An investigation of product quality modification capabilities during wire drawing

Robert B. Gifford
Lehigh University

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An Investigation of Product Quality Modification Capabilities During Wire Drawing

January 2001
AN INVESTIGATION OF PRODUCT QUALITY MODIFICATION CAPABILITIES DURING WIRE DRAWING

by

Robert B. Gifford

A Thesis
Presented to the Graduate and Research Committee of Lehigh University in Candidacy for the Degree of Master of Science in Mechanical Engineering and Mechanics

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6/28/00
Date

John P. Coulter, Thesis Co-Advisor

Wojciech Z. Misiolek, Thesis Co-Advisor

Charles R. Smith, Chairperson of Department
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ABSTRACT

The process parameters in wire drawing are still not fully understood. Further understanding of these variables would enable better control of outgoing material properties. During this numerical investigation the total effect and interdependence of die angle, bearing length, lubrication, and draw speed on the hardness distribution in wire drawing was studied and verified with physical micro-hardness measurements. In addition, the ability to create desired hardness levels in a wire specifically targeted for subsequent deformation was evaluated. The analyses were based on the utilization of DEFORM-2D, a commercially available finite-element software package. Using DEFORM-2D, the total effect and interdependence of the input parameters was quantified utilizing full factorial designs.

Results show that the hardness distribution in the final wire was affected primarily by die angle and that interaction between parameters was negligible. Furthermore, a capability was developed to obtain desired material output simply by knowing the ultimate tensile strength of the incoming material. Detecting and correcting inherent variation in incoming wire with this new knowledge is crucial in producing high quality wire, especially where subsequent processes demand specific properties.
CHAPTER 1

INTRODUCTION TO WIRE DRAWING

1.1 The evolution of wire drawing

Wire manufacture was documented as early as biblical times when gold sheets were cut, hammered, and filed into wires of circular cross-section. In general these primitive wires were very short and many pieces would be brazed together to form wire of longer lengths. Developments in wire manufacture led to the creation of primitive wire drawing apparatuses consisting of a die and fixture. A human wire drawer produced the drawing force and therefore only wire that could be pulled through a die by human power could be drawn. This limited wire production to thin wire except for exceptionally soft materials. Also during this time products of various profiles (other than circular) were being drawn. Beginning in the 1300's human wire drawers became obsolete with the advent of waterpower and a couple of centuries later with the development of the steam engine and finally electric power.

The industrial pull of the technology, however, really began with the development of the telegraph, wire fencing, bridges, piano wire, wire nails, fasteners and strangely
enough hoopskirts in the mid 1800’s. One of the leading producers of copper for the transatlantic telegraph was Thomas Bolton & Sons (TB&S). At their factory in Birmingham, England the process of drawing wire at that time was as follows:

1. Copper blocks or slips that were 1.37 m long, 0.10 m wide and 6.35 mm thick were rolled to 0.13 m wide and 1.59 mm thick.

2. Giant 0.30 m hardened steel discs were used to cut this now 0.13 m wide sheet into 26 thin strips.

3. These square strips were then taken from the slitting mill to the wire mill to be drawn from square to round.

4. The rod or wire was then drawn through several other dies under steam power to make finer wire.

5. In between rolling or wire drawing the rod or wire would be batch annealed.

Although the first attempt to lay wire across the Atlantic failed, it sped up the improvement of rolling and drawing processes. Since the cost of this endeavor was so high, many well-known individuals including Faraday and Lord Kelvin were called on to help determine the reasons for failure. Their findings helped establish a conductivity standard that pushed TB&S and others to improve drawing practices, especially batch annealing. The second and third cables were successfully laid across the Atlantic Ocean in 1865 with great improvements in conductivity (Morton 1999). Oddly enough, Alfred Bolton who supervised the production of the wire for the transatlantic cables celebrated
by purchasing a piano, and at this time in America, especially Boston, the piano was driving the production of wire from producers like Washburn & Moen. As a result of the huge demand for piano wire, Ichabod Washburn realized that continuous rather than batch wire-handling methods were the future. In Ichabod’s own words, “The object of my invention is to harden and temper steel wire or other steel in pieces of considerable length by one continuous operation.” Today his invention is known as oil tempering.

Bridge cable was a smaller volume product but was important to the development of the wire and cable industry because of the need for higher strength and longer lengths. Even hoop skirts created a need for wire. Springy wire to support the bell-shaped dresses led to improvements in wire drawing simply by increasing demand.

