and a periphery, and are usually used for cutting pockets or slots (slotting operation). When they are not used to cut slots (full immersion), the operation is called peripheral end milling (e.g., half immersion).

In milling machine tests, the criteria commonly used for machinability evaluation are the cutter life (in minutes or inches cut for a given wear value on the clearance face) and surface roughness. Other indicators include the cutting forces obtained.

One of the examples that Friedman and Zlatin [36] gave in their study on the variability of tool life as a function of its mean value was a peripheral end milling (half immersion) test. Other examples included turning, drilling, and tapping. An HSS M-2 end mill of 1 inch (25.4 mm) diameter was utilized on a stainless steel material. The tool life criterion was based on a desired flank wear value and was given in inches. Their examples showed larger variances for the regions of short tool life. They, hence, advised that in building predicting equations like the Taylor equation, which includes data in the range of short tool life, special precaution should be given to the assurance of constant variance.

Tipnis and Friedman [119] applied the concept of the cutting rate-tool life (R-T) characteristic function, described in [38], on a peripheral end milling operation. An HSS M2 end mill of 1 inch (25.4 mm) diameter was used on 12-in. (305 mm) blocks of AISI 4340. Their tests were run at different combinations of speed and feed, while other variables were held constant. The end mill life was based on a desired flank wear criterion. From the results, a multiple regression model was found using a stepwise procedure. The partial differentials of this model with respect to speed and feed rate were set equal to similar differentials applied to the logarithmic transformation of the material removal rate equation. From that, the equation of the R-T curve was determined. Figure 2.5 shows the R-T characteristic curve obtained for their peripheral end milling operation. From figure 2.5 it can be noticed that any slight variation in the material removal rate could result in drastic tool life reduction. This was also observed during the preliminary tests of the End Milling- Slotting Test (EMST).

Tipnis and Christopher [120] reported several case studies, three of them were on end milling operations, that were performed at Metcut Research Associates Inc. In one case study, the performance of brazed carbide end mills was compared to those of HSS material based on a tool life criterion. In another case study, the effect of cutting fluids on high cycle fatigue and other mechanical properties of end milled and ground specimens of an aerospace alloy was examined. The last case study addressed the selection of machining conditions for adaptive control end milling operations. A cutting force sensor system was used.

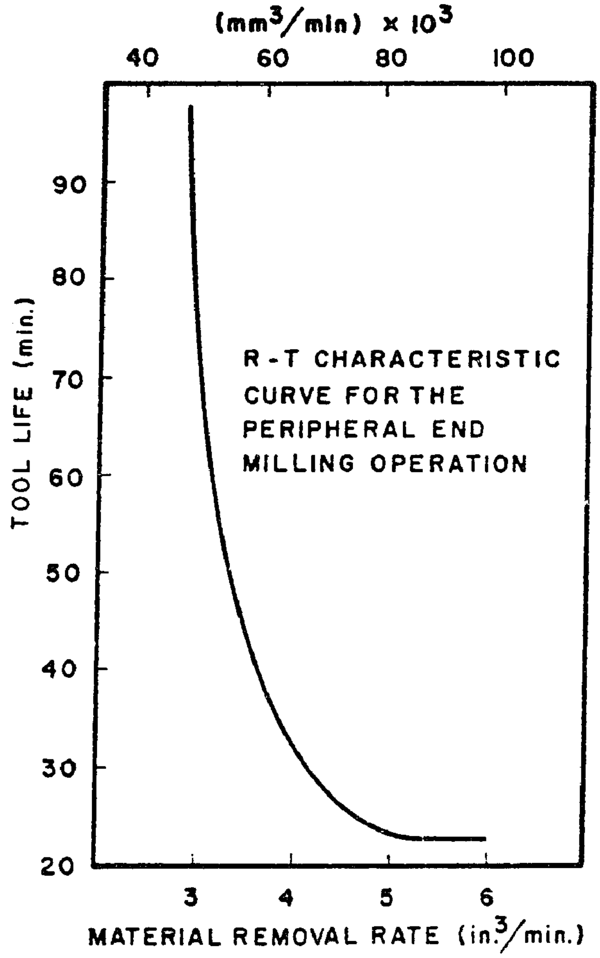


Fig. 2.5 Cutting Rate-Tool Life Characteristic Curve in R-T Domain For A Peripheral End Milling Operation [119, p. 489]

Wijenayake [121] investigated the performance of different coated end mills, in terms of the wearland of cutters, cutting forces obtained, and the quality of machined surfaces. Seven solid film lubricants (coatings) were evaluated on three work materials. The coated end mills were tested under a constant cutting condition, which was previously selected to yield a tool life of 30 to 90 minutes. Although earlier laboratory tests had shown the coated end mills to have better lives than the uncoated ones, under production environment, there were no significant differences in performance.

In a study by Yellowley and Barrow [64], the influence of thermal cycling on tool life in peripheral end milling was examined. They mentioned that for some combinations of tool and work materials, the feed/tooth had shown no influence on tool life and, thus, the varying undeformed chip thickness could be ignored. Under these conditions, any variation in tool life could only be related to mechanical or thermal effects, or a combination of both. They also mentioned that previous opinions on these two effects are divided. German investigators consider the entry conditions all important, while Japanese and Russian workers emphasize the thermal effects. For this reason, they utilized an end milling process where entry and exit conditions could be kept constant. An HSS M-2 end mill of 1 inch (25.4 mm) diameter was used in peripheral end milling with half immersion. However, their preliminary tests addressed the effect of the mode of milling (up and down milling), and the differences between peripheral and slotting operations in terms of thermal effects. Both milling operations did not show any significant differences due to the milling mode, but the slotting operation had shown considerable increase in tool life over the peripheral milling process. This was attributed to the thermal effects. From their analysis of the peripheral end milling results, a thermal fatigue parameter was developed to characterize the influence of the thermal cycling at constant peripheral speed on tool life.

Others [106] utilized a milling test to simulate gear cutting. An HSS milling cutter of 16 - teeth was employed to cut gear teeth on flat surfaces of billets from four different casehardening steels. Some savings in work material consumption was achieved through the utilization of another face cutter to remove the machined teeth so that the test can be continued on a new surface on the same billet. The number of machined teeth (or cutting time) for a given tool life criterion was the machinability indicator.

Okusa, Kitagawa, and Akasawa [118] developed what they called a short-term face milling test. A face mill of 10 inch (254 mm) in diameter was utilized in face milling cylindrical workpieces of plain carbon and low alloy steels. The tool life criterion was based on a desired flank wear value. The constants of Taylor's tool-life equation were determined using this method and two other methods. These were turning of cylindrical specimens and face milling of rectangular workpieces. The last two tests were called standard cutting tests. The tool life results for a given material varied between turning and milling. They, hence, concluded that this variation is an indication that a material could have a different performance under different processes. However, this is an unrealistic conclusion since it is based on one material only. This difference in performance could be due to the fact that turning is of the continuous cutting type while milling is of the interrupted one. They claimed that their short-term method can determine the Taylor's v-T curve with less material removed than the standard milling test. Examination of their results indicate that the slopes of the v-T lines of the two tests are different enough to give a large difference between the values of the C constant. No valid statistical analysis was utilized. Also, the entry and exit conditions of milling cylidrical and rectangular workpieces are different enough to result in different tool failure modes.

In conclusion, none of the above mentioned milling machine tests is of the short-term type, in terms of required testing time and/or material consumption. Further, the majority of these tests are of the Taylor's type where a tool life criterion based on a certain flank wear value is utilized. In addition, the end milling-slotting operation has never been utilized for evaluating the machinability of work materials. It might be mentioned here that one of the short-term tests developed in this study, an End Milling-Slotting Test, utilizes a slotting operation. Briefly, the width of the machined slots was measured over twenty minutes of cutting. Three replications were taken on each material. For each replication, the rate of the slot width variation (an indicator to dimensional stability) was determined using simple linear regression.

Although the required testing time would seem as long as that of the Taylor test, the test is still regarded as a short-term test. The material consumption is far smaller than that required for an equivalent Taylor test. This was achieved through machining four slots on the work materials' bars, one inch (25.4 mm) in diameter and four inches (102 mm) long. Several advantages were realized from using the dimensional stability of the machined slots instead of the tool wear rate. For example, materials with a high tendency to BUE formation were easily identified. Other advantages along with the results obtained are given in Chapter 5.

(D) Sawing Machine Tests

Sawing machines are of three types; (1) power hacksawing, (2) band sawing, and (3) circular sawing. They can be further classified based on the feeding mechanism into; (1) Constant Feed Rate (CFR), and (2) Constant Feed Force (CFF), or Constant Pressure.

As mentioned earlier, on page 57, the concept of the cutting rate-tool life function was developed on a lathe machine equipped with a circular saw attachment [38]. Simply stated, the function provides a tradeoff between the metal removal rate and tool life. The circular sawing test was based on cutting-off slugs 0.125 inch (3.175 mm) apart from a 1.5 inch (38.1 mm) diameter steel tube under different feeds and speeds. The slugs were sawed until total saw failure. However, this concept is only valid when the material removal rate, tool life, or both are at least second order or nonlinear functions in the log transformed cutting variable space. Other circular saw tests were mentioned in reference [122].

Colwell and McKee [123] investigated the capability of a band sawing machine in cutting-off titanium materials and its alloys. Their preliminary results indicated that neither hand nor dead-weight (CFF) feeding mechanisms were capable of sawing titanium alloys. A positive displacement feeding mechanism (provides a CFR) was, hence, employed. The workpieces were machined to certain dimensions prior to sawing. This was to achieve constant thicknesses and to remove surface oxides. Cutting forces were continuously recorded under different feeds and speeds. The saw life was based on the cutting time required for the feed force to reach an arbitrary value. From the sawing results and other turning results, they concluded that the relative machinability of the work materials studied was about the same for band sawing as it was for turning. Other investigators [124] developed relationships between the wear rate of different bandsaw blades and relevant sawing parameters, such as speed, machine load and workpiece geometry. The tests were performed on a certain material, which is frequently used by English manufacturers of bandsaw blades in their quality control wear tests. It might be mentioned here that Thompson and Sarwar [122] stated that for large sections of difficult-to-machine metals, power hacksawing was quicker and cheaper than band sawing.

The feeding mechanisms employed in power hacksawing machines are of the CFF type except for the positive displacement (CFR) ones, which are not commonly used ([122] & [125]). Boston and Kraus [126] investigated the performance of eleven cutting fluids when power hacksawing eight metals. The bars were machined to a section 1 1/2 inches (38.1 mm) square. A medium feed pressure and a speed of 120 strokes per minute were held constant during all tests. The time required to saw a 0.125 inch (3.2 mm) thick slice from the bars was the indicator. They, however, ran preliminary tests, dulling tests. The performance of three cutting fluids was investigated on one material using tungsten- and high-speed- steel hacksaw blades. A new hacksaw blade was assigned for each cutting fluid, and seventy slices were sawed. From the results, they concluded that a cutting fluid giving a short sawing time with a new saw blade does not necessarily continue to give relatively short times after the saw has become dull. For their comparison tests, a new HSS hacksaw blade was assigned to each cutting fluid. For each cutting fluid, three series of cuts were taken on the eight metals (one after the other). The sequence of the materials in the second series was in reverse order to the first and third ones. This was to obtain three replications while minimizing the effect of the blade wear rate on the obtained results. The performance of the cutting fluids was evaluated based on the averages of these three replications. However, it is questionable whether the effect of the blade wear rate on the results had been reduced using these three series of cuts. The results of the first series were far smaller than those of the second and third ones. Further, the findings from the dulling tests seem to contradict the design of the experiment for the comparison tests. Also, no valid statistical analysis was utilized.

Cook and Davis [17], in their investigation of the free-turning brass machinability, utilized a power hacksawing test. A HSS hacksaw blade was utilized in sawing eight materials. The number of strokes required to cut through one inch (25.4 mm) diameter bars was the indicator. Six replications were taken on each material. Frequent checks were made on a standard material to insure that the blade wear rate did not influence the results. The averages of these replications were compared with other results obtained from a penetration test (described on page 58). The sawing results were in reverse order to the drilling ones. They, hence, concluded that the machinability of a material is dependent on the employed test, and that caution is required when interpreting the results of machinability tests. However, it is questionable whether the materials had equal variances. The variability of the data should be first analyzed before any conclusions based on the averages can be drawn. It might be mentioned here that Crampton [110] utilized both penetration and sawing tests in his evaluation of the machinability of copper alloys. The results obtained were similar.

Thompson and Sarwar [122] investigated the mechanics and economics of power hacksawing. Their objective was to develop a quality control test for blade manufacturers. They mentioned that because of the traditional method of manufacturing hacksaw blades, the cutting edge profile differs considerably from one tooth to the next on the same blade. However, when the average of all profiles of a blade was compared with the average for other blades having the same teeth pitch, small variations were observed. The variations were significant when the blades had different pitches. A hacksaw machine with a hydraulic feeding mechanism of the CFF type was utilized for their tests. The cutting forces were measured using a dynamometer. They mentioned that the typical criteria used by blade manufacturers are; (1) a certain number of cuts, given that the sawing time does not exceed some value, or (2) the number of cuts needed for the sawing time to double its initial value. From their results, they concluded that the feed load should be measured when using hydraulic type machines. They claimed that the variations in the results of different manufacturers can only be explained with the measurement of thrust loads.

Thompson and Taylor [127] investigated the factors influencing the wear rate of power hacksaw blades using dimensional analysis. Their results indicated that if the stroke rate was to be doubled, the wear rate would have increased more than six-fold. Others [128] used the number of sawed sections required to achieve a certain cut-off value for the cutting time per section as an indicator to the useful life of the blade.

In conclusion, with the exception of a few studies ([17], [110], [123] & [126]), the majority of sawing machine tests was directed towards the investigation of the blade wear rate and/or sawing wear mechanisms under certain conditions. Three of the few studies were performed on sawing machines of the power hacksaw type ([17], [110] & [126]. One of the three tests [126] addressed the performance of cutting fluids.

while the other two investigated the machinability of free-turning brass and copper alloys. However, there are disadvantages to the experimental designs of these tests. None of the three tests utilized a valid statistical analysis. The data variability was never analyzed. Possible sources of error, such as the tolerances of the workpieces, had not been addressed. Differences due to tolerances can be significant at low feed pressures. A better indicator which takes these differences into account and minimizes other sources of error (mentioned in Chapter 4) is the number of strokes per cross section area.

Finally, none of the previous studies has evaluated the free-cutting steel machinability on a power hacksaw machine. Also, the potential of this machine as a quality control tool for evaluating the machinability of a work material in daily production has never been addressed. Although there were attempts to develop a power- hacksaw quality-control test for assuring the quality of manufactured blades, a quality control test for the machinability of a work material requires different considerations. The work material variations should be minimized for a blade quality test, while blade variations should be kept minimum when the quality of a work material is of concern. In a blade quality test, the cutting would be under practical sawing conditions, while in a work-material quality test, the cutting would take place under low pressure. This is to increase the dominance of the work material on the obtained results. Due to the above reasons and other considerations mentioned in Chapter 3, one of the tests developed in this study, a Power Hacksaw Test, utilizes a power hacksaw machine for evaluating the free-cutting steel machinability. The results obtained along with a quality control procedure are given in Chapter 4.

(E) Automatic Screw/Bar Machine Tests

Automatic screw/bar machines are either of the single or multiple spindle type. They are usually utilized to produce parts in finished form, and, hence, commonly regarded as finishing processes. For this reason, automatic screw/bar machine tests utilize a measure of the machined part quality (surface finish, size accuracy, or both) along with a reasonable tool life value (6-8 hours), in their machinability evaluation.

Murphy and Aylward [2] mentioned that during World War II, a four-spindle machine, in the laboratory of Bethlehem Steel Corp. (HRL), was utilized for the commercial production of a part. This situation gave them an opportunity to study the operation day-by-day. After the war, the concept of simulating the actual production of a part (in the laboratory) on an automatic screw/bar machine began its wide spread usage among the manufacturers of work materials. This was, perhaps, to overcome the shortcomings in the machinability tests that do not test under conditions close to production environment. Also, it is commonly accepted that the closer the testing conditions to actual production, the more reliable the results.

Although the literature contains many automatic screw/bar machine tests ([2], [3], [12], [13], [108] & [129] to [132]), also called production performance tests (PPT) [2], or simulated production tests [9], their testing procedures are almost identical. The differences could be in terms of parts produced and/or testing domain where feed, speed, or both feed and speed are varied. Basically, these tests simulate the actual production of a certain part on an automatic screw/bar machine of the single or multiple spindle type in a laboratory (i.e., under controlled input factors, such as tool material, tool geometry and cutting fluid). Normally, the objective is to determine the maximum production rate (pcs/hr) for each material. This is through searching the feed, speed, or both feed and speed cutting domain by trial-and-error and under some constraints. Usually, these are an upper surface-roughness (size-accuracy, or both) limit and an average tool life of some 6-8 hours of actual running time (cutting and indexing times).

Since the main objective of this study was to develop a short-term test that would correlate well with the production performance test (PPT) of Bethlehem Steel Corp., their testing procedure will be explained in some detail. A six-spindle automatic screw/bar machine is utilized for the PPT. Figure 2.6 shows the original test piece [2]. Current tests employ the same test piece, but without the tapping operation [3]. The surface roughness of the surfaces machined by the three form tools (rough, medium, and finish form tools) and the diameter increase (part growth) of the rough-formed surface are usually measured [3].

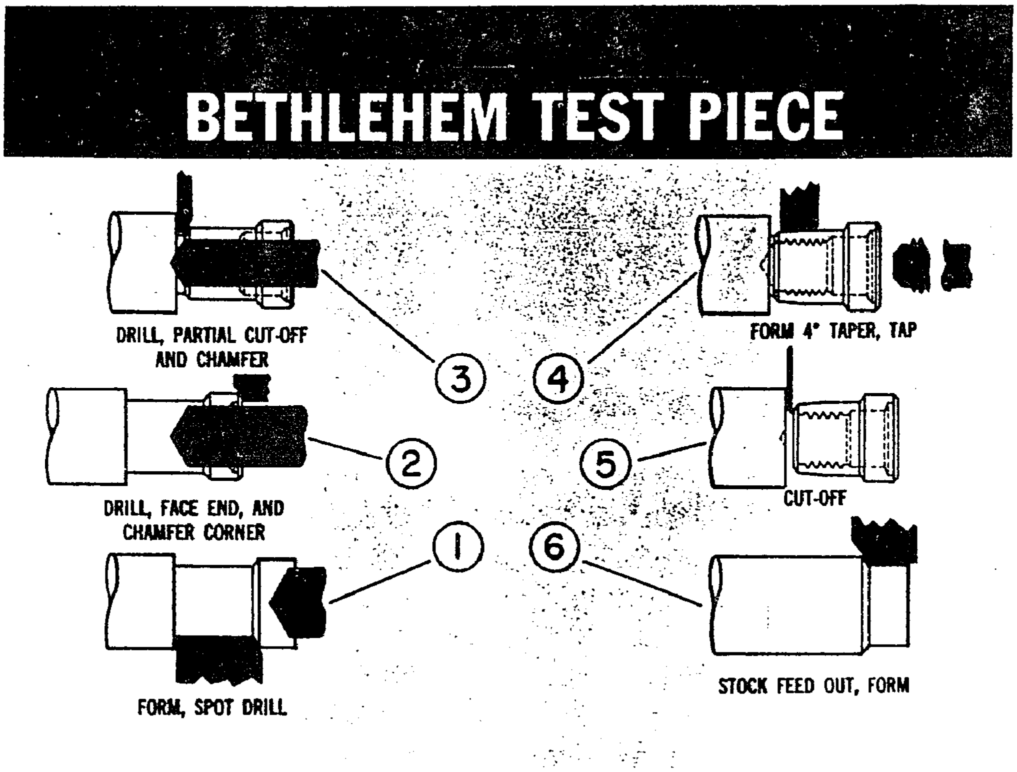


Fig. 2.6 <u>The Test Piece of The PPT [2]</u>

Murphy and Aylward [2] utilized the following testing procedure for the PPT:

(1) A certain work material is first declared as a standard steel (i.e., its performance would be taken as the base in determining the comparative rating of the performance of other materials). Since different production heats would provide different machining performances, the standard (or base) material is varied from a study to another (heat to another). That is, it is desirable, if possible, to produce the materials including the base metal, subject to machinability evaluation, from the same heat.

(2) The maximum production rate of this standard steel is determined through searching the feed and speed cutting domain by trial-and-error and under specified constraints. These are in terms of specified surface roughnesses for the three form tools over a 6-8 hour tool life. Typically, for the rough form tool, the surafce roughness limit is 300 micro-inches (7620 micro-mm), while it is 150 micro-inches (3810 micro-mm) for both the medium and finish form tools. The maximum production rate (pieces/hour) is based on zero-index time. Simply stated, it is equal to the inverse of the cycle time (hours/piece), excluding indexing.

(3) For each test material, the feed and speed cutting domain is searched through trial-and-error and under the same specified constraints for the standard steel until its maximum operating conditions is found. These are the conditions at which the

parts produced of the test material have approximately similar quality to that of the standard steel, and for which a 6-8 hour tool life was attained.

(4) When the above conditions have been met, the performance of the test material is compared to that of the standard steel on the basis of maximum production rates (pcs/hr). This is through calculating a machining productivity index (MPI), which is the ratio of the production rate of the test material to that of the standard one.

Instead of the trial-and-error search procedure, Litwa [3] employed an experimental design with three levels for each of the feed and speed (maximum, middle and minimum). A slightly different end-point criterion for the PPT was utilized. The surface roughness resulting from either the rough or finish form tool should not exceed 300 micro-inches (7620 micro-mm) during the first eight hours of production. Part growth was also measured and showed a similar trend to that of the surface roughness evaluation. The production rates, also called theoretical hourly production rates [12], of the fifteen work materials under study are given in Appendix B. Figure 2.7 shows the rough-form-tool test results obtained under a production rate of 302 pcs/hr for four materials [3]. These are the 9T, 10T, 11T, and 12T as indicated in Appendix B, where the 9T was the standard steel. The test was terminated for both the selenium materials, while it was concluded that the other two are of equal machinability.

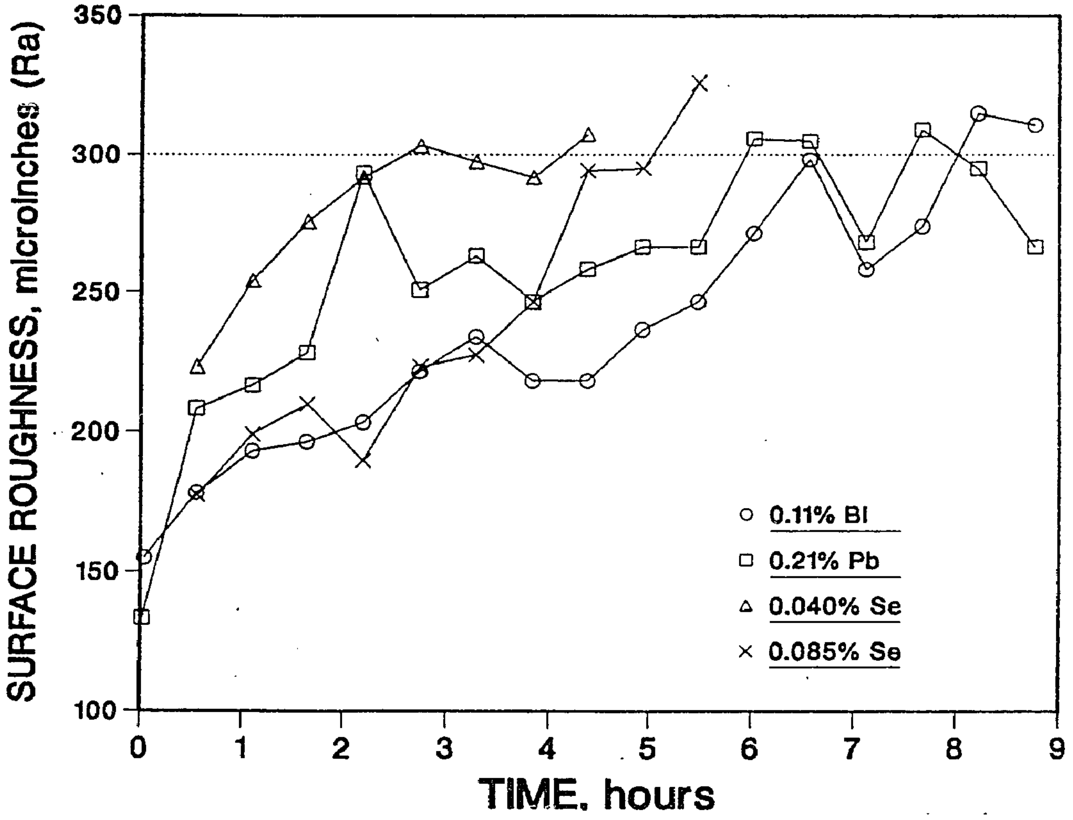


Fig. 2.7 The Rough-Form-Tool Test Results For a PPT [3]

Since the production rate (or cycle time) depends on the test piece geomtery and other factors, efforts were made to standardize the test piece as well as the testing procedure [12]. The ultimate objective is to provide a basis for valid comparisons among the manufacturers of work materials, who are the only users of such a simulated production test.

The standardized method is similar to that of the PPT. The method calls for the production of a certain test piece from a one inch (25.4 mm) bar diameter using specified tools in a specified sequence. Other bar sizes could be used provided that the material removed and the material remaining was in the same cross-sectional proportion as in the test piece. It also allows for varying the form tool rake angles when changes of cutting speed and feed fail to produce test pieces of similar quality among different materials. Other specifications cover the method of determining the machine capability and the requirements in the surface roughness measuring instrument. Recommendations for the surface roughness limits as well as for the maximum diameter increase are given for the two form tools, specified for the production of the test piece. For example, the maximum diameter increase (part growth), from the starting size on a test piece in a sample set of six test pieces, recommended for the rough-formed surface is 0.005 inch (0.13 mm).

Watson, Davies and Ramalingam [13] utilized the standard test method on twelve heats of AISI 12L14 free-cutting steel originating from the USA, UK, Japan and Australia. A single spindle machine equiped with a dynamometer to measure the thrust force on the rough form tool and a heat exchanger fitted to the coolant sump to maintain the coolant temperature constant was used. The standard method has shown considerable uncertainty as to the appropriate manner in which to present and interpret the results obtained. First, in calculating the theoretical production rate for a single-spindle machine, the cycle time excluding the time when no tools are cutting should be changed to the cycle time excluding the inactive time of the rough-form tool only. Second, a 6-8 hour tool life based on the total running time should be changed to that based on the cycle time excluding indexing (for a multispindle machine) or inactive time of the rough-form tool (for a single spindle machine). These changes would allow for comparisons between the single-spindle and multispindle machines' results.

Watson, Davies and Ramalingam also had a problem with the meaning of maximum production rate. Perhaps, this is due to the bad wording of the standard method. In any case, they suggested to utilize the concept of the cutting rate-tool life (R-T) function, described in [38], on the results obtained. The function depends on the existence of a certain relationship between tool life and cutting conditions and at least eight values of tool life to obtain reliable values. For the part growth data, there were no problems in applying this concept. However, for the surface roughness data, an empirical model that satisfies the R-T function requirements was not found. They, hence, used a model developed by Abeyama and Nakamura [103] to demonstrate, in principle, how the maximum production rate can be found using the R-T function under the constraints of part growth and surface roughness. However, since the concept of the R-T function is limited in application to some experimental results, this analysis should not be enforced on the standard method. Only those recommendations concerning the comparsions between the single and multiple spindle machines' results should be adopted by the standard method. Finally, their thrust force measurements on these different heats of AISI 12L14 steel showed heat-to-heat differences of up to 40 %.

With regard to the meaning of maximum production rate, the standard method meant the following [12]; (1) when the machining performance of a single material is subject to evaluation, one would search through trial-and-error for its maximum production rate under some specified constraints, and (2) when the relative machining aspects of several metals is subject to evaluation, they must be compared under similar trends of part quality. Otherwise, the relative machining performance of different materials can be only evaluated when the test pieces produced are of equal quality with respect to surface roughness and dimensional limits over comparable periods of time. Clearly, this requirement for comparisons among materials may not be at the maximum production rates of some materials. The question is, therefore, what is the advantage of locating the maximum production rate for a certain material given that it can not be used for comparisons with other materials? Also, this maximum production rate depends on other factors beside those of the work material, such as machine power, available range of speeds and feeds, collet pressure, and machine rigidity. Perhaps, if the standard method specifies a certain standard material (with a specified maximum production rate and part quality trend) to which the machinability of all other materials can be related, this problem would be solved. Finally, the standard method recommends any commercially available coolant to be used. Clearly, this is in conflict with the main objective of standardization. Different cutting fluids give different machining performances. Nonetheless, any attempts to standardize machinability tests should be welcomed. That is, through standardization only, machining data can be exchanged.

In conclusion, as with any machinability test, automatic screw machine tests have advantages and disadvantages. The advantages can be summarized in that they simulate an actual production environment. There are, however, several disadvantages in addition to the above mentioned ones. One of them is mentioned in the standard method [12]. For a single test run of easy-to-machine materials, from 1500 to 2000 lbs (700 to 900 kgs) of bars would easily be consumed. Other disadvantages would include difficulties in changing cutting conditions and poor repeatability due to the multiplicity of the parameters involved [133].

(F) Other Machines Tests

Other machines that were utilized for machinability tests included grinding machine, gear hobbing machine, planer, and machinability tester machine tests.

In one of the case studies, reported by Tipnis and Christopher [120, p. 23], the effect of cutting fluids under low stress and abusive grinding of some areospace alloy components were examined in terms of high cycle fatigue and other mechanical properties.

Rabezzana and Tipnis [133] developed an accelerated hobbing test for evaluating gear steel machinability. Simply stated, the hob tooth wear was accelerated on some teeth (i.e., different hob sections) by not advancing the hob, in contrast to normal production conditions. With this semi-simulated production test, a given gear steel can be evaluated in one day.

Boston [5] utilized four different machinability tests on eighteen ferrous and twenty-one nonferrous metals. Four machines were employed; a planer, a conventional drilling machine, a penetration drilling machine, and a machinability tester machine. In the planer tests, the cutting force resulting from the cutting action of a semi-form tool during a planing operation was measured. The torque and thrust force were measured in the conventional drilling machine tests. The drilling depth obtained by 100 revolutions was measured in the penetration drilling machine tests. In the machinability tester machine tests, the energy absorbed by a single tooth milling cutter, similar to a cutting-off tool, was measured. Boston reported that this machinability tester machine was designed by Carl Oxford around 1920. Briefly, the design is similar to an impact testing machine. A single tooth fly cutter is mounted on a horizontal shaft to provide rotations in a vertical plane. At the other end of the shaft, a weighted lever arm (pendulum) is attached. The swinging of this weight provides the necessary power to drive the cutting edge into the workpiece, which can be fed with different feeds and desired depths of cut. The absorbed power (energy) is indicated by the pendulum rising past dead center. Boston converted all the measurements from the four tests into a common measure (horsepower required for a one unit of metal removal rate) for his machinability evaluation. The four tests' results were almost similar in ranking the metals and were independent of hardness. However, there is no one tool geometry nor one cutting speed existing for the practical or optimum machining of this range of metals [3, p. 698].

Others ([44] & [48]) utilized a chip formation machine, which is similar in principle to that of the machinability tester machine. Two cut-off tools were mounted symmetrically to produce two chips on a plate specimen under a specified speed and depth of cut. The cutting forces generated by these two tools were measured. The chips were also weighed, and the length and width of cuts were measured. From these measurements the specific cutting energy was calculated and utilized as a machinability indicator. The specific cutting energy results were in agreement with some screw machine handbook ratings. However, only six data points were compared. Further, this special machine and measuring requirements should be weighed against other alternatives, such as the Power Hacksaw Test.

Cohen and Black [134] designed what they called a standard machining data machine to provide metal cutting properties in terms of flow stress and specific horsepower. They mentioned that this machine would provide standard machining data in a similar fashion to those standard machines utilized for measuring mechanical properties, such as hardness and impact strength. The tool with the desired geometry and material is attached to a free falling pendulum arm. The tool velocity, prior to and after an orthogonal cut, was measured to calculate the consumed kinetic energy, from which the specific horsepower was determined. Measurements of forces and shear angle were utilized to calculate the flow stress. However, these machines, based on the concept of having a machinability tester machine, underestimate the machinability problems or oversimplify the metal cutting process. There are so many different tool failure modes, due to different interactions between the workpiece, cutting tool, cutting fluid, and even the cutting machine, that cannot be determined except under normal production conditions. One of the main problems of machinability is that data obtained on one machine may not be obtainable on a similar machine. If machinability is that simple, why, to date, is there no acceptable definition for it?

From the above mentioned machinability tests, the following conclusions can be drawn:

(1) A universally acceptable system for classifying machinability tests does not exist.

(2) There are no cut-off values, in terms of consumed material and/or testing time, to aid in identifying whether a given test is of the long-, medium-, or short-term type. Nevertheless, the Taylor-type and simulated production tests are considered of the long-term type.

(3) Machinability tests include those that require special machine setup (i.e., Variable Rate Turning Test), work material preparation (i.e., Taper Turning Test), tool preparation (i.e., Softened Tool Test), measuring devices (i.e., IR Photography), or a combination of these.

(4) The ultimate machinability tests are the actual production ones. They are the most expensive, but the most reliable ones. The second most accurate, but still expensive tests, are those that closely simulate actual production conditions in the laboratory (i.e., Automatic Screw/Bar Machine Test (ASMT), a standardized PPT). Hence, the further the testing conditions move away from production situations, the lower the reliability of the results.

(5) Tests that closely simulate actual machining in the laboratory (i.e., PPT) are usually considered most reliable. However, laboratory test results can be significantly different from production environment [121]. Further, industrial ratings

from different sources have shown a poor correlation [9]. Therefore, caution should be exercised when analyzing and interpreting the results of machinability tests.

(6) Although the ISO test, a standardized Taylor test, is the only internationally accepted testing procedure for machinability evaluation, it is not widely used. That is; (a) it is a long-term test, (b) it limits the testing variables' flexibility to achieve comparable results, and (c) it does not consider the feed effects on tool wear or life. Furthermore, a variable speed drive system is usually required.

(7) Since none of the short-term tests has been adopted in a wide spread fashion, their validity is limited to their testing domain. Therefore, they should not be used in isolation but rather in conjunction with the long-term test results of a given testing domain.

(8) Due to the inherent variation in work material, cutting tool and cutting fluid lots, deterministic analyses are not appropriate for machinability testing.

(9) Work material characteristics dominate when machining under constant feed force (pressure or load).

(10) The ranking of work materials can be dependent on the type of test as well as the machining performance indicator.

2.3 Machinability - Data

In this section, the available machinability ratings are discussed in terms of advantages and disadvantages. Table 2.1, abstracted from reference [1], shows the estimated minimum mechanical properties and average machinability ratings for some resulfurized carbon steel bars. The ratings were based on a value of 100 % for AISI 1212 cold drawn steel. This 100 % value corresponded to turning at 180 sfpm (55 m/min) for feeds up to 0.007 (0.18 mm/rev) and depths of cut up to 0.25 inch (6.4 mm) and with the appropriate cutting fluids and HSS tools (T1 hardened to 63/65 RC).

Other information sources that were utilized in determining the average machinability ratings included various experimental data and actual shop production information obtained from results of machining cold drawn bars on single and multiple spindle automatic screw machines. It was also mentioned that these averages could be affected to some degree by the amount of cold reduction, mechanical properties, grain size, and microstructure. However, these four factors are not the only ones that could affect these averages. Other factors would include tool geometry, cutting fluid, machining performance indicator, and even the cutting machine rigidity. In other words, the sources of information are themselves factors. Troup [93] mentioned that handbooks differ by as much as 43 % in rating the machinability advantage of lead, and Groover [9] found a poor correlation between industrial ratings from different sources.

Table 2.1 Estimated Minimum Mechanical Properties and Machinability Ratings [1]

AISI[1] No.	Type of[2] Processing	Tensile Strength (psi)	Yield Strength (psi)	Elongation in 2 inch (%)	Reduction in area (%)	BHN	AVE.[3] M.R. (%)
1211	HR	55000	33000	25	45	121	
	CD	75000	58000	10	35	163	95
1212	HR	56000	33500	25	45	121	
	CD	78000	60000	10	35	167	100
1213	HR	56000	33500	25	45	121	
	CD	78000	60000	10	35	167	135
12L14	HR	57000	34000	22	45	121	
	CD	78000	60000	10	35	163	160

1- The 1200 series steels are rated on the basis of 0.10 % maximum silicon or coarse grain melting practice.

2- HR : Hot Rolled, and CD : Cold Drawn

3- Average machinability rating is based on a value of 100 % for AISI 1212 CD

Kahles [135] argued that since high speed steels have lost ground to carbides in turning, the basis of that 100 % value (which is turning under the above mentioned conditions) is no longer accurate. He stated that an index using HSS would be more relevant for other operations than for turning, such as end milling, drilling, tapping, etc. He, hence, proposed that if machinability indices should be used, a new speed base value for each operation and different types of tool materials should be first established. Some machining data obtained under different combinations of work materials, cutting tool materials and operations were utilized for demonstrating his proposal. For each operation, a 100 % machinability base value was selected based on cutting speed. The calculated indices reflected wide discrepancies from one operation to another. He, consequently, rejected the idea of basing indices on cutting speed only. He mentioned that when drilling a certain material, the index value would change from 92 to 132 %, if the feed was not specified, and from 92 to 146 %, if the type of cutting fluid was not given. He, thus, advised that machinability indices would be misleading unless accompanied by data for all important cutting variables (i.e., type of operation, speed, feed, depth of cut, etc.). Even so, he argued that if all the important cutting parameters are given, the indices would not be required, .

In addition to the above valid criticism, the variability of the results of any machinability test should be provided. The following data, from the Power Hacksaw Test results, demonstrate the importance of knowing the data variability:

Material	Ave. number of strokes per cross section area	Variance	Confidence Interval (95 %)
A	187.3	47.3	166.7 , 207.9
B	194.9	5.7	187.7 , 202.1

The average number of strokes per cross section area was determined from the results of five replications. If material A is selected to be the base metal, the machinability indices for materials A and B would be 100 % and 96.1 % respectively. That is, the lower the number of strokes per cross section area, the better the machinability. Considering these indices only, material A would be regarded as the best alternative in terms of machinability. However, when both means and variances are considered, material B would be the best choice. In summation, the method utilized in determining the machinability indices does not reflect the data variability.

The concept of relating the machining performance of a material to another by a single index has, therefore, several disadvantages. The index value does not take into account the data variability, unless the hypothesis of equal variances was first tested and accepted. The index value does not provide the user with important information regarding cutting conditions. A better approach to these indicies is to provide the machinability tests' results in terms of means and variances along with their testing conditions. Although with this approach the decision process of selecting a material based on machinability would not be as easy as having a single index, the advantages outweigh the degree of difficulty. This is demonstrated in Figure 2.8, cited from Tipnis and Joseph [25]. The comparison of the optimum machining responses (M_A/M_B) can be misleading without the comparison of cutting rates at the optimum (R_A/R_B).

Given the above mentioned disadvantages of machinability indices, the question was, then, who are the users of these indices? Kahles [135] mentioned that machinability indices should not be used in decisions regarding the purchase of machine tools, cutting tools and fluids, nor in determining the expected production rate. Others ([136] & [137]) used these indices to determine whether improved machinability would be profitable. Tipnis and Christopher [120] viewed machinability testing in terms of degree of sophistication and purpose. Testing for machinability ratings was considered the lowest degree of sophistication, while testing for the economic operating conditions based upon mathematical models that represent a response under some constraints was regarded as the highest one. The rough comparison of preliminary cost estimation was the only purpose given for using machinability ratings. They also regarded machinability testing for handbook data (i.e., reference [138]) as the second lowest degree of sophistication. Furthermore, they are for the purposes of determining starting recommendations and industrial engineering time standards computations. However, Cook [24] stated that because of the problems of tool life variability due to material variance and that tool life data are also machine-sensitive, any machinability data must be viewed with suspicion. He mentioned that predictions based on these data could miss the mark by a wide margin.

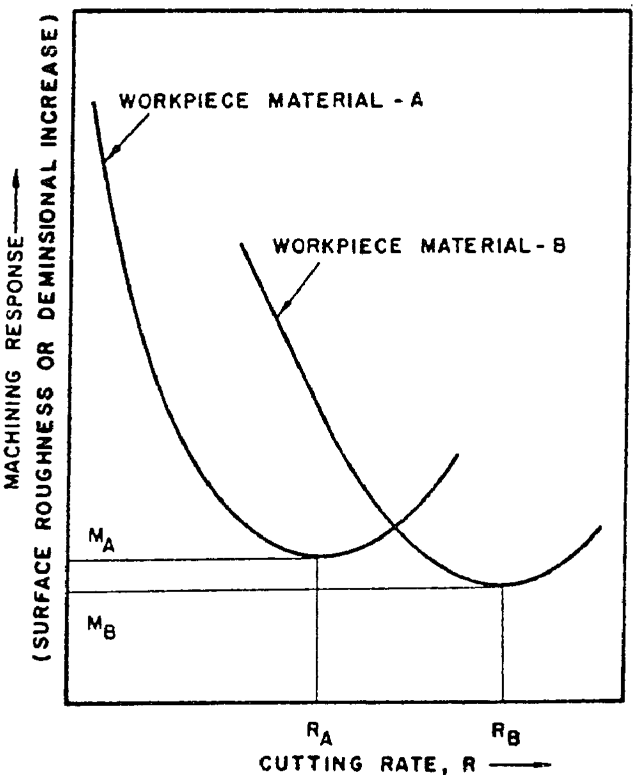


Fig. 2.8 Machining Response (Surface Roughness or Dimenstional Increase) Versus Cutting Rate For Two Work Materials [25, p.21]

The importance of defining and measuring machinability lies in the product design and manufacturing process. The machining aspects of work materials are usually considered during the materials selection process conducted by machine designers. If tables similar to table 2.1 are used for this process, the decision validity will be questionable. Although at a later stage, a manufacturing engineer would re-evaluate that decision, in terms of machining and raw materials costs (based on other sources of machining data that may or may not be valid), it is usually a time consuming process. Machinability data obtained from standardized machinability tests that reflect the optimum machining performance of work materials under different operations and cutting conditions including different tool materials, tool geometries and cutting fluids are, therefore, needed. A proposed approach for the development of such tests, which would be of the long- to medium-term type, is discussed in section 2.4.

Other short-term machinability tests that correlate well with the standard ones would be needed for testing the quality of work materials produced and incoming raw materials. Of course, the testing method of the short-term tests would be simpler than that needed for the standard ones. That is, the machinability space will be limited to some operations, cutting tool materials, etc. For example, milling and drilling operations are heavily used in airframe manufacturing [121], while the costs of turning and grinding are the highest in the manufacture of aircraft engines [139].

2.4 Problems of Defining Machinability

The conclusions of the first three sections of this chapter can be summarized in that the term machinability should stand for machining efficiency, where efficiency is the overall performance, and should be viewed as an input/output system.

Figure 2.9 shows the main input and output factors of the machinability system. The majority of the indicators used can be classified under the main output factors; machined part, cutting tool, cutting forces, consumed power, cutting temperature, ease of chip disposal, and others. The machined part is the objective of any metal cutting operation given that a reasonable tool life and/or cost are attained for the desired quality. Cutting forces can be utilized in determining consumed power and/or cutting temperature, of which its measurements are considered of academic interest only [10]. Although ease of chip disposal is important, especially for automated manufacturing systems, a good chip-breaker design [62] and/or slight modification to the input factors [6] make this criterion of least importance. Other output factors may include burr height [117], compound indicators, etc. The main input factors (work material, machining operation, cutting tool, cutting condition, cutting fluid, and others) are listed in the logical order that a manufacturing engineer would follow in developing a process plan. The work material specifications, required part qualities, and available facilities are the process plan input factors while the route sheet and operation sheets are its output. Other input factors to the machinability system may include system rigidity [140], etc.

Work by Wager & Barash [87] and Friedman & Zlatin [36] indicate that the machinability system should be a probabilistic type (versus deterministic). The main sources of variability are the work material, cutting tool and cutting fluid, where the variability of work material is the highest. Thomsen [28] stated that F.W. Taylor had considered himself fortunate for having uniform metal to work upon. Therefore, machinability should stand for the "machining efficiency", where efficiency is the overall performance, and must be viewed as a "probabilistic input/output system". If a certain input factor is subject to analysis, such as a work material, then the machinability of a work material is of interest (see Figure 2.10). Similarly, there is the machinability of a cutting tool and a cutting fluid. Since this dissertation is concerned with the machinability of free-cutting steels, the rest of the discussion is somewhat biased to the machinability of work materials.

Figure 2.11 presents a detailed machinability system for the purpose of explanation. The machined part indicators are usually in terms of surface roughness, dimensional accuracy (stability) and/or surface and functional integrity. The Automatic Screw/Bar Machine Test [12], for example, employs both surface finish and dimensional accuracy. Although surface integrity was studied as early as 1926 [141], it is relatively new to the machinability indicators ([24], [25] & [142]).

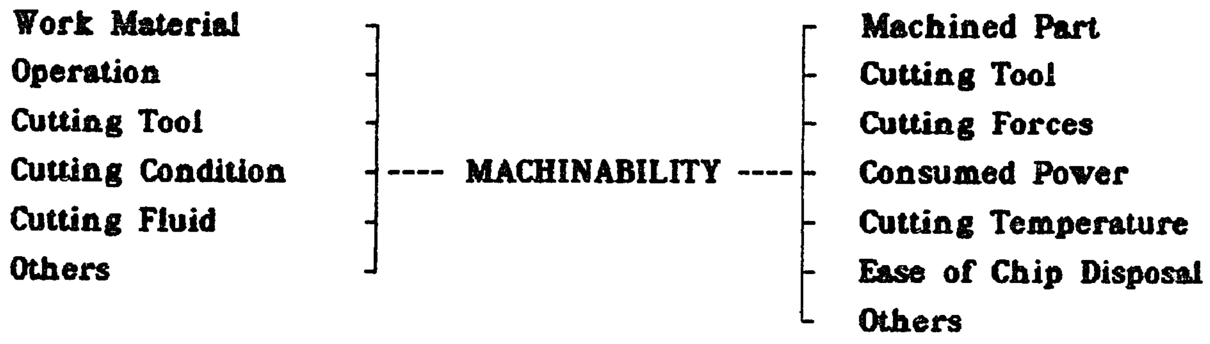


Fig. 2.9 Machinability as an Input-Output System

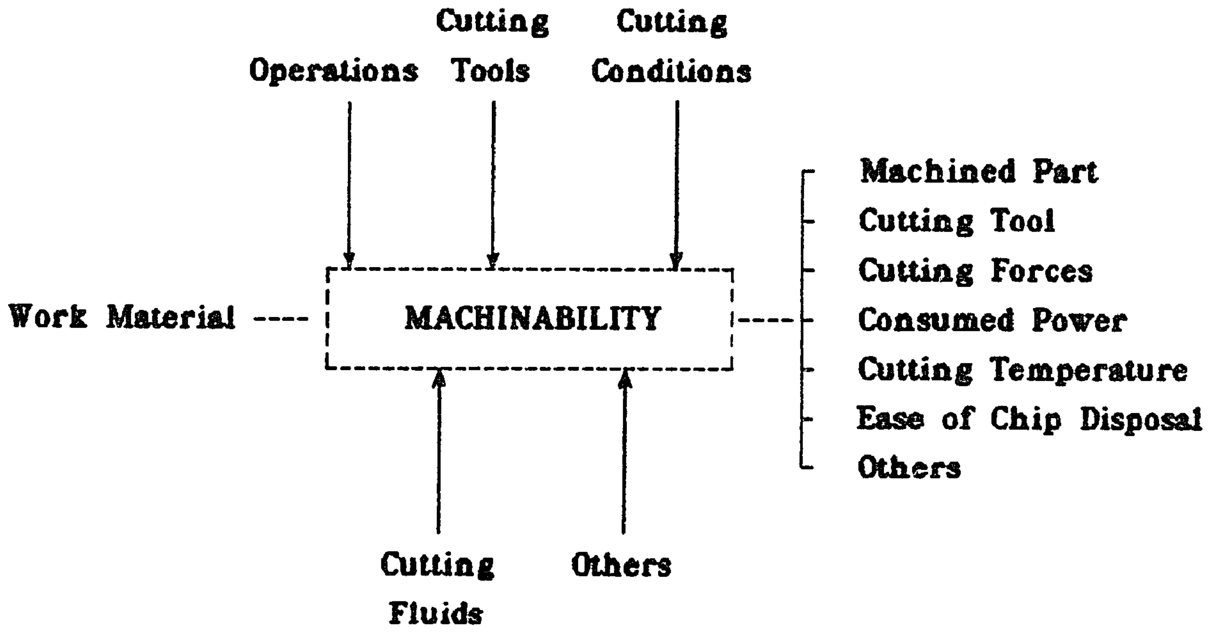


Fig. 2.10 Machinability System of a Work Material

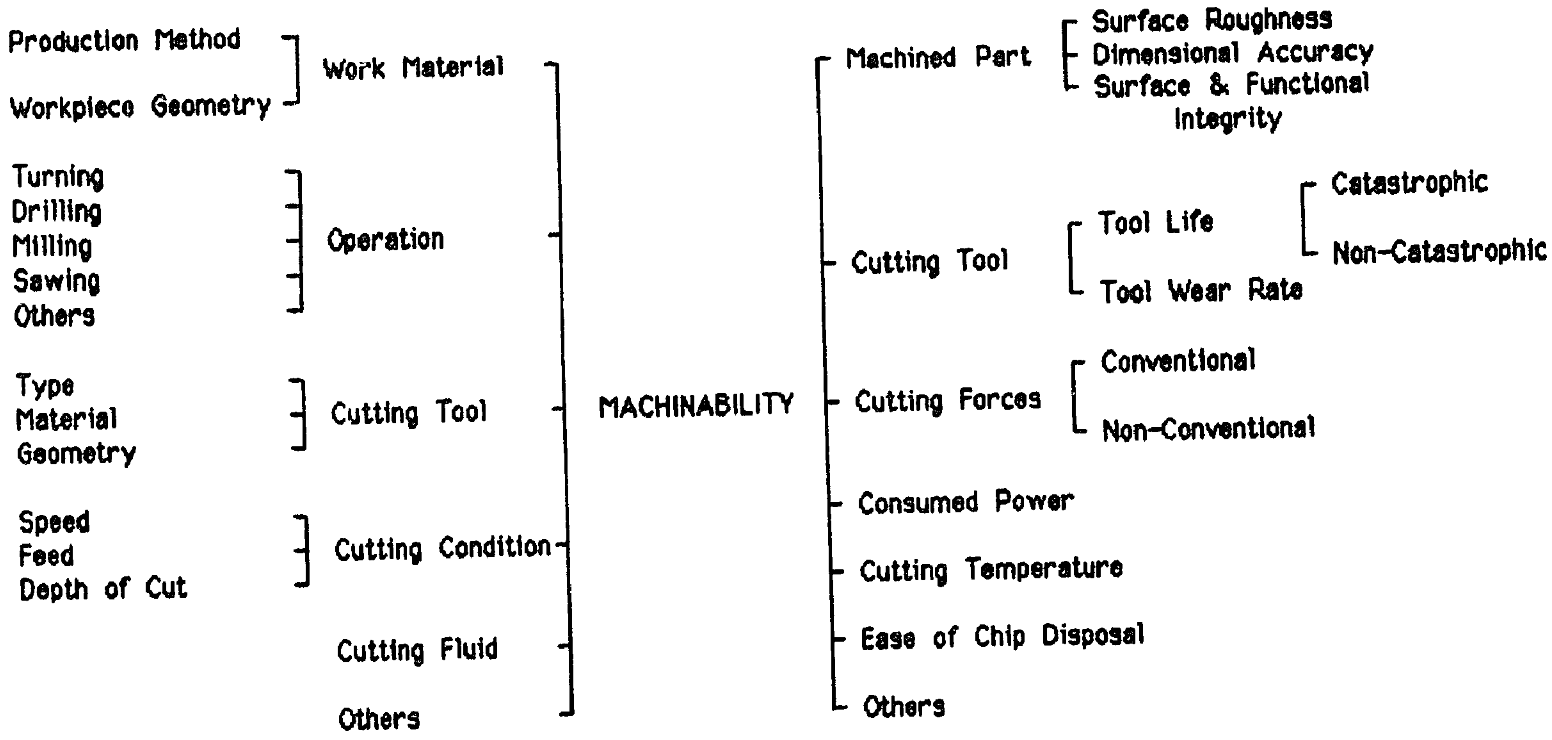


Fig. 2.11 A Detailed Machinability System

The cutting tool indicators are of two types; tool life and tool wear rate. The tool life indicators can be further classified into two groups; catastrophic and non-catastrophic. The catastrophic tool life indicators, which depend on total tool failure, are only applicable to HSS tool materials. Indicators such as; (1) time to total tool failure in turning or facing ([2] &[50]), (2) number of drilled holes ([6] & [116]) or machined gear-grooves [106] prior to complete breakdown, and (3) go no-go critical feed values [109] are typical examples of this group.