The Bedson rolling process spurred big changes in the wire industry. This system enabled wire producers to continuously anneal, clean and galvanize wire. This process was applied to iron products first, but other materials then followed. Both English and American companies utilized the Bedson process. It significantly increased the maximum length that could be achieved and eliminated the slitting machine. The size of the billet and the size of the mill were the only limit on the length of wire products. There were problems, especially in the production of iron wire, because obtaining uniform input material was difficult in the days before the Bessemer and open-hearth steel processes were introduced. Steel making as a result of these processes improved greatly. Barbed wire fencing alone created inconceivable demands on wire producers. At the beginning of the 20th century steel rod production was eclipsing one million tons per year (Sayenga 1988).
Electric lighting also played a large role in improving wire drawing. Filament production necessitated much improved drawing practices. TB&S patented one of the first continuous wire drawing machines that was capable of drawing 0.23 mm wire to 0.025 mm wire using 14 diamond dies. A large number of American and Canadian companies purchased this machine to handle the large demand for Edison’s filament lamps (Morton 1999).

Between 1840 and the early 1900’s improvements in rolled and drawn products was due almost entirely to the demands of technology. In some sense this remains true today, except that government support (in the form of import/export tariffs) is not as helpful as it was in the late 1800’s. For example, today’s nonferrous wire market is growing most rapidly in the communication area. Computers and the Internet are the main driving forces that will provide growth rates as high as 15 percent for the next few years (McNulty 1999).

Efforts in wire drawing and rolling mills today are focused towards automation. In Sweden, Laemnea Gruk AB, have experimented with fully automatic wire drawing systems capable of running over the weekend completely unattended. These machines take coils and descale, pickle and lubricate incoming wire, which is then drawn and spooled automatically. This greatly increases the production window and at the same time reduces labor requirements (Hagstedt 1988). At Alcatel (located in Canada), producers of copper rod for the wire magnet industry, a number of technical improvements in real-time inspection during rolling have been realized. Their product is monitored in two ways as it is produced. First, an eddy current tester is used to monitor
surface defects. Defects on the wire surface can cause electrical shorts in magnetic devices utilizing defective wire coated with thin insulating films. Second, a ferrous inclusion tester is used to detect ferrous particles that get imbedded in their copper wire from wearing steel rollers. Both of these monitoring tools are run continuously in real-time to reduce refractory inclusions, rolled-in inclusions and surface defects (Adam and Sanchez 1999).

These are just two examples of the current technology in the rolling and wire drawing industry. Current trends in production machinery, process accessories, quality control and materials handling are shown in Table 1.1 (McNulty 1999). It is easy to see that computer control is becoming more prevalent in every area. Process machinery is becoming programmable, process equipment like draw dies will be created to optimize the properties of the material being drawn, and wire will be produced to maximize data transfer rates for data networks. Overall, trends in the industry show that higher line speeds, automation, process simulation, environmental friendliness and material development will remain hot areas in the future.

1.2 Introduction to product modification

During drawing, the materials and processing parameters utilized combine to yield a modification of workpiece attributes. This product modification could potentially be controlled by sensing and adjusting appropriate parameters in real-time to obtain a desired final product. A secondary effect of doing so could be the extension of the draw die life, as well as the lives of tools used in subsequent operations.
Table 1.1 – Trends in the wire drawing industry