The non-catastrophic (predetermined) tool life and tool wear rate indicators require the measurements of the mean or maximum width of the flank wear, crater wear depth, and/or notch wear length ([6], [7], [10], [56] & [66]). However, it is the mean flank wear value that is commonly used and has been shown to provide the lowest coefficient of variation, standard deviation per mean [143]. The non-catastrophic tool life group would include indicators such as speed for a given tool life ([2], [4], [22] & [50]), speed for a given tool life obtained in removing two cubic inches [144], tool life under certain cutting conditions ([4], [6], [35] & [145]), and tool life or material removal rate per tool grind ([22] & [50]). The utilization of tool wear rate as a machinability indicator is not an easy task, due to its variability with time. Normally, there are three tool wear zones; break-in, gradual and accelerated. However, it is the gradual tool wear rate that is usually utilized [67]. Because of the possibility of having an inflection in the gradual wear rate at low cutting speeds and feeds [86], two gradual wear rates can be present and, therefore, caution should be exercised.

The cutting forces indicators can be classified into two groups; conventional and non-conventional. For the first group, typical indicators include forces obtained under certain cutting conditions ([3], [4] & [22]), feed for a given feed force value or feed force resulted at a certain feed [2], unit force (cutting force per chip cross section area) [5], coefficient of friction ([6] & [101]), time to reach a certain feed force [123], speed that gives 50 % increase in feed force within two minutes of cutting [89], torque and thrust in drilling ([4], [5] & [6]), horsepower calculated from forces or torque and thrust [5], and specific cutting energy determined from cutting force measurements ([6], [44] & [48]). For the second group, the cutting speed at which the cutting force doubles its initial value when turning at increasing speed [98], the feed rate obtained when turning at constant feed force [18], and the feed load resulted from power hacksawing with a hydraulic type machine [122] are typical examples.

The consumed power is usually measured by a wattmeter. The flank wear resulting in a certain power was employed as an indicator [50]. The cutting temperature is usually measured by a thermocouple. The wear-temperature gradient was utilized by Redford [34] for on-line assessment of tool wear. The indicators for ease of chip disposal would include chip equivalent (cutting edge length per chip cross section area) ([7] & [11]), fracture strain [60], chip form and size ([6], [50], [87], [101] & [106]), chip contraction (cut length per chip length), and chip formation as a function of downtime to clean it [130]. Other indicators which were used for machinability evaluation would include BUE height

[103], burr height [117], and the acceleration of microparticles in the cutting zone [148].

For the input factors, the machinability of a work material would depend on the entire process utilized in producing it and on its semi-finished geometry. The production method of steel would, for example, include the melting, deoxidation, solidification, rolling, heat treatment and cold drawing processes [26]. For this reason, the ISO test [66], an international standard tool-life testing procedure, specifies a certain production method to be applied in preparing the work materials for testing. This is to minimize possible sources of work materials variability, and, thus, allow for valid comparisons among and within different countries. References [20], [95], [130] & [145] to [147] are examples of studying some of the production method effects on the work material performance under specific (limited) input and output factors. The workpiece geomtery may influence machinability through thermal effects. Other input factors include; (1) type of operation, such as turning, facing, drilling, and so on, (2) cutting tool, in terms of type (single-point, multiple-edges, or form tool), material, and geometry, (3) cutting condition, such as speed (constant or variable), feed (constant feed rate or constant feed force), and depth of cut, (4) cutting fluid, and (5) others, such as the machine rigidity [140].

Examination of the input/output machinability system, given in figure 2.11, confirms that during any metal cutting operation, an output indicator would reflect an interaction between a work material, a cutting tool, and a cutting fluid (if used). This interaction could vary with the cutting conditions, over the machining time, and from one setup to another. Machinability is, therefore, not a material property. Instead, it should stand for machining efficiency and should be viewed as a probabilistic input/output system. Further, all combinations of input and output factors would constitute what can be called the machinability space, and machinability improvement can be indicated by; (1) a better machined part, (2) a higher tool life or smaller tool wear rate, and/or (3) lower cutting forces, consumed power, or cutting temperature.

In turn, the ranking of work materials under limited (certain) input and output factors should not be called the machinability (machining efficiency), but rather the partial performance (or performance), of work materials. For example, if the analysis was performed under turning with a HSS tool and using the tool life as a criterion, this is a partial performance (not overall performance) of work materials under certain input and output factors. That is, the ranking of work materials can vary from one operation to another, one cutting tool to another, and from one indicator to another. The machinability of a work material would, hence, depend on the entire process utilized in producing it, its semi-finished geometry, and on all other combinations of input and output factors. Finally, the machinability improvement of work materials may not be the only objective. Perhaps, a compromise between machinability, weldability, and workability is the desired goal.

The question was, then, whether a commonly accepted, quantitative definition for the term machinability can exist. From the literature survey given in the first three sections of this chapter, it can be concluded that there are two schools of thought. One school recognizes the many facets of machinability, and, thus, instead of defining the term, prefers to rely heavily on the purpose of testing (i.e., solving a specific machining problem) ([24], [25], [26], [40], [63], [101], [120], [133] & [149]). This school provides testing methodologies (strategies) rather than facing the question of whether machinability data and experience are transferable. The second school of thought, whether purposely or not, over simplifies the machinability definition, in order to facilitate valid comparisons for the results obtained by different investigators ([7], [8], [11], [30], [44], [66], [79], [109], [115], [134], [148], etc.). Although the objective of the second school is noble, the acceleration of microparticles in the cutting zone [148], for example, is an over simplification that should no longer be accepted. The question was, then, whether a compromise definition between these two extremes is feasible. Examination of figure 2.11 confirms that a commonly accepted, quantitative definition for the term machinability will never exist.

The only solution between the two schools of thought is to have several standardized machinability tests, where each test would be testing a limited (certain) portion in the machinability space. In other words, several definitions for the term machinability (machining efficiency) as applied to these portions of the machinability space are needed. The question was, then, how would the machinability space be partitioned? The machinability space should, first, be viewed in terms of one input factor at a time. For example, figure 2.10 indicates that there is a machinability space for work materials. Similarly, there is a machinability space for cutting tools and for cutting fluids. These machinability spaces can, then, be divided into sub-spaces of limited (certain) input and output factors.

The sub-division of the machinability space of work materials, for example, can be based on a logical classification system. The system must consider the requirements of end users (design and manufacturing engineers) in addition to other factors, such as chemical compositions, production methods, etc. For example, the manufacture of parts made from free-cutting steels is usually done on automatic screw/bar machines of the single or multiple spindle type. Therefore, the machinability space of free-cutting steels can be limited to these machines. This limited space can be further restricted to HSS tool materials, since the achievable cutting speeds are in the economical range of the HSS tool materials. This is due to the structure of these machines and that they normally accomodate bars up to two-inches (50.8 mm) in diameter. After improving the testing procedure of the standardized PPT [12], it can be used for the machinability evaluation of this group of materials.

With a similar analogy, other groups of materials with a common limited machinability space, in which they compete, can be identified.

Once these groups are identified, standardized testing procedures, similar in nature to the standardized PPT (i.e., simulate an actual production condition), can be developed. Rabezzana and Tipnis [133], for example, developed a simulated production test for gear steels. If the manufacturers of gear steels can agree on a standardized testing procedure, the machinability of gear steels can be evaluated within their machinability space. That is, the machining requirements for gear steels are different than those for free-cutting steels. In other words, the performance of a gear steel on a PPT should not be used as an indication to its performance under gear cutting conditions. Finally, since the further one moves away from a practical cutting condition, the lower the reliability of the information obtained, these tests should simulate or test near actual production conditions. Although each standardized test may not cover its entire machinability sub-space, at least the results obtained would be the closest to reality and, hence, can be used for valid comaprisons. For example, although the results of the standardized PPT could vary with variations in the geometry of the part produced, fixing the geometry is a reasonable trade-off for having comparable data.

In conclusion, the term machinability should stand for machining efficiency and should be viewed as a probabilistic input/output system. This system should be further viewed in terms of one input factor at a time. The machinability space of work materials should be divided into sub-spaces, in which group of materials compete among themselves for industrial applications. For each machinability sub-space, a standardized testing procedure should be developed. These tests should be testing near production conditions. Of course, if a material is competing in two machinability sub-spaces, it should be evaluated by two tests. Finally, testing for the machinability of work materials would be the responsibility of the manufacturers of work materials who are seeking markets for their products.

2.5 HRL Machinability Evaluation System

Figure 2.12 shows the machinability evaluation system of Homer Research Laboratory (HRL) at Bethlehem Steel Corp. The diagram is the outcome of a personal interview with Mr. R. Litwa of the machinability (Constructional Steels and Manufactured Products) group at HRL. The demand for machinability evaluation of a new material can be triggered by customer demands, published articles, and/or other sources, such as new OSHA regulations, etc. For example, the last seven materials in Appendix A were investigated due to a new OSHA standards for occupational exposure to lead. In July 1979, OSHA reduced the permissible human exposure level to lead from 200 to 50 micrograms per cubic meter per eight hours [3].

The machinability evaluation system of HRL can be divided into two stages; (1) preliminary, and (2) production and machinability evaluation. In the first stage, chemical compositions and microstructure analysis are performed on small ingot sizes, such as 100, 300, or 500 lb (45, 135, or 225 kg) ingots. However, it is the 500 lb (225 kg) ingot that is usually used. Other sources that may influence the final decision of how many heats (materials) should be produced in the second stage include HRL previous data (experience) and likely trends as indicated by publications. If the results of this early investigation do not show very high potentials for the new material, the process is stopped at this point, due to the very high costs of the second stage.

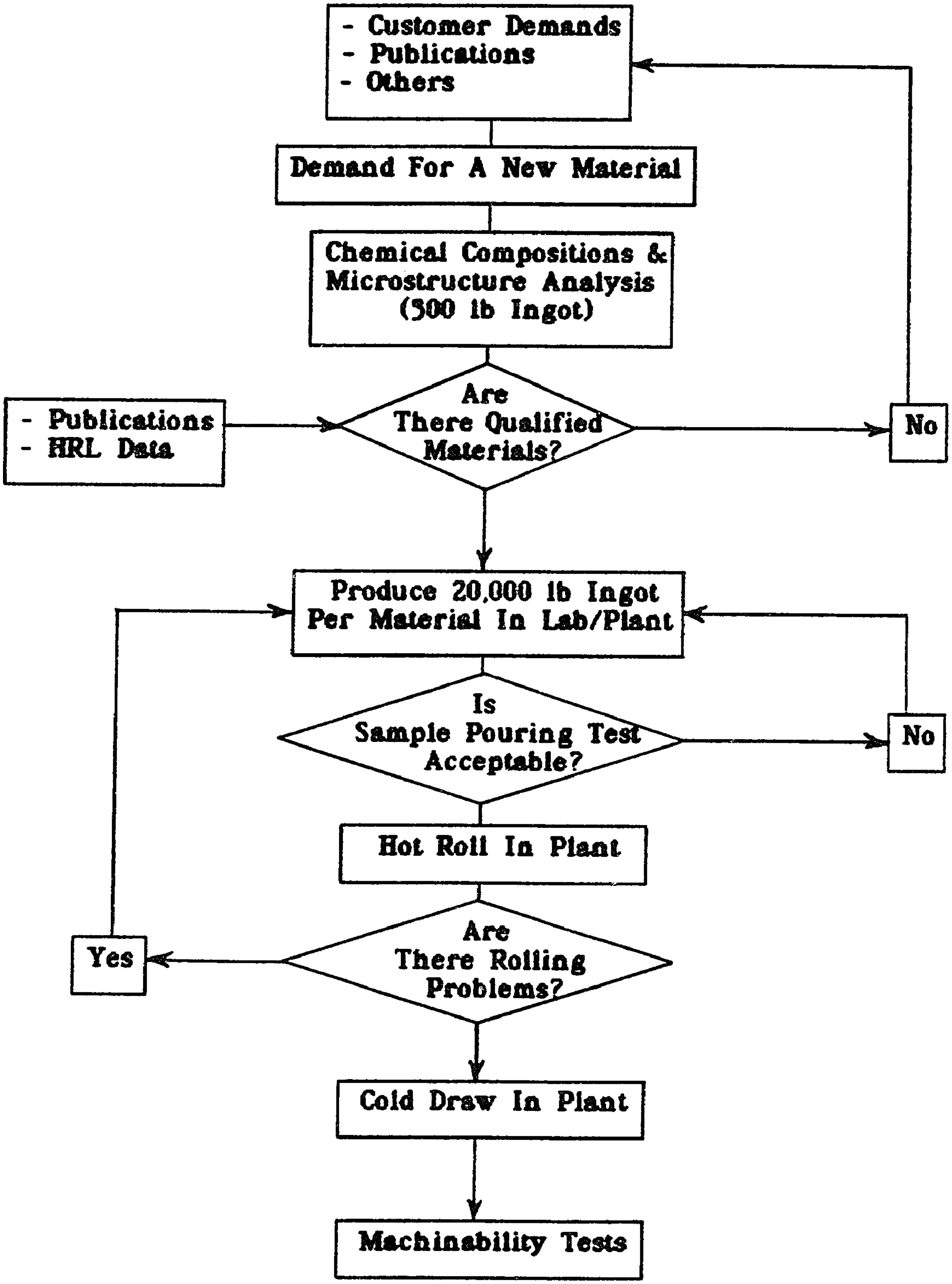


Fig. 2.12 Block Diagram of HRL Machinability Evaluation System

The maximum number of heats that were qualified at one time for the second (production and machinability evaluation) stage was nine. The second stage starts with the production of a 20,000 lb (9000 kg) ingot for each highly qualified material identified in the first stage. The chemical composition is checked, and the material is then hot rolled in one of Bethlehem steel plants. If there are rolling problems, a second ingot would be produced. At most, two ingots would be needed to adjust the hot-rolling process parameters. The bars are then shipped to one of the plants of Bethlehem's customers to receive the cold drawing process. The mechanical properties are usually determined before and after the cold drawing process. Typical reduction of area in cold drawing ranges from 7 to 11.4 per cent. The bars utilized for this study had an 11.4 % reduction of area in cold drawing.

Abeyama and Nakamura [103] studied the effect of different reduction of areas on tool wear when turning a material on a lathe and on an automatic screw/bar machine. The lathe results showed the tool wear to decrease with an increase in the reduction of area in cold drawing. For the automatic screw/bar machine, minimum tool wear values were observed between 15 and 20 % reduction of areas. This difference was attributed to that turning on a lathe is of the continuous cutting type, while it is of the intermittent type for the automatic screw machine.

Two machinability tests are then utilized on the cold drawn bars; the Taylor tool life test and Bethlehem's Production Performance Test

(PPT). In the Taylor test, the bars are turned on a lathe until an HSS tool fails catastrophically. The time to failure as well as the resulted cutting forces are recorded for a series of speeds. In the PPT, described in more detail on pages 75 to 80, the production of a certain part is simulated on an automatic screw/bar machine of the multiple spindle type. The Taylor tool life test has never differentiated between the materials nor have the results of this test shown a valid correlation with the PPT results ([2] & [3]).

2.6 Demand For Short-Term Tests

Due to the increasing trend towards the application of automation in manufacturing, the machinability of work materials, cutting tools and cutting fluids are becoming more important. The consistency of work materials, cutting tools and cutting fluids are vital factors to the reliability of modern manufacturing systems, Flexible Manufacturing Systems. The high demand for accuracy and consistency in the input factors of metal cutting operations intensifies pressure on the manufacturers of work materials, cutting tools and cutting fluids. The pressure is, however, highest on the manufacturers of work materials, due to the work materials higher variability relative to other input factors.

The machinability of work materials has no standard definition nor a commonly accepted testing procedure. In turn, there are no contract specifications for it, but rather specified ranges for the chemical compositions. As mentioned earlier, on page 14, it has been shown that small variations in the chemical composition of work materials can have significant effects on machinability which could, thus, vary between the high and low ends of each element [22]. This has led to the high demand for a narrower chemical composition range, especially for the elements that are harmful to machinability. For example, although AISI calls for a minimum of 0.15 % sulfur for stainless steels, contracts call for a maximum of 0.40 % sulfur [150]. However, there are other factors beside chemical composition that can influence the final microstructure and, thus, the machinability of work materials. Any small variations in bar size, final rolling temperature, cooling rate, heat treatment, etc. could lead to a variation in microstructure and, therefore, an unknown machinability level. At the same time, there are no valid predictive models based on microstructure analysis, but rather general trends to microstructure effects on machinability. That is, two microstructures can have no significant differences, but yet provide different machining performances [42]. Further, machinability ratings do not correlate well with either physical or mechanical properties.

In summation, machinability evaluation through chemical composition, microstructure analysis and physical or mechanical properties is not reliable. Testing for machinability is, therefore, the only valid and available alternative. The machinability group of HRL at Bethlehem Steel Corporation recognizes this, and believes that machinability assurance in the steel mill is the only means to improve manufacturing competitiveness. This is through producing materials with accurate and consistent machinability ratings. In other words, there is a high demand for a short-term test that would require a small amount of work material and time, and that can be utilized in the steel mill for machinability assurance. For this reason, one of the main requests of HRL, mentioned on page 4, was to find or develop a shot-term test that correlates well with the PPT and can be utilized in production lines for daily machinability evaluation.

Chapter 3: APPROACH TO SHORT-TERM TESTING

The main requests of HRL were; (1) to find or develop a short-term test that correlates well with the PPT and can be utilized in production lines for machinability assurance, and (2) to provide recommendations, if any, on their machinability evaluation system with an emphasis on the Automatic Screw/Bar Machine Test [12], a standardized PPT.

Although there are no cut-off values, in terms of consumed material and/or testing time, to aid in identifying whether a given test is of the long-, medium-, or short-term type, some tests are usually regarded as short-term tests ([4] to [11]). These and others are critically viewed on pages 30 to 89 and briefly listed in Table 3.1. The long-term tests include the Taylor type (i.e., ISO test) and all the simulated production ones, such as the PPT.

Examination of the machinability dilemma, in terms of the many definitions and descriptions, various predictive models and developed tests, and its current data disadvantages, confirms that machinability should stand for machining efficiency and should be viewed as a probabilistic input/output system. The many combinations of input and output factors constitute the machinability space, and machinability improvement can be indicated by; (1) a better machined part, (2) a higher tool life or smaller tool wear rate, and/or (3) lower cutting forces, consumed power, or cutting temperature.

Table 3.1 Some Short-Term Tests

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(1) Facing Tests
(2) Taper and Variable Turning Tests
(3) Step Turning Tests
(4) Other Short-Term Taylor Type Tests
    1- Sliding Wear Tests
    2- Micro Wear Tests
    3- Softened (Degraded) Tool Tests
    4- Radioactive Tracer Tests
    5- Shortened Conventional Tests
    6- Extrapolated Cutting Conditions Tests
(5) Conventional and Non-Conventional Cutting Forces Tests
(6) Cutting Temperature Tests
(7) Double Tool Tests
(8) Go No-Go Feed Tests
(9) Penetration Tests
(10) Short-Term Face Milling Tests
(11) Power Hacksawing Tests
(12) Machinability Tester Machine Tests

Due to the inherent variation in work material, cutting tool and cutting fluid lots, deterministic analyses are not appropriate for machinability testing. In a given machining space, the machinability of various batches (lots) of a work material can be assumed to have a normal distribution with a mean and a variance, where the variance would reflect the consistency of the work material manufacturer. Also, variations from one lot to another can be in terms of means (machinability levels) and variances (homogeneities). The true mean and variance of a work material should be the norms for which the material was originally designed. Any quality control test should, thus, be capable of identifying any mean and/or variance deviation from these norms. Studies that utilize only one lot of a commercially available material and claim high correlation with industrial ratings are, therefore, questionable. The ISO test, the only international machinability test, recognizes this fact and, in turn, specifies a certain production method to be applied in preparing the work materials for testing.

The most reliable machinability tests are the actual production ones. They are the most expensive, but the most reliable ones. The second most accurate, but still expensive tests, are those that closely simulate actual production conditions in the laboratory, such as the PPT. Hence, the further the testing conditions move away from production situations, the lower the reliability of the results. Therefore, any short-term test should not be used in isolation but rather in conjunction with the long-term test results of a given testing domain.

In other words, it is unrealistic to market a new material based only on the outcome of some short-term test results.

None of the short-term tests, given in Table 3.1, has been adopted in a wide spread fashion. Therefore, their validity is limited to their testing domain. Examination of these tests indicates that the majority was developed to correlate with the speed for a given tool life (i.e., Taylor test results). Meanwhile, several investigators concluded that the Taylor test results do not correlate well with those of the PPT ([2], [3], [25] & [103]). This was attributed to the fact that the desired tool life in a PPT is at least two or three times that of a conventional turning test [25]. Also, turning on a lathe is of the continuous cutting type, while it is of the intermittent type for the automatic screw machine [103]. With the exception of the cutting temperature test developed by Kane and Groover [99], none of the short-term tests has shown good correlation with the PPT. However, the main drawback to the utilization of the cutting temperature test as a quality control tool for machinability assurance is the time required to accurately calibrate each combination of tool and work material lot.

It was, therefore, decided to set some requirements that should be fulfilled by any published short-term test in order to be considered as having the potential for satisfying HRL's first request. The short-term test should; (1) closely simulate production situations (i.e., be performed on a conventional machine, employ commercial cutting tools, require the least possible setup, and test near production cuting conditions), (2) require small amount of work material and time, (3) be very sensitive to machinability variations, (4) have high repeatability, and (5) be capable of being utilized in the steel mill for machinability assurance. In addition to these requirements, the test should be performed on one of the machines available at either LU or HRL.

Based upon these requirements none of the testing procedures of the short-term tests qualified. Nonetheless, the setup of the power hacksawing tests is the simplest. This is followed by the conventional cutting forces tests. It was, therefore, decided to develop a power hacksaw test. However, examination of the PPT procedure and results pointed to possible flaws in the HRL machinability evaluation system. For example, it is questionable how two materials' results differ by only five pieces per hour (383 & 388 pcs/hr), given that there are so many input factors that can sometimes be beyond control in such a long-term test (i.e., cutting fluid variations).

Examination of the PPT procedure (described on pages 76 to 80) as applied by different engineers at HRL over a period of years ([2], [3] & [151]) indicates the following:

(1) In the study by Murphy and Aylward [2], the surface roughness limit was 300 micro-inches (7620 micro-mm) for the rough form tool and 150 micro-inches (3810 micro-mm) for both the medium and finish form tools. Litwa [3] utilized a different end-point criterion, a 300 micro-inch (7620 micro-mm) for both the rough and finish form tools.

(2) In both studies by Murphy & Aylward [2] and Litwa [3], some standard material was utilized for the comparative performance of other materials. Yet, Aylward [151] did not use a material as a base steel. He just searched through trial-and-error until similar trends of part quality for eleven materials were found.

(3) The trial-and-error search procedure (to determine the maximum production rate of the standard material and to locate the production rates of other materials at which they provide similar trends of part quality to that of the base steel) was applied in the three studies ([2], [3] & [151]), except for the last four materials (9T, 10T, 11T & 12T in Appendix A) tested by Litwa [3]. He used an experimental design with three levels instead.

(4) The standard material varied from one study to another. For the work materials given in Appendix A; (a) the 9T was the base steel for the last four materials, (b) the 625L286 was the standard steel for the middle three materials, and (c) none was utilized for the first eight materials. If the base material varies from one project to another, how can the materials' performance from different studies be related?

From the above, it can be concluded that the PPT procedure has changed over time. In addition, the process of locating similar trends of part quality is subjective. Additional examination of these final project reports indicates that there is no standard format to be followed by different engineers to evaluate the machinability of new materials. For example, Litwa [3] employed a metallurgical test to determine the number of metal inclusions per unit area, while this test was not utilized in the other studies. Further, from observing an operator running the PPT, it was noticed that testing for 6-8 hours of production was not performed in one day. Sometimes the test was run for just half an hour to take a reading. It is questionable whether starting and stopping the machine in a test run can influence the results, due to variations in the machine and cutting fluid steady-state conditions. Finally, from a personal interview with Mr. R. Litwa of HRL, he mentioned that any of the first eight materials utilized for this study can be considered an outlier. That is, these materials exhibited different performances than those found by Aylward [151] when re-tested. It should be mentioned here that initially, the objective was to utilize only work materials of production rates for which the current (at the time this study was initiated) machinability group of HRL have enough confidence. However, this changed to include other screw machine materials, because the group tested only seven materials and two of them did not yield any production rates.

It was, therefore, decided to assume that the maximum production rates of the work materials under investigation are the ones given in Appendix B. The main objectives were, hence, to develop three short-term tests (instead of one) that would;

(1) test different aspects in the machinability space of the free-cutting steel with the least possible sources of error,

(2) screen among the materials under investigation with high sensitivity and repeatability,

(3) provide reasonable correlation with the PPT results, and

(4) be capable of evaluating the machinability level in daily production.

The underlying hypothesis was that if none of the three short-term tests correlates well with the PPT results, but at the same time they correlate well among themselves, the changes of the PPT procedure over time could be the reason.

The strategy followed for developing the three short-term tests was based on; (1) the above mentioned requirements in a short-term test, (2) available machines at either LU or HRL, (3) HRL machinability evaluation system (described in section 2.3), (4) the machinability space of free-cutting steels (explained in section 2.4) , and (5) the desired applications for these tests. The ultimate goal is to utilize these tests in the HRL machinability evaluation system for;

(1) qualifying potential materials for the PPT,

(2) assuring the quality of the screw machine material, and

(3) determining the machinability level in daily production.

The strategy involved decisions ranging from how many work materials should be utilized to what type of testing methodology should be excercised. Since valid correlations should be based on a reasonable number of test points, it was decided to utilize at least ten materials, especially those from which the current machinability group have enough confidence. As mentioned above, the group had only confidence on the last seven materials, given in Appendix A. Further, the group was still testing the last four materials when this study was initiated. Due to that and other factors, such as the limited stock of the screw machine materials and the desire to have production rates with small and large differences, it was decided to utilize fifteen materials (described in section 3.1). That is, if one or more of the materials would turn to be an outlier, the validity of the correlation would still be maintained. Although two of the last four materials did not yield any production rates, they were still included in this study. The idea was to utilize their results in predicting their possible production rates and to compare that with the cutting conditions under which they were tested.

The selected work materials for this study are described in section 3.1. Section 3.2 covers the reasons behind the developed three short-term tests. These tests are named the Power Hacksaw Test (PHT), End Milling-Slotting Test (EMST), and the Cutting Forces Test (CFT). Finally, the testing methodology followed for the three tests is described in broad terms in section 3.3.

3.1 Work Materials

Appendices A and B present the fifteen work materials utilized for this study in terms of chemical compositions, mechanical properties and the PPT results. Basically, the work materials are different designs for the 12XX series of free-cutting steels (they are, simply, low-carbon cold-drawn steels with additives to enhance their machining efficiency).

The first eight materials are different designs for the 1213 grade. They were a part of a study aimed at the development of non-leaded free-machining strand-cast steels [151], instead of ingot-cast steels. The objective was to determine the optimum base composition for strand-cast 12XX steels through varying phosphorus, sulfur, and nitrogen contents and the deoxidation method. For example, the 703C034 material was only vacuum deoxidized, while the others were vacuum deoxidized and then treated with different amounts of chemical deoxidizers (rare earth metals/mischmetal).

The last seven materials are different designs for the 12L14 grade. They were a part of a study directed at the development of substitutes for leaded steels [3]. For the first three materials of the last seven, the objective was to compare the performance of non-leaded bismuth-treated steels versus a leaded one (623L286) as a standard material. For the last four materials, the objective was to compare the performance of non-leaded selenium-treated and low bismuth-treated steels versus a leaded one (9T) as a standard steel.

3.2 Short-Term Tests

As mentioned earlier, on page 106, the machinability space of free-cutting steels is limited to automatic screw/bar machines of the single or multiple spindle type. These machines are usually utilized to produce parts in finished form. For this reason, the part quality (in terms of surface finish and size accuracy) obtained for a reasonable tool life is the objective of all the automatic screw/bar machine tests. The space is further restricted to HSS tool materials, since the achievable cutting speeds are in the economical range of the HSS tool materials. This is due to the structure of these machines and that they generally accommodate bars up to two inches (50.8 mm) in diameter. Also, normally form tools made of HSS tool materials are utilized on these machines. This space is further complicated by the presence of built-up-edge (BUE). Abeyama and Nakamura [103] have shown both surface finish and size accuracy to be more related to the BUE height than to the tool wear. They concluded that the most suitable steels for the automatic screw/bar machines are those that do not have the tendency for BUE formation. This is most likely due to BUE instability. Finally, turning on an automatic screw/bar machine is of the intermittent type.

The reasoning behind the developed tests are, thus:

(1) The Power Hacksaw Test (PHT) was developed due to the simplicity of the power hacksaw machine setup, the small diameter of the utilized bars, one-inch (25.4 mm) in diameter,

and the fact that the work material becomes the dominant factor to the outcome of the cutting process when machining under constant feed force. The experimental designs of previous power hacksawing studies that addressed the machinability of work materials ([17] & [110]) lacked valid statistical analyses. Perhaps the statistical tools were not that familiar around the time these investigations took place. Tipnis and Joseph [25] mentioned that statistically planned machinability tests were introduced in the 1960's.

(2) The End Milling-Slotting Test (EMST) was developed to duplicate the above mentioned characteristics of the machinability space of free-cutting steels. The literature survey of milling machine tests, given on pages 63 to 69, indicates that the end milling-slotting operation has never been utilized for evaluating the machinability of work materials. Briefly, the test revolves around measuring the width of machined slots over twenty minutes of cutting. Three replications were taken on each material. For each replication, the rate of the slot width variation (an indicator to dimensional stability) was determined using linear regression. Dimensional stability or accuracy is usually important when adjustments for tool wear can not be made (i.e., for complex form tools which are usually used on automatic screw/bar machines and in end-milling slots).

(3) The Cutting Forces Test (CFT), which is of the conventional type, was developed due to the fact that the setup

requirements are the second easiest after those of the power hacksaw machine. Although the literature survey of cutting forces tests, given on pages 40 to 51, indicates that none of them has shown good correlation with industrial ratings (i.e., the PPT results), a cutting forces test was still developed. That is, the cutting forces are the main sources of the heat generated during cutting, which raises the cutting temperature that has correlated well with commercial ratings [99]. In addition, none of the previous studies addressed the relative sensitivity of the cutting forces components (cutting, feed and radial forces) in differentiating among the machinability of work materials. Particularly, the radial force is often neglected due to its smaller magnitude relative to the other two components, while it is the one that directly affects the tool nose wear and, thus, lowers the dimensional accuracy. Cook [32] mentioned that the degree of tolerance degradation is associated with the wear of the tool nose radius and flank, and that it generally correlates well with the tool flank wear.

The above three tests did, thus, investigate the performance of the utilized work materials on different operations (machines), under various cutting conditions, and with different cutting tools.

3.3 Testing Methodology

The procedure below was followed for all three tests. Simply, the procedure was to;

(1) define the test objective in terms of specific purposes, input and output factors, and likely sources of error. Since the tests were developed to mainly correlate with the PPT results, all tests were performed dry to avoid possible sources of error, such as cutting fluid variations. In other words, it is more important to reduce the level of noise rather than to determine the ranking of the materials when using a cutting fluid.

(2) do preliminary testing on a representative random sample and on carefully selected test points,

(3) analyse the preliminary results, investigate the basic assumptions and proposed models, check measuring device(s) variations, and apply ANOVA,

(4) use the results from the above analyses without any extrapolation for decisions on future designs, and

(5) continue until the test objective is satisfied.

Chapter 4: POWER HACKSAW TEST

4.1 Introduction

Feeding mechanisms can be classified into two groups; (1) Constant Feed Rate (CFR), and (2) Constant Feed Force (CFF) or Constant Pressure. The CFR type is employed in most metal cutting processes. The CFF type is used in some bandsaw machines [124] and in all hacksawing equipment except for the positive displacement one, which is not commonly used [122] and would fall under the first group.

The underlying principle of applying the CFF concept in any metal cutting operation for machinability evaluation is that the work material would become the dominant factor to the outcome of that process. This is in terms of cutting time, tool wear, etc. Examination of previous work indicates that the CFF concept had been utilized by many investigators to study the machinability of work materials in mainly three operations; (1) Sawing ([17] & [110]), (2) Turning [18], and (3) Drilling ([17] & [110] to [115]). However, the main drawback for the last two operations is the special setup needed to convert a CFR machine to a CFF type. For this reason and for other considerations, mentioned in Chapter 3, the power hacksaw machine was selected for one of the three short-term tests.

In previous power hacksawing studies, explained in detail in Chapter 2, various indicators and experimental designs were adopted.

Briefly, in a work by Boston and Kraus [126] to investigate the performance of cutting fluids when sawing various metals on a power hacksaw machine, a new blade was assigned to each cutting fluid. The time required to cut a 1/8-in. (3.2 mm) thick slice from 1 1/2-in. (38.1 mm) square bars was the indicator. Eight metals were utilized for their investigation. The problem of reducing the effect of the blade wear rate on the obtained results was addressed through the utilization of three series of cuts, where the second series was in reverse order to the first and third ones, on the eight metals (one after the other). In a study by Cook and Davis [17] to investigate the machinability of free-turning brass, another approach was utilized. Only one blade was used, and the average of six determinations for the number of strokes to saw through a 1-in. (25.4 mm) diameter bar was the indicator. Frequent checks on a standard material was employed to insure the validity of the results. Others [128] used the number of sawed sections required to achieve a certain cut-off value for the cutting time per section (in minutes) as an indicator to the useful life of the blade.

However, there are disadvantages to these studies, one of which is the underlying assumption of a zero tolerance for the workpieces. Differences due to tolerances can be significant at low feed pressures. Further, none of these experimental designs analyzed the data variability. The variability of the data should be first analyzed before any valid conclusion can be drawn. In short, neither study investigated the 12XX steel series or the suitability of this test as a quality control tool for assuring the machinability of a work material.

nor had these earlier tests included a complete statistical analysis.

The main objective of the Power Hacksaw Test was, therefore, to investigate its potential in screening among the free-machining steels. This is through using an improved indicator and more rigorous statistical analysis. A second objective was to study its capability as a quality control means for the determination of the machinability level in daily production.

4.2 PHT Testing Equipment

All tests were carried out on a Peerless high-speed standard-type power-hacksaw machine. It has an adjustable spring-tension feed pressure, a three-speed gearbox, a 9 by 9 in. (228.6 by 228.6 mm) capacity, and a 6-in. (152.4 mm) stroke. The feed-pressure lever which controls the tension in the feed spring can be engaged to any notch in the ratchet that has 29 notches corresponding to loads from around 5 to 225 lbs (2 to 102 Kg). Notch number one, located at the bottom of the ratchet, provides the lowest constant pressure, (see reference [125] for more detail).

The fifteen work materials utilized for this study, described in detail in section 3.1, are basically different-material designs for the 1213 and 12L14 grades of the 12XX series (SAE Numbers, [1]). Table 4.1, abstracted from reference [138], provides their recommended sawing conditions. These conditions are for a HSS hacksaw blade and materials' hardness ranging from 150 to 200 BHN. The condition marked by '*' was selected for the investigated work materials, bars of 1-in. (25.4 mm) in diameter. The blades were HSS material, 17 x 1.25 x .062 in. (431.8 x 31.8 x 1.6 mm) dimensions, 10 teeth per inch (.4 teeth/mm), Raker set (right-straight-left etc.), and from two different manufacturers (Rocket, used in preliminary tests, and Starrett, used in actual tests).

Table 4.1 <u>Recommended Sawing Conditions</u>

Material (in.)	Thickness (mm)	Teeth/ inch	Pitch (mm)	Speed strokes/min. 1213	12L14	Feed Pressure
< 1/4	< 6	10	2.5	170	180	M *
1/4 - 3/4	6 - 18	6	4.0	170	180	M
3/4 - 2	18 - 50	4	6.3	160	170	M
> 2	> 50	4	6.3	160	170	H

4.3 PHT Preliminary Tests

The first objective was to investigate whether the test would or would not differentiate among seven of the materials, and, if it did, at which feed pressure range (Low, Medium, or High), which speed value (120 strokes/min., the machine-maximum-limit, or 90 strokes/min.), and under which indicator the differences would be statistically most powerful.

Figure 4.1 shows the test as an input/output system, part of the first step in the planned testing methodology outlined in section 3.3. The procedure followed was to assign a new Rocket-hacksaw blade to each of the seven materials. Next to be determined was how to minimize the effect of the variations in the blades, in terms of the inherent deviations in the manufacture of hacksaw blades (given in [122]) and the possibility of having different wear-rates. The cutting speed is the main contributing factor among the other cutting conditions to the wear of tools. Thompson and Taylor [127, p. 46] had concluded that if the stroke rate was to be doubled the wear rate would have increased more than six-fold. For this reason, it was decided to saw only at a rate of around 90 strokes per minute (actual speed was 92 strokes/min.) even though the recommended speed was almost double that. Therefore, the lower the speed value, the more dominant the work material becomes. Thompson and Sarwar [122] mentioned that because of the traditional method of manufacturing hacksaw blades, the cutting edge profile differs considerably from one tooth to the next on the same blade. However, when the average of all profiles of a blade was compared with the average for other blades having the same teeth pitch, small variations were observed. The blades were from the same manufacturing batch, and consequently the assumption of insignificant blades' differences due to manufacture was made. Because the selected speed was very low, the possible differences in blades' wear-rates were also assumed to be insignificant. Later, in section 4.4.3, a test was run to validate this assumption. In addition, the common assumption of homogeneous work materials was employed.

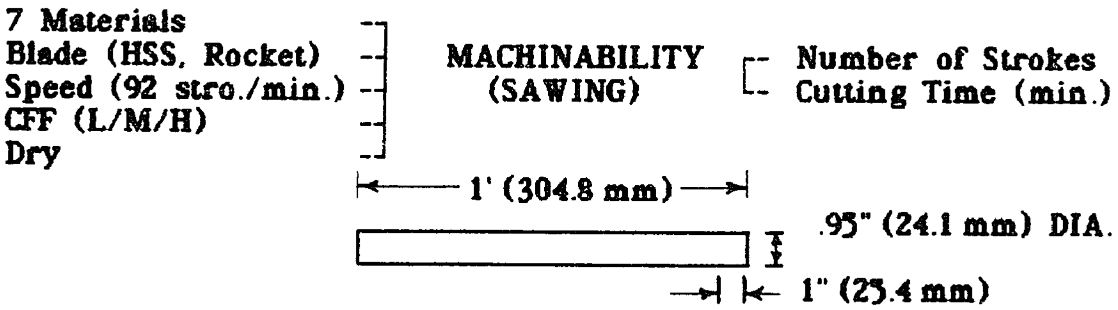


Fig. 4.1 Power Hacksaw Test (Preliminary Tests) as I/O System

Other possible sources of error that were identified could include the bars' outer-skins. The bars were, hence, turned down by a .025-in. (.64 mm) to remove the outer-skin and to achieve a smaller tolerance on the bars' diameters. Five replications were taken for each material at each of the three feed pressures, where L, M & H corresponded to notch numbers 5, 10 & 20 respectively, and an inch apart to prevent possible thermal effects. The test was conducted dry to avoid any possible source of error from the likely cutting fluid variations. The number of the strokes and the sawing time were both recorded by means of counting and using a stop watch.

Table 4.2 presents the obtained data at the Low feed pressure along with the analysis of variance (ANOVA) results. The number of strokes was chosen instead of the sawing time to be the indicator. That is, the sawing time would also reflect the variations in the speed of response for starting and stopping the stop watch. However, the sawing time was measured in subsequent testing as a check by calculating the ratio of the number of strokes to cutting time, which is constant and equal to 92 strokes per minute.

Examination of table 4.2 indicates that the average of first cuts (80.0 strokes/min.) was much smaller than the others and, thus, may not belong to the same population. The F-ratio of within materials is significant. This is attributed to the fact that the cutting edges of new blades are very sharp for first time usage. By regarding the first replication as blades' break-in and taking only the last four replications into account, the F-ratio of among materials increased to 146.95 and the F-ratio of within materials dropped to 1.81 and, hence, became insignificant.

Table 4.2 Sawing Results at Low Feed Pressure

Sawing Data (strokes/minute):

Material	Replication Number					Average	Variance
	1	2	3	4	5		
705 E001	76	75	77	77	74	75.8	1.7
705W002	91	97	100	95	94	95.4	11.3
705 E017	76	83	83	81	80	80.6	8.3
705 E014	98	109	109	104	109	105.8	23.7
705 E003	76	82	85	83	82	81.6	11.3
705 C034	73	78	76	74	74	75.0	4.0
705 E002	70	73	78	80	79	76.0	18.5
Average	80.0	85.3	86.9	84.9	84.6	84.31	

ANOVA Table:

Source	SS	df	MSE	F-ratio	
Among Materials	4170.343	6	695.057	130.00	> F(.01,6,24)= 3.67 Sig.
Within Materials	186.867	4	46.717	8.74	> F(.01,4,24)= 4.22 Sig.
Error	128.333	24	5.347		
Corrected Total	4485.543	34			

Figure 4.2 shows no dependency between the averages and their variances (VAR.), calculated from the last four replications' results obtained from the Low feed pressure. Therefore, data transformation to stabilize the variance was not needed. This same conclusion was also reached for the results of the Medium and High feed pressures. The 705E002 variance (15.00) is much higher relative to other materials' variances. This could be an indication of a nonhomogeneous material or may suggest the need for additional samples. However, it was concluded that additional sampling for nonhomogeneous materials would prevent the utilization of the Duncan Multiple-Range Test [152, p. 279]. This is one of the statistical tools planned for use in data analysis and requires equal sample sizes to provide a materials' ranking based upon averages and variances. Further, higher variances point to materials of high variability and they should be identified.

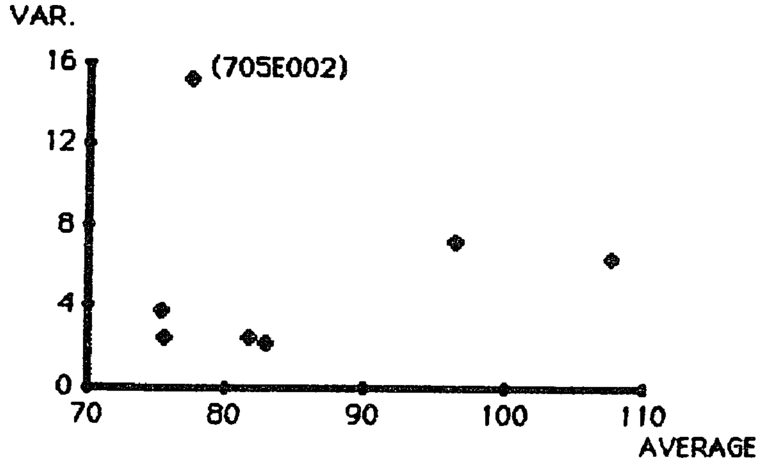


Fig. 4.2 Variances Versus Averages in Sawing at Low Feed Pressure

Table 4.3 provides the Duncan Multiple-Range Test results for the three feed pressures. Figure 4.3 presents their F-ratios for both among and within materials. Table 4.3 shows no overlapping among the possible groups of the Low feed pressure. The materials ranked almost similarly at both the Low and Medium positions. The 705E014 performance was independent of pressure, while the 705C034 gave a different behavior at the High feed pressure. From table 4.3 and figure 4.3, it was concluded that screening among materials is statistically most powerful at the Low feed range, (based upon the highest value in the F-ratios of among materials given that the ones of within materials are insignificant). This is in agreement to a similar conclusion reached by Crampton [110, p. 281]. He found that when sawing copper alloys at higher pressures and speeds the differences between materials would become very small.

The correlation coefficient between the HRL production rates and the sawing Duncan results (after determining each group average) of the Low feed pressure was equal - .134 (- 13.4 %). As expected, the correlation was negative and meant that materials ranked good by the screw machine test required fewer number of strokes. However, the magnitude of the coefficient was very small and it was questionable whether there was an assignable cause, possible outliers in the production rates of HRL, or a small representative sample size (seven materials).

Table 4.3 Duncan Multiple-Range Test Results For Low, Medium & High Feed Pressures

Low Feed Pressure (Sample Size = 4):

Material	C034	E001	E002	E017	E003	W002	E014
Average	75.5	75.8	77.5	81.8	83.0	96.5	107.8

Medium Feed Pressure (Sample Size = 5):

Material	C034	E002	E001	E017	E003	W002	E014
Average	32.6	32.6	32.8	33.4	34.0	35.2	39.0

High Feed Pressure (Sample Size = 5):

Material	E001	E002	E003	W002	E017	C034	E014
Average	17.6	18.6	19.0	19.4	19.6	19.8	21.4

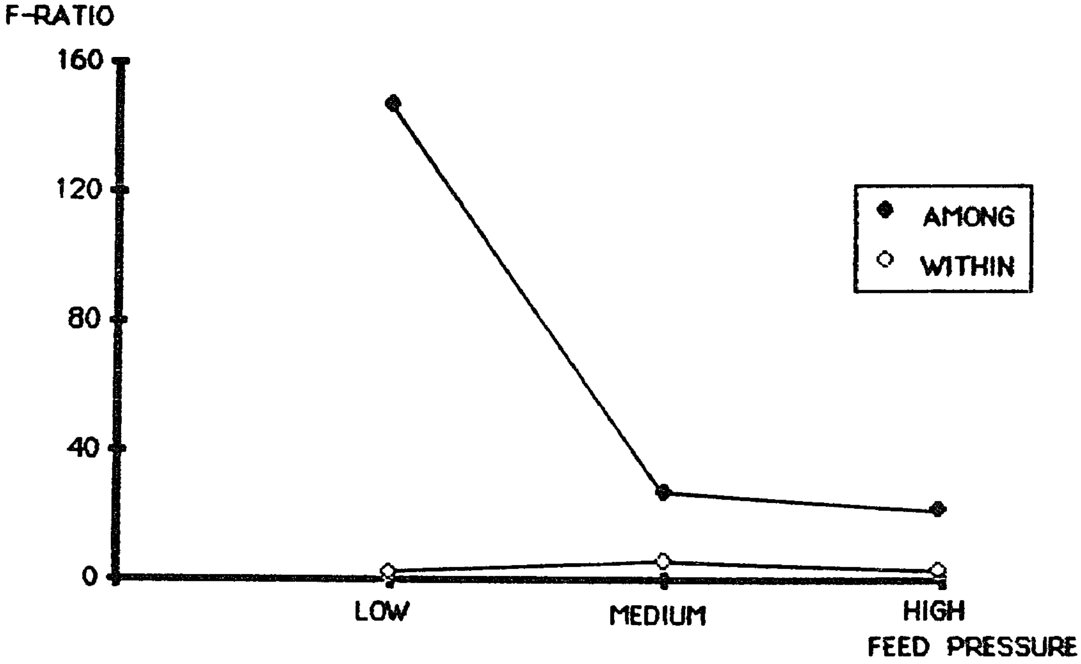


Fig. 4.3 F-Ratios in Sawing at Low, Medium & High Pressure

In search for the assignable cause, it was discovered that the bars were not of constant diameters (small tolerance) and were tapered, due to a misalignment in the turret lathe that was used in removing the bars' outer-skin. The presence or absence of this misalignment would have not altered many of the previous conclusions. At medium and high feed pressures, these variations can be neglected. Nevertheless, it was decided to measure the bars' diameters in subsequent testing, and to apply the test on a larger sample (fifteen materials).

The preliminary testing conclusions were therefore:

(1) The Power Hacksaw Test does screen among the materials.

(2) Screening is statistically most powerful at the Low feed range.

(3) The machinability indicator should be the number of strokes per cross section area.

(4) A sample size of five replications is sufficient.

(5) The ratio of number of strokes to sawing time can be used to check the accuracy of counting.

4.4 PHT Actual Tests

The objective was then to determine a position in the low feed-pressure range (notch numbers 1, 3, 5, & 7) at which screening is statistically most powerful.

Figure 4.4 shows the test as an input/output system. A new Starrett-hacksaw blade was assigned to each of the fifteen materials. The bars' diameters were measured at five places corresponding to the planned five replications. Each blade was employed to saw a sample of size five at notch numbers 1, 3, 5 and 7 respectively. Both number of strokes and cutting time were recorded and a complete randomization was utilized only among materials, in order to save setup time.

Figure 4.5 provides the obtained F-ratios for both among and within materials at a 99 % confidence level. At the lowest feed pressure (notch number one), the level of noise was much higher than the differences among materials. This is illustrated in the relative low F-ratio (28.22), and in the very high variances found at that position. It was, therefore, concluded that below a certain constant feed force value, the level of noise increases sharply. The probable sources of noise would include materials' impurities (variations within materials) and machine (system) rigidity. Otherwise stated, at the lowest pressure value, one will be looking at variations within materials reflected in very high variances rather than variations among materials. The obtained results at notch number one were then disregarded from further analysis due to their high variances that also seemed to be average-dependent. For the other positions, the variance was average -independent and, hence, data transformation was not required.

The F-ratio for within materials at notch number seven was significant, due to the first replication results that had a lower average value in comparison to the others. The likely explanation of such a phenomenon is due to thermal effects. That is, both bars and blades were cold for first cuts, and more heat is generated at heavier pressure values, especially when testing is conducted without a cutting fluid.

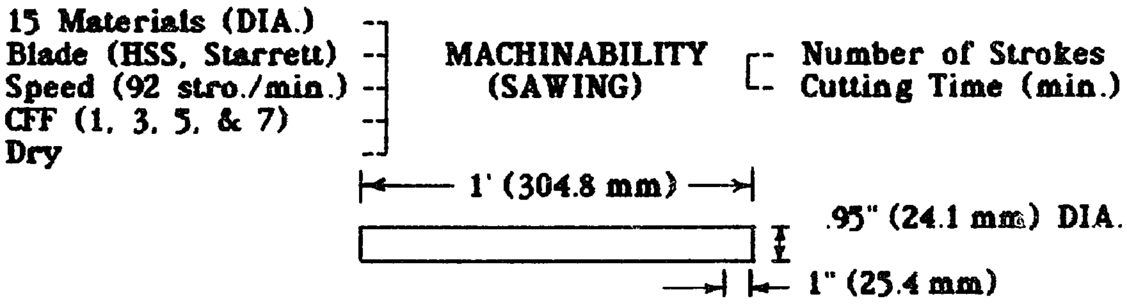


Fig. 4.4 Power Hacksaw Test (Actual Tests) as I/O System

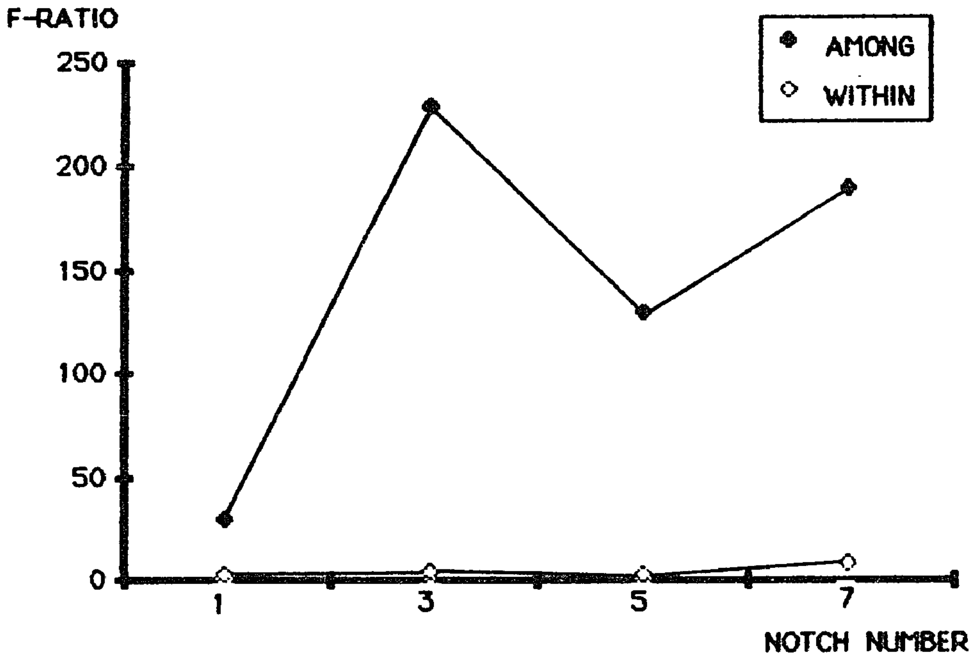


Fig. 4.5 F-Ratios in Sawing at Notch Numbers 1, 3, 5, & 7

Figure 4.6 presents a dot diagram of the results obtained at notch numbers 3, 5, and 7, and the following conclusions were made:

(1) Materials exhibit different variances which are feed pressure independent.

(2) Materials' variances become smaller with heavier feed pressure.

(3) Increasing feed pressure reduces differences among materials.

(4) Ranking of materials is feed pressure independent in the feed range.

From figures 4.5 and 4.6, it was concluded that the ranking of the materials is statistically most powerful at notch number three. The correlation coefficients between HRL production rates, available only for thirteen materials, and the various possible groupings from the Duncan results of notch number three ranged from - 62 to - 64 per cent. This is much better than the preliminary testing value (- 13.4 per cent).

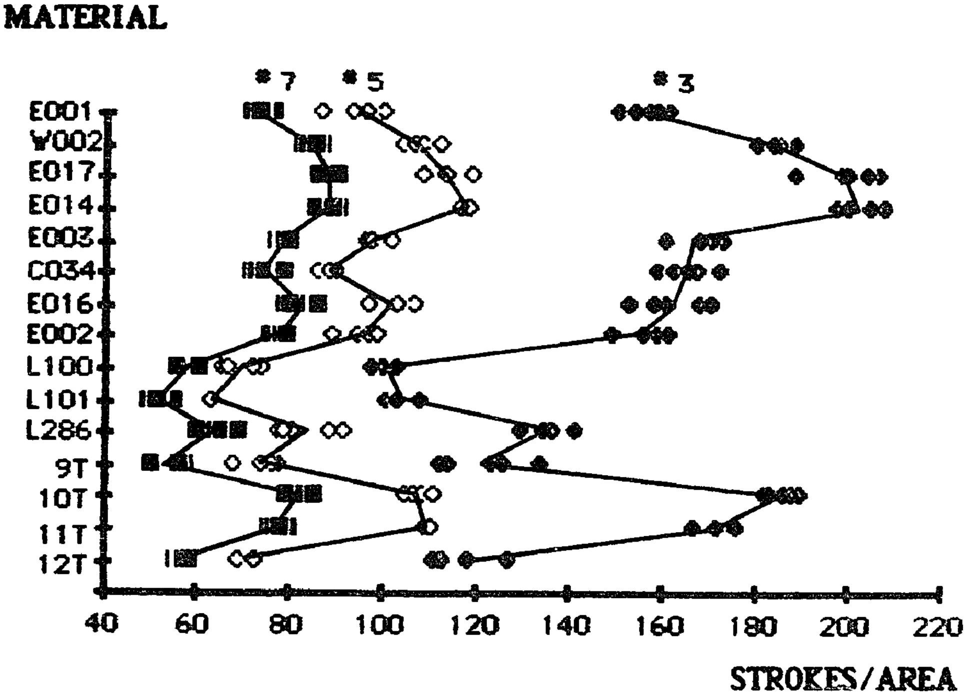


Fig. 4.6 Sawing Results at Notch Numbers 3, 5, & 7

4.4.1 Testing Outer-Skin Significance

The objective was, then, to test whether the outer-skin that was removed in previous testing is significant or not. If it is insignificant, the testing procedure would be far easier and shorter in time.

The fifteen materials were, therefore, sawed with the full cold reduction surface present at notch number three, hereafter designated "3S". The bars' diameters were still being measured because they ranged from .9983 to 1.0035 in. (25.4 to 25.5 mm) in diameter and the sawing was done at a very low feed pressure. While this range would be good for a tolerance, in sawing this slight variation is added almost every time a blade makes a stroke (pass). As a result, one may end up with a difference of up to a quarter of an inch (6.35 mm) in sawed lengths after one hundred strokes. Although it can be argued that this difference can be neglected relative to the total sawed lengths, it was decided that this variation is a source of error and can be influential when sawing at very mild cutting conditions. Unfortunately, this point was not further investigated due to the fact that bars of different sizes for each material would have been needed. The question of whether bars' diameters are significant or not was, then, left for the machinability group of HRL to answer. The bars' diameters were, hence, measured and their variation was eliminated through taking the strokes per area as the sawing indicator.

Figure 4.7 shows no dependency between the averages and their variances calculated from the results obtained at notch number 3S. The 705E016 variance (47.3) was much higher relative to other materials' variances. This same material had shown similar behavior at other sawing conditions. The Duncan results determined at the 3S condition gave less overlapping between the likely groups as compared to notch # 3 results. The correlation coefficient was slightly higher when the outer surface was present (- 65.1 %). The value increased to - 72.7 % when the 705E016 was considered to belong to a different population (a nonhomogeneous material). Additional correlation analysis is given in section 4.5.1.

Figure 4.8 shows a linear relationship between the results obtained for with and without the outer surface at notch number three. The correlation coefficient was 93 % and the null hypothesis (the estimated fitted line slope equals one) was accepted based upon the t-statistic's (described in [152, p. 234]) results. It was, therefore, concluded that the materials' outer surface has no effect on ranking. Therefore, there is no need to remove the materials' outer surface before sawing. As a result, the test becomes simpler.

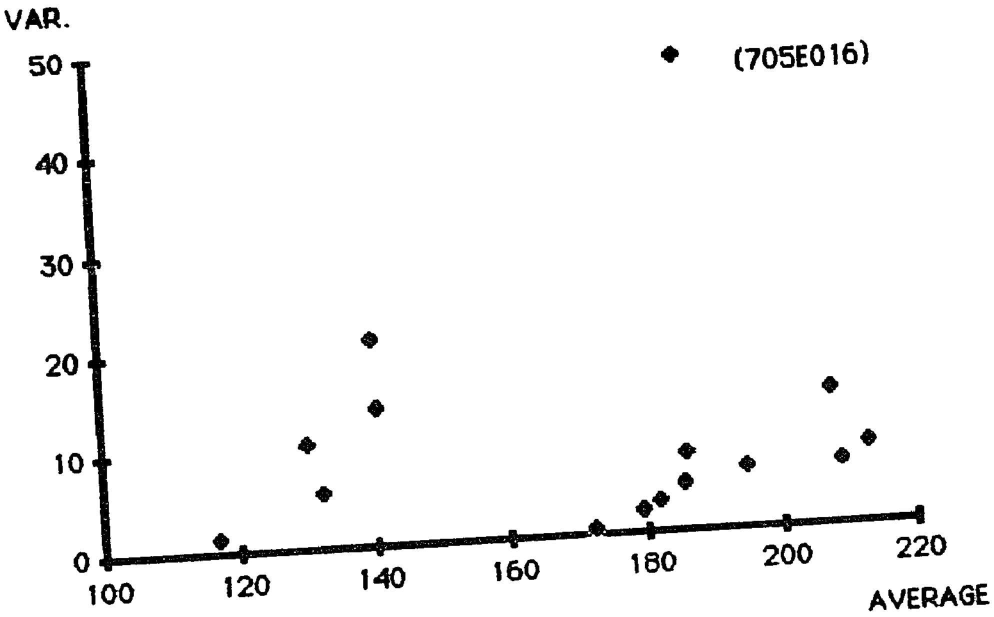


Fig. 4.7 Variances Versus Averages in Sawing at Notch # 3S

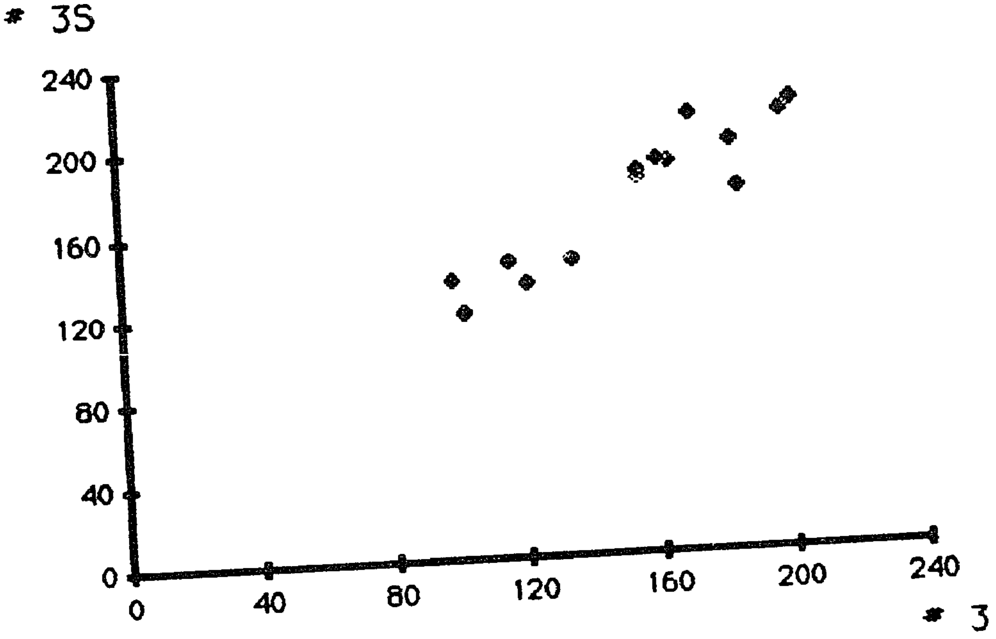


Fig. 4.8 Sawing Results at Notch # 3S Versus # 3

4.4.2 Testing Cold-Drawn Significance

The objective was, then, to investigate the effect of the cold drawing process on the materials' ranking. As mentioned in section 2.3, the materials are produced in one plant and then sent to another plant to be cold-drawn. The cold drawing process is not employed in the production lines of Bethlehem Steel Corp. If the cold drawing effects are insignificant on materials ranking, greater cost reductions can be realized. These are the costs of transportation and the cold drawing process itself. Further, the test can thus be utilized in the preliminary screening process (applied on small ingots produced at HRL) among the newly designed materials.

The following heat treatment was applied on the materials at HRL to remove the cold-drawn effects;

- heat at 1700 ^{o}F (922 ^{o}C) for an hour
- cool in furnace.

Figure 4.9 shows no dependency between the averages and their variances (VAR.) determined from the results of sawing the non cold-drawn bars at notch number 3, hereafter designated "3S-NCD". The 703E016 variance (43.6) was, again, higher relative to other materials' variances. Therefore, it was concluded that this material is non-homogeneous and violates the assumption of uniform work materials' characteristics.

Figure 4.10 presents a dot diagram of the results obtained from the 3S and 3S-NCD conditions. Examination of Fig. 4.10 points to the insignificance of cold-drawing on ranking except for the 705W002. This is the only material that had zerconium (Zr) and the highest carbon (C) per cent (see Appendix A). On the average, all materials (except the 705E001) required more strokes per cross section area after the removal of the cold-drawn effects. Although the additional strokes varied significantly among the materials, the Power Hacksaw Test does show the advantage of the cold-drawn bars over the hot rolled ones for the free-cutting steel.

Figure 4.11 shows a linear relationship between the results determined from sawing the bars with and without being cold-drawn at notch number three. The correlation coeffiecient was 96 % and the null hypothesis (the estimated fitted line slope equals one) was accepted. Therefore, it was concluded that the cold-drawing has no effect on ranking. The likely explanation to such a conclusion is that the bars' cores are the dominant factor in determining the required strokes per area. Possible cost reduction in applying the PHT for qualifying potential materials for the screw machine test is thus feasible. In addition, the test became more attractive as a quality control tool for determining the daily machinability level of hot-rolled bars in the production lines of the Bethlehem Steel Corporation.

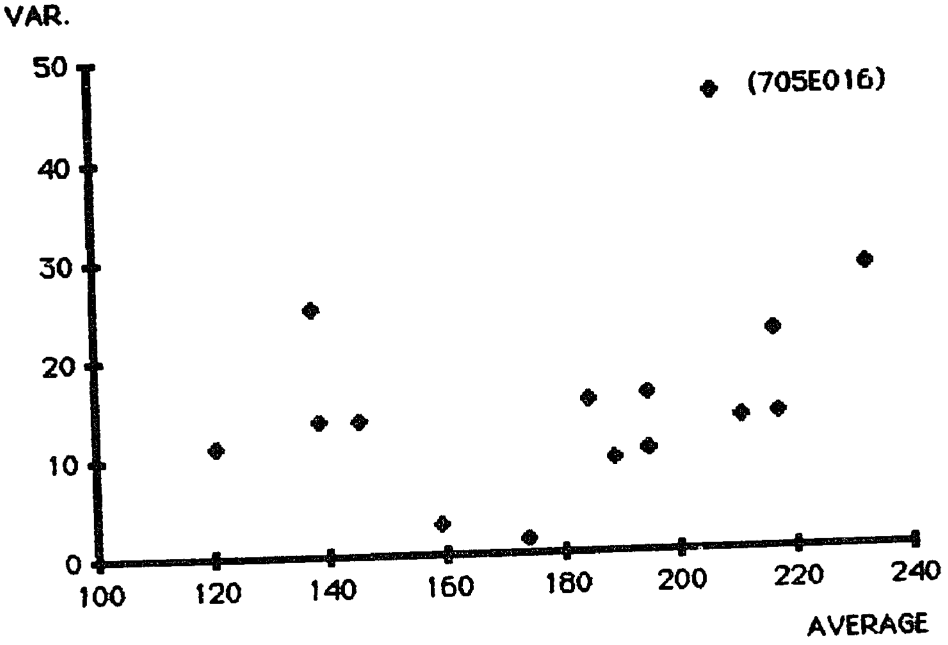


Fig. 4.9 Variances Versus Averages in Sawing at Notch # 3S-NCD

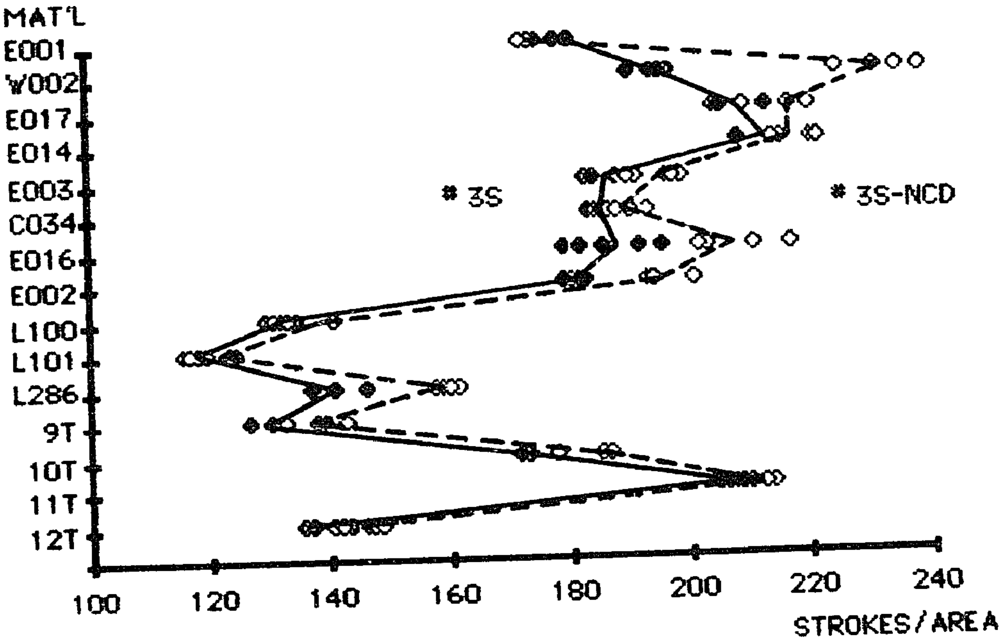


Fig. 4.10 Sawing Results at Conditions 3S & 3S-NCD

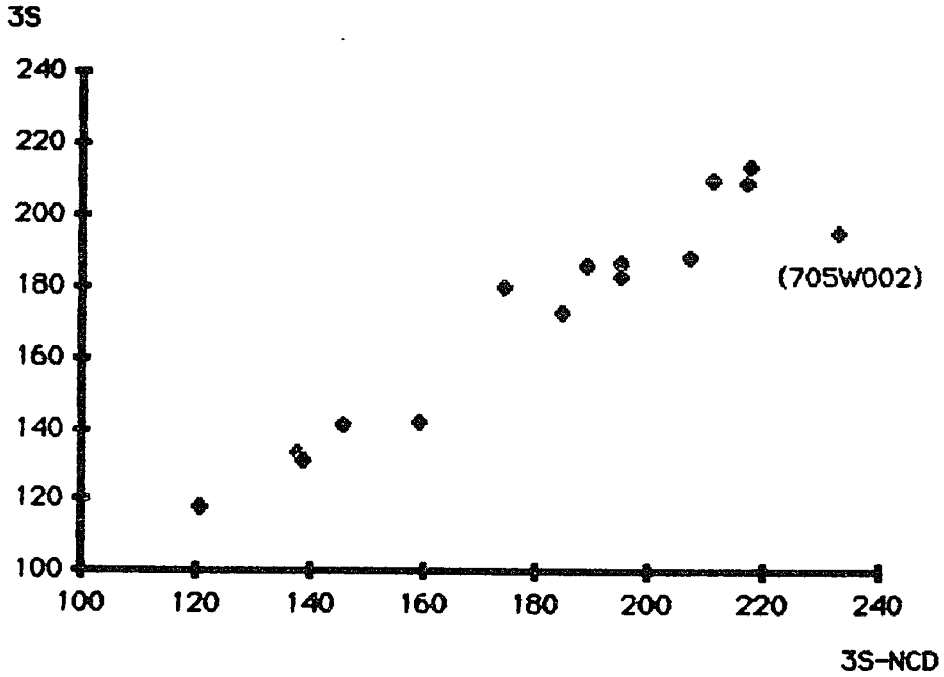


Fig. 4.11 Sawing Results of Condition 3S Versus 3S-NCD

4.4.3 Testing Blades' Wear-Rates Significance

The previous tests were executed under the assumptions of (1) homogeneous work materials, and (2) equal (insignificant) blades' wear-rates. As mentioned in section 4.4.3, the plot of the results' variances versus averages was utilized to determine whether a data transformation is required to stabilize the variance, and to validate the assumption of homogeneous work materials. Examination of these plots confirms the validity of the first assumption for all materials under investigation except the 703E016 which had shown very high variability.

For the second assumption, the following are good indicators of its validity:

(1) Testing was done at very mild sawing conditions. The work material characteristics dominate when machining at constant feed force, and this dominance increases with a decrease in speed and/or pressure.

(2) Only thirty cuts were put on each new blade at such mild conditions, and, hence, the blades' wear-rates were in the gradual-wear zone of the blades' lives.

(3) Table 4.4 shows high correlation values obtained among the results of different sawing conditions. From these high values, it was concluded that the ranking of materials is positively pressure independent in the low CFF range. In addition, the PHT is highly repeatable.

Although there was no strong evidence of any violation of the second assumption, a representative random sample of three materials (703E017, 703C034, and 631L100) was selected to further prove its validity. Table 4.4 provides a summary of the obtained results for these three materials along with their correlation coefficients with the HRL production rates.

A test was first run to determine whether there was a significant wear on the used (old) blades. Table 4.5 provides the results obtained from sawing, using five replications of the old and new blades on each material. Although the results had shown that wear did take place, examination of the differences 'd' between the results' averages of the old and new blades indicates that the amount of wear was almost equal. The variations in blades' wear-rates are, therefore, insignificant.

A dullness test was then applied on three new blades to examine whether the wear rates are significantly different. Figure 4.12 presents the dullness-test results along with the fitted linear-model obtained parameters. The vertical lines designate a change of bar. Due to the limited raw materials' stocks, only thirty five cuts were taken.

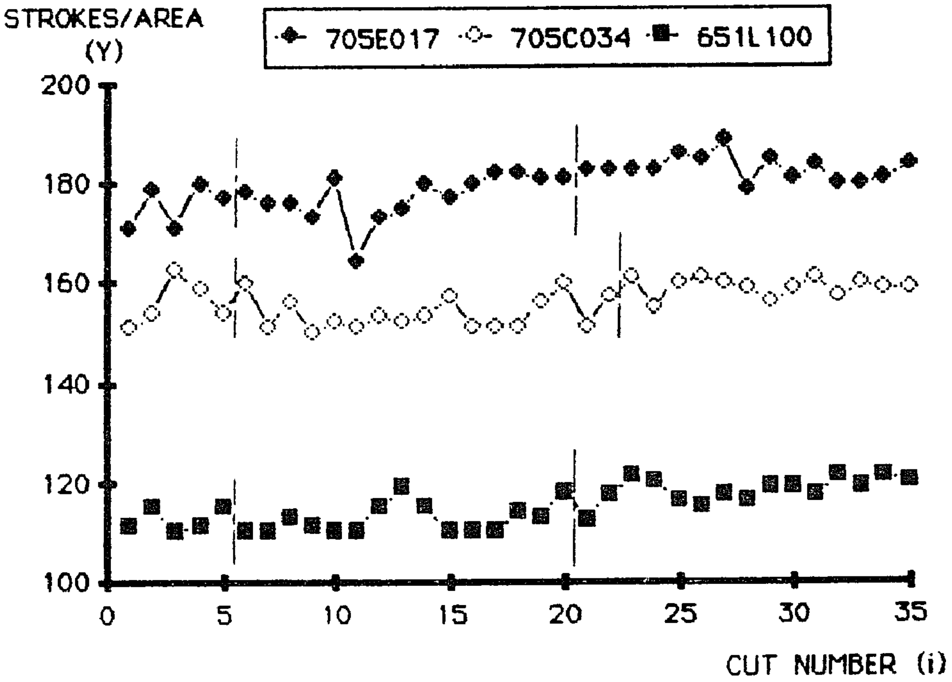
From the slopes' confidence intervals (99 % C.I.) in Fig. 4.12, it was concluded that variations in blades' wear-rates are insignificant, and thus the PHT assumptions are valid.

Table 4.4 Summary of 705E017, 705C034, and 651L100 Sawing Results

Material	HRL (pcs/hr)	Sawing Results (strokes/area) at Notch					
		# 1	# 3	# 5	# 7	# 3S	# 3S-NCD
705E017	388	943.5	200.4	114.2	88.3	208.2	217.3
705C034	440	642.9	165.9	88.2	75.8	185.7	189.2
651L100	538	443.1	100.0	69.5	57.6	132.6	137.9
	R	-.96	-1.00	-.96	-.99	-.99	-1.00

Table 4.5 Sawing Results For Old and New Blades

Material	Blade	Avreage	VAR.	d
507E017	OLD	202.8	14.9	27.5
	NEW	175.3	18.3	
705C034	OLD	180.3	2.0	24.6
	NEW	155.7	21.5	
651L100	OLD	135.0	4.4	22.7
	NEW	112.3	5.8	



705E017:	**Y = 175.0 + 0.25 (i)**	**Var(b1)**	**= 0.0042**
	R = 0.56	**99 % C.I.**	**= (0.08 , 0.42)**
705C034:	**Y = 152.7 + 0.17 (i)**	**Var(b1)**	**= 0.0034**
	R = 0.46	**99 % C.I.**	**= (0.02 , 0.32)**
651L100:	**Y = 109.7 + 0.28 (i)**	**Var(b1)**	**= 0.0020**
	R = 0.74	**99 % C.I.**	**= (0.17 , 0.40)**

Fig. 4.12 **Dullness Test Results For 705E017, 705C034 & 651L100**

4.5 PHT Summary and Applications

Table 4.6 provides a summary of the PHT conclusions drawn up to this point of testing. Other questions regarding test sensitivity, materials that reflected biggest disagreement between the sawing results and HRL production rates, and the ability to duplicate the obtained results on a different sawing machine are answered in the following section. The recommended procedures for applying the PHT in: (1) screening among materials, (2) qualifying potential materials for the screw machine test, and (3) determining the machinability level of a given material in daily production are then given in section 4.5.2.

4.5.1 Correlation with HRL Results

In the process of duplicating the PHT setup at HRL, six materials were chosen as a representative sample to evaluate the ability of reproducing the sawing results. Table 4.7 provides a comparison between the setups employed at Lehigh University (LU) and Homer Research Laboratories (HRL). The major differences are manifested in the feeding mechanism, blade condition (old and new), number of teeth per inch (pitch, mm), and the blades' manufacturers.

Figure 4.13 shows a linear relationship between the obtained results. The correlation coefficient was 98.8 %, and the following conclusions were drawn:

(1) The PHT results are reproduceable even on a different machine.

(2) Variations in blades' specifications are insignificant. As a result, the assumption of insignificant blades' differences due to manufacture is valid.

(3) The assumption of equal blades' wear-rates is further proven to be valid.

Table 4.6 Summary of Some PHT Conclusions

From Preliminary Testing:

- PHT does screen among materials.
- Sawing indicator should be strokes per area.
- Five replications are sufficient.
- Ranking at Low and Medium pressures is similar.
- Screening is statistically most powerful at Low feed pressure.
- The ratio of strokes to time can be employed to check the accuracy of counting.

From Actual Testing:

- Variations within materials (noise) increases sharply below certain feed force value.
- Materials exhibit different variances that are feed pressure independent.
- Increasing feed pressure decreases materials' variances and differences among materials.
- Materials' ranking is positively pressure independent in the low feed force range.
- Screening is statistically most powerful at notch number three.
- Hot-rolled bars require more strokes per area than the cold-drawn ones.
- Cold drawing has no effect on ranking.
- The PHT assumptions are valid:
  (1) Variations in blades' wear-rates are insignificant.
  (2) Materials are homogeneous except the 705E016 which had shown very high variability.
- Sawing results correlate with HRL-Index values (65 %).
- The correlation value increases to 73 % when 705E016 is disregarded.
- The PHT is very simple, and has very high repeatability.

Table 4.7 LU and HRL Power Hacksaw Setups

	LU	HRL
Machine		
- Manufacturer	Peerless	Racine
- Feeding Mechanism	Gravity with Spring Tension	Hydraulic
Blade Specifications		
- Manufacturer	Starrett	Lenox
- Condition	Old (20 cuts)	New
- Material	HSS	HSS
- Dimension (inch)	(17 x 1.25 x .062)	(14 x 1.25 x .062)
(mm)	(431.8 x 31.8 x 1.6)	(355.6 x 31.8 x 1.6)
- Teeth/inch (Pitch, mm)	10 (2.5)	6 (4.0)
- Tooth Setting	Raker	Raker
Sawing Conditions		
- Speed (stro./min.)	92	98
- Feed Force Position	# 3	# 4
- Cutting Fluid	Dry	Dry

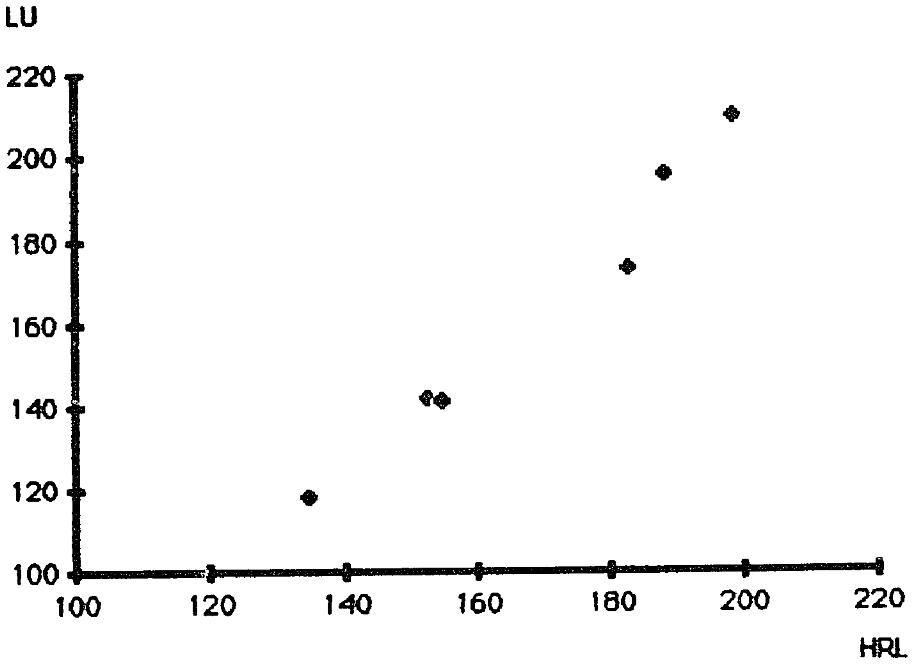


Fig. 4.13 Sawing Results of LU Versus HRL

Table 4.8 presents the HRL production rates, sawing results determined after the Duncan analysis, and the absolute difference between the two tests' ranking. The biggest disagreements among the two tests' ranks were reflected in two materials, the 705E001 and 705E016. The sawing test does not show the 705E001 as unmachinable as the screw machine test. The 705E016 that had shown high variability in sawing was ranked well according to HRL results.

There were eight groups based on the screw machine test results, while the PHT classified the thirteen materials into seven groups. It was, therefore, concluded that the PHT is as sensitive as the Screw/Bar Machine Test.

The two tests' results correlated with a - 65 %. The correlation value increased to - 73 % when the 705E016 was disregarded because of its high variability in sawing. Additional cross correlation analysis is given in section 7.1.

Table 4.8 HRL Production Rates and PHT Results

	HRL		PHT (Notch # 3S)		Absolute Difference
Material	pcs/hr	Rank	strokes/area	Rank	in Ranking
705E001	336	8	180.70	4	4 *
705W002	383	7	194.90	6	1
705E017	388	6	210.80	7	1
705E014	440	5	210.80	7	2
705E003	440	5	186.37	5	0
705C034	440	5	186.37	5	0
705E016	572	2	186.37	5	3 *
705E002	572	2	180.70	4	2
651L100	538	3	131.65	2	1
651L101	620	1	117.20	1	0
625L286	620	1	140.65	3	2
9T	502	4	131.65	2	2
12T	502	4	140.65	3	1

Correlation Coefficient: -.6511
-.7266 (without 705E016)

4.5.2 Applications with Procedures

The following PHT applications are mainly for work materials of round-bar type and up to 2 or 3 inches (50.8 or 76.2 mm) in diameter. For non round bars, the sawing indicator should include one or two of the cross section dimensions. For larger diameters, the author believes that other tests could be more appropriate, such as the Cutting Forces Test (described in Chapter 6).

The Power Hacksaw Test can be utilized for;

(a) screening among materials

(b) qualifying potential materials for the Screw Machine Test

(c) determining the machinability level in daily production.

(a) Recommended Procedure For Screening Among Materials

(1) Blade Specifications:

For each grade of materials, the recommended teeth per inch (pitch) can be determined from a machining data handbook [138]. Other blade specifications, such as dimensions, are machine and blade manufacturer dependent. A compromise between these specifications can be achieved for all materials. Any deviation from the recommended specifications would be insignificant. That is, the materials' characteristics are the dominant factor when cutting under constant pressure.

(2) Sawing Conditions:

The speed should be set at a value 30 to 50 per cent lower than the lowest recommended speed. This is to reduce the blades' wear-rates effects and, thus, increase the work materials dominance.

The CFF range should be established so that the lower limit is slightly higher than the lowest possible pressure available on the machine, and the upper limit is the recommended pressure values' average. This range is divided into equally spaced testing points, where the objective is to locate a feed pressure position at which screening among materials is statistically most powerful (based on ANOVA analysis).

(3) Testing Procedure:

a - A new blade is assigned to each material. Blades are assumed to be from one batch. Bars' diameters are measured.

b - Ten replications an inch (25.4 mm) apart should be taken at the lower pressure limit. The first five cuts can be considered blade break-in. Another way to break-in the blades would be to saw five pieces from a standard material.

c - ANOVA is applied on the sawing indicator (strokes/area) results.

d - Steps "a" to "c" are repeated at the following pressure positions until the planned testing points are covered.

e - From ANOVA results, the CFF at which screening is statistically most powerful is identified. The materials are assumed homogeneous and thus insignificant variations within materials is a must.

f- From Duncan test results, the likely materials' groups are determined.

(b) Recommended Procedure For Qualifying Potenial Materials

(4) Linear Regression Model:

A linear model is determined between the screw machine test results and the groups' averages. The model validity should be examined, especially identifying influential points [153]. An influential point is, simply, the one that significantly affects the model parameters in terms of estimated values and variances. For example, the 705W002 in Fig. 4.11 is an influential point.

(5) A new blade from the same batch is assigned to each new material. If a new-blades batch is received, one should investigate the hypothesis that the old and new batches are statistically the same. The blade is broken-in and the new material is tested at the feed pressure determined in "(3) - e".

(6) The expected number of pieces per hour along with a 99 % confidence interval (C.I.) is obtained for each new material through utilizing the above regression model. Table 3.9 provides the 10T and 11T expected production rates (pcs/hr). From the 10T C.I., the probability of this material producing more than 546 pcs/hr is .005. Therefore, neither the 10T nor the 11T would have qualified if the cut-off value was, for example, 550 pcs/hr. These two materials were tested at HRL

at the following production rates [3]:

10T: 502, 636, 637, 660, 814, 861, 1137

11T: 471, 502, 562, 660

The cost of testing at the above underlined rates would, therefore, have been saved, if the materials were expected to provide more than 550 pcs/hr.

(7) From the qualified materials' confidence intervals, the joint testing space (in terms of speeds and feeds) is determined. Once new production rates become available, the regression model must be updated.

Table 4.9 10T and 11T Estimated Production Rates

Material	Ave.(stro./area)	VAR.	Expected pcs/hr	C.I.
10T	172.3	.3	482.8	419 - 546
11T	209.2	6.0	413.6	310 - 517

(c) Recommended Procedure For Quality Control Application

The utilization of the PHT as a quality control tool requires different considerations than those mentioned in the previous applications. That is, the machinability assurance of a given material deals with; (1) the detection of any deviation (in terms of means and/or variances) from the material norm, and (2) the utilization of each blade over its entire useful life.

Figure 4.14 illustrates such means' deviations. The material norm is assumed to be that material's microstructure obtained under controlled production conditions for the screw machine test. A deviation would denote a change in this microstructure. Deviations would occur due to changes in chemical compositions and/or rolling parameters (usually, the final rolling temperature). There are positive and negative deviations but machinability would deteriorate with the negative ones. For this reason, the quality control charts were designed for single limits. Although other properties, such as hardness and tensile strength, would be affected by such deviations, it is not of concern in this test (testing the machinability level).

The machinability and other properties of a material would depend on the ingot rolled-section (top, middle, and bottom). Therefore, three norms should be established along with their associated charts. Figure 4.15 provides the different possible states for a given material. The states would depend upon the production batch and the ingot section. Each state is assumed to be normally distributed with a mean (μ) and a variance (σ^2). Batches could differ in averages, variances, or both. For a given batch, it is most likely to have three different means and variances corresponding to the three sections of the ingot.

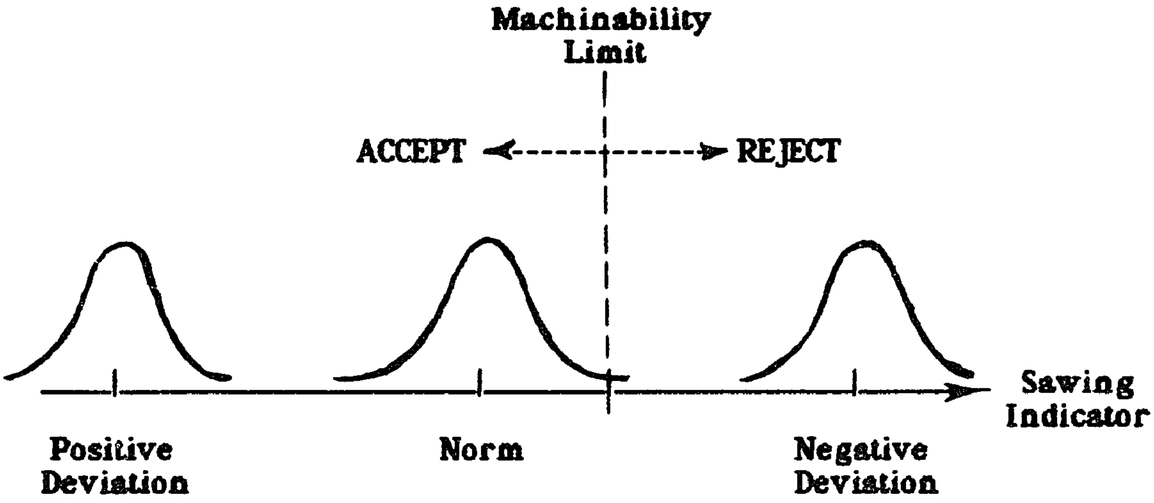


Fig. 4.14 Deviations in Means from a Machinability Norm

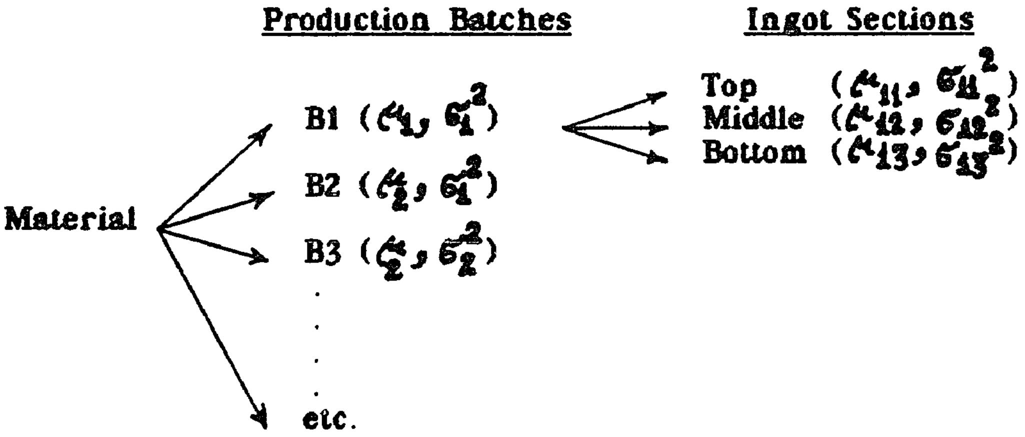
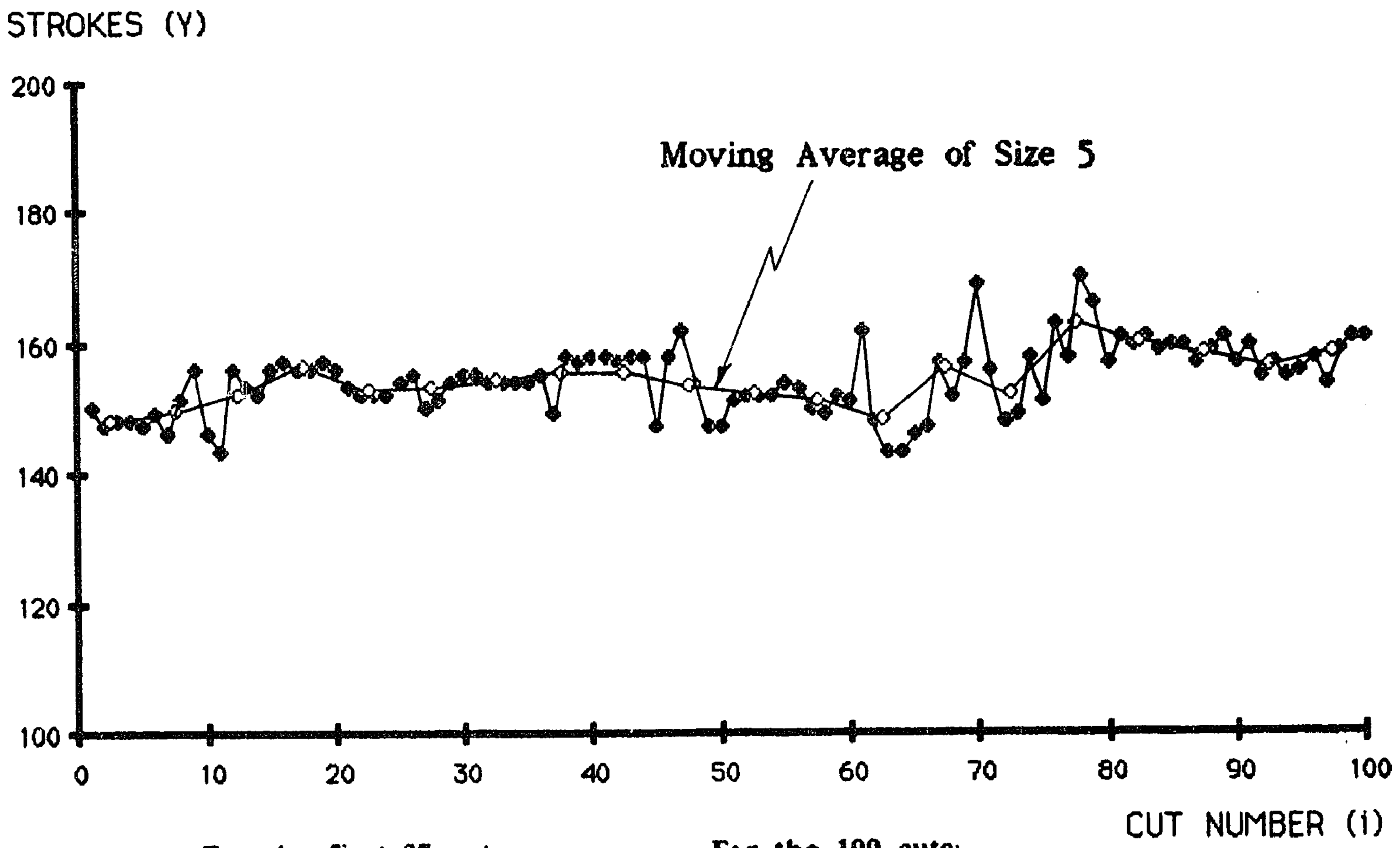


Fig. 4.15 Possible Production States of a Material

A dullness test was run on the 705W002 at HRL. Figure 4.16 presents the results obtained, where the sawing indicator was the required strokes. That is, bars' diameters were not measured. When the test is to be employed in a production line (i.e., not under controlled production conditions), the bars' diameters should be measured. This is to incorporate their variations into the indicator (strokes/area or strokes/diameter). Normally, the required strokes per cross section area would reflect the microstructure uniformity and blade wear-rate. The dullness test results obtained mainly reflected the material homogeneity (wear rate = .082 stro/cut). The rate was .204 for the first thirty five cuts. This supports the results and conclusions drawn from figure 4.12.

The fluctuations of the required strokes in Fig. 4.16 can be flattened (smoothed) through; (1) moving averages - a moving average of size five is shown in figure 4.16, or (2) sawing at a heavier feed force value. The choice between these alternatives would depend on economical and other factors. The larger the sample size the higher the sampling cost. The heavier the pressure the higher the blade wear-rate (shorter tool life). Since it is easier to smooth the curve through moving averages than to locate a feed force value at which the level of noise is minimum, the first alternative should be chosen. In other words, the first alternative doesn't require sawing at a different cutting condition than that used in determining the regression model.



For the first 35 cuts:

$Y = 148.5 + 0.204\ (i)$
$R = 0.54$

For the 100 cuts:

$Y = 150.2 + 0.082\ (i)$
$R = 0.44$

Fig. 4.16 705W002 Dullness Test Results

The main problems that the following recommended quality control procedure had to overcome were; (1) the acceptance of a bad batch due to using a new blade, and (2) the rejection of a good batch because of high blade wear-rate. The chances of having these types of error are only reduced through employing three blades (one old and two new, or vise versa) at any moment of time. The recommended quality control procedure is thus:

(1) Dullness Test:

a - A dullness test is applied on each state of a material norm (top, middle, and bottom sections of the ingot) at the sawing condition used for the regression model.