<table>
<thead>
<tr>
<th>Area in Industry</th>
<th>Trends</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Process</strong></td>
<td>Flexible rod breakdown – multiple capstans driven by independent motors. This reduces slip and provides for variable elongation per capstan</td>
</tr>
<tr>
<td><strong>Machinery</strong></td>
<td>Quick die changes for electronic final product size selection</td>
</tr>
<tr>
<td></td>
<td>Multi-wire drawing for automotive, appliance and building</td>
</tr>
<tr>
<td></td>
<td>Grouping of production processes (drawing, annealing stranding)</td>
</tr>
<tr>
<td></td>
<td>Simplification – integrated machinery offering non-slip drawing and multiple reduction choices while rotational speed is taken care of automatically</td>
</tr>
<tr>
<td><strong>Process Accessories</strong></td>
<td>Wire drawing dies</td>
</tr>
<tr>
<td></td>
<td>• Supplier service</td>
</tr>
<tr>
<td></td>
<td>• Re-cutting/polishing of draw dies</td>
</tr>
<tr>
<td></td>
<td>• Selection of die profile design to match material and performance</td>
</tr>
<tr>
<td></td>
<td>• COMPUTER SIMULATION USING DEFORM – measures the impact of lubrication and die design</td>
</tr>
<tr>
<td><strong>Lubrication</strong></td>
<td>Mist monitoring / ventilation control</td>
</tr>
<tr>
<td></td>
<td>Environmental concerns</td>
</tr>
<tr>
<td><strong>Quality Control</strong></td>
<td>Inline quality control</td>
</tr>
<tr>
<td></td>
<td>• Inline wire diameter measurement (i.e. Wirescan laser gauge from Beta Laser-Mike-1 micron accuracy)</td>
</tr>
<tr>
<td></td>
<td>• Computers are providing product traceability, production control, streamlined machine setup procedures and simplified machine maintenance</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>Energy savings through the use of new AC motors</td>
</tr>
<tr>
<td></td>
<td>• Superplastic wire-979 MPa 15% elongation used in eyeglass frames and spring industry</td>
</tr>
<tr>
<td></td>
<td>• Higher strength, lower corrosion, lower weight, and higher temperature resistance materials</td>
</tr>
<tr>
<td></td>
<td>• New platings and coatings</td>
</tr>
<tr>
<td></td>
<td>• Optical fibers – higher performance, greater bandwidth</td>
</tr>
<tr>
<td></td>
<td>• Superconductive wire – replacing old infrastructure (i.e. Detroit Edison)</td>
</tr>
</tbody>
</table>
In order to control the wire product the input parameters must change when an adjustment in the output parameters is necessary. There must be a capability to sense a change in output and an algorithm and subsystem to make the appropriate changes in real-time. For the correct change to be implemented a database or model must be available. Ultimately, a completely automated process would be the most desirable, but the technology to control all the process parameters today is not readily available. The geometry of the draw die, specifically die angle and bearing length, can not yet be changed automatically. In most cases the lubrication of the wire during wire drawing is not well understood and can not be changed over a large range. Draw speed can be altered easily with the proper control system, but knowing when and how to vary speed is complicated.

Despite these problems steps toward the implementation of an intelligent wire drawing system can still be taken. Initially, the system will have to be a stepwise, manually adjustable process. This means that changes in material input parameters will not vary continuously, but instead from coil to coil. With incoming material properties and an appropriate model for process parameters like die angle, bearing length, lubrication and draw speed the desired results can be achieved.

This capability can only come to fruition if the process of wire drawing is well understood. This means that when a specific coil of wire is to be processed it will require a model that includes information on all significant process parameters. Therefore, the creation of a process model is necessary.

Modeling the wire drawing process is not an easy task. The variety of materials that are wire drawn today is large and the properties of these materials vary widely. For
this reason applying intelligent wire drawing in industry would require developing a model for each material and product geometry being considered. In this thesis a numerical model for single-pass drawing of header quality wire was utilized. This kind of wire is used for a variety of products including screws, bolts, nuts, rivets, fuel injectors and many others. Before discussing the details of the following chapters an introduction to the drawing process is presented.

1.3 Wire drawing process

Wire drawing processes change and reduce the cross-section of a wire, rod or tube by pulling it from the exit side of the die. Wire drawing is mainly used to reduce circular rods or wires to a desired diameter. Circular and square rod can also be drawn to create unique profiles. Usually these profiles are created by a progression of dies that develop the final shape.

Another common drawing practice is that of tube drawing where tube stock is drawn through a die much like stock with a solid cross-section. In this case a mandrel is placed inside the tube during drawing. However in some cases a mandrel is not used and this process is appropriately named tube-sinking (Kalpakjian 1995).

1.3.1 Drawing machinery

Draw bench and bull block systems are the two main types of machinery used in drawing. A draw bench carries a single die and looks much like a horizontal tensile testing machine. The rod or wire stock is reduced in diameter and fit through the die. A clamp is used to grasp the stock and a mechanical or hydraulic drive is used to pull the
wire through the die. A simple schematic is shown in Figure 1.1. These machines are usually used to draw single lengths of material up to about 30 m long. The maximum pulling force can be as much as $1.3 \times 10^6$ N and the pulling rate can reach 30 m/min (Kalpakjian 1995).

![Figure 1.1 - Schematic of a draw bench](image)

(Adopted from (Kalpakjian 1995))

Extremely long rod and wire stock with a smaller cross-section (< 13 mm) can be drawn by a bull block or capstan system. These systems can be single- or multi-pass depending on the reduction required in a specific application. A single-block system reduces a piece of stock in a single pass and can be used to reduce the cross-sectional area up to 45%. In multi-pass drawing the stock material is drawn through many dies and can be used to achieve larger area reductions. These machines pull with less force, but are capable of drawing wire at speeds of up to 450 m/min for steel and 1800 m/min for
nonferrous materials (Avitzur 1983). A top and side view of a multiple bull block system is shown in Figure 1.2.

![Figure 1.2 - Schematic of a multi-pass wire drawing machine](image)

(Adopted from (Kalpakjian 1995))

1.3.2 Die geometry

For both systems the typical geometry of a die is shown in Figure 1.3. Usually the entrance of the die is shaped like a bell in order to draw lubrication into the die. Past the bell section is the tapered entrance of the die where the reduction in diameter is achieved. The half-angle included in the conical section is referred to as the approach angle or die-angle and is an important process parameter. Further along the die is the bearing area where the stock takes its final shape and surface finish. Lastly the die has a back relief or reverse taper that strengthens the die and lessens the chance that galling or abrasion will occur if the drawing stops or the die is out of alignment (Dieter 1986).
1.3.3 Die material

Drawing dies are typically made from very hard materials. Carbide materials (tungsten and tantalum), and tool steels are often used in normal drawing conditions, but diamond dies are also used, especially in the drawing of fine wires. While these materials are rather hard they are also brittle (especially carbides) so they are housed in mild steel casings to impart extra strength and toughness.

1.3.4 Lubrication

Lubrication is another integral part of the drawing process. Since heat generation is rather rapid in drawing, proper lubrication is essential. Dry lubricants like soap powders, lime and greases, or lime and tallow can be used. In wet drawing soap
solutions and oils are commonly used. Some cutting edge lubricants that can be used at elevated temperatures include graphite solutions, polymer coatings, and glass coatings (Hillery and McCabe 1995). Wire may also be coated with another more ductile material like copper, brass, or bronze prior to being lubricated by the previous methods. In some cases ultrasonic vibration is applied to the die to reduce friction, increase the quality of the surface finish, and improve die life. However, even with proper lubrication heat generation is a concern due to the low surface area of the die. For this reason, some drawing dies are water-cooled.

1.3.5 Material preparation

To successfully draw materials certain steps must be taken to obtain good results. Cleaning incoming stock is extremely important. When rod for subsequent drawing is created a layer of oxide called scale forms and this must be removed. If it is not removed this layer can cut into the die and cause premature wear or poor surface finish on the finished workpiece. Some of the most common processes to remove scale are to immerse the rod in a pickling treatment, molten salt bath, or mechanical descaler. A pickling treatment consists of immersing the rod in an approximately 10% solution of sulfuric, nitric, hydrochloric or hydrofluoric acid in water heated to 150 degrees Celsius. The solution usually includes an inhibitor so the solution doesn’t attack the cleaned metal after the scale is removed. A molten salt bath consists of sodium hydride which removes scale chemically. Mechanical descaling, on the other hand, removes scale by a sandblasting or deforming action.
Once the scale is removed a coating solution is introduced to the rod to neutralize any leftover acid before drawing (if it was chemically treated). In some cases the rods are submersed in a lime emulsion, a phosphate base solution, or other solutions. The rods are then baked in an oven (heated to 250 C – 450 C) to neutralize any leftover acid and to deposit a coating to aid in carrying lubrication during drawing.

1.3.6 Defects in wire drawing

In the process of drawing wire or rod there are ranges of die angle and percent area reduction that should be used as guidelines. Straying from these ranges can cause defects in the workpiece. In a range known as the “danger zone” a defect known as a central burst can form (also called chevroning or cup-and-cone fracture). This kind of defect occurs when voids form in the center of the workpiece. Since it isn’t apparent from the surface of the wire central bursts can be the cause of catastrophic failure in the field. Chip and dead zone formation can also occur when operational stress and area reduction is improperly prescribed. The graph in Figure 1.4 displays the safe and unsafe ranges in conventional drawing (Avitzur 1983). In this figure $\sigma_f$ represents the operational stress. Another defect known as a seam can occur when folds or deep scratches form in the drawing process. Seams and scratches can be a result of poorly rolled wire or a result of improper die finish, especially if the entrance of the die is galling or the transition to the relief angle is rough. This defect can be especially troublesome when subsequent forming operations are performed. Even if the workpiece is being drawn under properly configured geometric conditions improper lubrication can cause surface scratching and premature die wear.
1.4 Focus of thesis