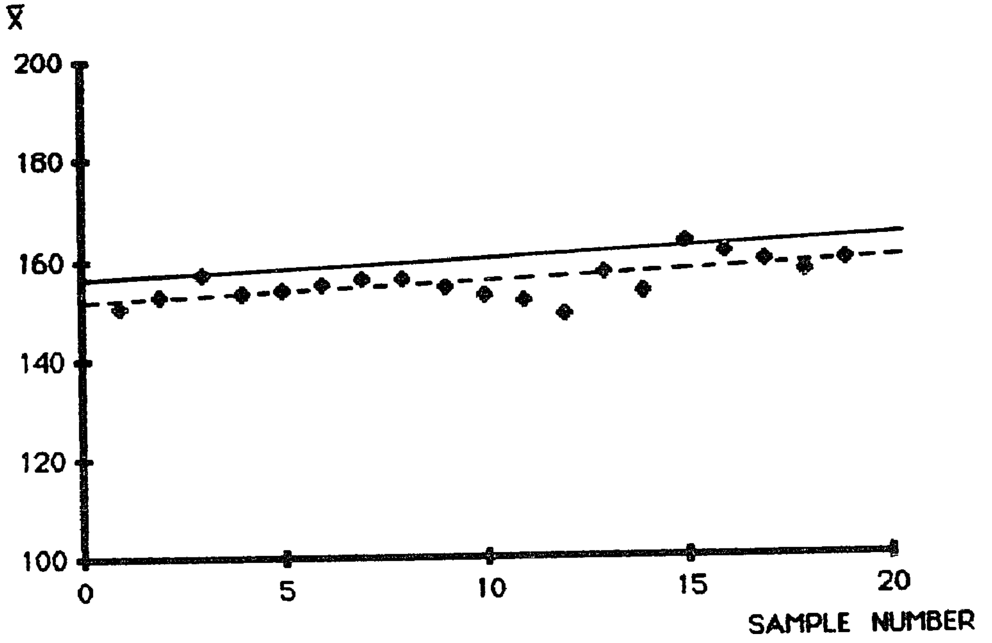
b - A sample size that would minimize the level of noise within each state would be determined using moving averages. The sample size should be of at least size five, where a sample size greater than five may be needed for the top section of the ingot. The first sample should be disregarded due to blade break-in. Results for twenty five samples, usually required in establishing quality control charts, should be obtained.

(2) Quality Control Procedure:

a - Three blades (the dullness test blade should be one of them) are assigned to each state of a material norm. Before collecting any data, the new blades should be broken-in with a similar procedure that was used on the dullness test blade.

b - The quality control charts are then established using the dullness test results, see reference [154, pp. 164 - 166] for the basis of how to utilize the time dependent control lines in the $\bar{x}$ chart. A slanting control line is, simply, a parallel line to the best straight line that passes through the $\bar{x}$ points. For the purpose of illustration, Figure 4.17 shows the $\bar{x}$ and s charts for samples of size five. They were determined from the dullness test results after considering the first five cuts as blade break-in. The $\bar{x}$ chart shows good control for all samples except sample number 15. Examination of this sample data did not point to possible outliers, and it can be ignored. Sample numbers 12 and 13 are shown out-of-control in the s chart. Examination of these two samples pointed to two readings that can be considered outliers. Another approach would be to establish the charts with a larger sample size, for example, six or seven

c - Table 4.10 presents the various possiblities for a sample to be out-of-control along with the likely causes and recommended actions. Since the blades are broken-in before use, the chance of a new blade showing a bad batch to be in-control is very slim. Finally, a new blade should replace the old one when it reaches its rapid-wear zone. The charts should be revised every fifteen samples. The batches of low machinability level should be isolated for corrective actions, such as heat treatment, for customer notification, or to lower the price.



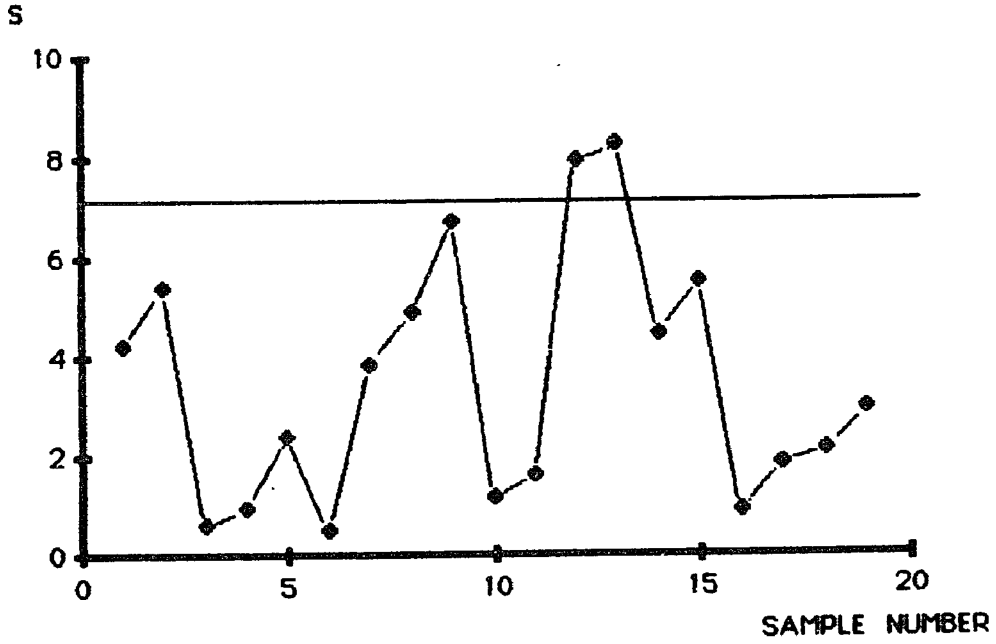


Fig. 4.17 **PHT Quality Control Charts**

Table 4.10 <u>Out-Of-Control Samples and Corrective Actions</u>

Chart		Blade			
$\bar{x}$	s	New	Old	Likely Causes	Recommended Actions
IN	OUT	YES		- change in material variance - new blade effects	Check with an old blade. If s is still out, material variance changed.
OUT	IN	YES		- change in material mean	Check with an old blade.
OUT	OUT	YES		- change in material mean and variance	Check with an old blade.
IN	OUT		YES	- change in material variance	Check with a new blade.
OUT	IN		YES	- change in material mean - blade wear-rate effects	Check with a new blade. If $\bar{x}$ is still out, material mean changed.
OUT	OUT		YES	- change in material mean and variance - blade wear-rate effects	Check with the other two blades.

Chapter 5: END MILLING-SLOTTING TEST

5.1 Introduction

The first devloped test, the PHT, has satisfied the objective (a short-term test that correlates well with the PPT and can be used on the production line for machinability assurance), and also its setup, testing procedure, and results have been successfuly duplicated at HRL. In turn, one could question the need for developing any further tests, such as the End Milling-Slotting Test (EMST) or the Cutting Forces Test (CFT). As mentioned in Chapter 3, the characteristics of the EMST are the closest to those of the PPT, and could, hence, provide better correlation than that of the PHT with the PPT. The CFT (described in Chapter 6) had another objective besides that of correlating with the PPT results, which was to investigate the sensitivity of the cutting forces components, especially the radial force, in differentiating among the tested materials. In addition, the ranking of work materials according to their machinability may vary from one operation to another and/or with the output criterion. For example, a material can be ranked first in a turning operation while ranked last in a drilling operation, or ranked first in a turning operation when the indicator is the cutting force while ranked last when the indicator is the obtained surface finish.

The work materials under investigation, free-cutting steels, are often machined on automatic screw/bar machines of the single or multiple spindle type and, hence, their machinability space is limited by such machines. These machines are usually utilized for the manufacture of finished parts and, in turn, commonly regarded as finishing processes. For this reason, the machined part qualities (in terms of surface finish and size accuracy) are the PPT main indicators, given that a reasonable tool life (6-8 hours) is attained. This space is further restricted to HSS tool materials, since the achievable cutting speeds are in the economical range of HSS tool materials. This is due to the structure of these machines and that they generally accommodate bars up to two-inches (50.8 mm) in diameter. Also, form tools, made of HSS tool materials, are normally utilized on these machines. This space is further complicated by the presence of built-up-edge (BUE). Abeyama and Nakamura [103] have shown both surface finish and size accuracy to be more related to the BUE height than to the tool wear. They concluded that the most suitable steels for the automatic screw machines are those that do not have the tendency for BUE formation. This is most likely due to BUE instability. Finally, turning on an automatic screw/bar machine is of the intermittent type.

The machinability space of the free-cutting steels is, therefore, characterized by automatic screw/bar machines, machined part qualities, HSS tool materials and the presence of BUE. It is believed that their most reliable ranking is determined by the PPT. However, such production tests have several disadvantages. In addition to being expensive and time consuming, they require a high degree of control over the input factors (such as machine setting, resharpening tools, cutting fluid, operator accuracy and precision, etc.), and they do not utilize any replications. This, in turn, makes it difficult to assess the real variables that affect machinability.

The EMST was, hence, designed to: (1) focus on the interaction between a HSS tool material and the free-cutting steels, (2) utilize an indicator based on the part quality (dimensional stability of machined slots), and (3) employ three replications. In addition, the slotting operation is of the intermittent type and the cutting was conducted dry to avoid possible cutting fluid variations and/or thermal effects. In other words, the main objective of the EMST was, therefore, to insure the quality of the screw machine materials within their machinability space. This was through duplicating the characteristics of the PPT, and eliminating or minimizing possible sources of error.

5.2 EMST Testing Equipment

All tests were performed on a Cincinnati horizontal milling machine. The cutting tools were HSS (M7) double-end end mills with R.H. cut, R.H. helix, 3/8 inch (9.5 mm) diameter and shank, and two flutes. They were manufactured by the Weldon Tool Company, BB12-2. The 3/8 inch (9.5 mm) diameter end mill was selected, due to the following:

(1) Larger end mill diameters would not allow for better utilization of work materials. The low material consumption was achieved through machining four slots on the one inch (25.4 mm) diameter bars (see Figure 5.1 on page 182), and with half the end mill diameter as the axial depth of cut, which was required for measuring purposes. Due to the small diameter of the workpieces, one inch (25.4 mm), and the desire to minimize the consumption of work materials, the available range for the axial depth of cut was very small. It was, therefore, decided to keep the axial depth of cut constant.

(2) Since the machine maximum RPM is 1500, smaller end mill diameters would not provide a wider range of cutting conditions, and also the measuring device cost would double.

The measuring device was a Mitutoyo 526-122 bore gauge with a range of 0.3 to 0.4 inches (7.62 to 10.16 mm). It was selected among several devices (i.e., vernier caliber, internal micrometer and block gauges), because it requires fewer operator skills and provides a 1/10000 inch (0.0025 mm) increment for a moderate price ($ 200 at the time this study was initiated).

As mentioned before, the fifteen work materials utilized for this study are basically different material designs for the 1213 and 12L14 grades of the 12XX series. Table 5.1, abstracted from reference [138], provides their recommended end milling-slotting conditions. These conditions are for a HSS 3/8 inch (9.5 mm) diameter end mill (i.e., a slot width with that dimension).

Table 5.1 Recommended End Milling-Slotting Conditions

Material	BHN	Axial Depth of Cut	Speed (sfpm)	Speed (m/min)	Inch(mm) Per Tooth	HSS Tool Material
1213 CD	150-200	dia/2	105	37	0.001 (0.025)	M2,M3,M7
12L14 CD	150-200	dia/2	125	38	0.001 (0.025)	M2,M3,M7

5.3 EMST Preliminary Tests

The preliminary testing objectives were to; (1) locate a practical cutting region, (2) decide on the machinability indicator, (3) investigate the test repeatability, and (4) establish the statistical tools required for analyzing the data and, hence, the experimental design for actual testing.

Figure 5.1 shows the EMST as an input/output system along with the machine part characteristics and the expected dimensional stability of the slot widths. It might be mentioned here that the size accuracy was chosen instead of the surface finish to be the machinability indicator, due to the fact that; (1) HRL has concluded that both surface finish and size accuracy lead to the same results [3], and (2) measuring surface roughness depends more on the person performing the measurements than the measurement of size accuracy. The use of dimensional stability when turning, face milling, etc., has several disadvantages, one of which is the error induced from machine setting. Further, dimensional stability is only important when adjustments for tool wear can not be made (i.e., for complex form tools and end milling slots). Therefore, measuring the slot widths instead of their heights eliminates any possible errors from machine setting and would only reflect the tool wear with the presence or absence of BUE formation. Hence, a machinable material is expected to show no BUE formation and a small tool wear rate or slot width variation (SWV).

4 Materials (6")
3/8 End Mill (HSS-M7)
2 Cutting Conditions
Dry

MACHINABILITY
(SLOTTING)

Slot Width
Cutting Time (min.)

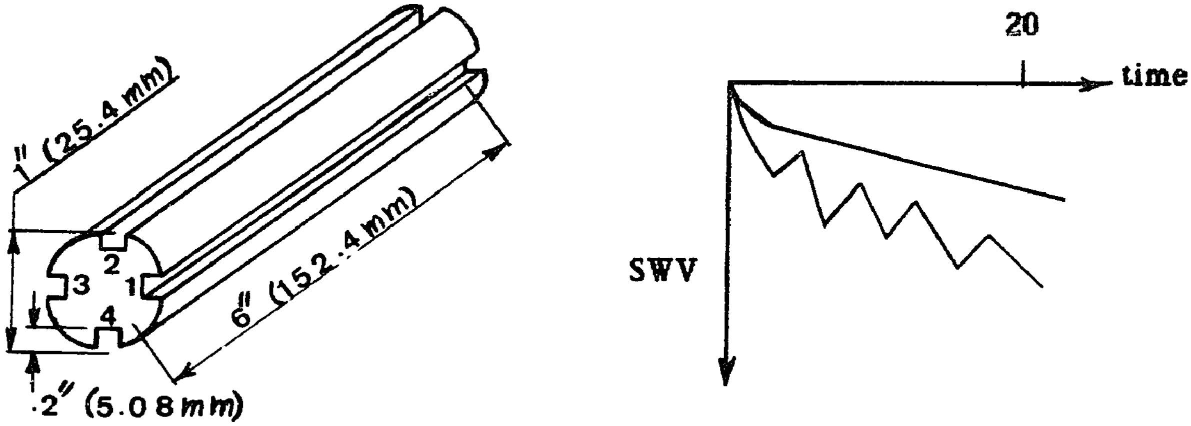


Fig. 5.1 End Milling-Slotting Test (Preliminary Tests) as I/O System

For locating a practical cutting condition, the first preliminary testing objective, a material with a good machinability rating in terms of the PPT and PHT results, such as the 9T material (see Table 4.8, on page 162), was initially machined under a cutting condition near that recommended in Table 5.1. Six inch (152.4 mm) long bars were prepared and cut at the following cutting condition (* 2 in Figure 5.2):

- Revolution/Minute (RPM) = 1200

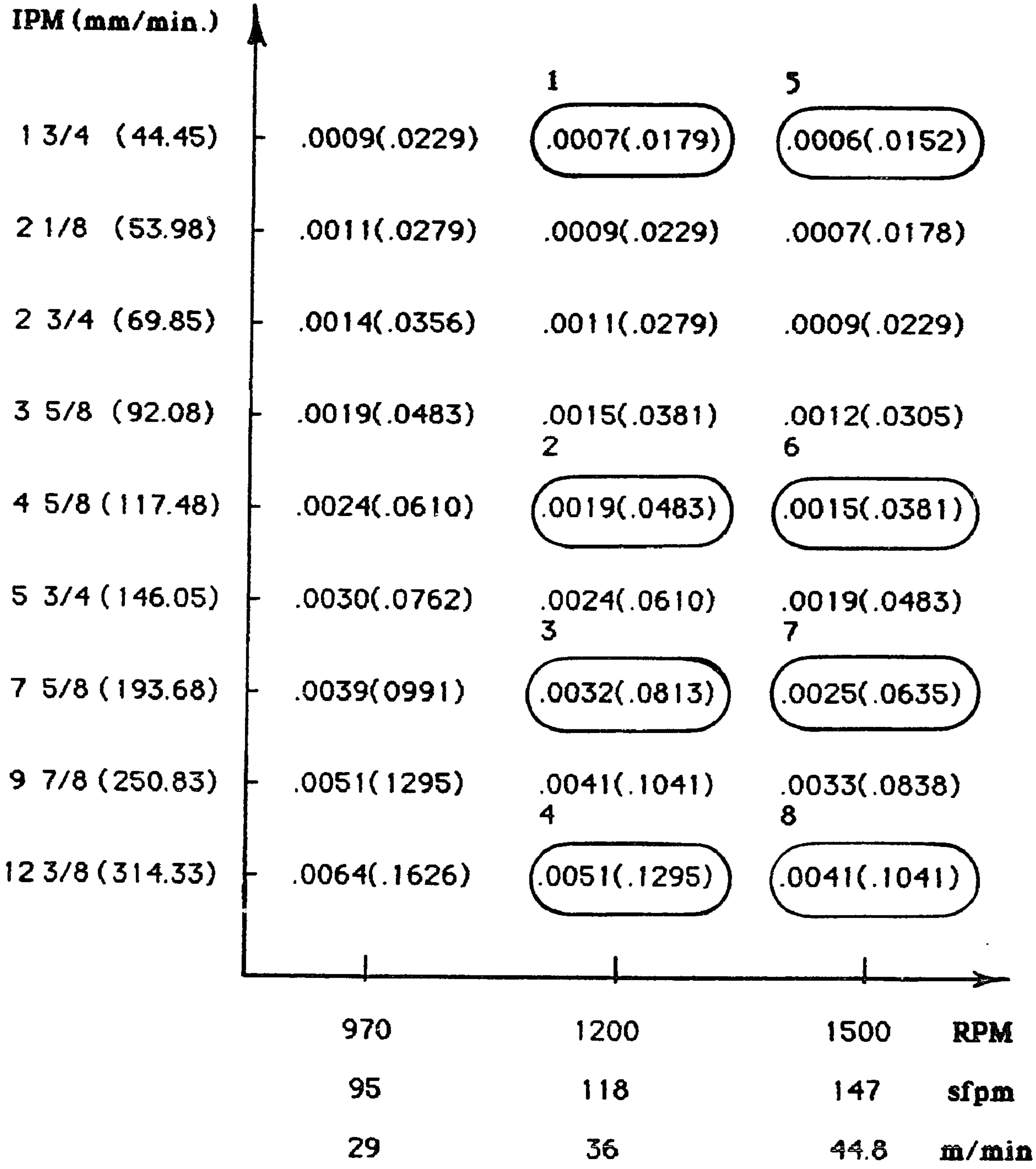
  (i.e., 118 sfpm (36 m/min))

- Inch/Minute (IPM) = 4 5/8 (117.5 mm/min)

  (i.e., 0.0019 in./tooth (0.04826 mm/tooth)

- Axial Depth of Cut (da) = 0.200 inch (5.08 mm)

The cutting process was very slow and tool marks were observed on the machine surfaces as shown on Figure 5.3. The slot widths were measured at the beginning of the first slot on each bar (four slots were cut on each bar in order to achieve low material consumption). Figure 5.4 shows the plot of the slot width variation (SWV), where only -0.0003 inch (0.0076 mm) of tool wear had occured after 52 minutes of cutting. It was, hence, decided to locate a cutting condition at which no tool marks appear. This was through machining eight slots under the cutting conditions circled in Fig. 5.2. The tool marks disappeared at cutting condition numbers 3, 4, 7 & 8, but only the last two conditions seemed practical for a production shop.



IPM (mm/min.)			
1 3/4 (44.45)	.0009(.0229)	1 .0007(.0179)	5 .0006(.0152)
2 1/8 (53.98)	.0011(.0279)	.0009(.0229)	.0007(.0178)
2 3/4 (69.85)	.0014(.0356)	.0011(.0279)	.0009(.0229)
3 5/8 (92.08)	.0019(.0483)	.0015(.0381)	.0012(.0305)
4 5/8 (117.48)	.0024(.0610)	2 .0019(.0483)	6 .0015(.0381)
5 3/4 (146.05)	.0030(.0762)	.0024(.0610)	.0019(.0483)
7 5/8 (193.68)	.0039(0991)	3 .0032(.0813)	7 .0025(.0635)
9 7/8 (250.83)	.0051(1295)	.0041(.1041)	.0033(.0838)
12 3/8 (314.33)	.0064(.1626)	4 .0051(.1295)	8 .0041(.1041)
RPM	970	1200	1500
sfpm	95	118	147
m/min	29	36	44.8

Fig. 5.2 **Cutting Conditions in Terms of IPM, RPM and Inch/Tooth**

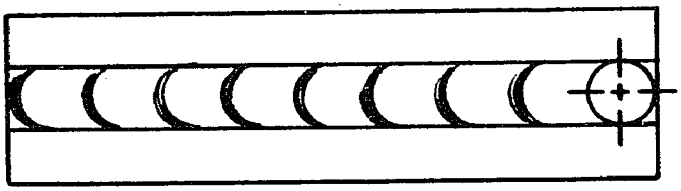


Fig. 5.3 <u>Tool Marks on The Machine Surface</u>

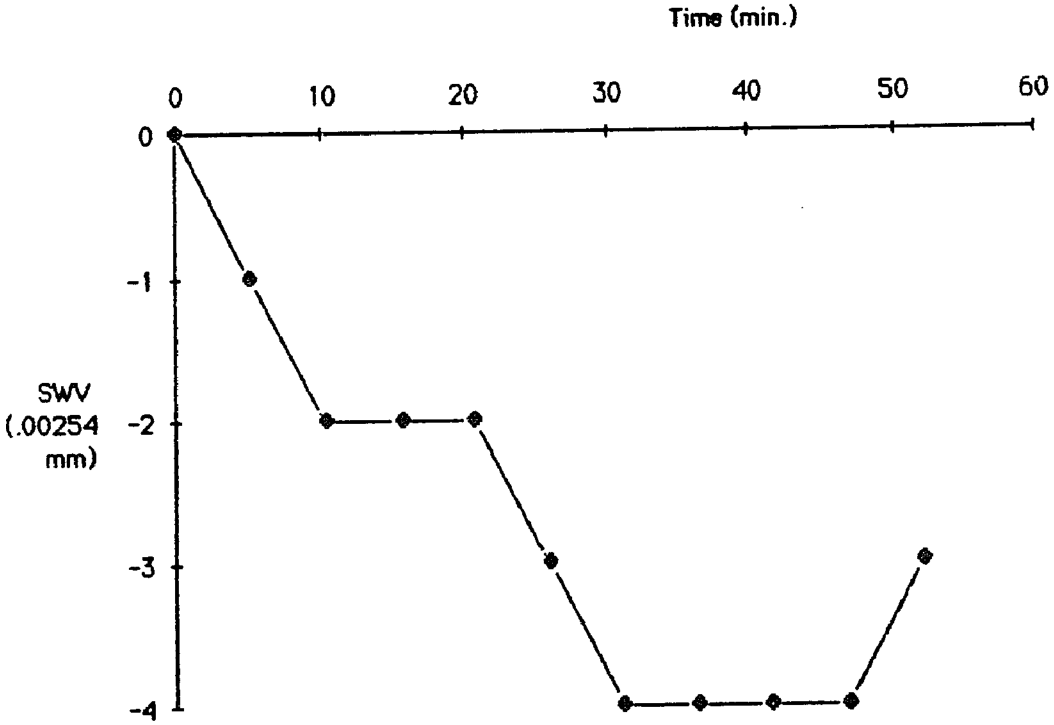


Fig. 5.4 <u>9T Slot Width Variations at Cutting Condition # 2</u>

Four materials were, hence, selected randomly from ten materials. That is, HRL production rates were available only for thirteen materials, but the stocks of 631L101, 9T and 12T were discovered to be low. Therefore, they were omitted from the random selection. The four selected materials, 703E001, 703W002, 703E014 and 631L100, were then machined at cutting condition numbers 7 and 8 (see Fig. 5.2).

The following steps were first applied in measuring the slot width variations; (1) to set the dial at zero at the start of the first slot on the first bar of each material, and (2) to measure the deviation at the start of the first slot on subsequent bars. This process was discovered to allow for three possible sources of error; the zero setting, the dial precision and the person performing the measurements. It was, then, decided to set the dial at zero at one of the slots, and to check the setting every time a material is subject to measurements, where the readings would be adjusted when a shift occurs. The zero setting as a source of error was, thus, eliminated. In order to investigate the other sources of error, some bars were measured more than once and over different periods of time. It was, hence, concluded that the repeatability of the measuring procedure is within ± .0001 inch (± .0025 mm).

Figures 5.5 and 5.6 show the results obtained before zeroing, while Figures 5.7 and 5.8 show the results after zeroing. The differences in the first bars' readings can be attributed to the tolerance of the end mill diameter, eccentricity between the cutting edges and their shank, and/or the tool break-in with or without BUE formation (see Fig. 5.3 for the measuring position of the bore gauge anvil). These possibilities, except perhaps the tool break-in, are dependent on the end mill manufacturer and their effects can be minimized through replications.

From Figure 5.7, it can be concluded that the EMST expectations are valid. A machinable material such as the 651L100 gave the best dimensional stability while the 705E001, the worst, showed a high tool wear rate and BUE formation. Examination of Figures 5.7 and 5.8 indicates the following:

(1) Fig. 5.8 shows more erratic slot width variations and BUE formations than Fig. 5.7. Therefore, it can be concluded that cutting condition number 7 is more practical (for a production shop) than number 8 for the work materials under investigation.

(2) The ranking of the four materials, based on the slope (rate) of the slot width variation, is independent of feed. This further supports the conclusion drawn from the PHT that ranking of the materials is independent of feed. This may indicate that within a given machining space, the ranking of work materials is independent of cutting conditions. In other words, variations in cutting conditions have little effect on the ranking of work materials. Due to the small range of the axial depth of cut and the limited RPM (1500) of the machine, this concept was not further investigated. However,

it was studied in more depth in the CFT, described in the next chapter.

From the above and that it required around twenty minutes of cutting to establish the pattern of the slot width stability, it was decided that locating the cutting condition at which screening among the materials is statistically most powerful is an expensive approach. In addition, some of the stocks of the work materials were limited. It was, therefore, decided to examine the ranking of the work materials under cutting condition number 7 only.

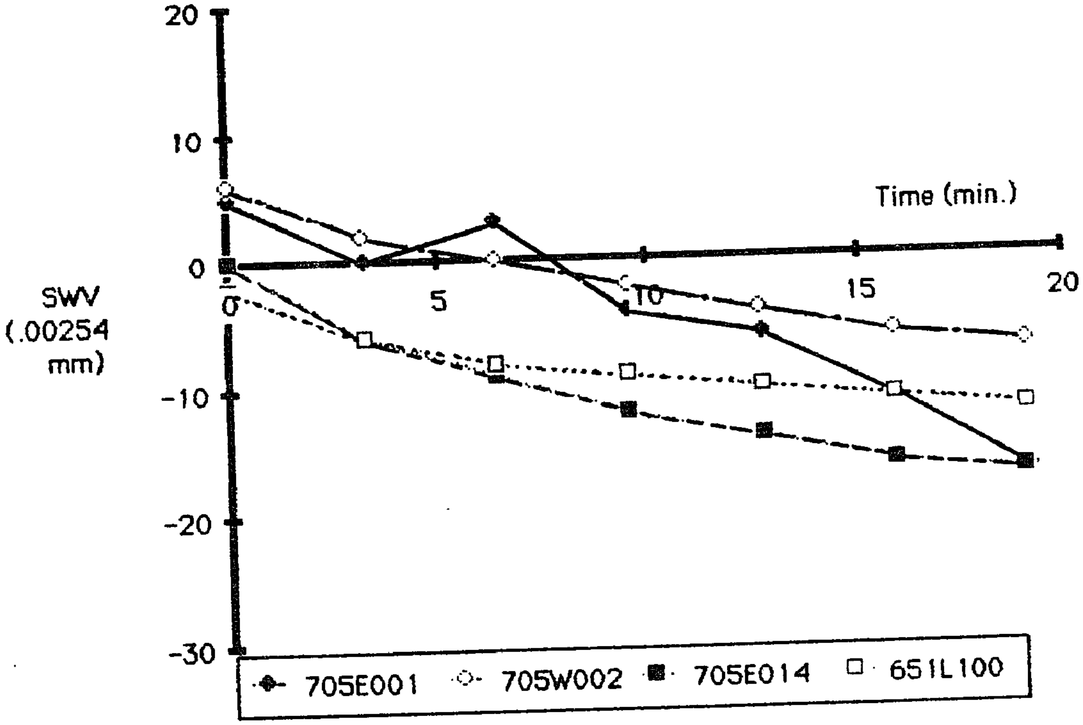


Fig. 5.5 Slot Width Variations at Cutting Condition # 7

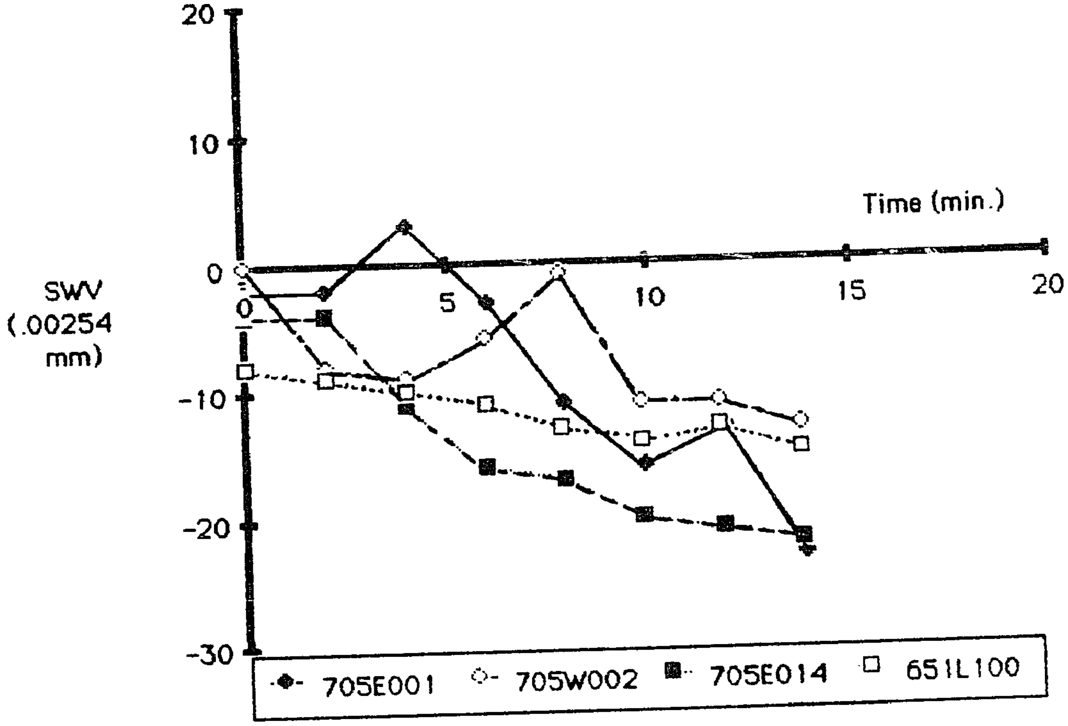


Fig. 5.6 Slot Width Variations at Cutting Condition # 8

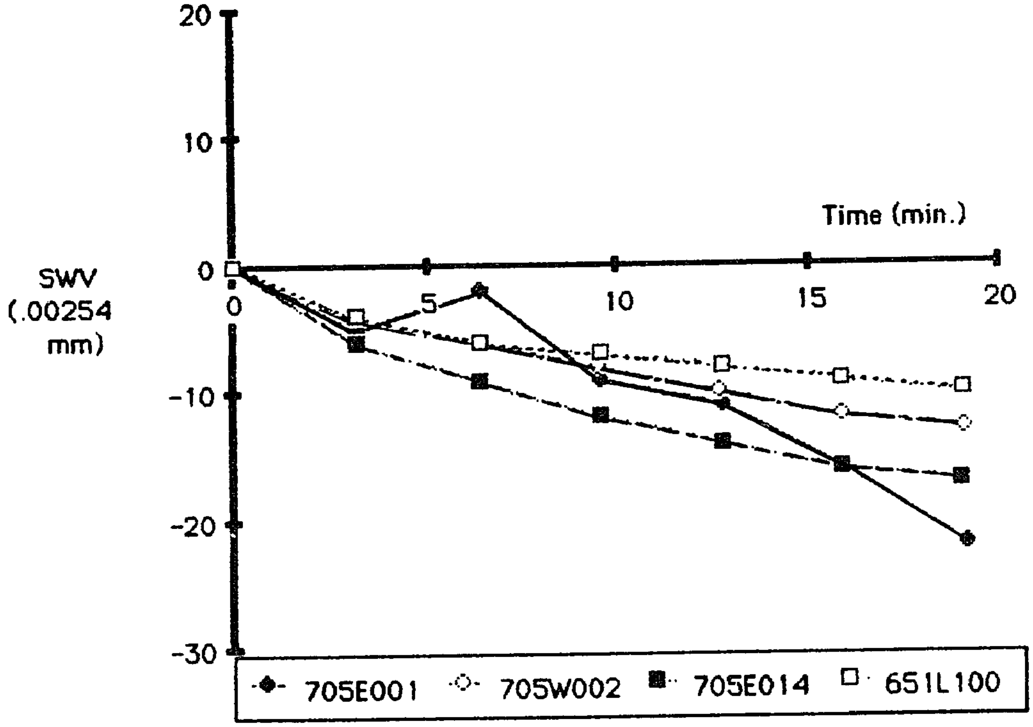


Fig. 5.7 Slot Width Variations at Cutting Condition # 7, after Zeroing

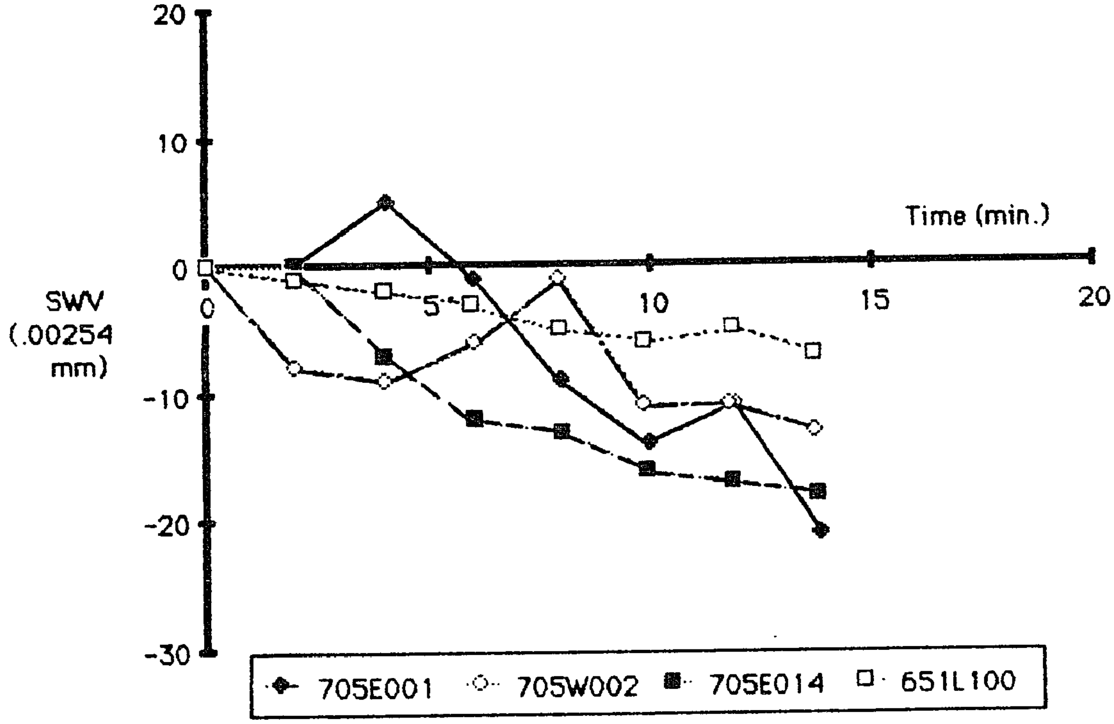


Fig. 5.8 Slot Width Variations at Cutting Condition # 8, after Zeroing

The second objective, to decide on a machinability indicator, was approached through examining the following possible indicators;

(1) slot width variation at a given time,

(2) time to reach a certain slot width limit, and

(3) slope (rate) of the slot width variations.

The first indicator, slot width variation at a given time, ignores the pattern of the slot width variation and would be affected by the presence or absence of BUE formation and, thus, was rejected.

The second indicator, time to reach a certain slot width limit, requires a personal judgement for selecting a critical value for the slot width limit. For example, the maximum recommended part growth limits from the starting size for the Automatic Screw/Bar Machine Test [12] are as follows:

Finish Form Tool: .003 inch (.076 mm)

Rough Form Tool: .005 inch (.127 mm)

Figure 5.9 shows the 12T part growth for the rough form tool as an example [3], where the difference between highest and lowest readings was .0016 mm per 8 hours only. The figure indicates that at this cutting condition this material would not reach the maximum permissible limit due to BUE formations. Consequently, there are two alternatives for the utilization of this indicator; (1) to machine the work materials for, say, thirty minutes and then choose the critical value so that it intercepts all curves, or (2) to select a relatively high critical value for the slot width limit (e.g., - .0035 inch (- .0889 mm)). Both choices were rejected, since the first one would overlook the BUE formations, and the second one would require a long cutting time, especially for those materials that have good machinability and/or high tendency for BUE formation. Since the objective was to maintain the status of the EMST as a short-term test, the second indicator was also disregarded.

The third indicator, slope of the slot width variations, takes the material behavior during the whole period of machining into account, allows for replications without violating the stock limits, and keeps the EMST as a short-term test. The third indicator was, therefore, selected to be the machinability indicator.

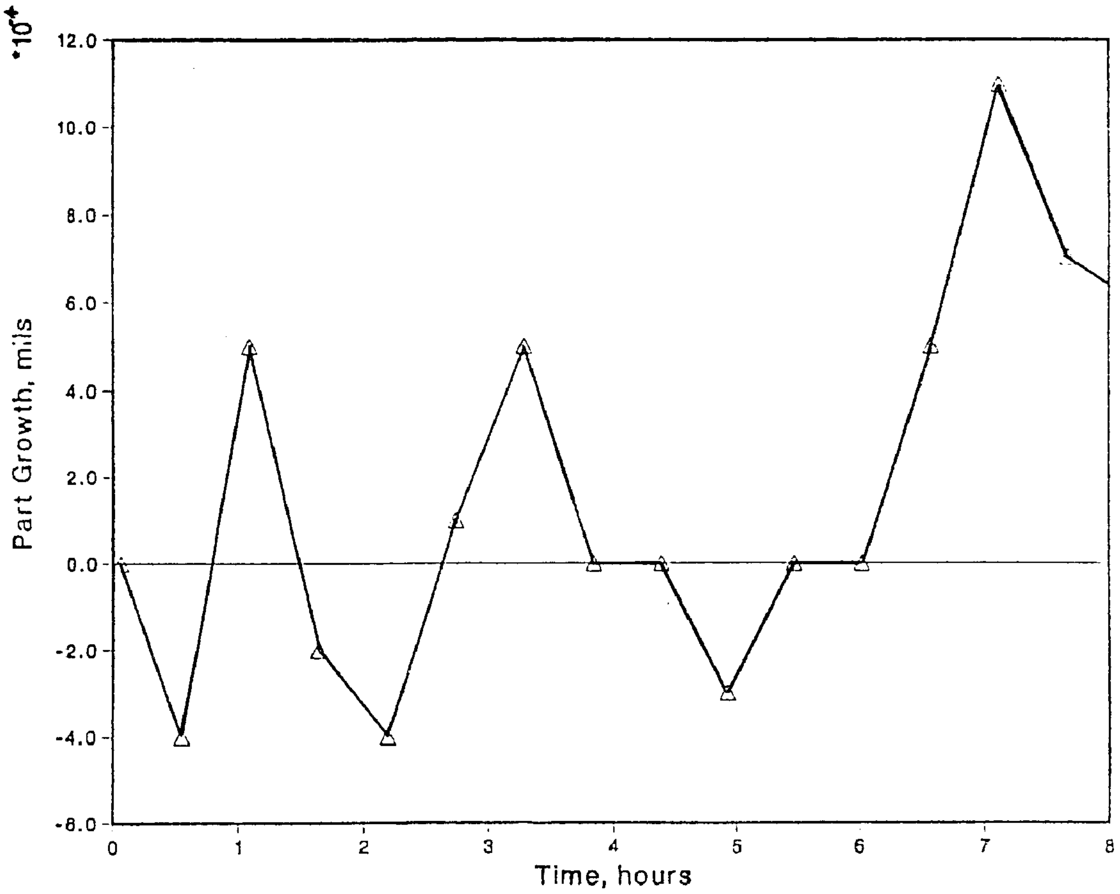


Fig. 5.9 **12T Part Growth at 502 pcs/hr. [3]**

The third objective, to investigate the test repeatability, was achieved through cutting three replications. Figures 5.11 to 5.14 show the plot of the results obtained. Examination of these figures indicates the following:

(1) The 705E001 third replication showed no BUE formation and, hence, higher tool wear rate than the other two replications that exhibited BUE formation.

(2) The 705W002 third replication and the 651L100 second replication showed small tool wear rates in relation to the other replications.

(3) The 705E014 was the only consistent material.

The question was, then, whether the scatter in the data was by chance or due to an assignable cause. Although the second and third replications were performed on a different fixture design (see Figure 5.10), the results do not show the fixture to be an assignable factor.

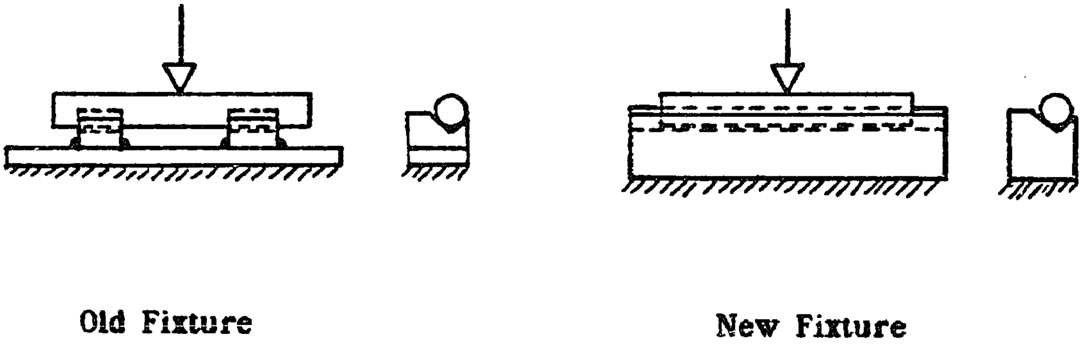


Fig. 5.10 <u>EMST Old and New Fixture</u>

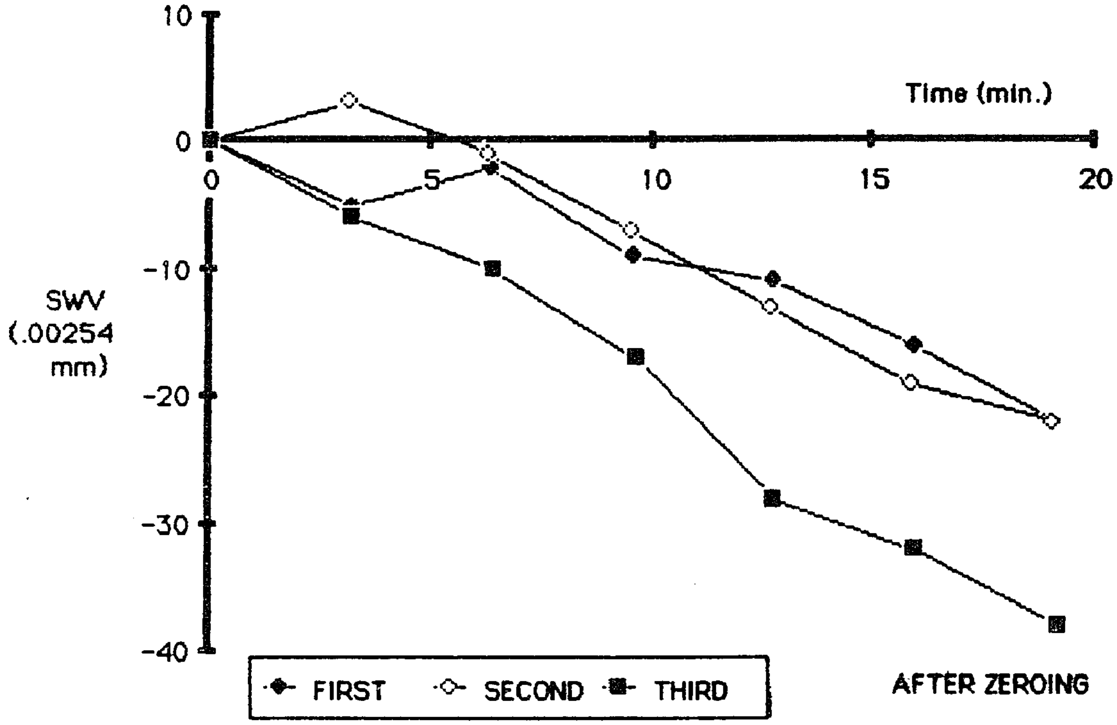


Fig. 5.11 705E001 Slot Width Variations of Three Replications

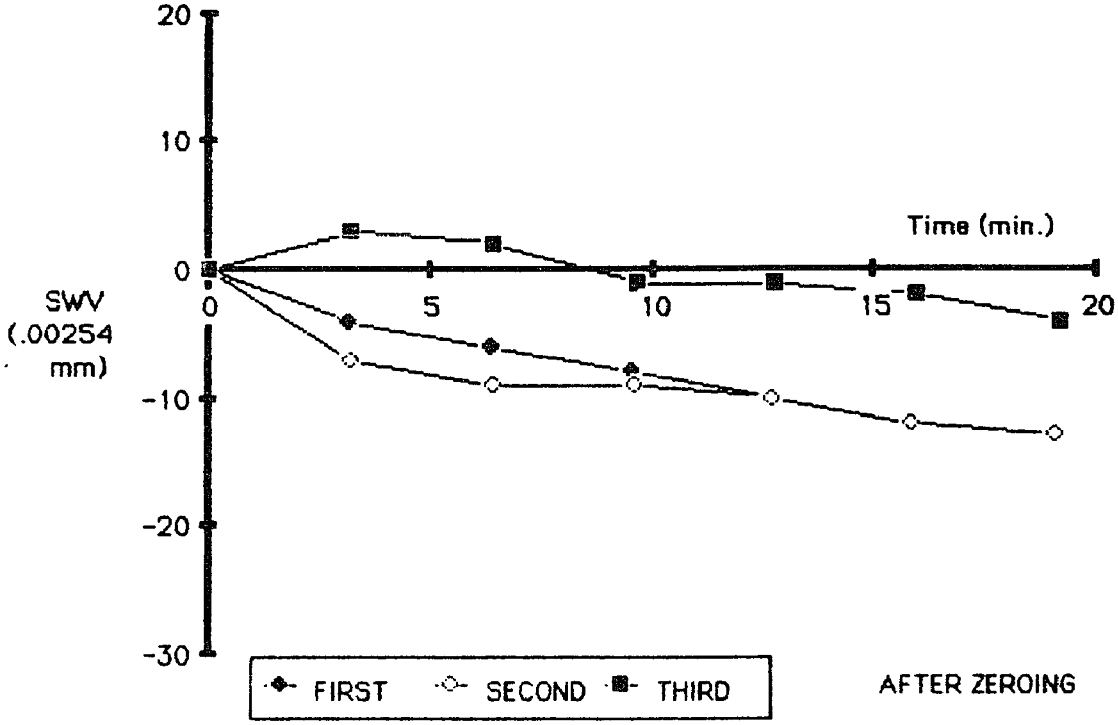


Fig. 5.12 705W002 Slot Width Variations of Three Replications

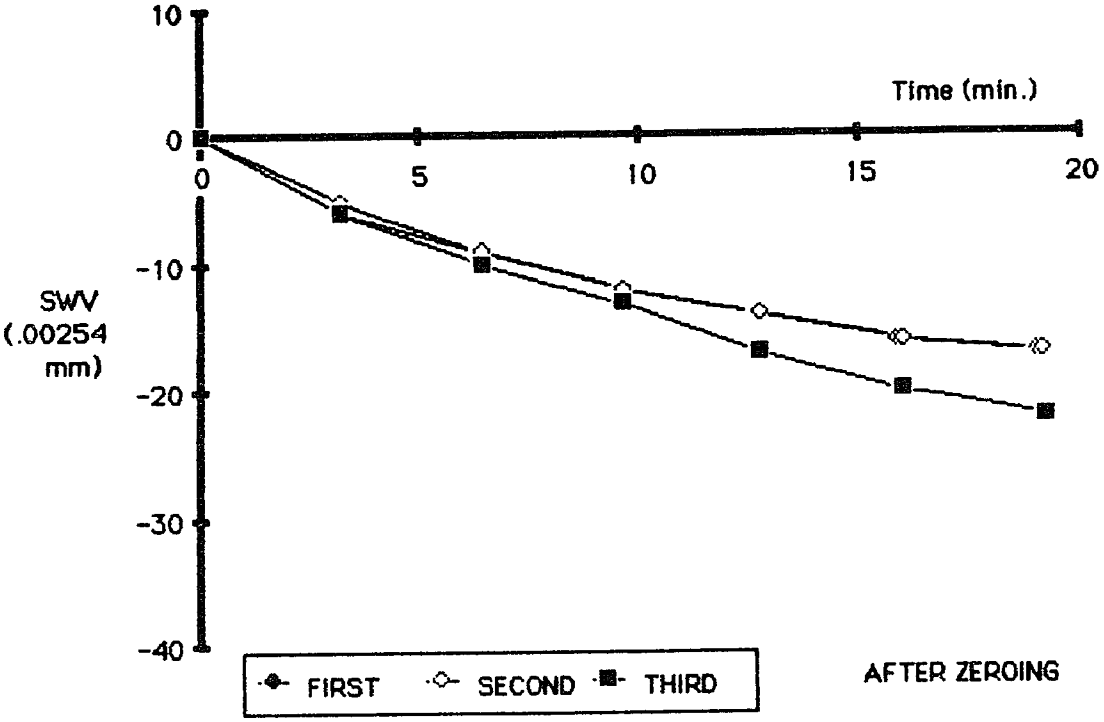


Fig. 5.13 <u>705E014 Slot Width Variations of Three Replications</u>

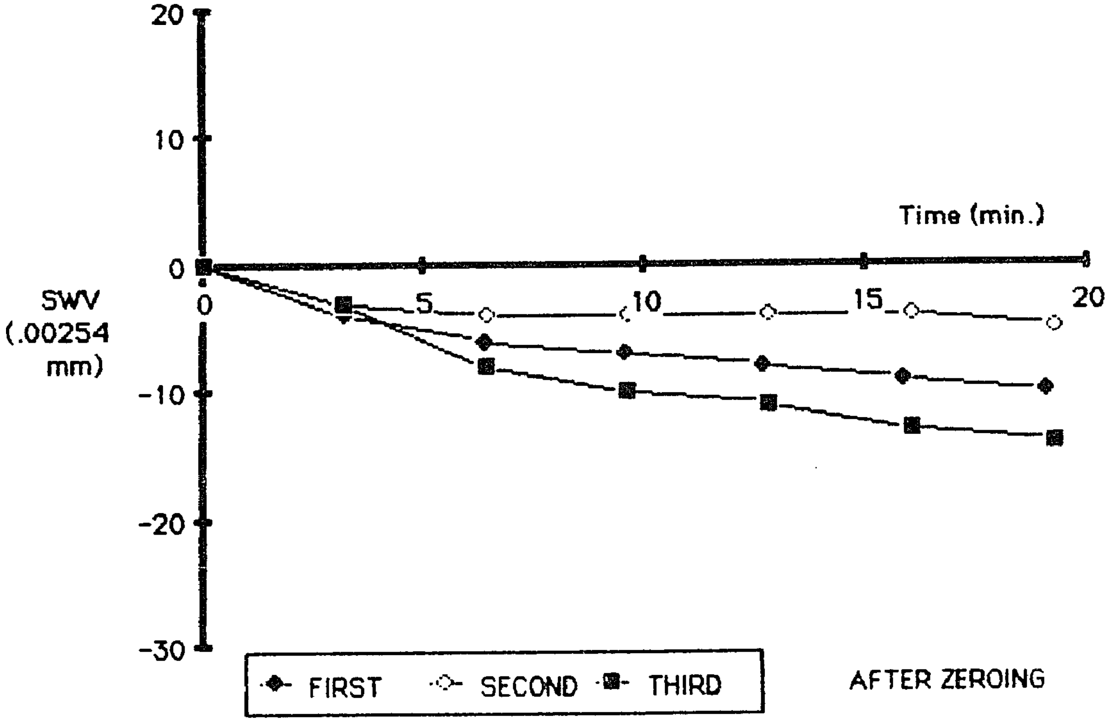


Fig. 5.14 <u>651L100 Slot Width Variations of Three Replications</u>

In order to insure that the above data scatter was not biased by the measuring position (at the start of the first slot) and/or the slot number (the first slot of each bar), the measuring procedure was revised to accommodate for two readings per slot (at the start and end of each slot).