In this thesis a numerical investigation of the total effect and interdependence of die angle, bearing length, lubrication and draw speed on single-pass drawing of header quality wire was conducted. In addition, the ability to create desired material hardness in a wire specifically for subsequent forming was evaluated. The analyses were based on the utilization of DEFORM, a commercially available finite-element software package. Figure 1.5 shows how DEFORM was used to predict product quality attributes.

Using DEFORM, the total effect of the input parameters was quantified. More specifically numerical simulations were performed based on a factorial design including...
the parameters above. The results were analyzed and the factorial effect of each parameter and the interactions between them were evaluated.

Before the DEFORM finite-element software was used, it was verified that it in fact produces a realistic simulation of the physical process. Experimental micro-hardness data was collected from a physical drawing process, since the wire did not have a large enough diameter to be sectioned and gridded accurately to directly measure the effective strain distribution across the wire. These results were then compared to the effective strain distribution produced by DEFORM simulations through an effective strain / micro-hardness conversion. This process allowed a partial verification of the DEFORM software package's modeling capabilities.
the parameters above. The results were analyzed and the factorial effect of each parameter and the interactions between them were evaluated.

![Diagram](image)

**Figure 1.5 – Product property prediction system**

Before the DEFORM finite-element software was used, it was verified that it in fact produces a realistic simulation of the physical process. Experimental micro-hardness data was collected from a physical drawing process, since the wire did not have a large enough diameter to be sectioned and gridded accurately to directly measure the effective strain distribution across the wire. These results were then compared to the effective strain distribution produced by DEFORM simulations through an effective strain / micro-hardness conversion. This process allowed a partial verification of the DEFORM software package's modeling capabilities.
Commercially available dies were measured with a coordinate-measuring machine to extract the die profile. These dies, which were used to produce experimental samples, were included in the verification of the software. Subsequently these profiles were used as a guideline for creating dies with different geometry for the numerical study. The primary output parameter from the numerical study was the micro-hardness distribution of the drawn specimen and a factorial design was utilized to study the effect of the aforementioned parameters on this distribution. Based on the initial results more simulations were conducted and evaluated to further improve the results.

As a result of this study, it was determined how process variables change output properties both individually and collectively. Furthermore, a capability was developed to obtain desired material output simply by knowing the tensile strength of the incoming material and adjusting processing parameters appropriately. Finally, recommendations were made for the implementation of a manually adjustable wire drawing system based on the numerical model.

1.5 Structure of thesis

The structure of this thesis following the introduction is shown in Figure 1.6. In Chapter 2 the literature review focuses on research in the areas of die geometry, lubrication, environmental issues and temperature effects. In addition, studies on sensing, control and adjustment of these parameters that relate closely with product modification are reviewed.

The governing equations used to develop the commercial software DEFORM are presented in Chapter 3. A look into the formulation of these equations was made to
justify using a commercial code like DEFORM. Then DEFORM was tested and evaluated to ensure that reasonable results could be obtained.

Chapter 4 contains the details of the numerical experiments. The material, wire drawing dies and process parameters are described in detail. After the problem statement, the factorial design approach is presented and the use of DEFORM to perform the simulations specified in the factorial design is explained. This includes constructing
justifying the use of a commercial code like DEFORM. Then DEFORM was tested and evaluated to ensure that reasonable results could be obtained.

Chapter 4 contains the details of the numerical experiments. The material, wire drawing dies and process parameters are described in detail. After the problem statement, the factorial design approach is presented and the use of DEFORM to perform the simulations specified in the factorial design is explained. This includes constructing
the geometry, setting the boundary conditions, and configuring the software. Next a model was developed from the results of the factorial designs. Lastly, implementation of this model into a manually adjustable system is presented.

The experimental validation of the numerical model is presented in Chapter 5. The value of DEFORM for modeling wire drawing is shown and verified again. A brief look is taken into implementing this method of optimization to other wire drawing processes.