Figures 5.15 to 5.18 present the results for the first replication, where the semi-vertical bars represent the readings at the start and end of the slots. From these figures, it can be concluded that the trends of the slot width variations were unbiased to either the measuring position or the slot number, but the variations within and among slots point to an assignable cause(s). For example, why were some of the slots larger at the end of the bar than at the beginning given no BUE effects were seen on the surface texture?, and/or why were some of the slots smaller at the beginning of a bar than at the end of the previous one given no BUE was present?

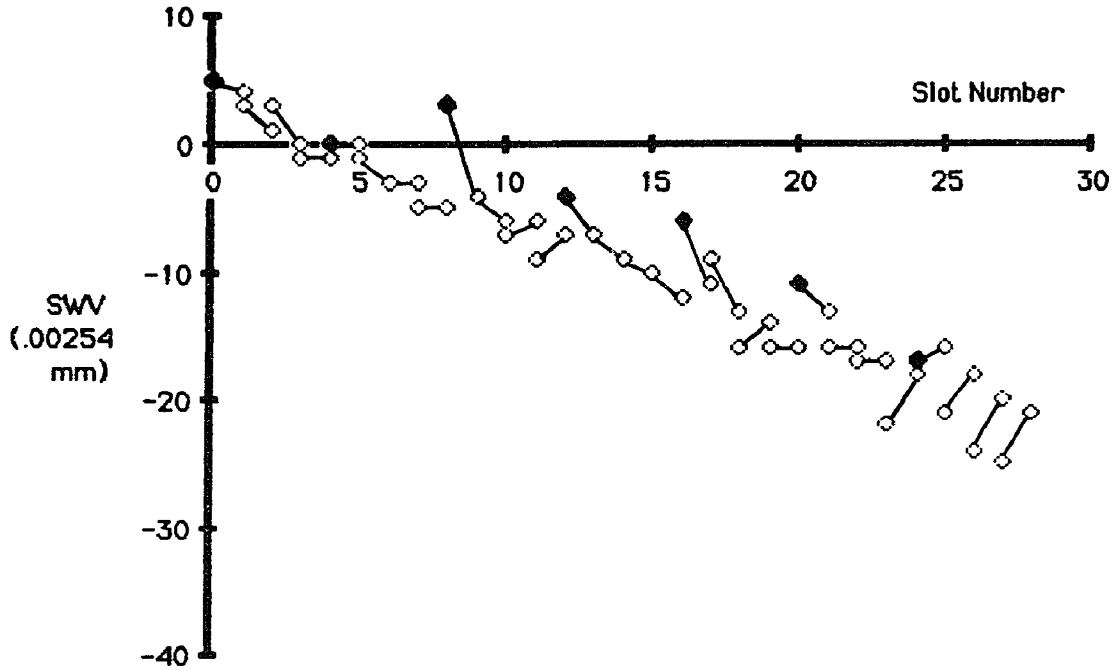


Fig. 5.15 705E001 SWV of First Replication Versus Slot Number

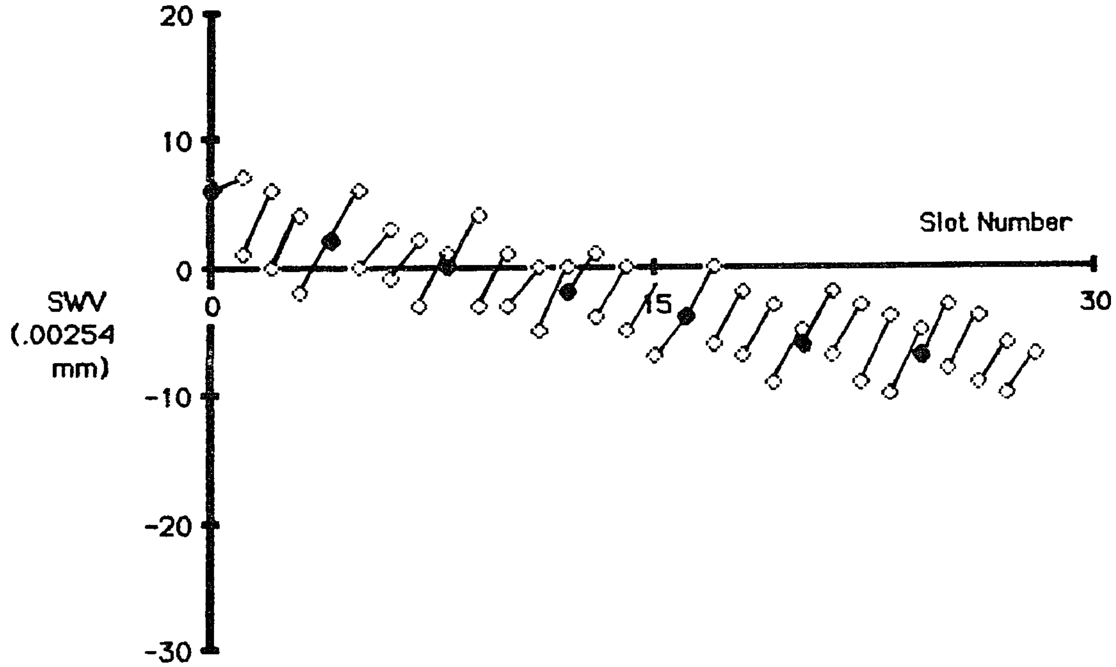


Fig. 5.16 705W002 SWV of First Replication Versus Slot Number

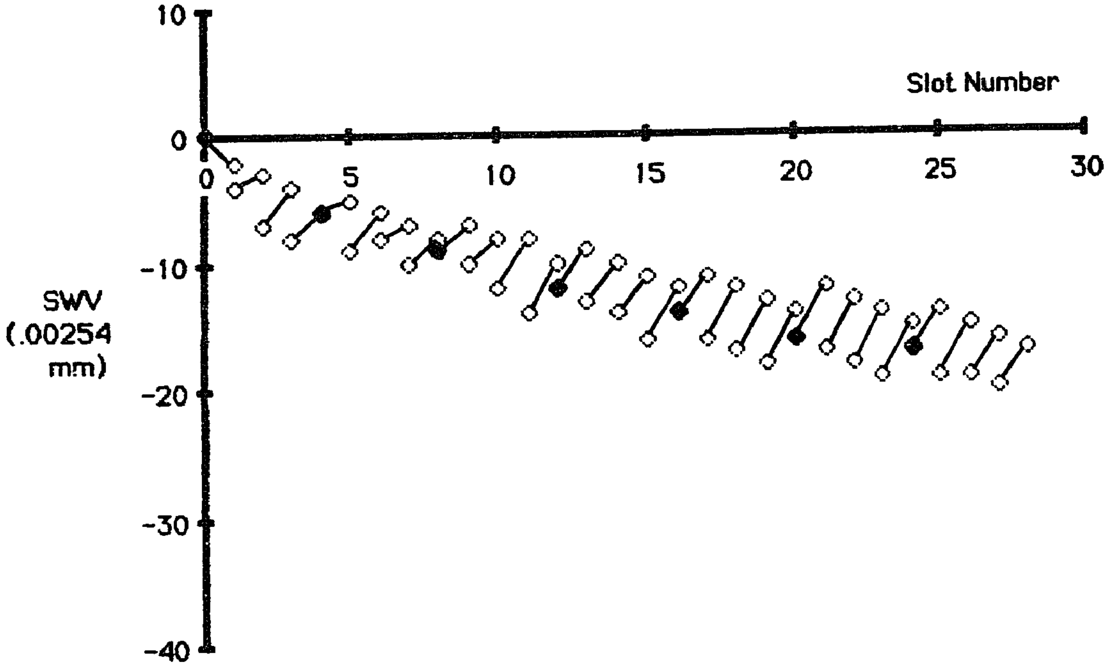


Fig. 5.17 705E014 SWV of First Replication Versus Slot Number

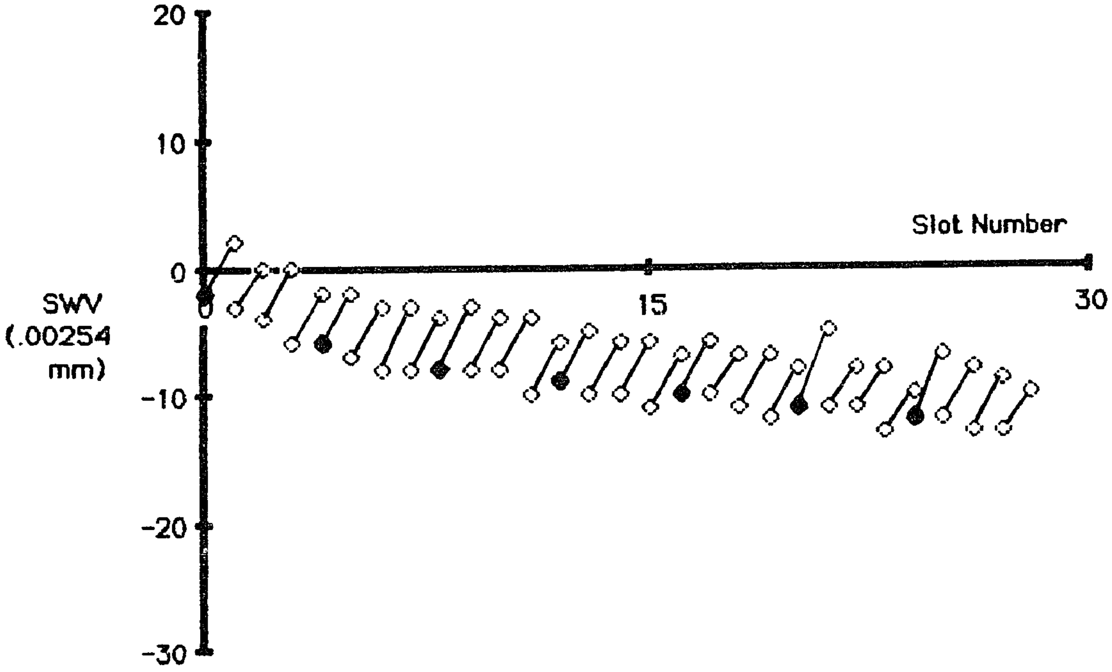


Fig. 5.18 651L100 SWV of First Replication Versus Slot Number

The following factors were identified as the likely assignable causes to the variations within and among the slots:

(1) Entry and exit conditions.

(2) Mode of milling (up or down milling).

(3) Thermal effects.

The entry and exit conditions were investigated through measuring the slot widths further away from the measuring position (see Fig. 5.3). The widths were unchanged and, therefore, this factor was disregarded.

The mode of milling (i.e., bad entry for down milling and bad exit for up milling) was investigated through machining two slots in opposite directions. The normal cutting direction was the down milling and the opposite direction was up milling. The results were identical for both directions. Therefore, the direction of cut did not influence the results.

The third factor (thermal effects) was, hence, the likely assignable cause to the above data scatter. The thermal expansion of the end mill due to the generated heat during cutting was the only explanation for having a slot larger at the end of the bar than at the beginning in the absence of BUE. The cooling of the end mill between cuts, and, hence, the smaller the diameter was the only explanation for having a slot smaller at the beginning of a bar than at the end of the previous one given that there was no BUE formation.

Therefore, there are three mechanisms in the end milling-slotting test; tool wear, BUE formation and thermal effects. The tool wear results in smaller slot widths when it is the dominant mechanism, while BUE formation and thermal effects result in larger slot width. Examination of the surface texture, which would point to the BUE formation, if it did take place, is the only way to differentiate between the last two mechanisms.

The results obtained at cutting condition numbers 7 and 8 were re-examined in the light of the above mechanisms and it was determined that the heating and cooling cycles did not influence the conclusions drawn from them.

The question was, then, whether the thermal effects were the cause for the differences in the replications' results. Figures 5.19 and 5.20 present the results of the 705E001 & 705W002 first and third replications, while Figure 5.21 presents the results of the 651L100 first and second replications. Examination of these results indicates the following:

(1) The thermal effects on the variations within slots were similar to the first and third replications of 705E001 (Fig. 5.19). However, for the 705W002 and 651L100 (Fig's. 5.20 & 5.21), the variations within slots were higher in the third and second replications than the first one. For example, for the 651L100, on the average, the difference between the start and the end of a slot was .0004 inch (.0102 mm) for the first

replication, while it was .0005 (.0127 mm) for the second replication. This could be attributed to the slightly longer bars (i.e., more machining time or heating cycle per slot) of the second replication. Some of the 651L100 third replication bars were measured and gave identical differences to the ones obtained from the second replication's results. Therefore, for a given material, the thermal effects on the variations within slots depend on the bar length. In turn, a tighter control over the bars length would be required in future testing.

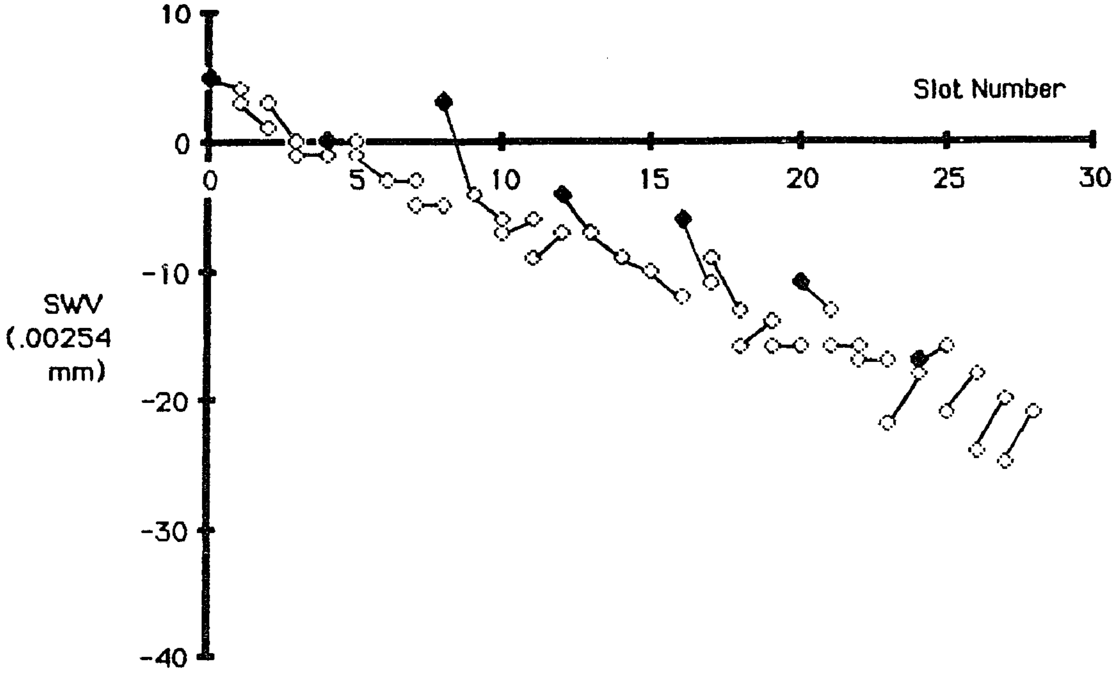
Due to the following factors, the thermal effects on the variations within slots were different among materials:

(a) The amount of heat generated during the cutting process which depends on the interaction between the cutting tool and the work material, where the tougher the material the higher the amount obtained.

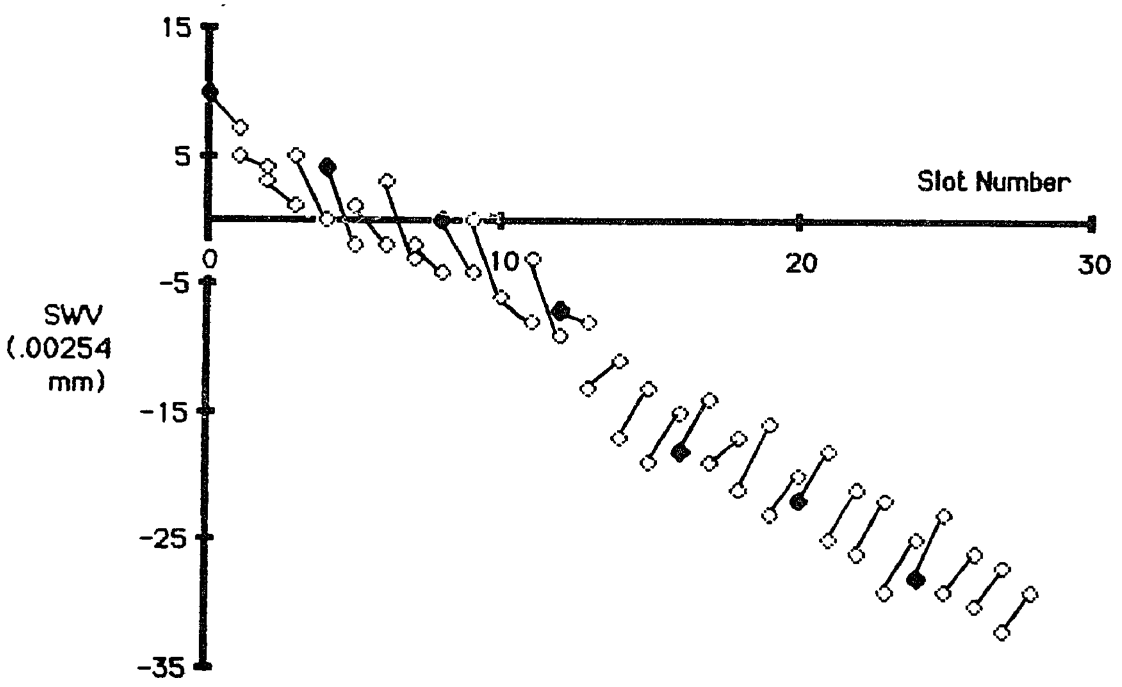
(b) The tool wear, which varies from one material to another and, hence, the amount of heat generated.

(c) The amount of heat passed to the workpiece which depends on the ability of the work material to absorb heat. The chip carries the highest per cent of the generated heat. The rest is passed to the tool and to the workpiece. The less the ability of the work material to absorb heat, the higher the amount of heat passed to the tool and, thus, higher thermal expansion for the end mill.

(2) The thermal effects on the variations among slots which depend upon the heating and cooling cycles. Figure 5.22 presents a typical heating and cooling cycle for the end mill. A sharp increase in the cutting temperature occurs as soon as the cutting process starts. This is usually followed by a gradual increase in the cutting temperature, especially in the absence of a cutting fluid. A sharp drop in the cutting temperature also occurs at the beginning of the cooling cycle followed by an exponential decrease in temperature. The pace of loading, unloading and setting the bars was not constant among replications. Therefore, the thermal effects are the most likely assignable cause for the scatter of the data among replications. In addition, the tool hang varied from 1 3/8 to 1 1/4 inches (34.93 to 31.75 mm) in some of the third replications by mistake.

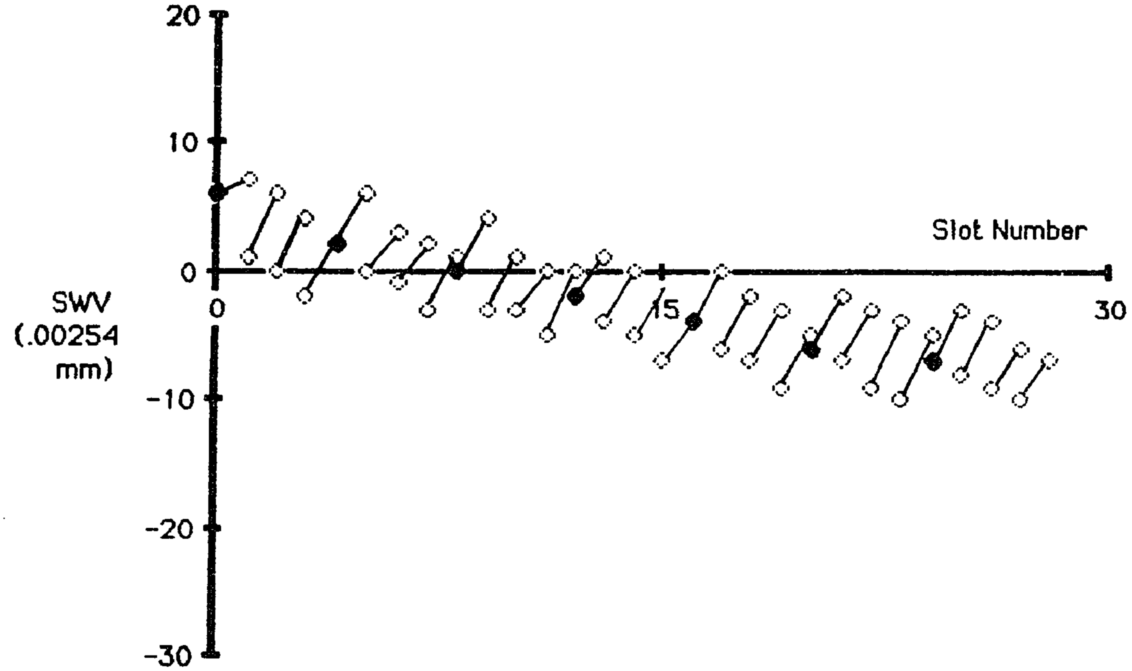


FIRST REPLICATION

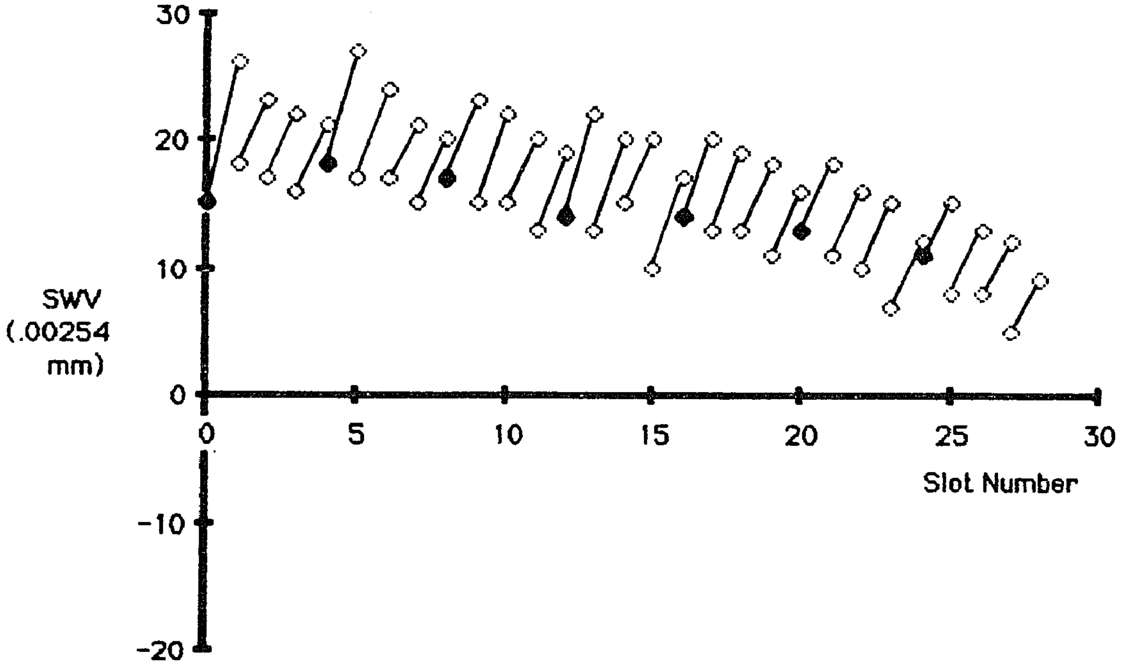


THIRD REPLICATION

Fig. 5.19 705E001 Slot Width Variations Versus Slot Number

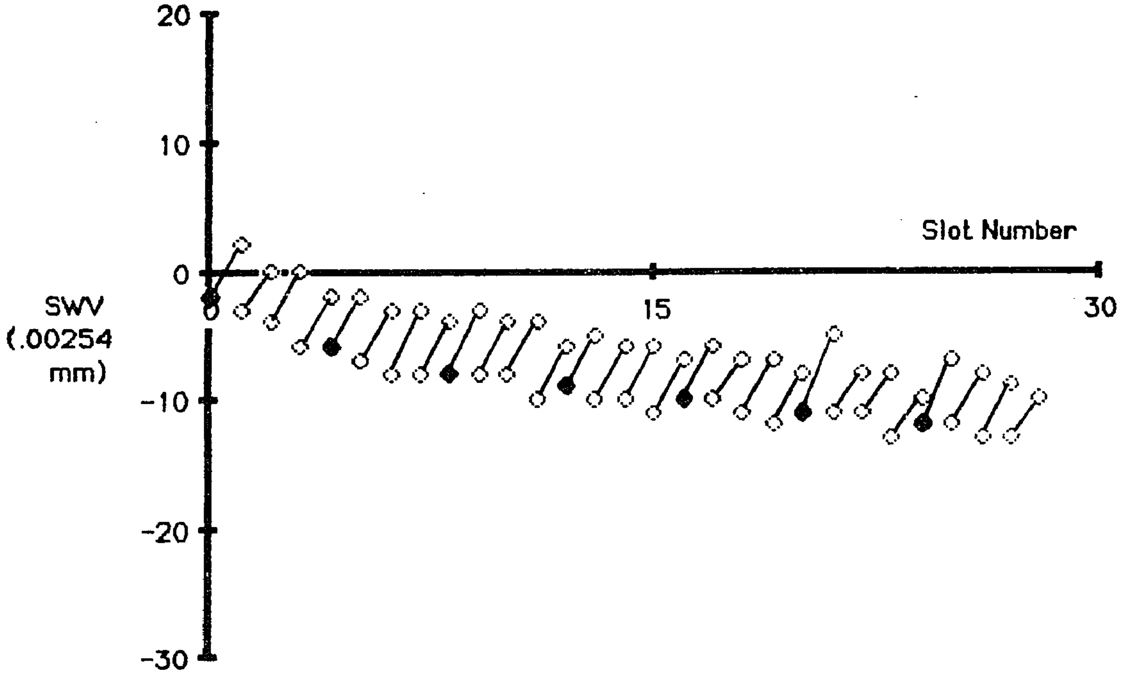


FIRST REPLICATION

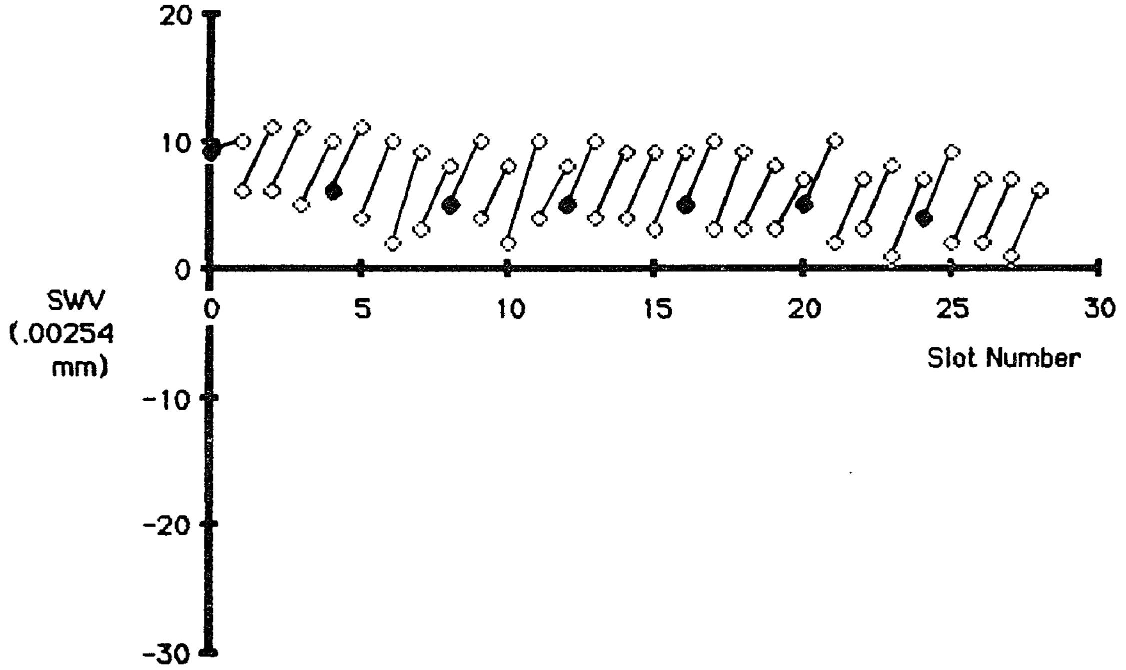


THIRD REPLICATION

Fig. 5.20 705W002 Slot Width Variations Versus Slot Number



FIRST REPLICATION



SECOND REPLICATION

Fig. 5.21 651L100 Slot Width Variations Versus Slot Number

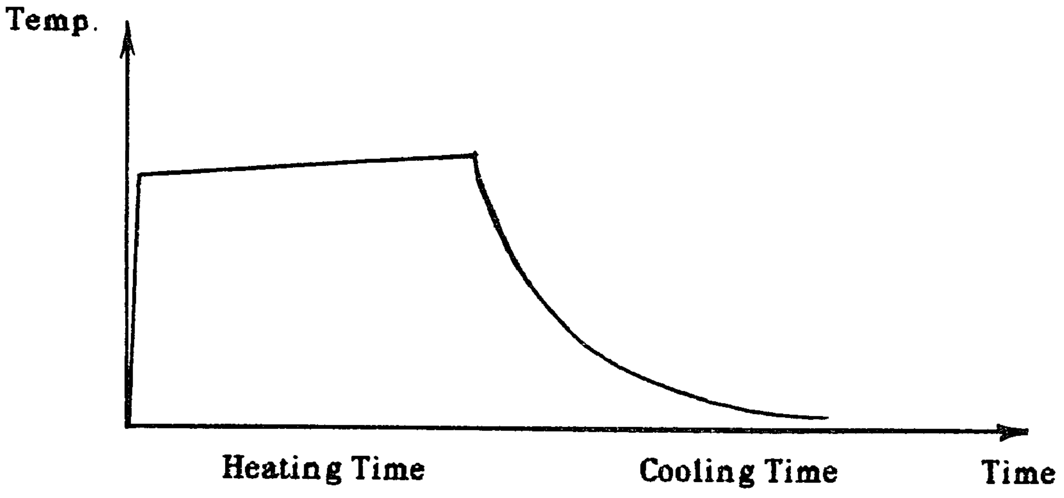


Fig. 5.22 Typical Heating and Cooling Cycle for the End Mill during a Slotting Operation

It was, then, decided to repeat the three replications with the following changes:

(1) To reduce the bars length from 6 to 4 inches (152.4 to 101.6 mm) and to exercise tighter control over the bars length. This would result in fewer thermal effects on the variations within slots and would provide more data points over the twenty minutes of cutting time for a more valid regression analysis.

(2) To keep the cooling time constant among slots and more important, among bars.

(3) The tool overhang would be reduced to the least possible value that the set up would allow and kept constant. This is to reduce vibration effects, if any.

It was decided to maintain the cooling time of the end mill between slots on a bar at three minutes and between bars at five minutes, to further reduce the heating cycle effects among bars, for two reasons. First, the loading of a new bar required longer time than that needed for setting up a bar for additional slotting. Second, it was planned to utilize only the slot width variations at the beginning of the first slot of each bar for evaluating the machining performance of the work materials. This is to have a reasonable cutting time interval, roughly 2.2 minutes per bar, between measurements. In addition, the tool overhang was reduced to 7/8 inch (22.23 mm) and kept constant.

Figures 5.23 to 5.26 provide the results obtained after the above mentioned modifications were applied, where R1, R2 and R3 stand for first, second and third replications respectively. With the exception of the 705E001 material, the variations among replications (in terms of the slope/rate of the slot width variations) were reduced substantially. According to HRL production rates (see Appendix B), the 705E001 was the least machinable material among the ones investigated. The differences between the replications of this material can be attributed to the instability of the BUE that was observed on the surface textures. For the other materials (705W002, 705E014 & 651L100), the BUE was not observed.

Figures 5.27 to 5.30 show the solt width variations (SWV) of the first replication (R1) of each of the four materials versus the slot number respectively. The darker dots indicate the measurements of the slot widths at the start of the first slot of the bars. Examination of these figures and Figures 5.15 to 5.18 indicates that; (1) the reduction of the bars length to four inches (101.6 mm) reduced the thermal effects on the results obtained within slots (the beginning and end of a slot), as it was expected, and (2) the four inch (101.6 mm) bars provided similar trends to those found for the six inch (152.4 mm) bars.

From Figures 5.23 to 5.26, it was, therefore, concluded that the EMST repeatability was established. Further, the slope/rate of the slot width variations, the performance indicator, would reflect the tool wear rate with the presence or absence of BUE formation.

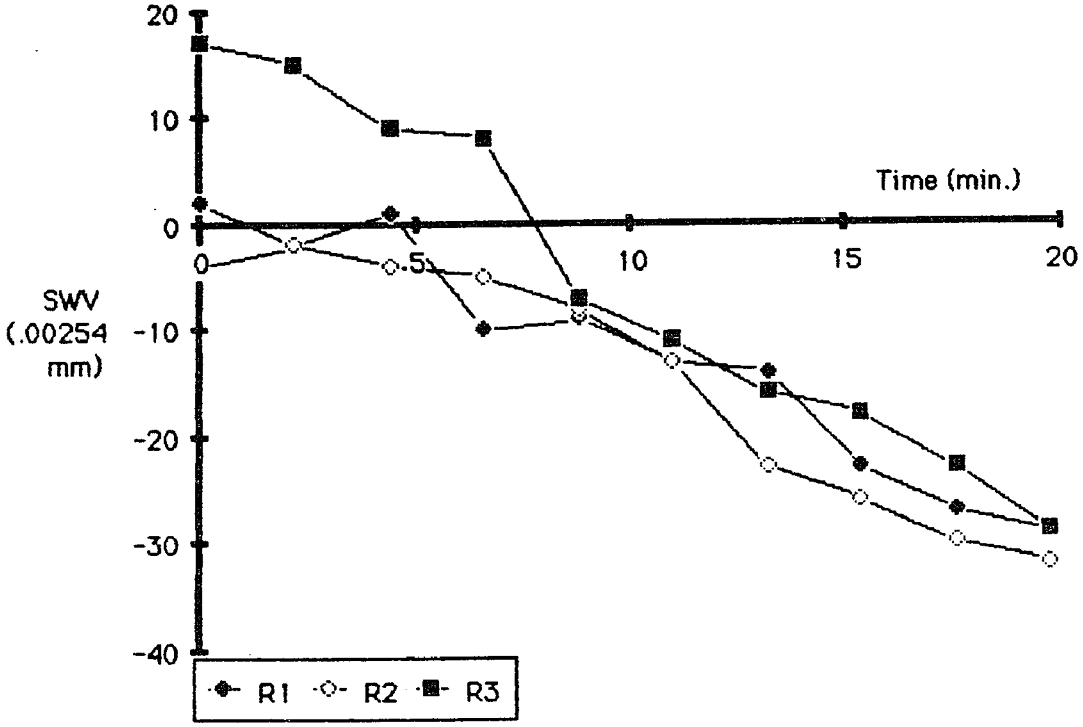


Fig. 5.23 705E001 SWV of Three Replications

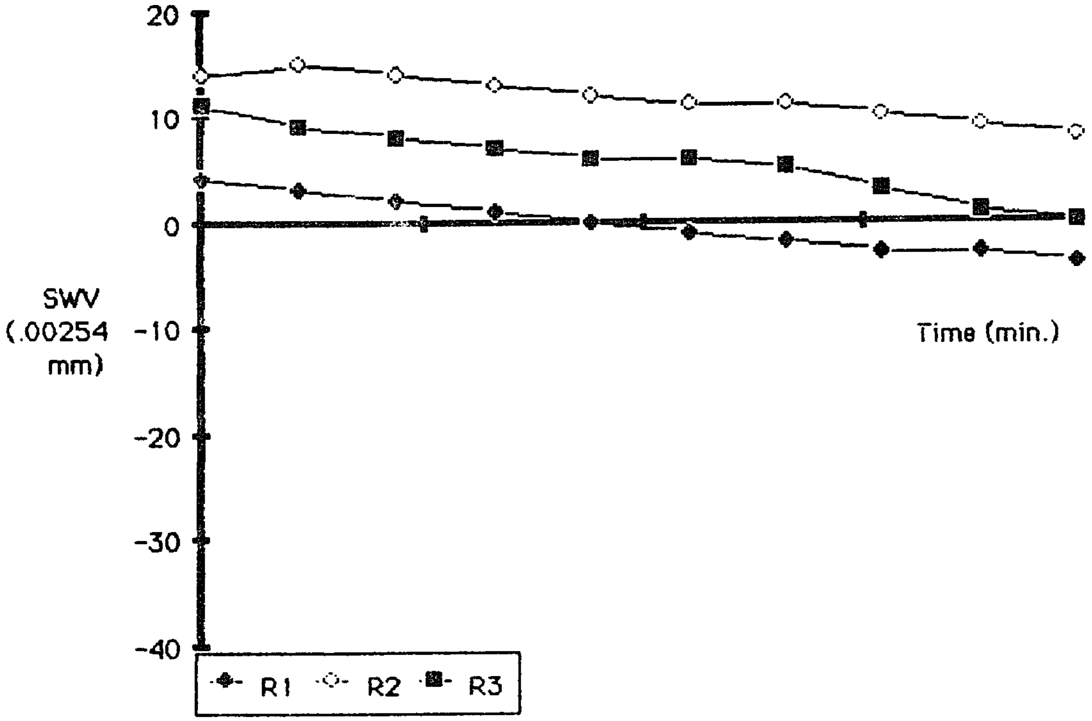


Fig. 5.24 705W002 SWV of Three Replications

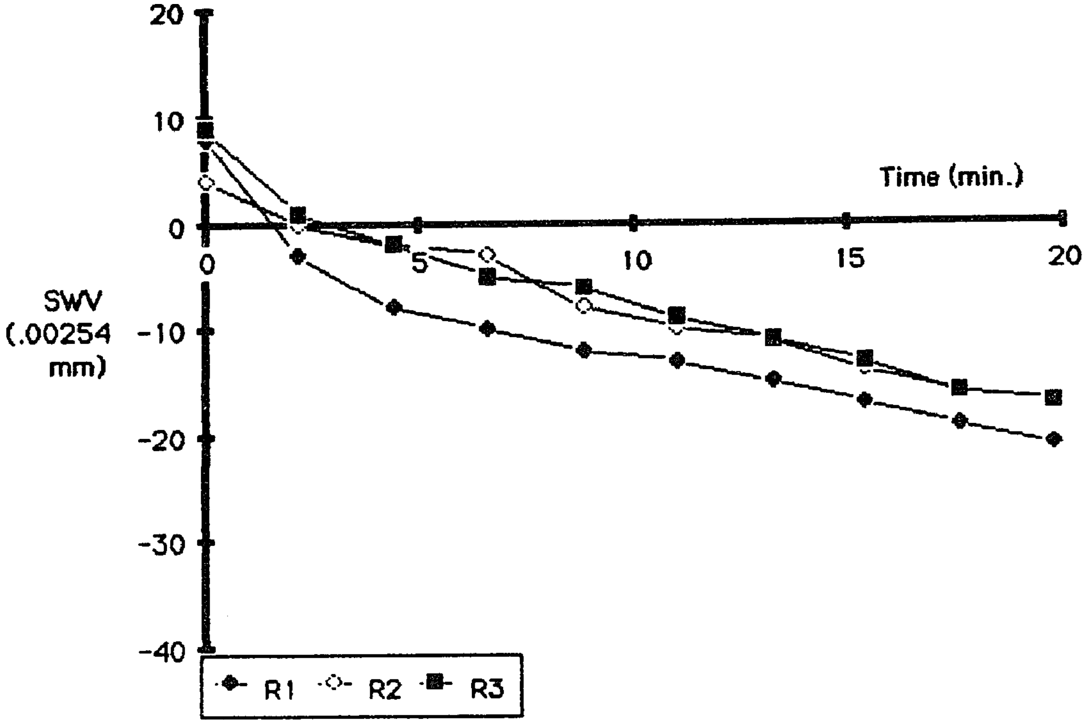


Fig. 5.25 705E014 SWV of Three Replications

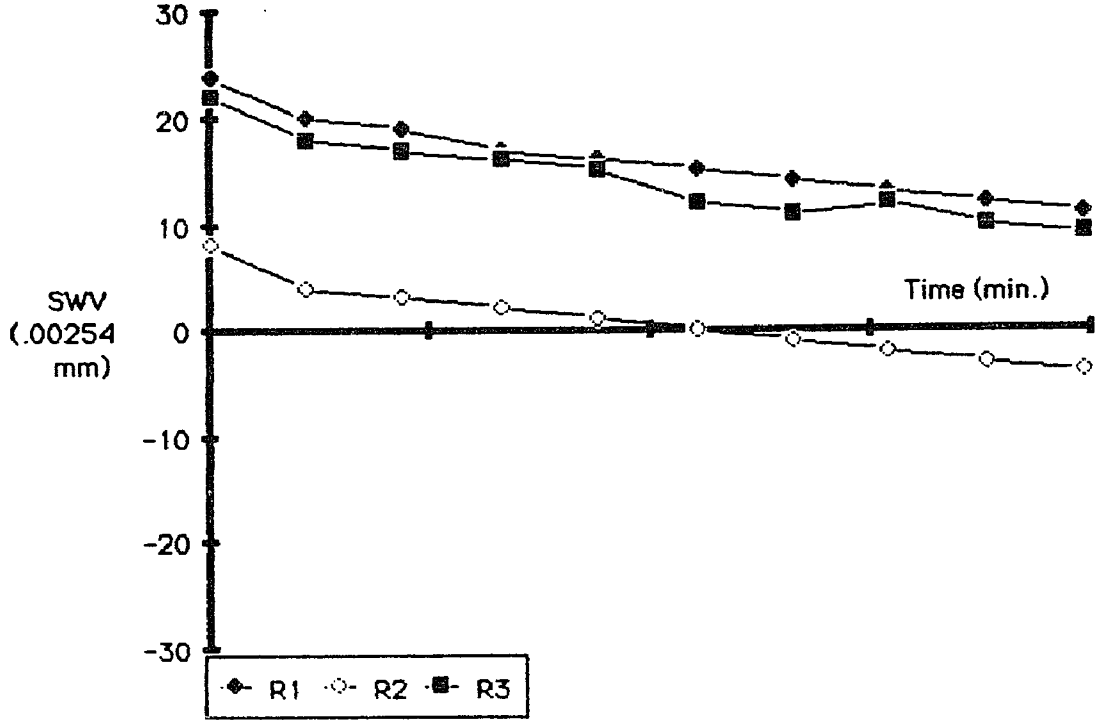


Fig. 5.26 651L100 SWV of Three Replications

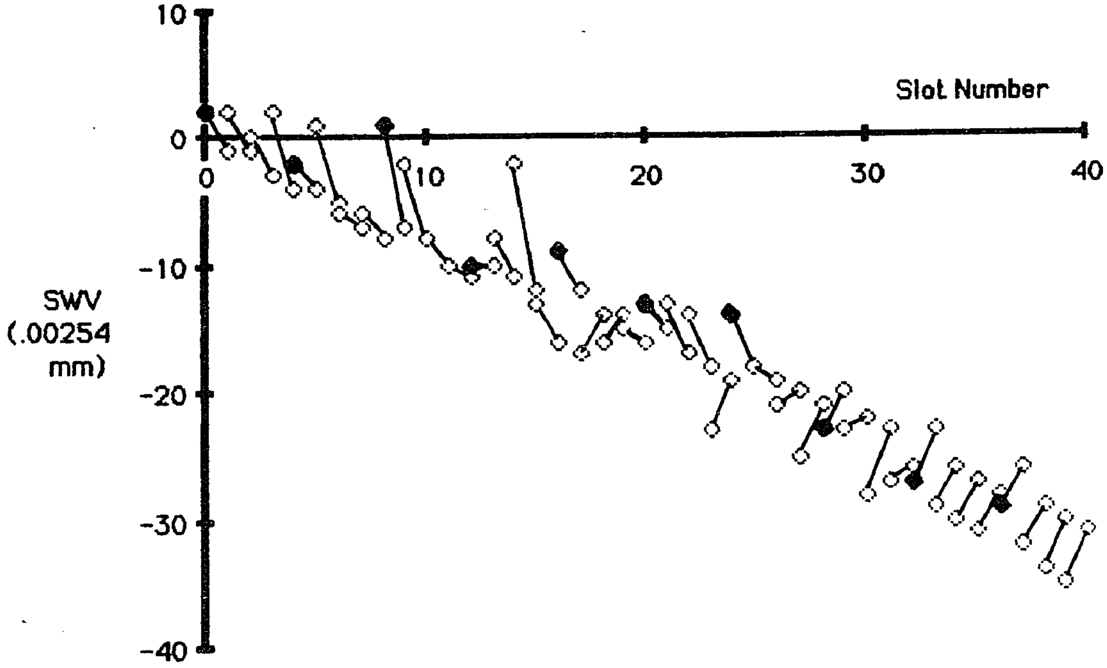


Fig. 5.27 <u>705E001 SWV of R1 Versus Slot Number</u>

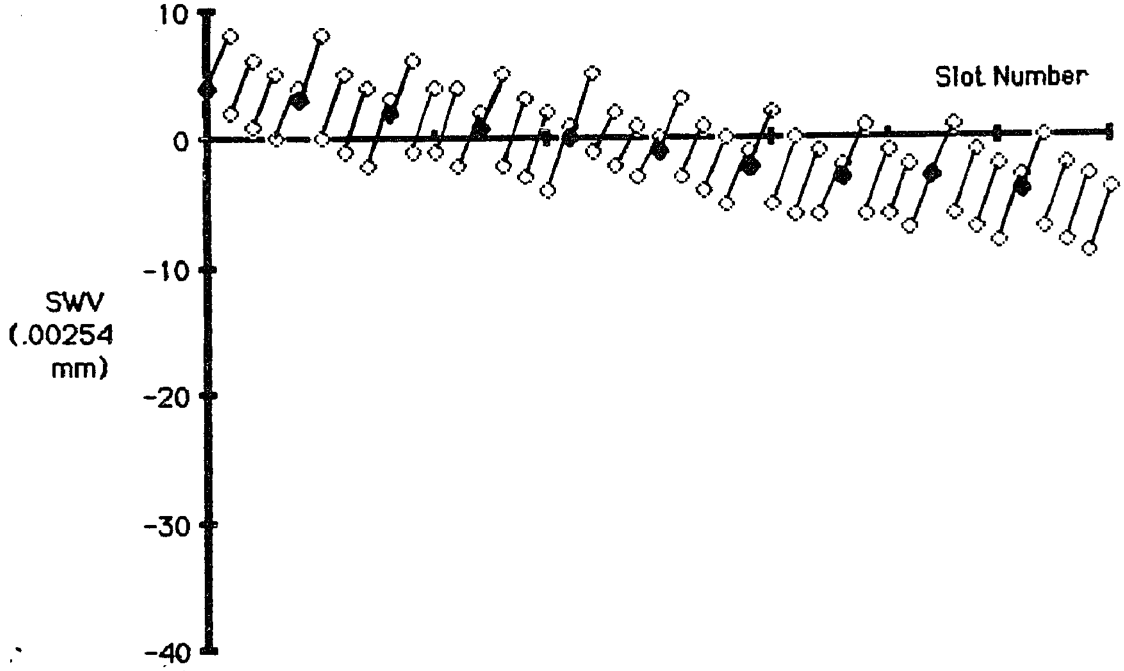


Fig. 5.28 <u>705W002 SWV of R1 Versus Slot Number</u>

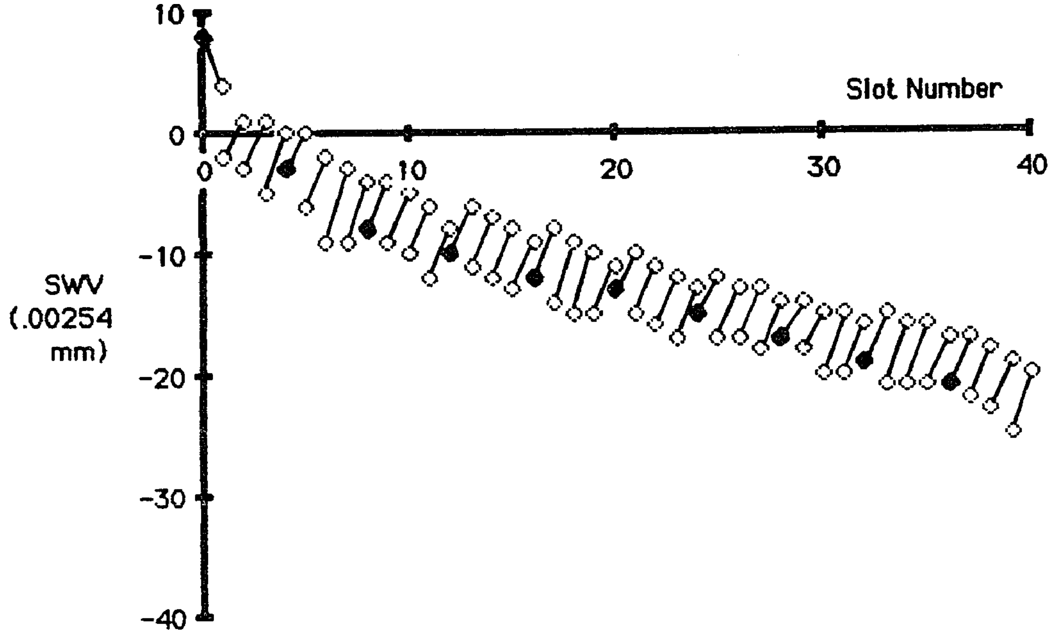


Fig. 5.29 705E014 SWV of R1 Versus Slot Number

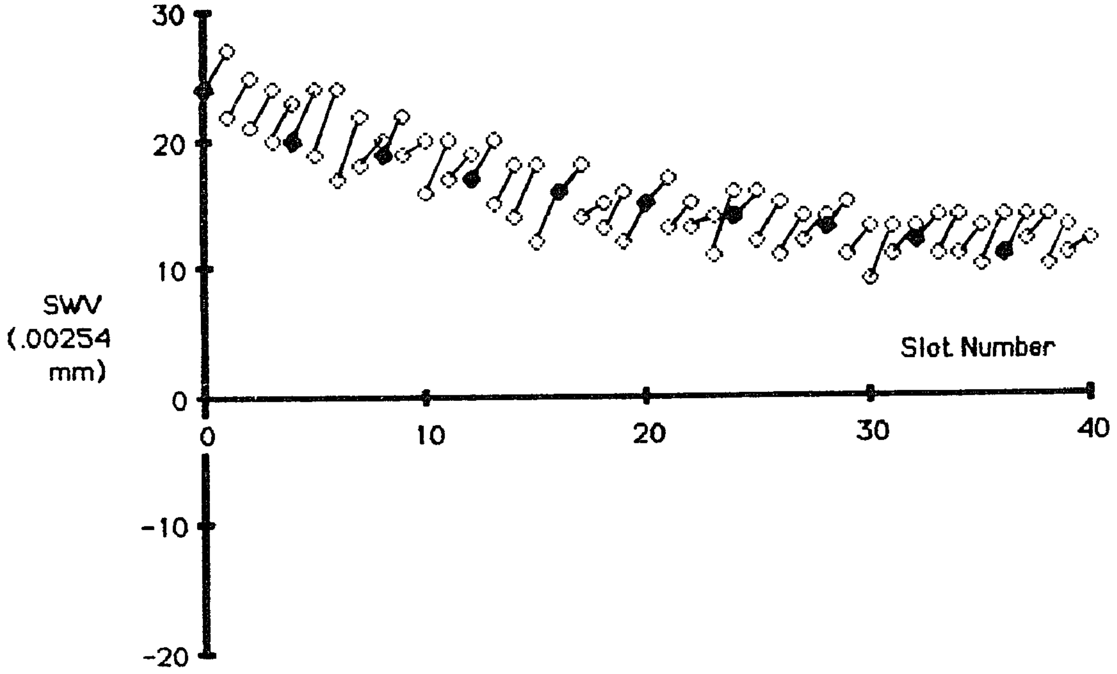


Fig. 5.30 651L100 SWV of R1 Versus Slot Number

Finally, the last objective of the EMST preliminary testing was to establish the statistical tools required for analyzing the data and, hence, the experimental design for actual testing. As mentioned before, the slope/rate of the slot width variations determined from measurements of the slot widths at the beginning of the bars was the selected slotting-performance indicator. Measuring the slot width instead of the tool wear has several advantages, one of which is the direct reflection of any BUE formation, if present, on the machine surfaces. The tool wear may not be affected as much as the machine surfaces with the presence/absence of BUE depending on the BUE size and stability. Also, the slot width measurements are taken after completing the required cutting and, thus, there are no setup disturbances during testing.

Examination of Figures 5.25 and 5.26 indicates that the slot width variations reflect two tool wear zones, the break-in and gradual wear zone. Since the tool wear rate is not constant during the break-in period, it was decided to disregard the first readings, the slot width measurements at roughly zero cutting time. It was, also, questionable whether the accelerated tool wear zone (which also, exhibits non-constant tool wear rate) would appear in the twenty minutes cutting time, especially for the work materials of low machinability. Additional bars from the 705W002 material, regarded as a low machinable material according to HRL production rates (see Appendix B), were machined using the end mill of its first replication. Figure 5.31 presents the results obtained that may point to a slight change in the setup. The difference between the 10th and 11th readings was .0019 inch (.0483 mm). Examination of the slot width variation rate before and after these two readings indicate that they were similar. It was, hence, concluded that this difference could have resulted from a slight change in the eccentricity between the cutting edges and their shank due to dust or any other factors. Figure 5.32 shows the results after adjusting for this difference. These results indicate that the accelerated tool wear zone would not appear during the twenty minutes of cutting. In addition, Figures 5.31 and 5.32 further point to the advantage of measuring the slot width instead of the tool wear. Perhaps, these figures are the answer to why tool life data shows scatter of 20 to 30 per cent [26]. In statistical terms, it seems that whenever the tool is set in its holder, a new population is generated.

Figure 5.33 shows the plot of the averages versus variances of the three replications' results. Examination of the figure indicates that a transformation to stabilize the variance was not required (i.e. the variance was constant). A simple linear regression model was then utilized to determine the slope/rate of the slot width variations. Table 5.2 provides the regression results in terms of slopes, coefficients of correlation, and HRL production rates. It should be mentioned here that during regression analysis, influential points [153] were identified and disregarded. For example, for the results of the four materials, one point of the 705E014 first replication results was considered an outlier and was disregarded (i.e., the SWV rate was determined based on eight points instead of nine for this replication).

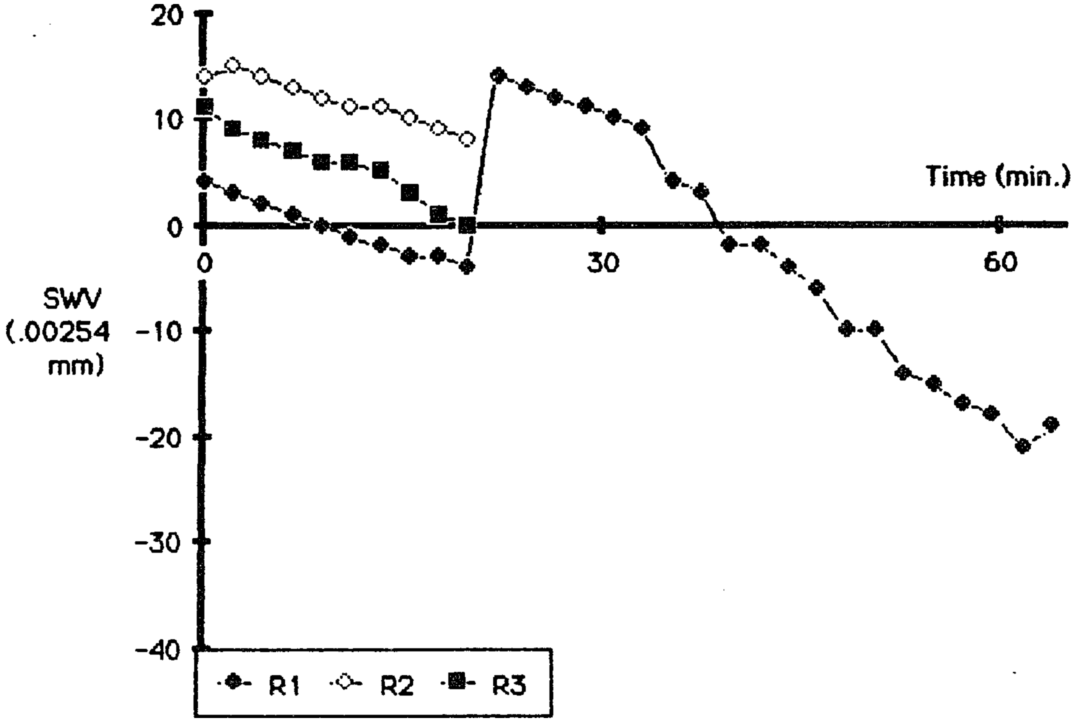


Fig. 5.31 705W002 SWV with a Longer Slotting Time

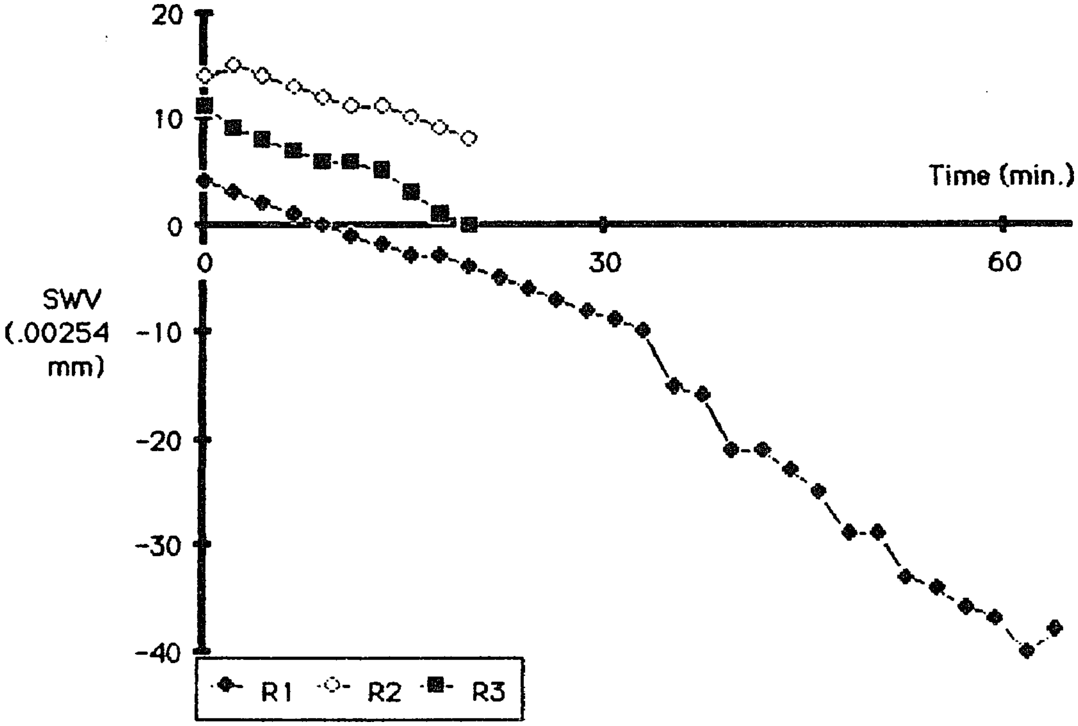


Fig. 5.32 705W002 SWV with a Longer Slotting Time, after Adjusting

Table 5.2 EMST Preliminary Testing Results

Material	Slope (correlation coefficient)			Average	HRL
	First	Second	Third	Rate	(pcs/hr)
705E001	-.000169(.94)	-.000193(.95)	-.000252(.97)	-.000205	336
705W002	-.000040(.98)	-.000038(.99)	-.000050(.96)	-.000043	383
705E014	-.000083(.99)	-.000102(.98)	-.000102(.99)	-.000096	440
651L100	-.000051(.99)	-.000045(1.0)	-.000052(.94)	-.000049	538

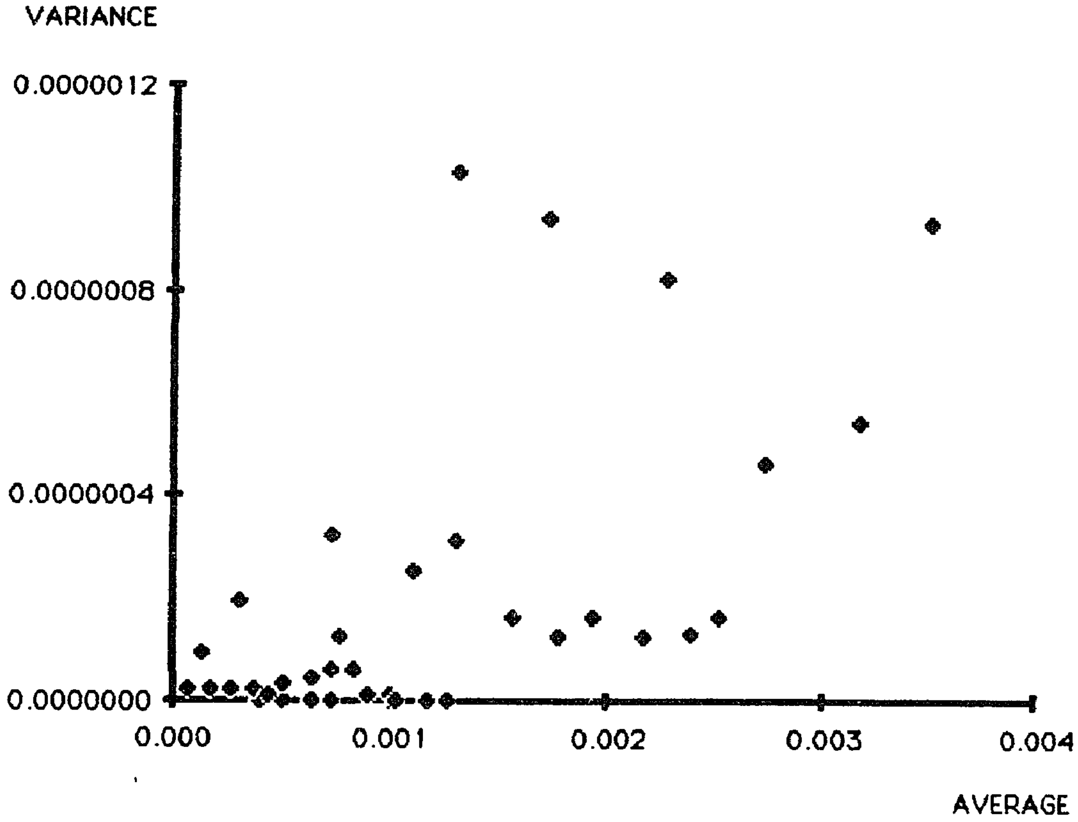


Fig. 5.33 Averages Versus Variances for EMST Preliminary Testing

Examination of Table 5.2 indicates that with the exception of the 705W002 material, the EMST and HRL results correlated well. Based on the two tests, the 705E001 was the lowest machinable material and the 651L100 was the most machinable one. The correlation coefficient between the two tests was .65. In other words, the larger the SWV slope/rate, the lower the production rate.

In conclusion, the EMST preliminary results indicate that the test does differentiate between the materials, is repeatable, and does correlate well with the PPT. Further, the EMST is quicker and more sensitive than the PPT in identifying those materials with a higher tendency for BUE formation, such as the 705E001.

5.4 EMST Actual Tests

The remaining eleven of the fifteen work materials were randomly machined under the same cutting condition utilized in preliminary testing (cutting condition # 7, see Fig. 5.2).

Figures 5.34 to 5.44 present the three replications' results obtained for the eleven materials, where the 9T material had two replications due to stock limit (Fig. 5.41). Figure 5.45 which shows the plot of the averages versus variances of these results indicates that a transformation to stabilize the variance was not required. Examination of the surface textures of the machine bars indicated that the 705E001, 705E017, and 705E002 had exhibited BUE formation. The first two materials gave low production rates according to the PPT results (see Appendix B), and, hence, the EMST did point to two materials of low machinability. However, the 705E002 material which also exhibited BUE formation was ranked well based on HRL results.

In addition to BUE formation, examination of the surface textures indicated that for some materials the chip did get between the cutting edge and the machine surface and, in turn, lines engraved on the machine surfaces were the result. Originally, it was thought this was due to the gravity force effects when horizontal milling. However, the marks were seen on both walls of the slots. Re-examination of the machine bars indicated that all work materials exhibited the engraved lines except the 9T, 10T, and 12T ones.

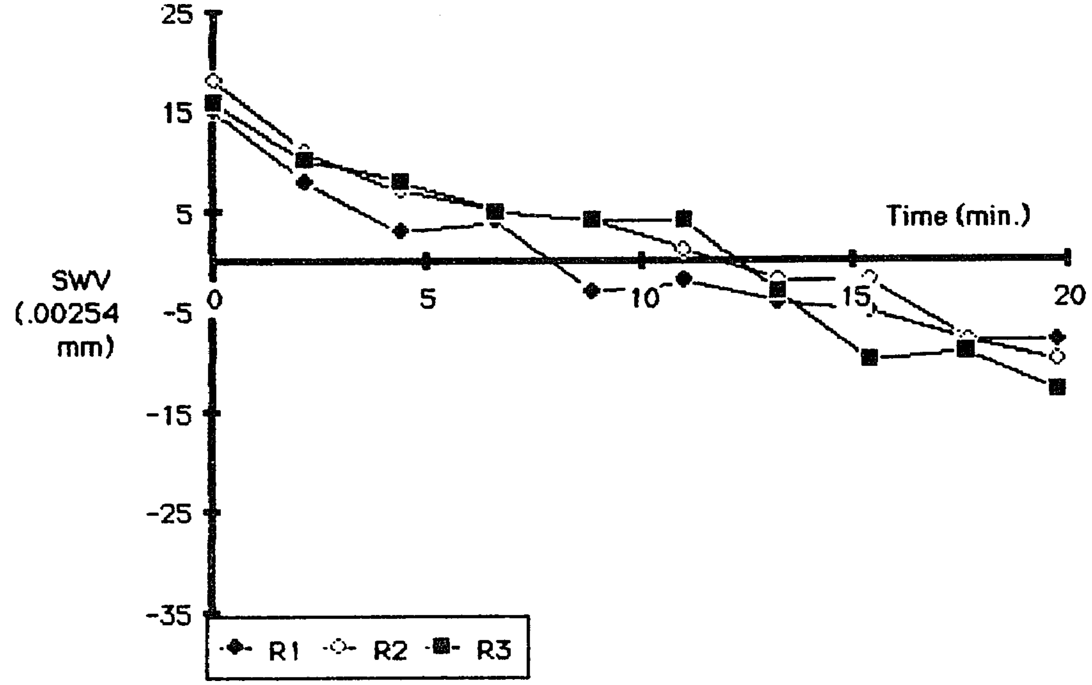


Fig. 5.34 **705E017 SWV of Three Replications**

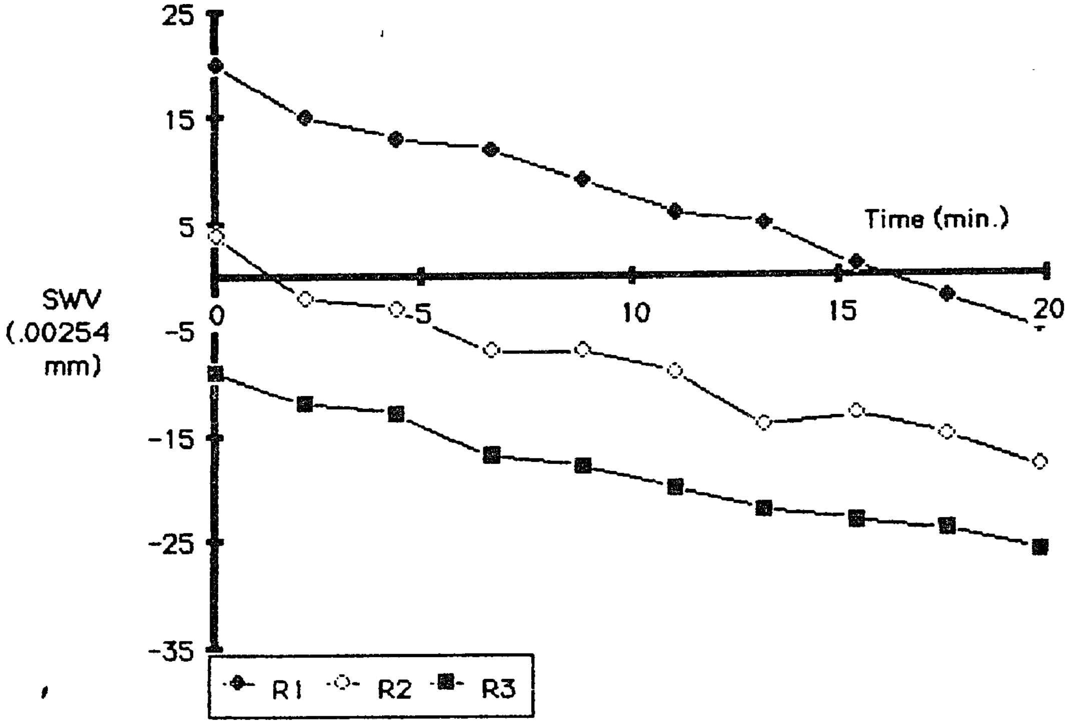


Fig. 5.35 **705E003 SWV of Three Replications**

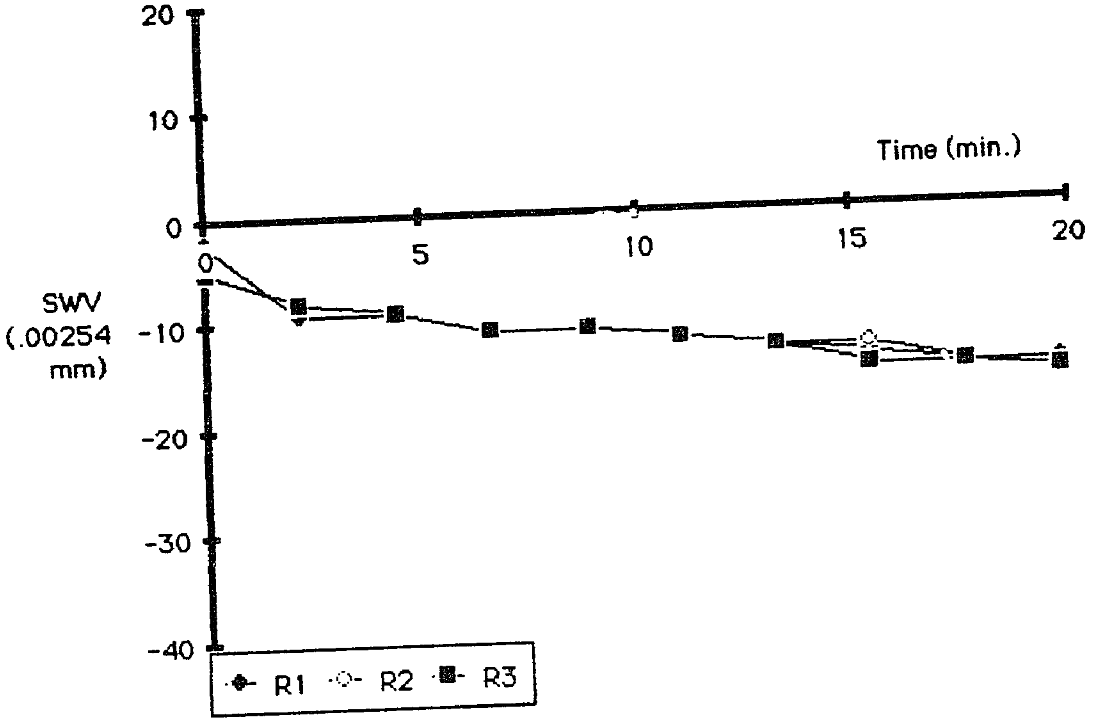


Fig. 5.36 705C034 SWV of Three Replications

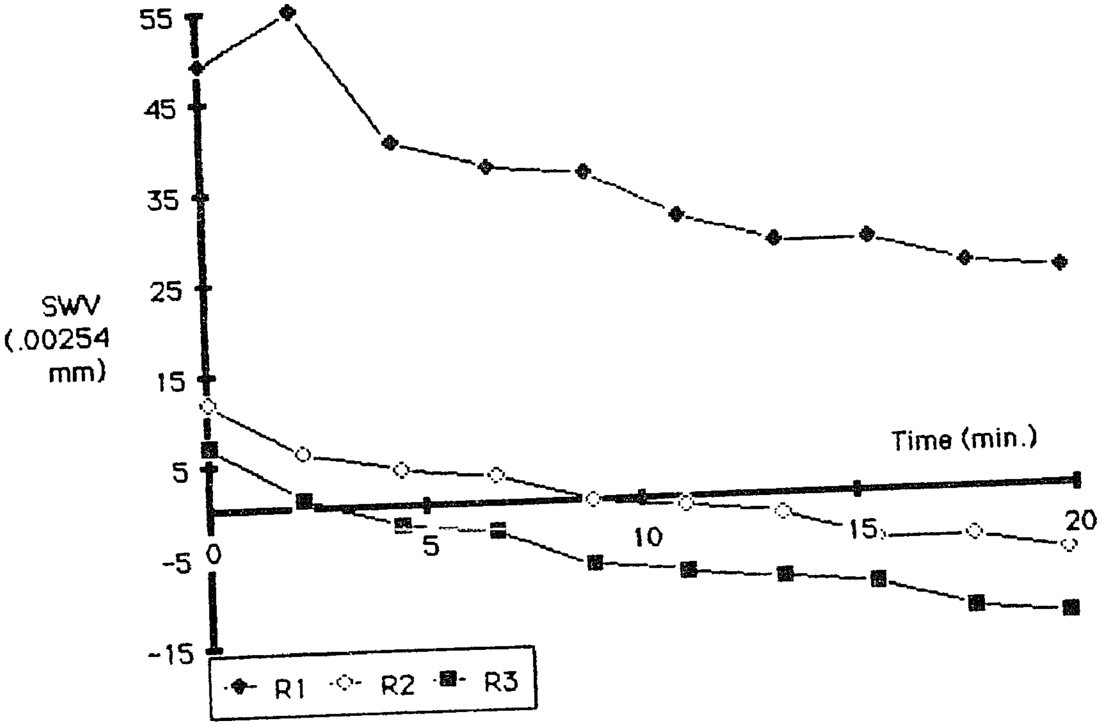


Fig. 5.37 705E016 SWV of Three Replications

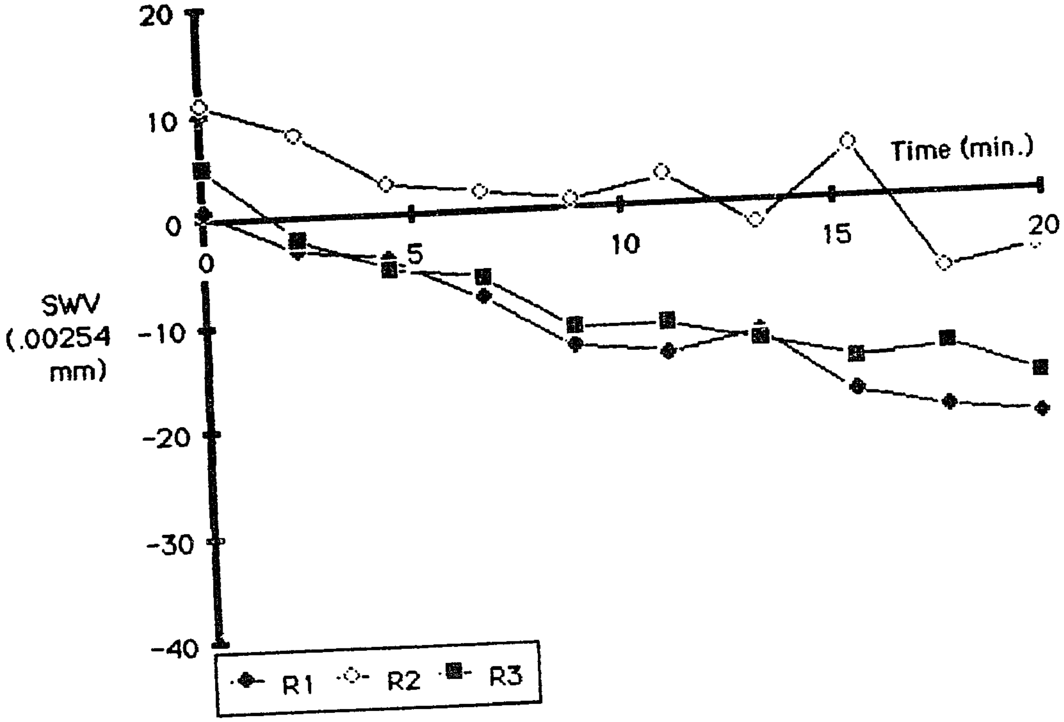


Fig. 5.38 705E002 SWV of Three Replications

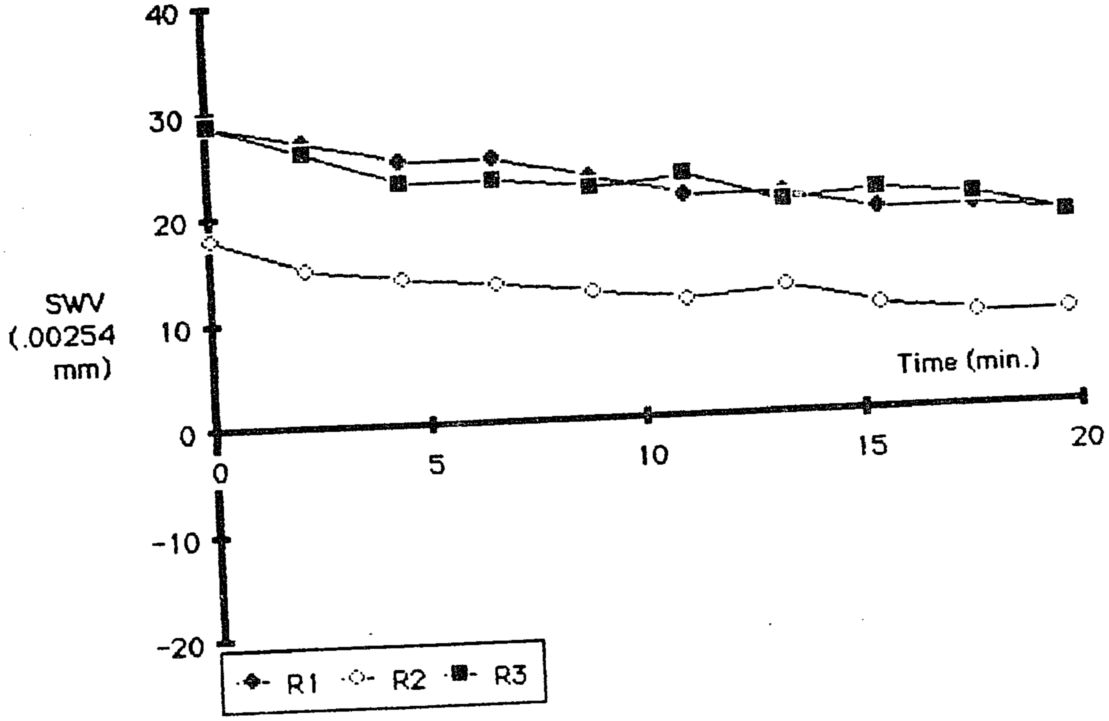


Fig. 5.39 651L101 SWV of Three Replications

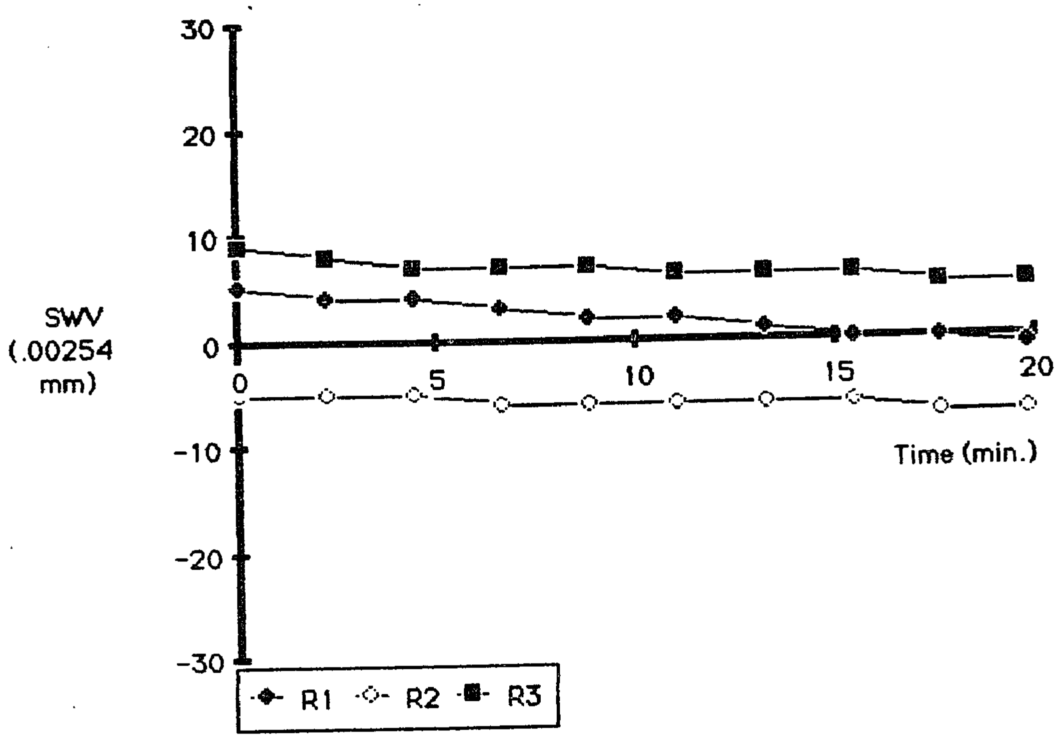


Fig. 3.40 **625L286 SWV of Three Replications**

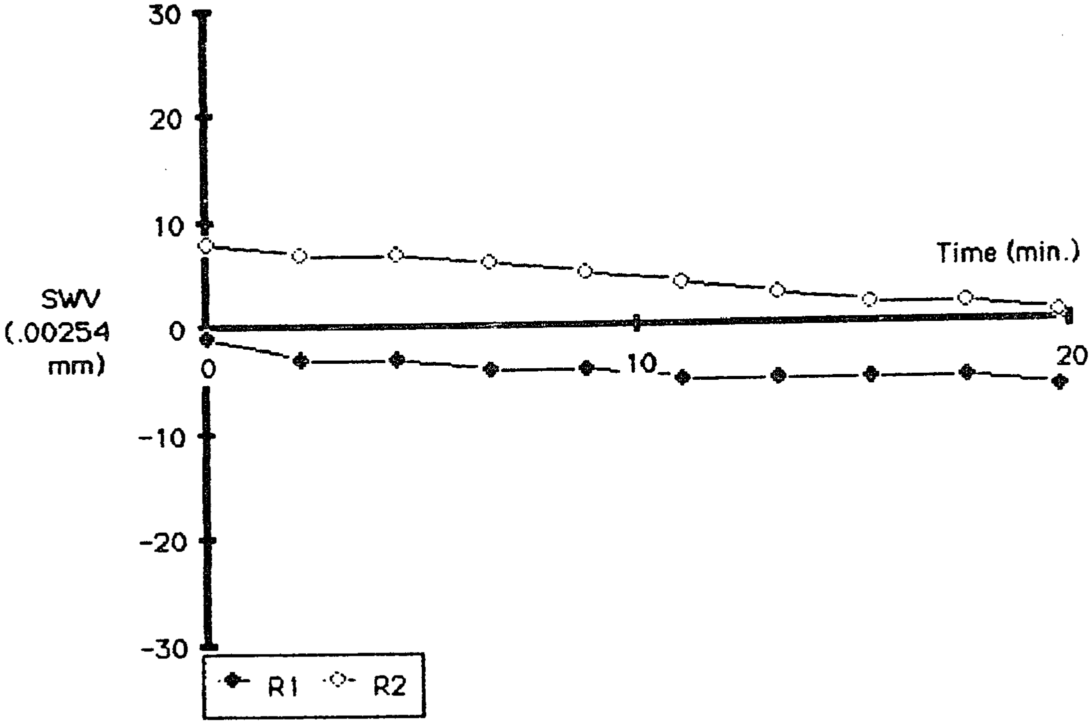


Fig. 3.41 **9T SWV of Two Replications**

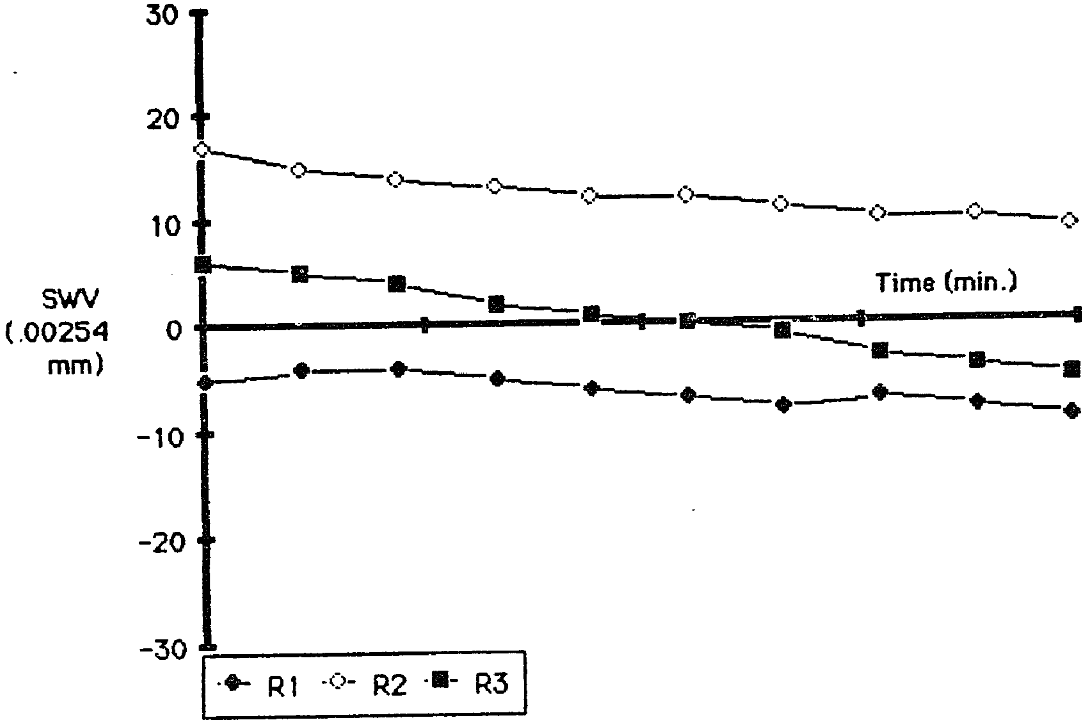


Fig. 5.42 **10T SWV of Three Replications**

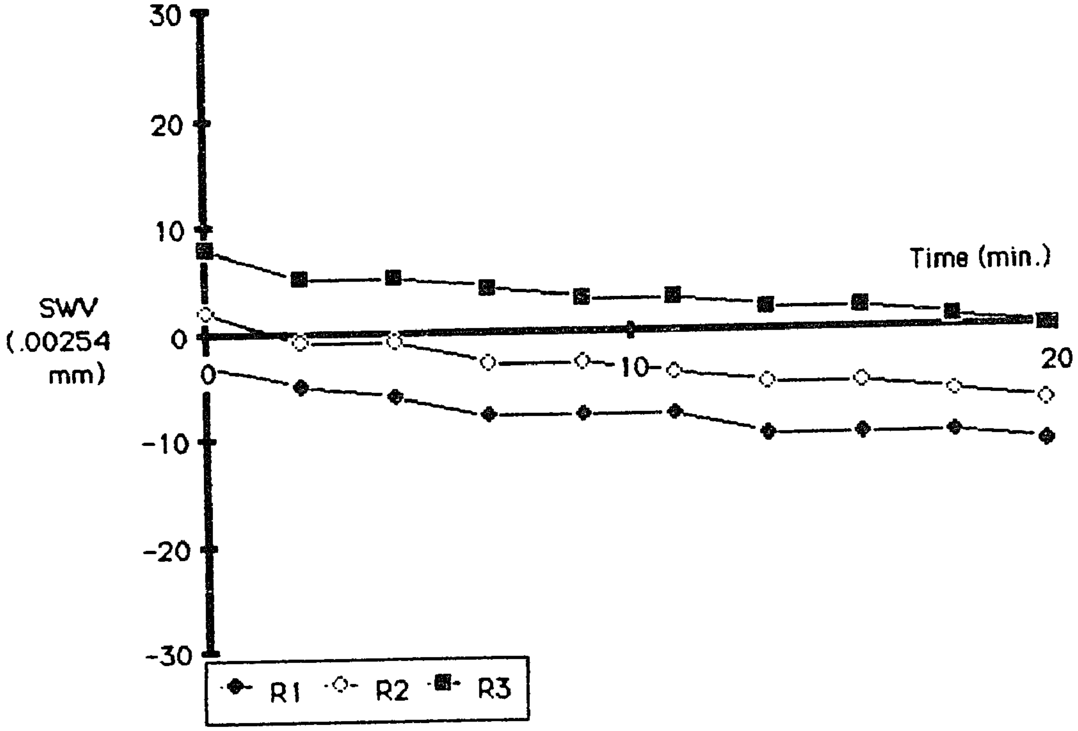


Fig. 5.43 **11T SWV of Three Replications**

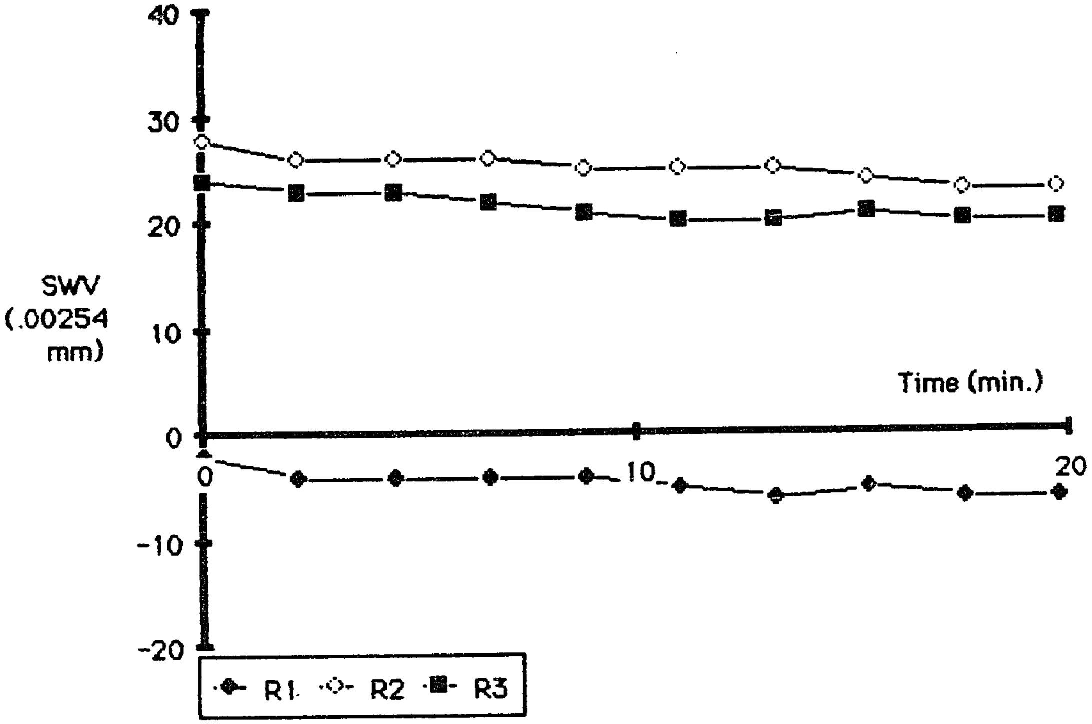


Fig. 5.44 <u>12T SWV of Three Replications</u>

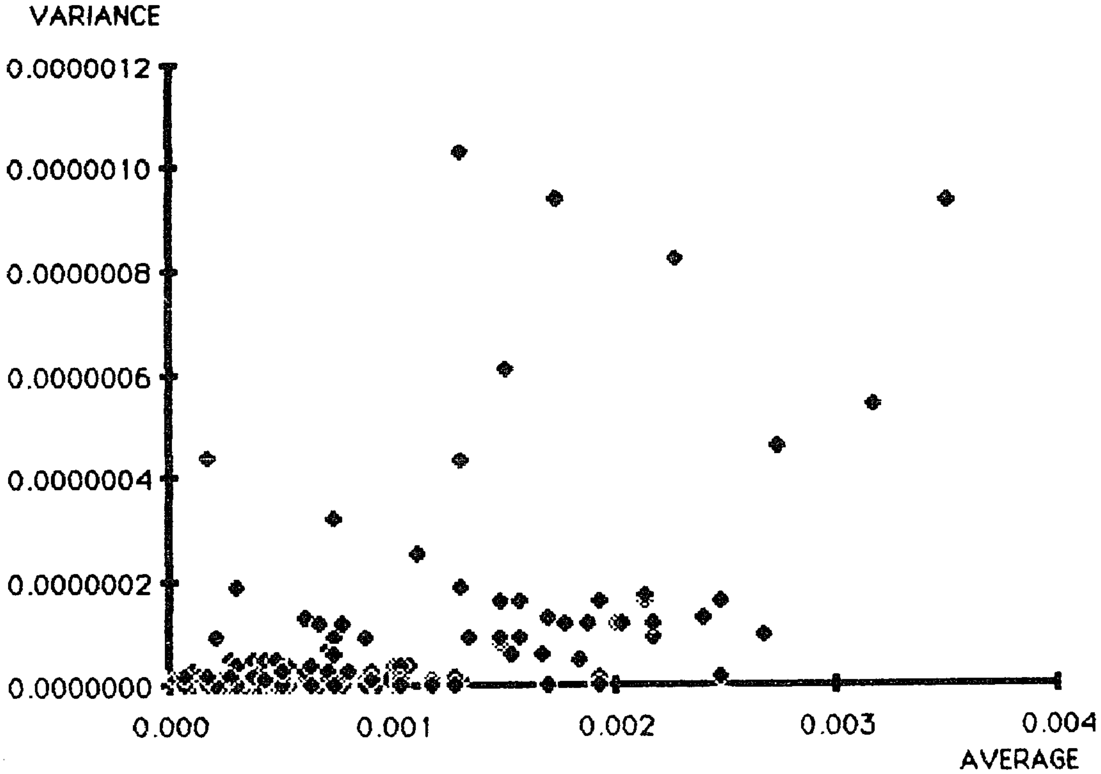


Fig. 5.45 <u>Averages Versus Variances for EMST Actual Testing</u>

Table 5.3 provides the regression results (after being rounded off from computer prints) in terms of slopes, coefficients of correlation, and averages and variances of SWV rates. Figure 5.46 provides the plot of these averages versus their variances. As mentioned before, during regression analysis, influential points were indentified and disregarded. However, only three influential points were found in the results of; (1) 705E014 first replication, (2) 705E016 first replication, and (3) 705E002 second replication.

Examination of Figure 5.46 indicates that the 705E001 had the highest variance. This was followed by the 705E017. Both materials and the 705E002 had a high tendency for BUE formation as was reflected on the machine surfaces. Since there were only two replications for the 9T material and the resulted variances were very small (with the exception of the 705E001) relative to the averages (see Table 5.3), it was decided not to apply the Duncan multiple-range test which requires equal sample sizes. However, the materials were still grouped relative to their results. For example, the average SWV rates of the 705E016 and 705E002 were -.000088 and -.000086 respectively, and, hence, were grouped with a -.000087 value.

Table 5.4 presents the HRL production rates, the EMST results determined after subjective grouping, and the absolute difference between the two tests' ranking. The biggest disagreements among the two tests' ranks were reflected in two materials, the 705W002 and 12T as indicated by an asterisk on Table 5.4. The slotting test does not show the 705W002 as unmachinable as the screw machine test. However, the EMST did differentiate among the materials. The two tests' results had a 58 % correlation. Additional cross correlation analysis is given in section 7.1.

Table 5.3 EMST Actual Testing Results

Material	Slope (Correlation Coefficient)			Average Rate	Variance
	First	Second	Third		
705E001	-.000169(.94)	-.000193(.95)	-.000252(.97)	-.000205	1837.2E-12
705W002	-.000040(.98)	-.000038(.99)	-.000050(.96)	-.000043	41.5E-12
705E017	-.000088(.91)	-.000113(.97)	-.000136(.93)	-.000112	587.8E-12
705E014	-.000083(.99)	-.000102(.98)	-.000102(.99)	-.000096	126.5E-12
705E003	-.000114(.98)	-.000090(.96)	-.000080(.98)	-.000095	319.0E-12
705C034	-.000038(.97)	-.000042(.97)	-.000045(.97)	-.000042	14.5E-12
705E016	-.000108(.96)	-.000073(.98)	-.000082(.97)	-.000088	313.7E-12
705E002	-.000105(.94)	-.000072(.86)	-.000081(.93)	-.000086	292.5E-12
651L100	-.000051(.99)	-.000045(1.0)	-.000052(.94)	-.000049	12.8E-12
651L101	-.000051(.96)	-.000034(.94)	-.000036(.85)	-.000040	93.2E-12
625L286	-.000030(.98)	-.000011(.82)	-.000016(.92)	-.000019	95.5E-12
9T	-.000016(.89)	-.000037(.98)	-	-.000027	225.0E-12
10T	-.000029(.92)	-.000033(.98)	-.000058(.99)	-.000040	244.7E-12
11T	-.000032(91)	-.000034(.97)	-.000028(.97)	-.000031	9.4E-12
12T	-.000014(.78)	-.000019(.90)	-.000018(.74)	-.000017	8.2E-12

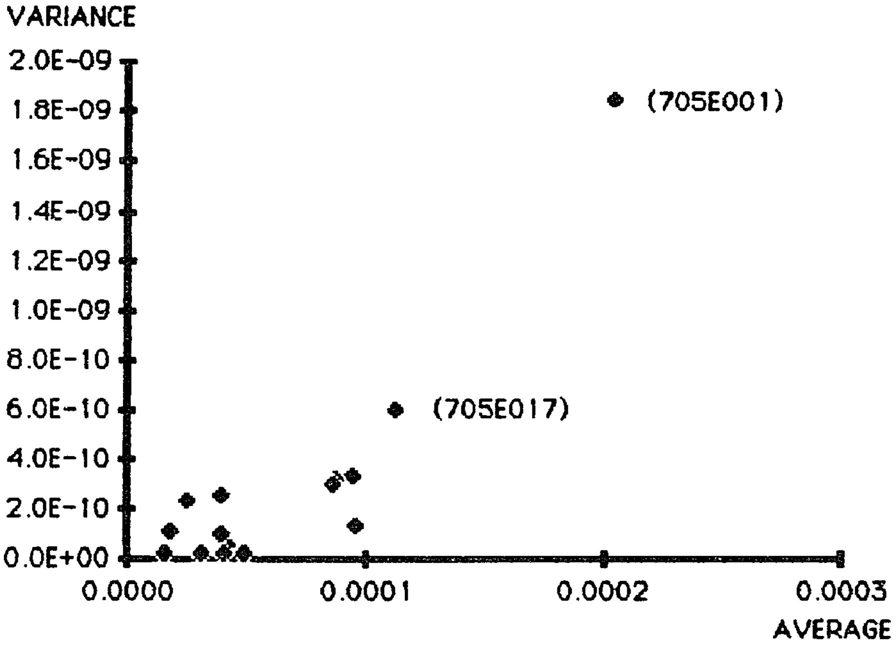


Fig. 5.46 Averages Versus Variances of SWV Rates

Table 5.4 HRL Production Rates and EMST Results

	HRL		EMST		Absolute Difference
Material	pcs/hr	Rank	SWV Rate	Rank	in Ranking
705E001	336	8	-.000205	7	1
705W002	383	7	-.000044	3	4 *
705E017	388	6	-.000112	6	0
705E014	440	5	-.000096	5	0
705E003	440	5	-.000096	5	0
705C034	440	5	-.000044	3	2
705E016	572	2	-.000087	4	2
705E002	572	2	-.000087	4	2
651L100	538	3	-.000044	3	0
651L101	620	1	-.000044	3	2
625L286	620	1	-.000018	1	0
9T	502	4	-.000027	2	2
12T	502	4	-.000018	1	3 *

Correlation Coefficient: +.577

5.5 EMST Summary and Applications

The EMST was designed to depict the machining characteristics of the machinability space of free-cutting steels. This was in terms of using a HSS tool material, an indicator based on the part quality (rate of dimensional stability of machined slots), and an intermittent type operation (slotting). Possible sources of error, such as thermal effects, were identified and minimized. The work materials were evaluated under a practical slotting condition. Due to the low material consumption relative to an equivalent Taylor type test, three replications were taken when the material stock was available. This was through machining four slots on four inch (101.6 mm) bars.

The EMST does differentiate between the materials, is repeatable, and more sensitive than the PPT in identifying those materials with a higher tendency for BUE formation. The test results correlated with the PPT results with a correlation coefficient of 58 %.

Although there are no replications for the PPT, a similar analysis to the one applied on the EMST results can be utilized for the PPT data. A simple linear regression model can be employed on the surface roughness results. The slope/rate of the fitted model can be utilized in comparing different materials. The advantage of using a fitted regression line is that the variance of the estimated parameter (slope) would be an indication to the data variability (work material's homogeneity).

The test was developed with the objective of employing it to insure the quality of the screw machine materials. It can, also, be utilized before the PPT for qualifying new materials, especially for identifying those materials with a high tendency for BUE formation. However, due to the high testing time required relative to that of the Power Hacksaw Test (PHT), it was decided not to recommend the EMST test for evaluating the machinability of work materials in production lines.

Chapter 6: CUTTING FORCES TEST

6.1 Introduction

The majority of the cutting forces tests performed on a lathe can be classified into two groups; conventional and non-conventional. The first group would include the ones that directly utilize cutting forces measured on a conventional setup in their analyses. The second group would include those tests that require an unconventional setup (i.e., turning at constant feed force tests [18] and turning at increasing speed tests [98]). The main drawback to non-conventional cutting forces tests is the special setup required. Such setups are not even available in most laboratories.

Conventional cutting forces tests can be further classified into orthogonal and normal turning. However, to achieve orthogonality on a lathe, some workpiece preparations and/or certain workpiece geometries, or a special tool geometry would be required. For normal turning, typical cutting forces indicators include forces obtained under certain conditions ([3], [4] & [22]), feed for a given feed force value or the feed force resulted at a certain feed [2], time to reach a certain feed force [123], and horsepower calculated from measured forces [5]. In the work of Fersing and Smith [88] and De Filippi [89], it was indicated that the feed force increases faster than the cutting force with tool wear. Meanwhile, Colwell, Mazur and De Vries [90] concluded that the feed force was a better indicator of the beginning of the accelerated tool wear region than the cutting force. In other words, the feed force is more sensitive to variations in the machining process than the cutting force. Perhaps due to that and the small magnitude of the radial force, the majority of the indicators utilized in cutting forces tests are related to the feed force.

Although the literature survey of the cutting forces tests, given on pages 40 to 51, indicates that none of them has correlated well with industrial ratings (i.e., the PPT results), a conventional cutting forces test was still utilized. The cutting forces are the main sources of the heat generated during metal cutting. This heat raises the cutting temperature which was shown to correlate well with commercial ratings [99], and it was, hence, questionable why the cutting forces do not correlate well with the PPT results while the cutting temperature does. Prehaps this can be attributed to the high scatter in the cutting forces readings. In a work by Redford [34] to investigate on-line tool wear assessment, the cutting forces readings gave more scatter than the cutting temperature measurements, especially when the tool was worn. For reliable machinability evaluation of work materials using cutting forces tests, the effect of this data scatter may be reduced through replications. Despite the added costs of replications, several advantages can be realized; (1) the setup of cutting forces tests is simpler than that of the cutting temperature ones, and (2) the machining time required for the cutting forces to reach the steady state condition is less than that needed for the cutting temperature. That is, the conversion of mechanical energy into heat which raises the cutting temperature takes time. The steady state temperature was reached after 25 seconds of cutting in a work by Redford [34], while 20 seconds was required in another work by Mills and Akhtar [41].

In addition, none of the previous studies addressed the relative sensitivity of the cutting forces components (cutting, feed and radial force) in differentiating among the machinability of work materials. Particularly, the radial force is often neglected due to its smaller magnitude relative to the other two components, while it is the one that directly affects the tool nose wear and, thus, lowers the dimensional accuracy. Cook [32] mentioned that the degree of tolerance degradation is associated with the wear of the tool nose radius and flank, and that it generally correlates well with tool flank wear. Finally, the ranking of the work materials was independent of feed pressure when sawing and of cutting feed when slotting. It was, then, desired to investigate whether the materials ranking is independent of other cutting parameters, such as the cutting speed and depth of cut.

Therefore, the Cutting Forces Test (CFT) was utilized; (1) to justify previous work conclusions ([2] & [3]) that cutting forces do not correlate well with the PPT results (or commercial performance ratings), (2) to investigate the sensitivity of the resultant force components (cutting, feed and radial force) in differentiating between the work materials under study, and (3) to determine whether the ranking of work materials is independent of cutting conditions.

6.2 CFT Testing Equipment

All tests were performed on a LeBlond 20 inch (508 mm) heavy duty lathe at HRL. The lathe was equiped with a Kistler 9257A dynamomter, 9403 tool holder, and 5008 charge amplifier. The data acquisition and display system consisted of a smartscope, a monitor and an oscilloscope (model 700) manufactured by T.G. Branden.

In order to avoid possible errors in resharpening HSS cutting tools, indexable carbide inserts (WC) were utilized. Table 6.1, abstracted from reference [138], provides the recommended cutting conditions and carbide tool material for turning the work materials under study. The utilized inserts were Kennametal TNG322 (i.e., a triangle insert of a 2/64 inch (.8 mm) nose radius) of the K45 type, an equivelant to the C-6 one. A Kennametal KTBR-643 INS TN-32 (i.e., tool geometry of -5, -5, 5, 5, 15, and 18 degrees) tool holder was also utilized. A negative tool holder was chosen, since a negative insert provides more cutting edges than a positive one. The above tool geometry was employed due to the small diameter of the bars, 1-inch (25.4 mm), and the fact that the larger the SCEA, the larger the radial force and, hence, vibration.

Table 6.1 Recommended Turning Conditions

Material	BHN	Depth-of-Cut		Cutting Speed		Feed		Tool Mat'l	
		inch	mm	sfpm	m/min	ipr	mm/r	C	ISO
1213 CD	150-200	.040	1	860	260	.007	.18	C-7	P10
		.150	4	650	200	.020	.50	C-6	P20
		.300	8	510	155	.030	.75	C-6	P20
		.625	16	400	120	.040	1.00	C-6	P20
12L14 CD	150-200	.040	1	1050	320	.007	.18	C-7	P10
		.150	4	840	255	.020	.50	C-6	P20
		.300	8	640	195	.030	.75	C-6	P20
		.625	16	475	145	.040	1.00	C-6	P20

6.3 CFT Preliminary Tests

The main objectives of the CFT preliminary tests were; (1) to investigate the sensitivity of the resultant force components (cutting, feed and radial force) in differentiating between the work materials, (2) to determine whether the ranking of work materials is independent of cutting conditions, and (3) to locate a cutting condition at which screening among the materials is statistically most powerful.

Figure 6.1 shows the CFT as an input/output system. Three materials (705E001, 705W002 & 651L100) were randomly selected from the four utilized in the EMST preliminary testing. Initially, it was planned to select testing conditions around the average of those recommended in Table 6.1. However, the machine was discovered to lose power above a certain cutting condition; a cutting speed of 650 sfpm (198 m/min.), a feed of .009 ipr (.225 mm/r), and a depth of cut of .050 inch (1.27 mm). It was, therefore, decided to test the materials under some conditions that would reflect the effects of speed, feed, depth of cut, and a rough cutting condition on the ranking of the materials. Table 6.2 presents an incomplete 2^3 factorial design that indicates the speed (v), feed (f), depth of cut (d), and the interaction term (fd) effects from the conditions at which all factors are low. The interaction term (fd) represented a rough cutting condition. Three replications were taken for each material under each of these cutting conditions.

The bars were held between a collet and a live center with around one foot (304 mm) exposure to avoid vibration. For each test, a new cutting edge was utilized to first remove a thin outer-skin, .005 inch (.13 mm) depth of cut, and then cut for 13 seconds under the test conditions. The removal of the outer-skin provides a uniform depth of cut and, thus, eliminates a possible source of noise. The first three seconds were regarded tool break-in period. Although this could result in different values for the initial flank wear among the materials and/or cutting conditions, breaking-in the tools on a standard material is a time consuming process. Further, as mentioned earlier, on page 215, whenever the tool is set in its holder, a new population is generated. In other words, breaking-in the tools on a standard material could result in a higher level of noise than having slight variations in the initial flank wear break-in values. Simply stated, the objective was to insure that each cuting edge was broken-in before any measurements were taken (i.e., measure cutting forces at the beginning of the gradual tool wear zone). The smartscope was, hence, set to record 500 readings per 10 seconds and to display the slope of a fitted line to these measurements. The slopes were examined to insure that all the readings were taken after the tool break-in period, and that they were not significantly different between materials and/or testing conditions. The average value of the 500 readings was, then, recorded for each cutting force component.

Table 6.2 An Incomplete Factorial Design

(1)	(d)	(f)	(fd)
$v_1 = 400$ sfpm (120 m/min) $f_1 = .009$ ipr (.225 mm/r) $d_1 = .040$ in. (1 mm)	$d_2 = .080$ in. (2 mm)	$f_2 = .018$ ipr (.457 mm/r)	$f_2 = .018$ ipr (.457 mm/r) $d_2 = .080$ in. (2 mm)
(v) $v_2 = 600$ sfpm (180 m/min)			

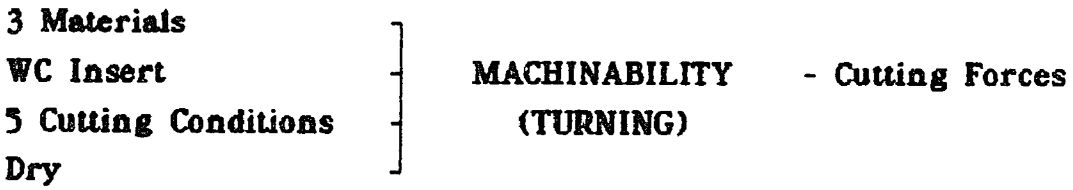


Fig. 6.1 Cutting Forces Test (Preliminary Tests) as I/O System

A similar analysis to the one applied on the PHT results was also utilized on the CFT data. Figures 6.2 to 6.4 present the averages versus variances of the three replications' results for each of the resultant force components; cutting force (Fr), feed force (Ff), and radial force (Fr). Examination of these figures indicates that the variance was constant, and, hence, a transformation to stabilize the variance was not needed. The 703E001 material again gave the highest variance, especially at the testing condition for the depth of cut effect (d). Table 6.3 shows, as an example, the ANOVA of the radial force (Fr) results along with the Duncan test results for the testing condition of the feed effect (f). Table 6.4 provides the averages of the three replications and the total averages under the different testing conditions. Examination of this table indicates that the effects of the different conditions were in agreement to the expected general trends. That is, the results indicated that the higher the speed, the lower the forces, and the higher the feed, depth of cut, or both, the higher the forces. Also, they indicated that at certain cutting conditions the feed force can be the largest resultant force component.

Table 6.5 summarizes the CFT preliminary test results in terms of F-ratios for among (Fa) and within (Fw) materials, and Duncan ranking results. Examination of Table 6.4 indicates the following:

(1) The cutting force did not differentiate between the materials, while both feed and radial forces did.

(2) The ranking of the materials based on either the feed or the radial force was ,in general, independent of the cutting

conditions (speed, feed, and depth of cut).

(3) The ranking of the materials was also independent of the type of cut, rough (fd) or finish (v) turning.

(4) Under the cutting condition of the feed effect (f), there was no overlapping in the Duncan ranking for both the feed and radial forces. Also, the feed force under the (fd) cutting condition effect, did not show overlapping. However, based on the radial force (Fr) at the feed-effect cutting condition (f), the screening among the materials was statistically most powerful. That is, the F-ratio for among materials (Fa) was the highest given that the F-ratio for within materials (Fw) was insignificant.

The correlation coefficient between the radial force results at the feed-effect cutting condition (f) and HRL production rates was 100 % (i.e., positive correlation). Normally, the higher the cutting forces, the lower the machinability. However, the following data indicates that the radial force results did also correlate well with the values of the hardness (but negative correlation). Since a negative tool holder was used, apparently more forces were needed to bring the materials to a state where they can be sheared under compression stresses.

Material	BHN	PPT (pcs/hr)	Fr, volts (newton)
705E001	192	336	1.8760 (417.2)
705W002	170	383	2.1553 (479.4)
6511100	156	538	2.2543 (501.4)

In conclusion, the CFT does differentiate between the work materials, the cutting force is not a reliable indicator to the machinability of work materials, both radial and feed forces are sensitive to variations in work materials, and the ranking of the work materials is cutting condition independent. Also, a cutting condition at which screening among the materials is statistcally most powerful was located, the cutting condition of the feed effect (f) in Table 6.2.

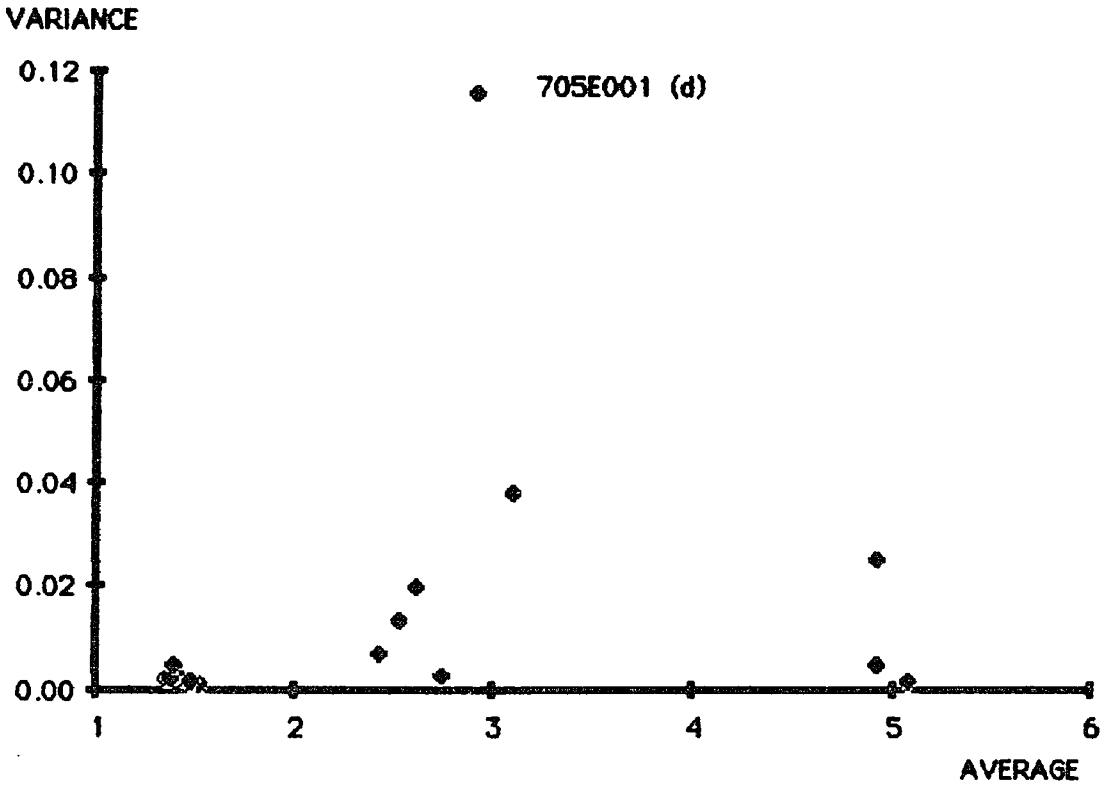


Fig. 6.2 Fc Averages Versus Variances (Preliminary Tests)

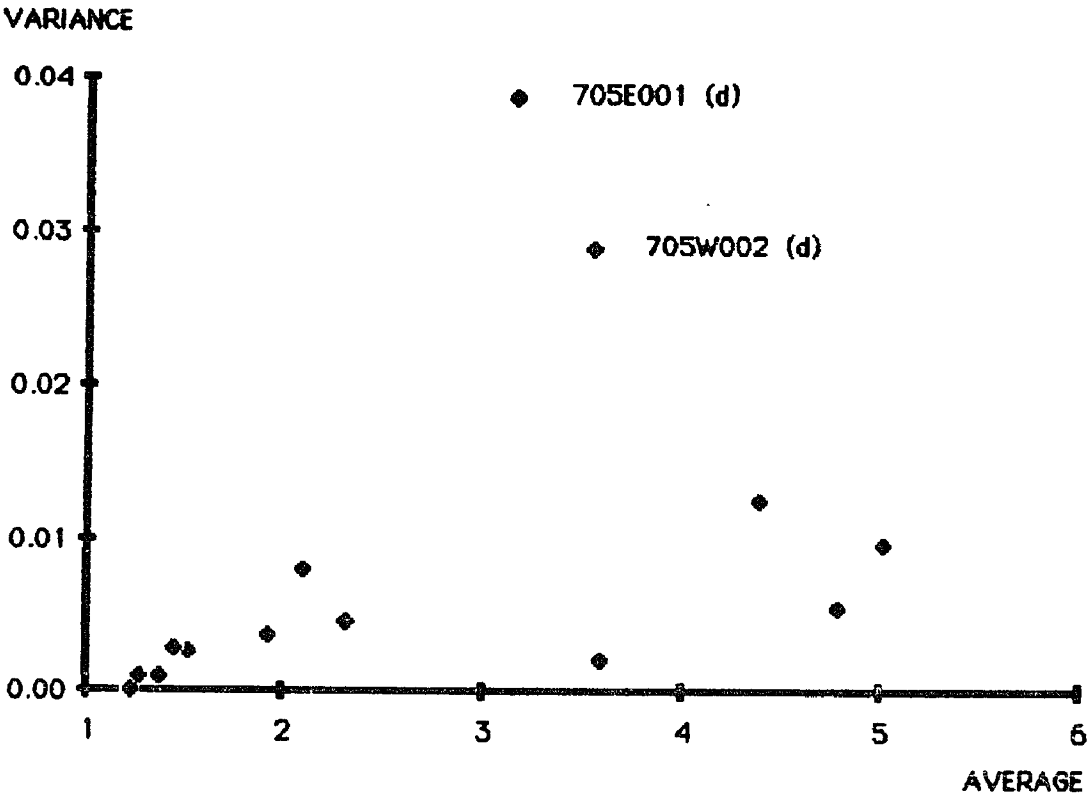


Fig. 6.3 Ff Averages Versus Variances (Preliminary Tests)

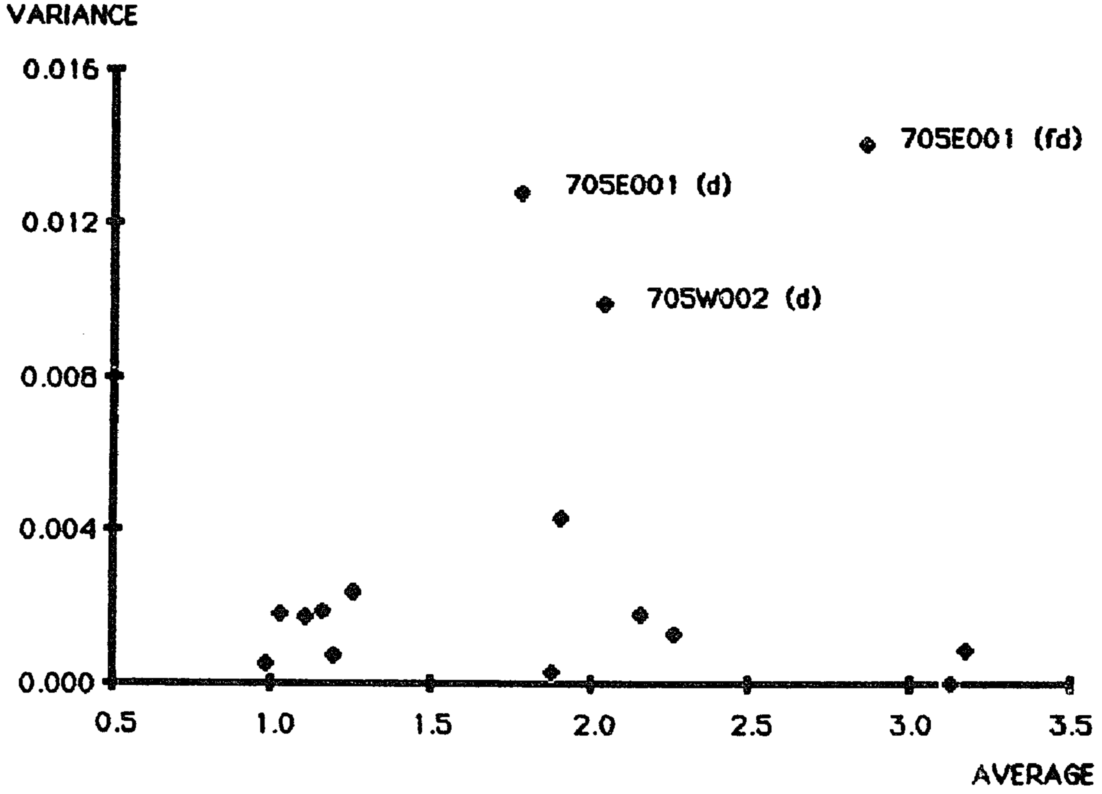


Fig. 6.4 Fr Averages Versus Variances (Preliminary Tests)

Table 6.3 Radial Force Results at the Feed-Effect Testing Condition *

Material	Replication Number			Average	Variance
	1	2	3		
705E001	1.8690	1.8630	1.8960	1.8760	.000309
705W002	2.1820	2.1780	2.1060	2.1553	.001829
651L100	2.2480	2.2930	2.2220	2.2543	.001290
Average	2.0997	2.1113	2.0747	2.0952	

ANOVA Table:

Source	SS	df	MSE	F-ratio		
Among Materials	.230964	2	.115482	97.212	> F(.05,2,4) = 6.94	Sig.
Within Materials	.002106	2	.001053	.886	< F(.05,2,4) = 6.94	Insig.
Error	.004752	4	.001188			
Corrected Total	.237822	8				

Duncan Multiple-Range Test Results (Sample Size = 3):

Material	705E001	705W002	651L100
Average	1.8760	2.1553	2.2543

(*) Force results are given in volts. For conversion to newton (N), multiply by 222.4.

Table 6.4 Averages of CFT Preliminary Results (Volts)[*]

Force	Material	(1)	(v)	(f)	(d)	(fd)
Fc	705E001	1.4407	1.3463	2.4303	2.9167	4.9217
	705W002	1.5267	1.3837	2.6123	3.0950	5.0763
	651L100	1.4797	1.3870	2.5183	2.7390	4.9110
	Average	1.4823	1.3723	2.5203	2.9169	4.9697
Ff	705E001	1.3757	1.2343	1.9280	3.1587	4.3903
	705W002	1.4573	1.2790	2.0937	3.5357	4.7857
	651L100	1.5223	1.4513	2.3143	3.5800	5.0190
	Average	1.4518	1.3216	2.1120	3.4248	4.7317
Fr	705E001	1.0983	.9781	1.8760	1.7900	2.8597
	705W002	1.1873	1.0185	2.1553	2.0367	3.1313
	651L100	1.2527	1.1547	2.2543	1.9063	3.1693
	Average	1.1794	1.0504	2.0952	1.9110	3.0534

(*) Force results are given in volts. For conversion to newton (N), multiply by 222.4.

Table 6.5 Summary of CFT Preliminary Results

	Cutting Force (Fc)			Feed Force (Ff)			Radial Force (Fr)		
	Fa	Fw	Rank	Fa	Fw	Rank	Fa	Fw	Rank
(l)	5.8	2.3	1 3 2	17.8	5.1	1 2 3	8.0	.15	1 2 3
(v)	.4	.1	1 2 3	55.8	3.2	1 2 3	13.9	.30	1 2 3
(f)	5.9	7.6	1 3 2	314.2	42.5	1 2 3	97.2	.90	1 2 3
(d)	2.2	1.6	3 1 2	4.8	.1	1 2 3	3.4	.01	1 3 2
(fd)	2.8	1.4	3 1 2	34.1	1.1	1 2 3	15.5	.70	1 2 3

Fa : F-ratio among materials
Fw : F-ratio within materials

6.4 CFT Actual Tests

The remaining twelve of the fifteen work materials were randomly machined under the feed-effect cutting condition (f), which is given in Table 6.2. This was the cutting condition at which screening among the materials was statistically most powerful during preliminary testing.

Figures 6.5 to 6.7 which show the plot of the averages versus variances of the results obtained indicate that a transformation to stabilize the variance was not required. Examination of these figures points to the higher variances of the cutting force results relative to those obtained for the feed and radial force. The 705E017 showed high variances for both cutting and radial forces. The results of the 705W002 feed force and the 705E016 radial force also showed high variances.

Table 6.6 presents the results obtained for the feed force along with the ANOVA results. A summary of the F-ratios in terms of among and within materials for the three forces is given below. The F-ratios confirm the preliminary testing conclusion that the cutting force is not a reliable indicator for evaluating the machinability of work materials. The reliability of those indicators based on cutting force measurements, such as horsepower and cutting temperature, is, hence, questionable. Although both the feed and radial forces have shown significant differences among materials, variations within materials (replications) were significant for the radial force. Perhaps a larger sample size (more than three replications) would provide insignificant variations within materials for the radial force (see the degrees of freedom in Table 6.6). Unfortunately, due to stock limit this was not investigated further. Nonetheless, it can be concluded that the feed force is the most reliable indicator among the the components of the resultant force for the machinability evaluation of free-cutting steel. This is followed by the radial force.

Force	F-ratio Among		F-ratio Within	
Fc	3.823	(Insig.)	34.278	(Sig.)
Ff	100.930	(Sig.)	2.661	(Insig.)
Fr	90.926	(Sig.)	18.997	(Sig.)

Table 6.7 presents the HRL production rates, the feed force results determined after the Duncan analysis, and the absolute difference between the two tests' ranking. The biggest disagreements among the two tests' results were reflected in the 703E001, 703W002, and 703E017. The CFT does not show these materials as unmachinable as the screw machine test. The two tests' results correlated with a +.34 % (additional cross correlation analysis is given in section 7.1). Nevertheless, the CFT divided the thirteen materials into five groups as compared to eight for the PPT. It can, therefore, be concluded that the CFT is as sensitive as the PPT.

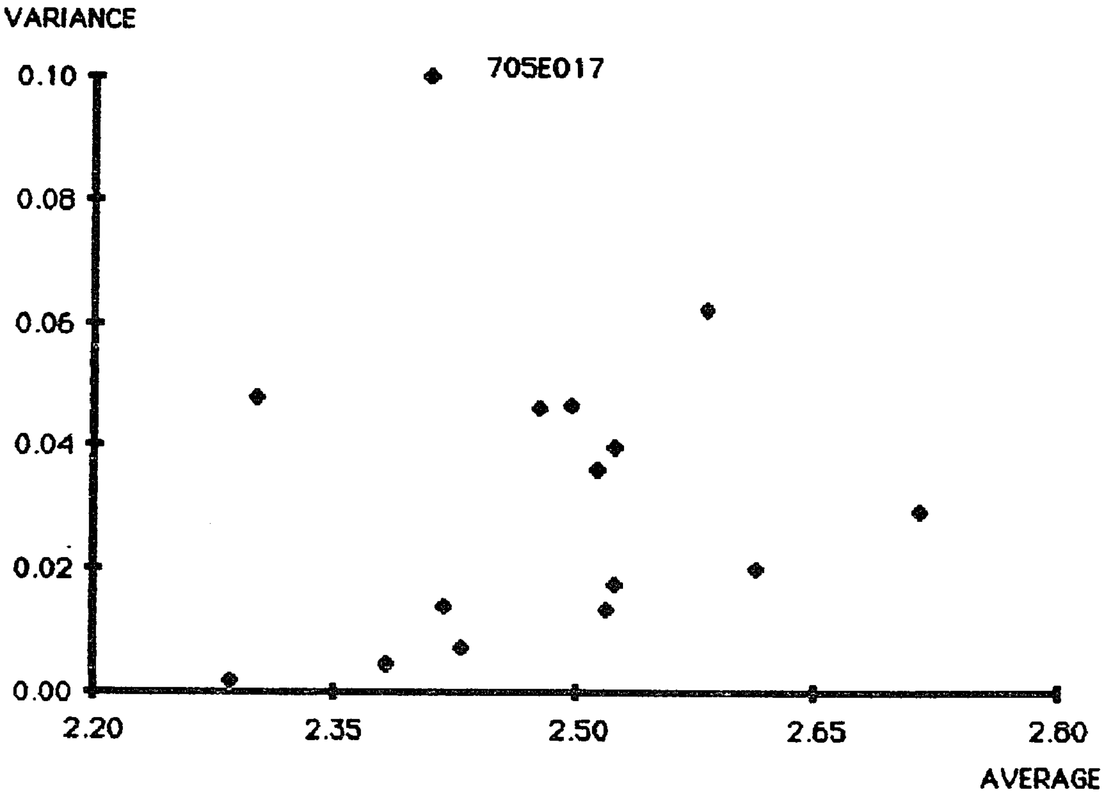


Fig. 6.5 <u>Fc Averages Versus Variances (Actual Tests)</u>

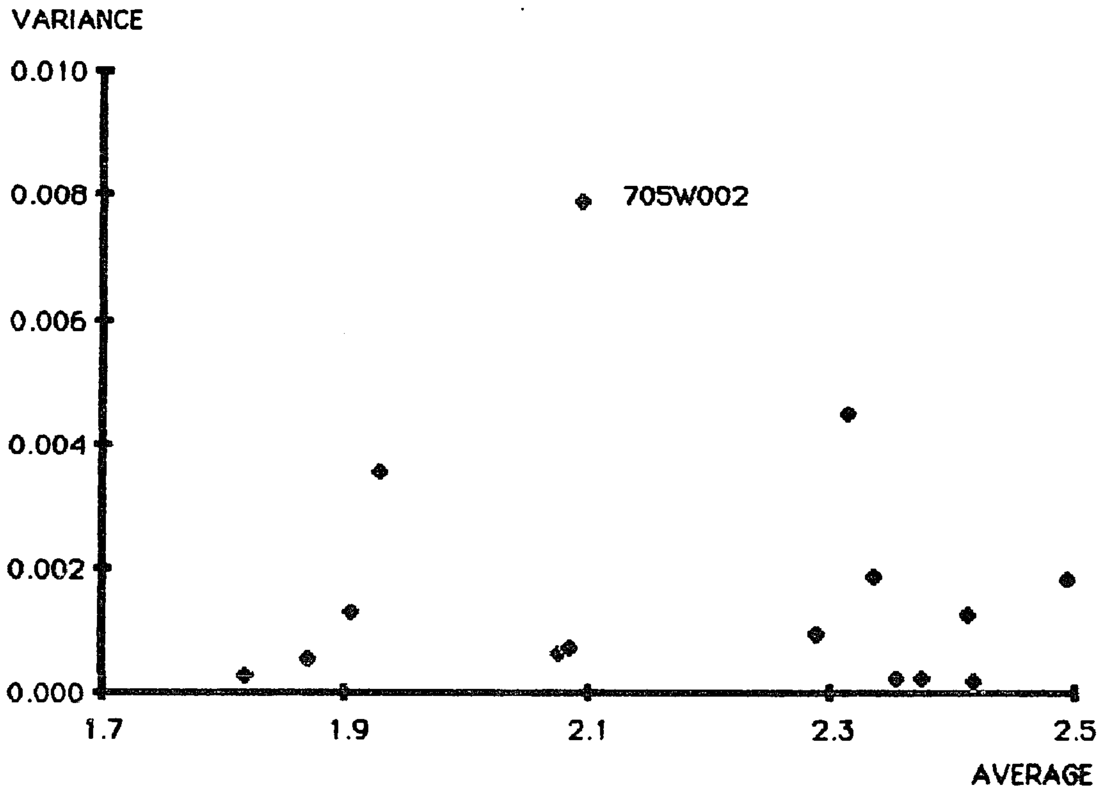


Fig. 6.6 Ff Averages Versus Variances (Actual Tests)

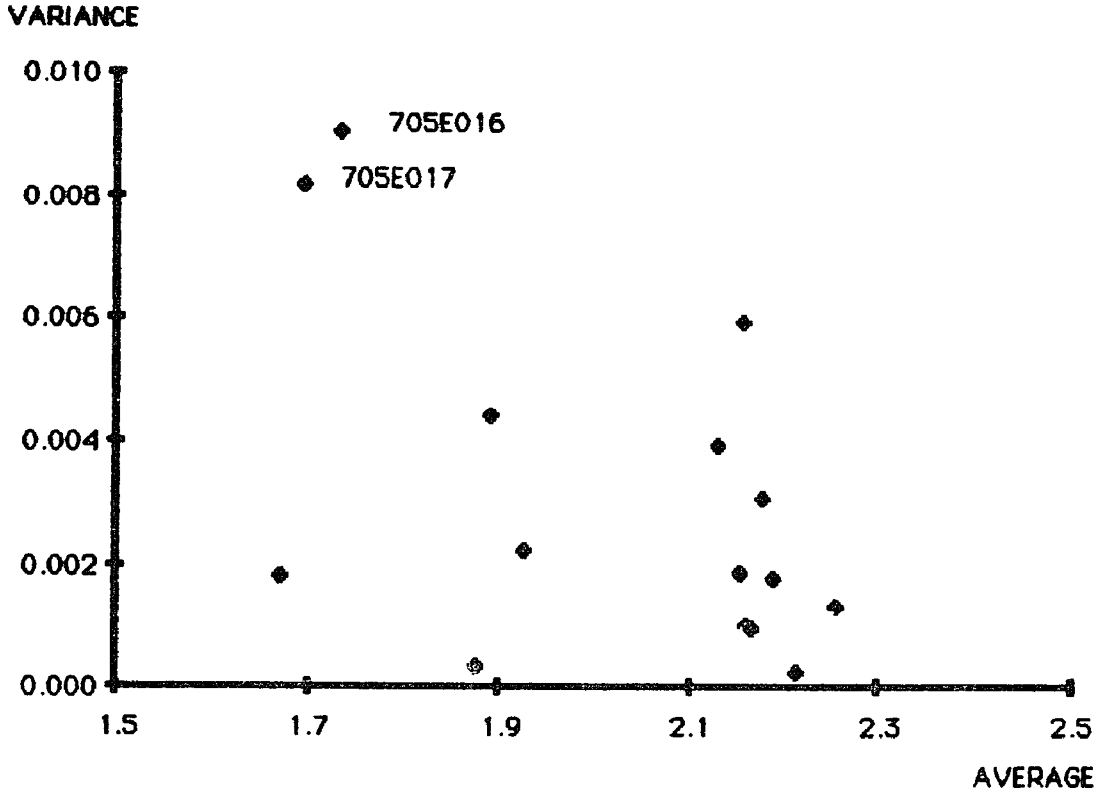


Fig. 6.7 Fr Averages Versus Variances (Actual Tests)

Table 6.6 Feed Force Results of CFT Actual Testing *

Material	Replication Number			Average	Variance
	1	2	3		
705E001	1.9920	1.9180	1.8740	1.9280	.003556
705W002	2.1870	2.0840	2.0100	2.0937	.007902
705E017	1.8860	1.8430	1.8760	1.8683	.000506
705E014	2.2540	2.3080	2.3040	2.2887	.000905
705E003	2.0810	2.0470	2.0950	2.0743	.000609
705C034	2.1140	2.0740	2.0630	2.0837	.000720
705E016	1.9420	1.8930	1.8730	1.9027	.001260
705E002	1.8320	1.8180	1.7990	1.8163	.000274
651L100	2.3910	2.2850	2.2670	2.3143	.004489
651L101	2.3340	2.2920	2.3780	2.3347	.001849
625L286	2.3670	2.3380	2.3540	2.3530	.000211
9T	2.3900	2.3620	2.3700	2.3740	.000208
10T	2.4240	2.4260	2.4020	2.4173	.000177
11T	2.4440	2.5100	2.5240	2.4927	.001825
12T	2.4010	2.3850	2.4520	2.4127	.001224
Average	2.2026	2.1722	2.1761	2.1836	

ANOVA Table:

Source	SS	df	MSE	F-ratio		
Among Materials	2.18122	14	.155801	100.93	> F(.05,14,28) = 2.06	Sig.
Within Materials	.00822	2	.004108	2.66	< F(.05, 2,28) = 3.34	Insig.
Error	.04322	28	.001544			
Corrected Total	2.23266	44				

(*) Force results are given in volts. For conversion to newton (N), multiply by 222.4.

Table 6.7 <u>HRL Production Rates and CFT Results</u> *

	HRL		CFT		Absolute Difference
Material	pcs/hr	Rank	Feed Force	Rank	in Ranking
705E001	336	8	1.8997	2	6 *
705W002	383	7	2.0839	3	4 *
705E017	388	6	1.8997	2	4 *
705E014	440	5	2.3227	4	1
705E003	440	5	2.0839	3	2
705C034	440	5	2.0839	3	2
705E016	572	2	1.8997	2	0
705E002	572	2	1.8163	1	1
651L100	538	3	2.3227	4	1
651L101	620	1	2.3227	4	3
625L286	620	1	2.3227	4	3
9T	502	4	2.3934	5	1
12T	502	4	2.3934	5	1
Correlation Coefficient:			+.3371		

(*) Force results are given in volts. For conversion to newton (N), multiply by 222.4.

6.5 CFT Summary and Applications

As mentioned earlier, on page 235, the CFT was utilized to; (1) justify previous work conclusions ([2] & [3]) that cutting forces do not correlate well with HRL production rates, (2) investigate the sensitivity of the resultant force components (cutting, feed and radial force) in differentiating between the work materials under study, and (3) determine whether the ranking of work materials is independent of cutting conditions.

The preliminary and actual tests' results indicated that the ranking of the work materials is independent of cutting conditions; speed, feed, and depth of cut. The feed force was the most sensitive resultant force component to variations in the machinability of work materials. This was followed by the radial force, which would be as sensitive as the feed force with more replications. The cutting force results gave the highest scatter, and it was, hence, concluded that it is not a reliable indicator to the machinability evaluation of free-cutting steel. Despite the fact that a poor correlation (38 %) existed between the CFT and the PPT, the CFT did differentiate between the work materials and classified them into five groups as compared to eight for the PPT. Additional cross correlation analysis, given in section 7.1, resulted in a better correlation coefficient than the above one. Finally, the CFT can be utilized to qualify potential materials for the PPT.

Chapter 7: RESULTS ANALYSIS AND RECOMMENDATIONS

7.1 Results Analysis

Table 7.1 provides a summary of the three short-term tests' results along with the HRL production rates and the rankings of the work materials based on each test results. Figures 7.1 to 7.3 show the HRL production rates versus the PHT, EMST and CFT results respectively.

As mentioned before, the 705E016 variance was much higher relative to other materials' variances during power hacksawing. This same material had shown similar behavior during slotting and turning. It was, therefore, concluded that the 705E016 is a nonhomogeneous material (belongs to a different population). The 705E016 was, hence, regarded as an outlier and was disregarded from further analysis. As a result, the correlation coefficient between the PPT and PHT results increased to - 73 %. Meanwhile, the 705E001 gave the highest tendency for BUE formation during slotting. It is also the material that gave the biggest disagreement with HRL ranking for both the PHT and the CFT ranks. Owing to the fact that the current (at the time this study was initiated) machinability group of HRL has less confidence in the results of the first eight materials, the 705E001 was also disregarded from any further analysis.

Table 7.1 HRL Production Rates and PHT, EMST & CFT Results

	HRL		PHT		EMST		CFT [1]	
Material	pcs/hr	Rank	Stro./area	Rank	SWV Rate	Rank	Ff	Rank
705E001	336	8	180.70	4 *	-.000205	7	1.8997	2 *
705W002	383	7	194.90	6	-.000044	3 *	2.0839	3
705E017	388	6	210.80	7	-.000112	6	1.8997	2
705E014	440	5	210.80	7	-.000096	5	2.3227	4
705E003	440	5	186.37	5	-.000096	5	2.0839	3
705C034	440	5	186.37	5	-.000044	3	2.0839	3
705E016	572	2	186.37	5	-.000087	4	1.8997	2
705E002	572	2	180.70	4	-.000087	4	1.8163	1
651L100	538	3	131.65	2	-.000044	3	2.3227	4
651L101	620	1	117.20	1	-.000044	3	2.3227	4
625L286	620	1	140.65	3	-.000018	1	2.3227	4
9T	502	4	131.65	2	-.000027	2	2.3934	5
12T	502	4	140.65	3	-.000018	1	2.3934	5
Correlation Coefficients:			-.651		+.577		+.337	

* Biggest disagreement with HRL ranking.

(1) Force results are given in volts. For conversion to newton (N), multiply by 222.4.

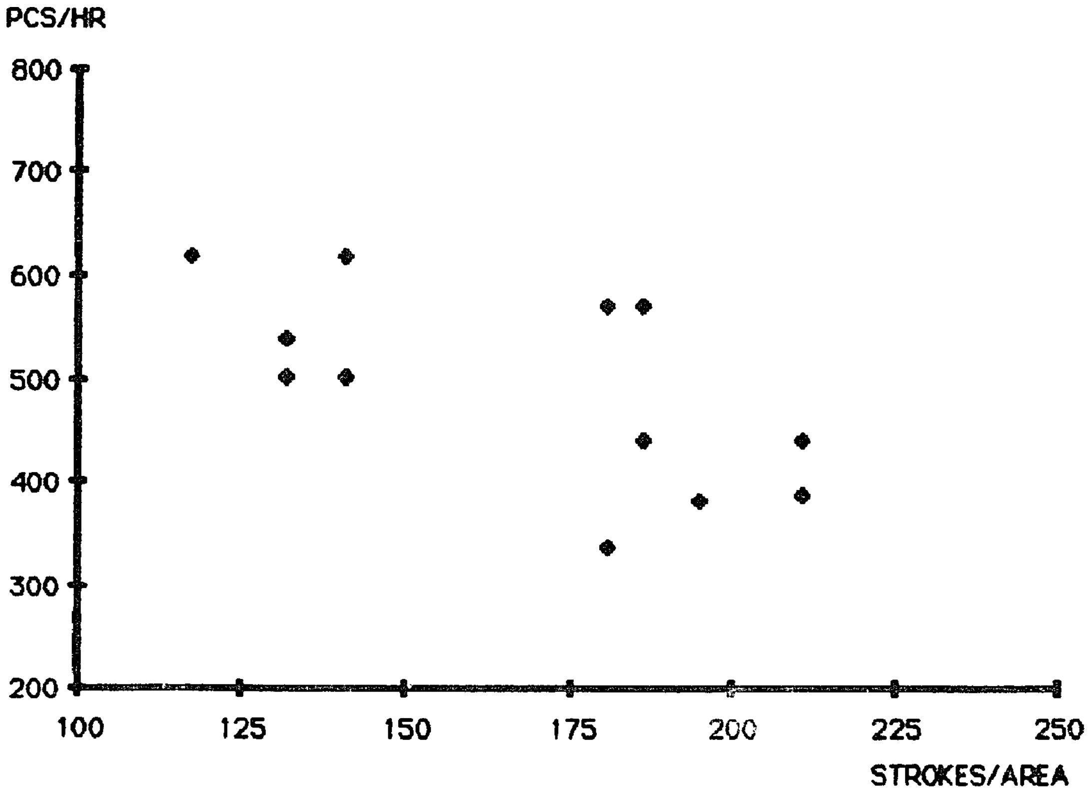


Fig. 7.1 <u>HRL Production Rates Versus PHT Results</u>

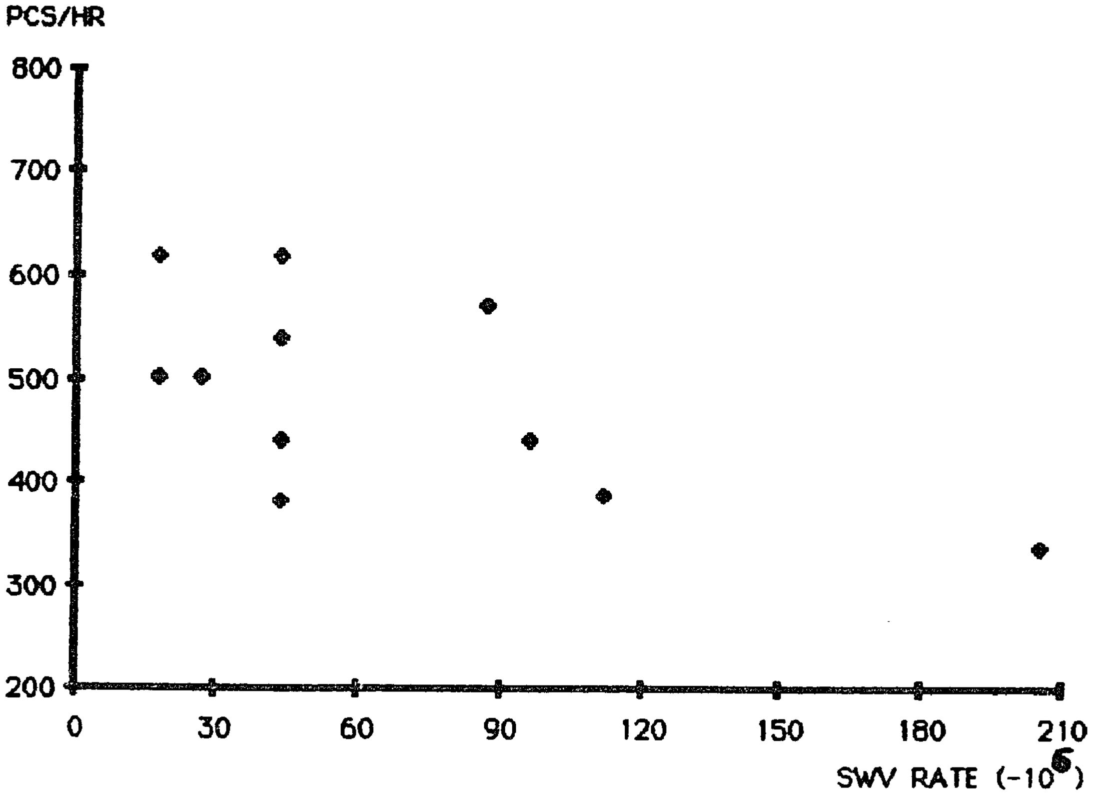


Fig. 7.2 HRL Production Rates Versus EMST Results

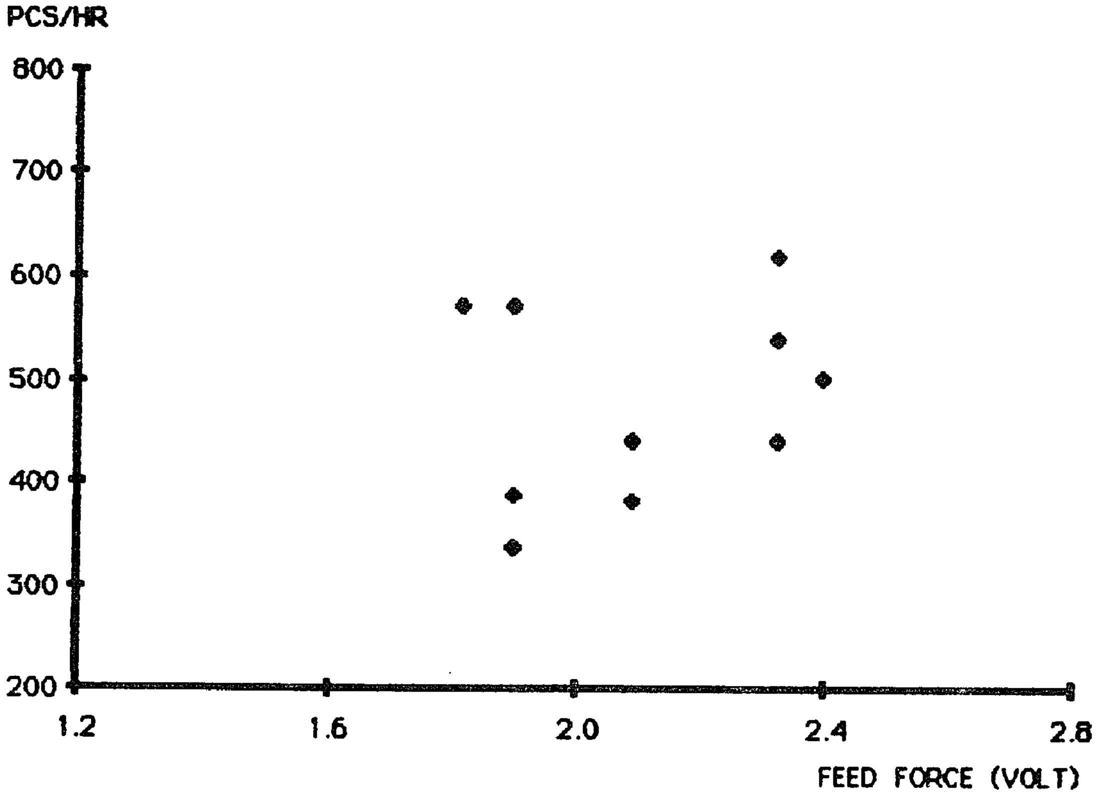


Fig. 7.3 HRL Production Rates Versus CFT Results

Cross correlation and regression analyses were, then, run on the remaining eleven materials' results. In addition to the correlation coefficients (in per cent) obtained for the eleven materials, Table 7.2 also shows the impact on these values when the 705E016 and 705E001 were disregarded. With the exception of the correlation coefficient between the PPT and CFT results (34 %), the results of the four tests (PPT, PHT, EMST & CFT) correlated well among themselves for the thirteen work materials. When the 705E016 data was disregarded (due to its high variability), the correlation coefficients between the PPT and the three short-term tests' results increased, while the correlation coefficients among the three short-term tests' results remained the same. The 705E001 data was also disregarded due to its high tendency to BUE formation as well as to its biggest performance disagreement in both the PHT and CFT relative to the PPT. After disregarding the 705E001, all values increased except those between the PPT and the EMST or CFT.

Simple linear regression analysis indicated that the 705E002 was an influential point for the PPT and CFT regression model. This material was also shown to have high tendency for BUE formation during slotting. The cross correlation coefficients between the four tests' results improved substantially when this material was also disregarded. That is, valid simple linear regression models between each of the three short-term tests and the PPT would be needed to predict the machining performance of the newly developed materials.

Based on the correlation coefficients obtained for the remaining ten materials (i.e., after disregarding the 705E016, 705E001 and 705E002), it was, therefore concluded that each of the three short-term tests correlated well with the PPT as well as with each other. These correlation coefficients could further improve when additional results for the PPT become available. It might be mentioned here that a correlation coefficient above 60 per cent is considered excellent when comparing the results of two machinability tests. That is, there are many input factors to the metal cutting process that can be dependent on, or independent of, each other based on the machinability space under investigation.

Finally, these results indicate that an easy to machine material would:

(1) require fewer number of strokes per cross section area in the PHT,

(2) show a low tendency for BUE formation and provide a small rate for slot width variations in the EMST, and

(3) require a high feed force in the CFT which is contrary to what is normally expected from cutting forces tests (the lower the cutting forces, the better the machinability).

The CFT results were, hence, examined against the HBN data (given in Appendix B). They were found to correlate well for the thirteen materials, but with a negative correlation coefficient (- 92 %). In other words, for the work materials investigated, the higher the hardness, the lower the feed force, and, at the same time, the lower the feed force, the lower the machinability. However, free-cutting steels have a unique machining space. They are usually machined on automatic screw/bar machines which utilize HSS tool materials and, thus, only positive tool geometries are used. The cold drawing process applied on these materials is aimed to bring their hardness levels to a range suitable for this machining space. On the other hand, the CFT employed a negative tool geometry and, apparently, materials with low hardness required more feed forces. Prehaps, this was to bring their hardness levels to a range suitable for machining under compression (versus tension) stresses. If so, different cold reductions for the cold drawing process would be needed when these machines can provide cutting speeds in the range of the carbide cutting-tool materials.

Table 7.2 Results of A Cross Correlation Analysis

		PHT	EMST	CFT
For the thirteen materials:				
	PPT	- 65	58	34
	PHT		- 55	- 66
	EMST			67
Without the 705E016:				
	PPT	- 73	63	47
	PHT		- 55	- 64
	EMST			68
Without the 705E016 & the 705E001:				
	PPT	- 77	45	35
	PHT		- 75	- 65
	EMST			66
Without the 705E016, 705E001 & 705E002:				
	PPT	- 86	59	70
	PHT		- 75	- 73
	EMST			63

7.2 Recommendations to HRL

Although the results of each of the three short-term tests correlated well with the production rates of HRL, especially the PHT results, none of them is recommended as a replacement for the PPT. This is due to the fact that the further one moves away from practical cutting conditions, the lower the reliability of the results.

Examination of the PPT procedure (described on pages 76 to 80) as applied by different engineers at HRL over a period of years ([2], [3] & [151]) indicates that the procedure has changed. These changes are given in detail on pages 119 to 120. Briefly; (1) the test end-point criterion changed, (2) sometimes a material was declared as a standard or base, while at other times a standard steel was not used, (3) the search procedure changed from trial-and-error to an experimental design with three levels, and (4) the standard material varied from one study to another. Meanwhile, examination of the procedure of the Automatic Screw/Bar Machine Test, a standardized PPT [12], indicates that it can not be recommended as is. The procedure does not cover some important points. For example, how would one use any commercially available cutting fluid and still be able to compare the results with those determined using a different cutting fluid? The performance of a work material can vary from one cutting fluid to another. Although, specifying a certain cutting fluid may limit the test's widespread usage, some restrictions are needed so that valid comparisons can be made. Other serious problems in these tests include the meaning of "maximum" production rate, the search procedure utilized (trial-and-error), the subjective location of similar trends of part quality among the tested steels, and the inability to relate the results of one test to another due to what is called a standard material that varies from one study to another.

From the above (discussed in detail on pages 75-84, 109-112 & 119-121), the recommendations can be summarized as follows:

(1) Since the materials can only be compared when they yield similar trends of part quality, locating the maximum production rate for each material is meaningless.

(2) If a new material design is to replace a current one, one would like the new design to perform better than the old one, and, hence, the old design was used as a standard material. However, when standardization is the objective, a fixed, standard, base metal must be specified so that all other materials can be compared against one base. A standard material with a well defined chemical composition, microstructure, etc. should, therefore, be defined and should not be changed from one study to another. An easier way would be the provision of some standard part quality trends that all other materials can be compared against. Either solution is the only way to allow for comparisons from one study to another (i.e., provide a continuity between past and current data as well as a means for comparing the results of one investigator to another). However, if the first solution is

chosen, an optimization technique other than trial-and-error is needed to locate the maximum production rate of the standard material.

(3) A quantitative procedure that would indicate when the similar trends are located is required. The procedure applied in the analysis of the EMST results could be utilized. Simply, when two materials have equal slopes based on regression results, they would provide similar trends of part quality.

(4) A detailed standardized testing procedure should be documented so that it can be followed by different engineers over time and would still give the same results. This is in terms of all metalurgical tests and other tests that should be applied. In other words, an outlined methodology of the steps and the type of tests to be applied should be stated clearly.

(5) As mentioned earlier, on page 112, the Taylor test has never differentiated between the materials nor have the results of this test shown valid correlation with the PPT results ([2] & [3]). Tha habit of running the Taylor test before the PPT was, therefore, questionable. Since the Taylor test does not provide any useful information, it is recommended to stop the utilization of this test.

Chapter 8: CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

Machinability is an important and complex concept which has acquired a variety of connotations that can be unclear or confusing to the uninitiated. The difficulty is not only how it should be defined, but also how it should be measured accurately.

From examining the machinability dilemma, in terms of the many definitions and descriptions, various predictive models and developed tests, and its current data disadvantages, it was concluded that:

(1) Machinability has no standard definition.

(2) A commonly accepted theoretical or empirical model that can be safely utilized for machinability prediction does not exist. Therefore, machinability is best evaluated by actual testing.

(3) A universally acceptable system for classifying machinability tests does not exist. Further, there are no cut-off values, in terms of consumed material and/or testing time, to aid in identifying whether a given test is of the long-, medium-, or short-term type. Nevertheless, the Taylor-type and simulated production tests, such as the PPT, are considered the long-term type.

(4) Although the ISO, a standardized Taylor test, is the only internationally accepted testing procedure for machinability evaluation, it is not widely used because; (1) it is a long-term

test, (b) it limits the testing variables' felxibility to achieve comparable results, and (c) it does not consider the feed effects on tool wear or life, and (d) it ususally requires a variable speed drive system.

(5) None of the short-term tests developed to replace the Taylor test is a valid replacement. The Taylor procedure is based on certain assumptions that must first be validated for the desired testing domain. Therefore, any short-term test should not be used in isolation but rather in conjunction with the long-term test results of a given testing domain.

(6) Since none of the short-term tests has been adopted in a wide spread fashion, their validity is limited to their testing conditions.

(7) The most reliable machinability tests are the actual production ones. They are the most expensive, but the most reliable. The second most accurate, but still expensive tests, are the ones which closely simulate actual production conditions. Hence, the further the testing conditions move away from production situations, the lower the reliability of the results. However, laboratory test results can be significantly different from production environment. Therefore, caution should be exercised when analyzing and interpreting the results of machinability tests.

(8) Due to the inherent variation in work material, cutting tool and cutting fluid lots, deterministic analyses are not appropriate for machinability testing.

(9) The concept of relating the machining performance of a material to another by a single index, such as the machining productivity index (MPI) of HRL, has several disadvantages. The index value does not take into account the data variability nor provide the user with important information regarding cutting conditions. Machinability results should be provided in terms of means and variances along with their testing conditions.

From viewing many machinability tests in terms of input and output factors, it became apparent that during any metal cutting operation, an output indicator would reflect an interaction between a work material, a cutting tool, and a cutting fluid (if used). This interaction could vary with the cutting conditions, over the cutting time, and from one setup to another. Machinability should, therefore, stand for machining efficiency and should be viewed as a probabilistic input/output system. Further, all combinations of input and output factors would constitute what can be called the machinability space, and machinability improvement can be indicated by; (1) a better machined part, (2) a higher tool life or smaller tool wear rate, and/or (3) lower cutting forces, consumed power, or cutting temperature. Finally, the machinability space of work materials should be divided into sub-spaces, in which groups of materials compete among themselves for industrial applications. For each machinability sub-space, a standardized test that would test near production conditions should be developed.

Due to the increasing trend towards the application of automation in manufacturing, the machinability of work materials, cutting tools and cutting fluids are becoming more important. The high demand for accuracy and consistency in the input factors of metal cutting operations intensifies pressure on the manufacturers of work materials, cutting tools and cutting fluids. The pressure is, however, highest on the manufacturers of work materials due to the higher variability of work materials relative to other input factors. Since machinability assurance by chemical composition, microstructure, and/or physical/ mechanical properties analysis is not reliable, there is a high demand for a short-term test that can be utilized in production lines for daily machinability evaluation. This dissertation was concerned with;

(1) to find/develop a short term-test that correlates well with the PPT and can be utilized in the steel mill for machinability assurance, and

(2) to provide recommendations on a standardized PPT.

None of the published machinability testing procedures qualified to fulfill the first request. Also, examination of the PPT procedure pointed to several flaws, such as the meaning of "maximum" production rate, the search procedure utilized (trial-and-error), the subjective location of similar trends of part quality among the tested steels, and the inability to relate the results of one test to another due to what is called a standard material that varies from one study to another. It was, thus, decided to develop three short-term tests, called the Power Hacksaw Test (PHT), End Milling-Slotting Test (EMST), and Cutting Forces Test (CFT).

From the results of the three developed short-term tests, it can be concluded that they;

(1) tested different aspects in the machinability space of the free-cutting steel with the least possible sources of error,

(2) differentiated among the work materials tested with high sensitivity and repeatability. For example, based on the PPT results, the materials can be classified into 8 groups, while from the results of the PHT, EMST and CFT, they were divided into 7, 7, and 5 respectively (see Table 7.1 on page 259).

(3) indicated that the ranking of the work materials can be independent of cutting conditions (cutting speed, feed, depth of cut, and feed pressure), but screening among the materials was only statistically most powerful at certain conditions.

(3) correlated well with the HRL production rates as well as among themselves. The correlation coefficients determined after disregarding three materials for vaild reasons (given in section 7.1) were as follows:

	PHT	EMST	CFT
PPT	-86	59	70
PHT		-75	-73
EMST			63

(4) can be used to qualify potential materials for the PPT, assure the quality of the screw machine material (such as tendency to BUE formation), and determine the machinability level in daily production.

In addition, the CFT results indicated that the feed force is the most sensitive resultant force component in differentiating between the work materials. This is followed by the radial force, while the cutting force was found to be an unreliable indicator to the machinability of work materials.

Since the three short term tests correlated well among themselves as well as with the PPT, any one of them can be used in the steel mill production lines. However, the PHT has the simplest setup, easiest testing procedure, and does not require high operator skill. Also, the PHT setup, testing procedure and results were successfuly duplicated at HRL. The PHT is, therefore, recommended for the machinability assurance in daily production along with the quality control procedure (described on pages 167 to 175) developed for it. If the machinability assurance of bars larger than one inch (25.4 mm) is of concern, the CFT could be a better test. Finally, recommendations on HRL machinability evaluation system, with an emphasies on the standardized PPT, are given on pages 268 to 269.

8.2 Future Work

Implications from the research done for this dissertation would indicate that:

(1) An optimization search technique other than the trial-and-error utilized in the PPT, to determine the maximum production rate of the standard material, should be developed and tested (in terms of repeatability).

(2) More analysis needs to be done to develop and test a quantitative method, instead of using subjective judgement, by which the location of similar trends of part quality for the tested steels can be valid.

(3) The potential of the number of metal inclusions per unit area as a microstructure machinability indicator should be investigated, if additional data becomes available.

(4) The division of the machinability space of work materials into sub-spaces and the development of standardized tests is needed.

REFERENCES

[1] SAE "Estimated Mechanical Properties and Machinability of Hot Rolled and Cold Drawn Carbon Steel Bars" SAE Standard J414a, SAE Handbook, 1981, pp. 3.14-3.17.

[2] Murphy, D.W. and Aylward, P.T. Machinability of Steel. Homer Research Laboratories, Bethlehem Steel Corp., Bethlehem, Pa., 1964.

[3] Litwa, R. "Development of Substitutes For Leaded Steels" Unpublished Report, File Ref. 1204-2CQz-30-81022 (Dec 1983), Homer Research Laboratories, Bethlehem Steel Corp., Bethlehem, Pa.

[4] Boston, O.W. "Machinability of Metals" Trans. of American Society For Steel Treating, Vol. 13 (1928), pp. 49-61.

[5] Boston, O.W. "Methods of Tests For Determining The Machinability of Metals in General, With Results" Trans. of American Society For Steel Treating, Vol. 16 (1929), pp. 659-710.

[6] Davies, D.W. "Machinability: A Review of Criteria For Assessing Workpiece Materials in Small-Scale Drilling and Turning Tests" Metallurgical Review, Vol. 13 (1968), pp. 41-52.

[7] Chisholm, A.W.J.; Mills, B. and Redford, A.H. "The Assessment of Machinability" Mfg. Engrg. Trans., Vol. II (1973), SME, pp. 21-26.

[8] Redford, A.H. and Mills, B. "Assessing Machinability" Metals and Materials, Vol. 7 (1973), pp. 85-88.

[9] Groover, M.P. "A Survey on The Machinability of Metals" SME Tech. Paper, MR76-269, 1976.

[10] Reiter, H. "Tool-Life/Cutting Temperature Relationships in Machining: A Review" The Metallurgist and Materials Technologist, Vol. 11 (1979), pp. 267-271.

[11] Redford, A.H. and Mills, B. "Review of Short-Time Tests For Prediction of Tool Performance" Towards Improved Performance of Tool Materials. The Metal Soc., Book 278, London, 1982, pp. 207-215.

[12] ASTM "A Method For Evaluating Machining Performance Using An Automatic Screw/Bar Machine" Annual Book of ASTM Standards, Part 10, E618-81, 1981, pp. 739-750.

[13] Watson, J.D.; Davies, R.H. and Ramalingam, S. "Experience With The Use of ASTM E618-81 For Machinability Testing of Free Cutting Steels" NAMRI Conf., Madison Wisconsin, 1983, pp. 363-371.

[14] Kessner, A. "A Method For Determining The Resistance of Metals to Drilling and Its Application to The Investigation of The Machinability of Metals" Testing, April 1924, pp. 270-285.

[15] Henkin, A. and Datsko, J. "Influence of Physical Properties on Machinability" Trans. ASME Ser. B, Vol. 85 (1963), pp. 321-328.

[16] Hebert, D.G. "Cutting Tools Research Committee, Report on Machinability" Proceedings, I. Mech. E., 1928, pp. 175-825. (Cited from [15])

[17] Cook, M. and Davis, E. "Free - Turning Brass" J. Institute of Metals, Vol. 65 (1939), pp. 65-78.

[18] Boulger, F.W.; Shaw, H.L. and Johnson, H.E. "Constant - Pressure Lathe Test For Measuring The Machinability of Free - Cutting Steels" Trans. ASME, Vol. 71 (1949), pp. 431-446.

[19] Boulger, F.W. "Materials and Machinability" Machining-Theory and Practice. American Society For Metals, 1950, pp. 69-109.

[20] Field, M. and Zlatin, N. "Evaluation of Machinability of Rolled Steels, Forgings and Cast Irons" Machining-Theory and Practice. American Society For Metals, 1950, pp. 341-376.

[21] Boston, O.W. Metal Processing. John Wiley and Sons, INC. 2 nd. Edition, 1951, pp. 126-174.

[22] Boulger, F.W. "Influence of Metallurgical Properties on Metal-Cutting Operations" American Society of Tool Engineers, paper number 80, 1958.

[23] Brown, R.H. and Tao, H.S. "Machinability Testing For The Production Workshop" Factory and Plant, Vol. 53 (1965), pp. 38-45.

[24] Cook, N.H. "What is Machinability ?" Influence of Metallurgy on Machinability. ASM, 1975, pp. 1-10.

[25] Tipnis, V.A. and Joseph, R.A. "Testing For Machinability" Influence of Metallurgy on Machinability. ASM, 1975, pp. 11-30.

[26] Tipnis, V.A. "A Strategy For The Development of Improved Machining Steels" International Symposium on Influence of Metallurgy on Machinability of Steel, Sep. 1977, Tokyo, Japan. The Iron & Steel Institute of Japan, ASM, 1977, pp. 1-14.

[27] Naylor, D.J. "The Workpiece-Ferrous" Machining: Autumn Review Course, Institution of Metallurgists, Northway House, Whetstone, London N20 9LW, 1980, pp. 30-41.

[28] Thomsen, E.G. "F.W. Taylor - A Historical Perspective" On The Art of Cutting Metals - 75 Years Later (A Tribute to F.W. Taylor). ASME, 1982, pp. 1-12.

[29] Usui, E. and Shirakashi, T. "Mechanics of Metal Machining - From 'Descriptive' to 'Predictive' Theory" On The Art of Cutting Metals - 75 Years Later (A Tribute to F.W. Taylor). ASME, 1982, pp. 13-36.

[30] Oxley, P.L.B. "Machinability: A Mechanics of Machining Approach" On The Art of Cutting Metals - 75 Years Later (A Tribute to F.W. Taylor). ASME, 1982, pp. 37-84.

[31] Turkovich, B.F. von "Thermodynamics in Metal Cutting" On The Art of Cutting Metals - 75 Years Later (A Tribute to F.W. Taylor). ASME, 1982, pp. 85-98.

[32] Cook, N.H. "Tool Wear and Tool Life" Jr. Engrg. Ind., November 1973, pp. 931-938.

[33] Takeyama, H.; Murata, R.; Yoshikawa, T. and Takada, K. "Modeling of Tool Life in Turning Steels" International Symposium on Influence of Metallurgy on Machinability of Steel, Sep. 1977, Tokyo, Japan. The Iron & Steel Institute of Japan, ASM, 1977, pp. 15-25.

[34] Redford, A.H. "On-Line Assessment of Tool Wear Using Wear-Temperature Gradient Relationships" Machinability Testing and Utilization of Machining Data. ASM, 1979, pp. 367-379.

[35] Wu, S.M. "Tool-Life Testing by Response Surface Methodology, Parts 1 & 2" Jr. Engrg. Ind., May 1964, pp. 105-116.

[36] Friedman, M.Y. and Zlatin, N. "Variability of Tool Life As A Function of Its Mean Value" NAMRC - II Proc., 1974, pp. 128-138.

[37] DeVor, R.E.; Anderson, D.L. and Zdeblick, W.J. "Tool Life Variation and Its Influence on The Development of Tool Life Models" Jr. Engrg. Ind., August 1977, pp. 578-584.

[38] Ravignani, G.L.; Tipnis, V.A. and Friedman, M.Y. "Cutting Rate-Tool Life Functions (R-T-F) General Theory and Applications" Annals of CIRP, Vol. 26 (1977), pp. 295-301.

[39] Colding, B. and König, W. "Validity of The Taylor Equation in Metal Cutting" Annals of CIRP, Vol. 19 (1971), pp. 793-812. (Cited from [10])

[40] Zdeblick, W.J. and DeVor, R.E. "An Experimental Strategy For Designing Tool Life Experiments" Jr. Engrg. Ind., November 1978, pp. 441-451.

[41] Mills, B. and Akhtar, S. "A Metallurgical and Machining Study of Free Machining Low Carbon Steels" Influence of Metallurgy on Machinability. ASM, 1975, pp. 73-88.

[42] Hazra, J.; Taraman, K. and Jagers, R. "How Microstructure Influences Tool Life" Manuf. Engrg., December 1976, pp. 32-34.

[43] Ramalingam, S. and Watson, J.D. "On Machinability Variations, Tool Wear and Steel Making Practice" International Symposium on Influence of Metallurgy on Machinability of Steel, Sep. 1977, Tokyo, Japan. The Iron & Steel Institute of Japan, ASM, 1977, pp. 67-76.

[44] Quinto, D.T.; Bhattacharya, D. and Thompson, W. "An Investigation of Cutting Energy and Metallurgical Properties in Leaded and Non-Leaded AISI 1215 Steels" International Symposium on Influence of Metallurgy on Machinability of Steel, Sep. 1977, Tokyo, Japan. The Iron & Steel Institute of Japan, ASM, 1977, pp. 433-447.

[45] Luong, L.H.S. "Influence of Microcracks on Machinability of Metals" Metals Technology, November 1980, pp. 465-470.

[46] Tipnis, V.A. "Influence of Metallurgy on Machining - Free Machining Steels" On The Art of Cutting Metals - 75 Years Later (A Tribute to F.W. Taylor). ASME, 1982, pp. 119-132.

[47] Milovic, R. and Wallbank, J. "The Machining of Low Carbon Free Cutting Steels With HSS Tools" The Machinability of Engineering Materials. ASM, 1983, pp. 23-41.

[48] Bhattacharya, D. "The Effect of Cerium on The Machinability and Mechanical Properties of AISI 1144 Steels" The Machinability of Engineering Materials. ASM, 1983, pp. 65-89.

[49] Janitzky, E.J. "Machinability of Plain-Carbon, Alloy and Austenitic (Nonmagnetic) Steels, and Its Relation to Yield-Stress Ratios When Tensile Strength Are Similar" Trans. ASME, Vol. 66 (1944), pp. 649-652. (Cited from [11])

[50] Boston, O.W. "Tool Life Testing" Machining-Theory and Practice. American Society For Metals, 1950, pp. 377-408.

[51] Ewell, J.R. "A New Machinability Index" Am. Mach., December 1965, pp. 72-74.

[52] Friedman, M.Y. and Lenz, E. "Effect of Thermal Conductivity of Tool Material on Cutting Forces and Crater Wear Rate" Wear, July 1973, pp. 39-44.

[53] Lorenz, G. "Machinability and Electrical Properties" Influence of Metallurgy on Machinability. ASM, 1975, pp. 455-470.

[54] Jeelani, S. "Measurement of Temperature Distribution in Machining Using IR Photography" Wear, Vol. 68 (1981), pp. 191-202.

[55] Levy, B.S. and Thompson, R.W. "A Compilation of Data on The Effect of Machining and Metallurgical Variables on The Chip-Tool Interface Temperature" Proc. North American Metalworking Res. Conf., 1973, pp. 334-345.

[56] Yellowley, I. "The Assessment of Machinability" SME Tech. Paper, MR75-147, 1975.

[57] Takeyama, H. and Murata, R. "Basic Investigation of Tool Wear" Jr. Engrg. Ind., February 1963, pp. 33-38.

[58] DeVries, M.F. "Carbide Cutting Tool Wear Models" Mfg. Engrg. Trans., Vol. III (1975), pp. 1-3.

[59] Bhattacharyya, A.; Faria-Gonzalez, R. and Ham, I. "Regression Analysis For Predicting Surface Finish and Its Application in The Determination of Optimum Machining Conditions" Jr. Engrg. Ind., August 1970, pp. 711-714.

[60] Spaans, C. and Goedemondt, A.A. "Breakability, An Aspect of The Machinability: A Computer Simulation of Chip Formation" Mfg. Engrg. Trans., Vol. I (1972), pp. 70-77.

[61] Schmidt, A.O.; Ham, I. and Wilson, G.F. "Comparative Performance Study of Different Tool Geometries" Proceedings, 7 th MTDR Conf., 1966, pp. 435-462.

[62] Kane, G. "The Effect of Tool Geometry on Chip Breaking" SME Tech. Paper, MR71-923, 1971.

[63] Ham, I. "Computerized Machinability Study For INCONEL - 718" Influence of Metallurgy on Machinability. ASM, 1975, pp. 324-346.

[64] Yellowley, I. and Barrow, G. "The Influence of Thermal Cycling on Tool Life in Peripheral Milling" Int. J. Mach. Tool Des. Res., Vol. 16 (1976), pp. 1-12.

[65] Taylor, F.W. "On The Art of Cutting Metals" Trans. ASME, Vol. 28 (1907), pp. 70-350. (Cited from [28])

[66] ISO "Tool-Life Testing With Single-Point Turning Tools" International Standard 3685, 1977, pp. 1-41.

[67] Akhtar, S.; Redford, A.H. and Mills, B. "A Short-Time Method For The Assessment of The Machinability of Low Carbon Free Machining Steels" Int. Mach. Tool Des. Res., Vol. 16 (1976), pp. 71-75.

[68] Kraus, C.E. and Weddell, R.R. "Determining Tool-Life Cutting Speed Relationship by Facing Cuts" ASME Fall Meeting, Erie, Pennsylvania, 1937, Oct. 4-6. (Cited from [11])

[69] Lorenz, G. "Machinability Testing" Australian Mechanical Engineer, Vol. 49 (1962), pp. 24-31. (Cited from [23])

[70] Janssen, W.G. "Short-Time Turning Tests with Carbide Tools" Microtecnic, Vol. 16 (1962), p.231. (Cited from [72])

[71] Colwell, L.V. and Mazur, J.C. "Tool Life For Cuts Wherein The Cutting Speed Varies During The Cut" ASME Trans. P Prod. 62WA-281. (Cited from [72])

[72] Lorenz, G. and Gibson, A.V. "Comprehensive Toolwear Equations Obtained From Accelerated Facing Tests" Microtecnic, Vol. XXVII (1973), pp. 194-196 & 216.

[73] Wallbank, J. "Structure of Built-Up-Edge Formed in Metal Cutting" Metals Technology, April 1979, pp. 145-153.

[74] Sun, E.Y.C. Ph.D. Thesis, Victoria University of Manchester (1955). (Cited from [78])

[75] Heginbotham, W.B. and Pandey, P.C. "Taper Turning Tests Produce Reliable Tool-Wear Equations" Proceedings, 7 th MTDR Conf., 1966, pp. 515-528.

[76] Heginbotham, W.B. and Pandey, P.C. "A Variable Rate Machining Test For Tool Life Evaluation" Proceedings, 8 th MTDR Conf., 1967, pp. 163-171.

[77] Poduraev, V.N. and Yaroslavtsev, V.M. "Tool Life in Interrupted Cutting" Russian Machines and Tooling, Vol. XV (1968), p. 37. (Cited from [78])

[78] Kiang, T.S. and Barrow, G. "Determination of Tool-Life Equations by Step Turning Test" Proceedings, 12 th MTDR Conf., 1971, pp. 379-385.

[79] Chisholm, A.W.J. and Hsu, T.C. "A Micro Technique For Studying The Wear of Cemented Carbide Tools and Its Application Mainly to The Variation of Machinability Within The Steel Bar" MERL Plasticity Report MF/MS60, 1952. (Cited from [8])

[80] Mills, B. and Redford, A.H. "Machining Study of Alfa/Beta Leaded Brasses" Annals of CIRP, 1978, pp. 45-48. (Cited from [11]

[81] Optiz, H. and Hake, O. "Wear Analysis of Hard Metal Turning Tools by Means of Radioisotopes" Microtecnic, Vol. 10, 1956. (Cited from [85])

[82] Merchant, M.E.; Ernest, H. and Krabacher, E.J. "Radioactive Cutting Tools for Rapid Tool Life Testing" Trans. ASME, Vol. 75, 1958. (Cited from [85])

[83] Colding, B. "Carbide Tool Wear Studies by Microscopic Radioactive and Frictional Methods" Jernkontorets Ann., Vol. 147, 1963. (Cited from [7])

[84] Cook, N.H. and Lang, A.B. "Criticism of Radioactive Tool Life Testing" Trans. ASME, Vol. 85, 1965. (Cited from [85])

[85] Thomas, J.L. and Lambert, B.K. "A Statistical Analysis of Accelerated Versus Conventional Methods of Tool Life Testing" NAMRC-II Proc., 1974, pp. 139-150.

[86] Kahng, C.H. and Patterson, G.A. "Investigation of The Optimum Tool-Life Under Varied Cutting Conditions" Proc. 3 rd. North American Metalworking Res. Conf. (1975), pp. 346-360. (Cited from [10])

[87] Wager, J.G. and Barash, M.M. "Study of The Distribution of The Life of HSS Tools" Trans. ASME Ser. B, Vol. 93 (1971), pp. 1044-1050.

[88] Fersing, L. and Smith, D.N. "Machinability Research with J & L Tool Dynamometer on Titanium 150A" ASME Paper No. 53-A-207; Abstracted in Mechanical Engineering, Vol. 76 (1954), p. 528. (Cited from [22])

[89] De Filippi, A. "Analysis and Proposal For Short-Time Machinability Tests" Influence of Metallurgy on Machinability. ASM (1975), pp. 396-412.

[90] Colwell, L.V.; Mazur, J.C. and DeVries, W.R. "Analytical Strategies For Automatic Tracking of Tool Wear" IMTDR Conf., 17 th, 1976, pp. 276-282.

[91] Mayer, JR., J.E. and Stauffer, D.J. "Effects of Tool Edge Hone and Chamfer on Wear Life" Trans. SME, Vol. III (1975), pp. 5-15.

[92] Loria, E.A. and Walker, D.R. "Force and Temperature Measurements Are A Rapid Guide to Tool Life Evaluation" Iron Age, 174 (1954), pp. 156-158.

[93] Troup, G.B. "Machinability Tests: A Critique" Am. Mach., 110 (1966), pp. 127-131.

[94] Shaw, M.C.; Smith, P.A.; Loewen, E.G. and Cook, N.H. "The Influence of Lead on Metal-Cutting Forces and Temperatures" Trans. ASME, Vol. 79 (1957), pp. 1143-1154.

[95] Araki, T. and Yamamoto, S. "An Evaluation of Machinability of Low Alloy Steel Materials With or Without Heat Treatment" Machinability Testing and Utilization of Machining Data. ASM, 1979, pp. 117-131.

[96] Nead, J.H.; Sims, C.E. and Harder, O.E. "Properties of Some Free-Machining Lead-Bearing Steels, Part 2" Metals and Alloys, Vol. 10 (1939), pp. 109-114. (Cited from [18])

[97] Schlesinger, G. "Machinability of Metals" The Tool Engineer, Vol. 17 (1947), pp. 18-27. (Cited from [18])

[98] Heritier, B; Duet, R.; Thivellier, D. and Maitrepierre, P. "Turning at Increasing Speed: A Convenient Method to Assess Machinability" The Machinability of Engineering Materials. ASM (1983), pp. 490-511.

[99] Kane, G.E. and Groover, M.P. "The Use of Cutting Temperature as A Measure of The Machinability of Steels" ASME Tech. Paper, MR67-199, 1967.

[100] ASME, Manual on Cutting of Metals, Second Edition, 1952, Tables V-2, V-3, and V-4, pp. 282-292. (Cited from [99])

[101] Zlatin, N. "Needed: Reliable Machinability Data" Am. Mach., Vol. 110 (1966), pp. 109-111.

[102] Bailey, J.A. and Boothroyd, G. "Critical Review of Some Previous Work on The Mechanics of The Metal-Cutting Process" Trans. ASME, Vol. 90 (1968), pp. 54-62.

[103] Abeyama, S. and Nakamura, S. "Machinability Evaluation of Steel in Automatic Screw Machining" Machinability Testing and Utilization of Machining Data. ASM, 1979, pp. 184-198.

[104] Kannatey-Asibu, Jr., E. and Dornfeld, D.A. "A Study of Tool Wear Using Statistical Analysis of Metal-Cutting Acoustic Emission" Wear, Vol. 76 (1982), pp. 247-261.

[105] Kennford, A.S. "A Laboratory Test For Machinability" Metal Progress, Vol. 39 (1941), pp. 354-356.

[106] Di Gianfrancesco, E. and Palladino, M. "New Quality Control Systems in Manufacturing Free Cutting Steels" Machinability Testing and Utilization of Machining Data. ASM 1979, pp. 104-116.

[107] Ivetich, M.J. and Schmitt, L.B. "The Use of A CNC Lathe for Machinability Testing" Machinability Testing and Utilization of Machining Data. ASM, 1979, pp. 51-65.

[108] Schmitt, L.B. and Wannell, P.H. "Improved Material Uniformity Through Machinability Testing" The Machinability of Engineering Materials. ASM 1983, pp. 465-489.

[109] Ivetich, M.J.; Schmitt, L.B.; Stucka, R.B. and Wannell, P.H. "Pretesting For Machinability" Mat'l. Engrg., April 1984, pp. 29-31.

[110] Crampton, D.K. "Machinability of Copper Alloys" Metal Progress, Vol. 46, August (1944), pp. 275-289.

[111] Schmidt, A.O.; Gilbert, W.W. and Boston, O.W. "A Thermal-Balance Method and Mechanical Investigation For Evaluating Machinability" Trans. ASME, Vol. 67 (1945), pp. 225-232.

[112] Dagnell, J. "Machinability Test by A Drilling Method" Annals of CIRP, Vol. 15 (1967), pp. 301-308.

[113] Dagnell, J. "Machinability Ranking by A Constant Feed Force Method" Annals of CIRP, Vol. 17 (1969), pp. 233-242.

[114] Lindgren, B. "Constant Feed Force Machinability Testing - Further Development and Industrial Applications" Annals of CIRP, Vol. 27 (1978), pp. 39-43.

[115] Lindgren, B. "Determination of Machinability with A Short - Term Test Method" METAUX - Corros - Ind., Vol. 54, June (1979), pp. 229-237.

[116] De Chiffre, L. "Testing The Overall Performance of Cutting Fluids" Journal of the American Society of Lubrication Engineers, May 1978, pp. 244-251.

[117] Siemonsen, F.A. "Machining (Deep-Hole Drilling) of Extruded Aluminum Alloys" The Machinability of Engineering Materials. ASM, 1983, pp. 232-251.

[118] Okusa, K; Kitagawa, R. and Akasawa, T. "Method of Testing Steel Machinability by Face-Milling End of Cylindrical Workpiece" Machinability Testing and Utilization of Machining Data. ASM, 1979, pp. 36-50.

[119] Tipnis, V.A. and Friedman, M.Y. "Cutting Rate-Tool Life Characteristic Functions For Material Removal Processes, Part 2: Verification and Applications" Jr. Engrg. Ind., May 1976, pp. 487-496.

[120] Tipnis, V.A. and Christopher, J.D. "Machinability Testing For Industry" Machinability Testing and Utilization of Machining Data. ASM, 1979, pp. 3-35.

[121] Wijenayake, A.P. "Machinability Testing and Utilization in Airframe Manufacture" Machinability Testing and Utilization of Machining Data. ASM, 1979, pp. 253-273.

[122] Thompson, P.J. and Sarwar, M. "Power Hacksawing" 15 th MTDR Conference, Sept. (1974), pp. 217-225.

[123] Colwell, L.V. and McKee, R.E. "Evaluation of Bandsaw Performance" Trans. ASME, Vol. 76 (1954), pp. 951-960.

[124] Taylor, R.W. and Thompson, P.J. "A Study of Bandsaw Blade Wear and Its Effects on Cutting Rates and Economics" Proceedings, 17 th MTDR Conference (1976), pp. 133-140.

[125] Boston, O.W. Metal Processing. John Wiley & Sons, Inc., Second Edition, 1951, pp. 246-273.

[126] Boston, O.W. and Kraus, C.E. "Performance of Cutting Fluids When Sawing Various Metals" Trans. ASME, Vol. 56 (1934), pp. 527-531.

[127] Thompson, P.J. and Taylor, R.W. "An Investigation Into Factors Influencing The Wear Rate of Power Hacksaw Blades Using Dimensional Analysis" International Journal of MTDR, Vol. 16 (1976), pp. 33-49.

[128] Soderberg, S.; Vingsbo, O.; Loryd, B. and Fredriksson, B. "Wear and Wear Mechanisms During Power Hacksawing" International Colloquium on the Cutting of Metals. Colloque International Sur La Coupe des METAUX, Nov. (1979), pp. 12-1:12-11.

[129] McClymonds, N.L. "Measuring Machinability" Metal Prog., Vol 92 (August 1967), pp. 183-184.

[130] Brandon, F.C. "Annealing Aids Machinability of AISI 4140" Metal Prog., Vol. 98 (July 1970), pp. 103-105.

[131] Armour, J.D. "Metallurgy and Machinability of Steels" Machining - Theory and Practice. ASM, 1950, pp. 123-168.

[132] Nagai, C.; Kaneda, T.; Futusawa, S.; Takeshita, H. and Yamamoto, Y. "Machinability of Low Carbon Resulphurized Free-Cutting Steels on An Automatic-Screw-Machine" International Symposium on Influence of Metallurgy on Machinability of Steel, Sept. 1977, Tokyo, Japan. The Iron & Steel Institute of Japan, ASM, 1977, pp. 57-65.

[133] Rabezzana, F. and Tipnis, V.A. "Production Evaluation of Gear Steel" The Machinability of Engineering Materials. ASM, 1983, pp. 338-365.

[134] Cohen, P.H. and Black, J.T. "Development of A Standard Machining Data Machine" Trans. SME, May 1980, pp. 258-265.

[135] Kahles, J.F. "Are Cutting Indexes Valid?" American Machinist, Vol. 113 (Sept. 1969), pp. 119-120.

[136] Troup, G.B. "Cost of Machinability" American Machinist, Vol. 109 (April 1965), pp. 79-86.

[137] Mayer, J.E. and Lee, D.G. "Influence of Machinability on Productivity and Machining Cost" Influence of Metallurgy on Machinability. ASM 1975, pp. 31-54.

[138] Machining Data Handbook. 3 rd. Edition, Vol. One, Machinability Data Center, Metcut Research Associates Inc., 1980.

[139] Gorsler, F.W. "Machinability Data Applied to Aircraft Engine Manufacture" Machinability Testing and Utilization of Machining Data. ASM 1979, pp. 253-273.

[140] Isaev, A.I. "Influence of The Rigidity of The Machine-Workpiece-Tool System on The Roughness of Machined Surface" Proceedings, 8 th. MTDR Conference, 1967, pp. 75-81.

[141] Graham, W. and Rubenstein, C. "An Investigation into The Degree and Depth of Work-Hardening Produced at The Surface of A Workpiece by Turning" Proceedings, 7 th. MTDR Conference, 1966, pp. 463-478.

[142] Bellows, G.; Field, M. and Kohls, J.B. "Influence of Material and Its Metallurgical State on Surface Integrity" Influence of Metallurgy on Machinability. ASM, 1975, pp. 272-295.

[143] Tseng, M.M. and Noujaim, R.A. "On The Measurement and Propagation of Flank Wear in Cutting Tools" Jr. Engrg. Ind., Vol. 101 (1979), pp. 109-115.

[144] Paliwoda, E.J. "Machinability of Type-A Leaded Steels" Trans. ASM, Vol. 50 (1958). (Cited from [22])

[145] Zlatin, N. and Christopher, J. "Heat Treatment, A Vital Factor in Machinability" Metal Progress, Vol. 90 (1966), pp. 105-107.

[146] White, L.; Christopher, J.L. and Wuebbling, G. "Evaluation of Permanent Mold Versus Sand Mold Gray Cast Iron" The Machinability of Engineering Materials. ASM, 1983, pp. 164-199.

[147] Abeyama, S.; Kimura, A. and Nakamura, S. "The Influence of Heat Treatment and Cold Forging on Machinability of Low Alloyed Steels" The Machinability of Engineering Materials. ASM, 1983, pp. 385-401.

[148] Buda, J. and Liptak, J. "A New Approach in Evaluation of Metal Machinability" Zbornik Vedeckgcl Prac Vysokj Skoly Technickej, 1980, pp. 307-318.

[149] Miller, J.C. and DeVor, R.E. "An Experimental Approach to Machinability Testing" SAE Technical Paper Series, No. 800487, 1980.

[150] Kovach, C.W. and Moskowitz, A. "How to Upgrade Free-Machining Properties" Metal Prog., Vol. 92 (August 1967), pp. 173-174.

[151] Aylward, P.T. "Development of Free-Machining Strand-Cast Steels" Unpublished Report, File Ref. 1204-2 & 1204-4 Qz-35-74123 (Feb. 1982), Homer Research Laboratories, Bethlehem Steel Corp., Bethlehem, Pa.

[152] Miller, I. and Freund, J.E. Probability and Statistics For Engineers. Prentice - Hall, INC., 1965.

[153] Cook, R.D. "Detection of Influential Observation in Linear Regression" Technometrics, Vol. 19 (1977), pp. 15-18.

[154] Burr, I.W. Statistical Quality Control Methods. Marcel Dekker, Inc., 1976.

APPENDIX - A **Work Materials Chemical Composition**

Material	C	Mn	P	S	Si	N	Al	Cr	O	Zr	Ce	Cu	Ni	Mo	Ti	Pb	Bi	Se
705E001	.084	.89	.120	.38	.032	.0076	.005	.06	.0053	-	.011	-	-	-	-	-	-	-
705W002	.130	.80	.120	.33	.010	.0079	.004	.05	.0087	.09	-	-	-	-	-	-	-	-
705E017	.087	1.00	.085	.35	.009	.0092	.005	.09	.0043	-	.010	-	-	-	-	-	-	-
705E014	.075	.75	.095	.27	.017	.0047	.005	.12	.0036	-	.015	-	-	-	-	-	-	-
705E003	.066	.94	.081	.37	.029	.0051	.005	.09	.0048	-	.011	-	-	-	-	-	-	-
705C034	.081	.87	.110	.36	.010	.0078	.005	.09	.0059	-	-	-	-	-	-	-	-	-
705E016	.076	.95	.130	.36	.011	.0114	.005	.13	.0050	-	.012	-	-	-	-	-	-	-
705E002	.082	.96	.130	.36	.036	.0117	.005	.08	.0034	-	.013	-	-	-	-	-	-	-
651L100	.090	1.05	.072	.25	.010	.0041	.005	.08	.0153	-	-	.02	.02	.02	.005	-	.25	-
651L101	.090	1.05	.073	.26	.010	.0043	.005	.07	.0153	-	-	.02	.02	.02	.005	-	.18	-
625L286	.090	1.06	.074	.25	.010	.0046	.005	.08	.0194	-	-	.02	.02	.02	.005	.17	-	-
9T	.070	1.04	.077	.32	.005	.0024	.005	.03	.0220	-	-	.10	.01	.01	-	.21	-	-
10T	.070	1.03	.075	.33	.005	.0025	.005	.03	.0210	-	-	.11	.01	.01	-	-	-	.040
11T	.070	1.03	.076	.33	.005	.0024	.005	.03	.0210	-	-	.11	.01	.01	-	-	-	.085
12T	.070	1.06	.070	.32	.005	.0025	.005	.03	.0230	-	-	.10	.01	.01	-	-	.11	-

Source: **HRL Inter-Office Correspondences ([3] & [151])**

C - Carbon
Mn - Manganese
P - Phosphorus
S - Sulfur
Si - Silicon

N - Nitrogen
Al - Aluminum
Cr - Chromium
O - Oxygen
Zr - Zirconium

Ce - Cerium
Cu - Copper
Ni - Nickel
Mo - Molybdenum
Ti - Tellurium

Pb - Lead
Bi - Bismuth
Se - Selenium

APPENDIX - B **Work Materials Mechanical Properties & PPT Results**

Material	S_Y (ksi)	S_T (ksi)	Elongation in 2" (%)	Reduction of Area	HBN	S_Y/S_T Ratio	Speed (sfpm)	Feed (ipr)	PR (pcs/hr)
705E001	82.3	86.0	14.5	47.5	192	.96	262	.0042	336
705W002	76.0	79.6	14.5	45.4	170	.95	213	.0059	383
705E017	84.3	88.0	13.5	45.0	192	.96	245	.0052	388
705E014	75.3	78.5	16.0	54.5	170	.95	343	.0042	440
705E003	72.5	78.0	16.5	52.0	167	.93	343	.0042	440
705C034	81.0	84.8	14.5	46.5	187	.96	343	.0042	440
705E016	88.8	92.5	14.5	45.0	207	.95	213	.0088	572
705E002	87.8	92.0	15.0	45.0	207	.96	213	.0088	572
651L100	67.8	70.5	17.3	54.7	156	.96	245	.0072	538
651L101	67.8	70.9	17.1	53.3	153	.96	245	.0083	620
625L286	69.1	72.6	15.9	49.5	156	.95	245	.0083	620
9T	66.7	70.0	18.3	-	156	.95	228	.0072	502
10T	66.7	70.4	17.8	-	156	.95	-	-	-
11T	67.7	71.5	17.8	-	156	.95	-	-	-
12T	66.2	69.5	17.8	-	159	.95	228	.0072	502

Source: HRL Inter-Office Correspondences ([3] & [151])

S_Y - Yield Strength, a 0.2 % offset determination
S_T - Tensile Strength
PR - Production Rate

VITA

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