Lastly, conclusions and opportunities for future work are presented.
CHAPTER 2

REVIEW OF RELATED RESEARCH

Wire drawing like other metal forming processes is evolving more quickly today due to the increased application of computers, controls and sensing equipment. Prior to any computer presence in the industry the main concern was to simply reduce the cross-section of a wire while trying to minimize wire breakage and surface defects. With new technology many opportunities have arisen and are beginning to be explored. There are opportunities in process optimization and control, but there are also new developments in machinery, tooling, lubricants and the environment. Fundamental research on process parameters like die angle, percentage area reduction and lubrication is still prevalent, but recently there have been a number of studies which have focused on how to use wire drawing processes to obtain desired tensile strength, surface hardness, microstructure or surface finish. Furthermore, some have designed machinery that can sense and control the drawing process by adjusting process parameters in real-time.

In the current literature review chapter developments in tooling, lubricants and environmental control are explored first. Secondly, intelligent manufacturing is defined and its effect on product quality is discussed. Then fundamental studies on wire drawing
and the methods used to conduct them are presented. Finally, the developments in real-time control, sensing and adjustment are discussed.

2.1 Draw die innovation

Wire drawing dies are typically made from carbide and diamond materials. Some common carbide materials are made from a mix of unsaturated carbide mixed with either tungsten, molybdenum or tantalum (Sen 1997). Commonly 6-12% cobalt powder is added to reduce the brittleness inherent in these materials. These materials are mixed and pressed into a die nib shape that is then sintered to obtain its hardness (Maxwell 1998). This nib’s outside diameter is ground precisely and pressed into a tool steel casing for added toughness.

In addition to carbide dies there are a number of diamond based materials used for producing draw dies. The three main types are natural, synthetic single crystal (SCD) and synthetic polycrystalline (PCD) diamond dies. Natural and SCD dies are similar in terms of die life. With each, wire manufacturers can expect to get 100 times the life of a carbide die (Sen 1997). Using PCD dies, which were first developed by General Electric under the brand name Compax, wire manufacturers can expect to get two to three times the life of natural diamond or SCD dies (DeJohn 1995). Extended die life, however, carries a price tag. Carbide dies range in price from $5 to $25, but natural diamond and SCD dies range from $40 to $1,100, and PCD dies cost anywhere from $45 to $1800. Current trends indicate that eventually SCD and PCD dies will replace natural diamond dies because of their ever-decreasing cost. In addition, the ability to tailor synthetic dies
to a specific drawing process is also becoming more popular because of the ability to optimize the cost / performance ratio (Yoshida and Nakamura 1999).

Despite these technological advancements, industry is not reaping the full benefit. This is mainly due to the characteristic lack of attention that wire drawing dies gets from wire drawers. Many die vendors are trying to instruct their customers on proper handling and use of draw dies and wire for subsequent drawing. Companies like Decatur Wire Die Services of Decatur, Indiana; Paramount Die Co. of Belcamp, MD; and Hoosier / Ajax Wire Die and Indiana Wire Die Company both of Fort Wayne, ID; agree that training operators on the care of wire dies and the incoming wire is essential. Most agree the key to good die life is clean incoming wire, regular oil changes, proper die repolishing and recutting, and good record keeping. With proper inspections a 14-gauge PCD die from Hoosier / Apex can be expected to be repolished up to six times before being recut to the next bearing diameter (DeJohn 1995). Without proper inspection the window for repolishing and recutting dies can be missed with costly outcomes.

One other important key to long die life that was not mentioned above is choosing the right die for the job. As discussed previously there are a variety of die materials to choose from. Moreover, practical included die angles up to 25 degrees and area reduction reaching 30 percent in single-pass drawing permits a large range of values to choose from. Since this is the case determining a good starting point for any single-pass wire drawing operation can be difficult. A general rule of thumb is that the distance from the beginning of the bearing land to where the wire contacts the approach angle should be
approximately 72-100% of the bearing diameter. Table 2.1 shows the correlation between included die angle and percentage area reduction (Maxwell 1998).

Table 2.1 – Contact point chart

<table>
<thead>
<tr>
<th>Included Angle</th>
<th>72% Contact Point</th>
<th>100% Contact Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>13% Area Reduction</td>
<td>18% Area Reduction</td>
</tr>
<tr>
<td>8</td>
<td>17%</td>
<td>23%</td>
</tr>
<tr>
<td>10</td>
<td>21%</td>
<td>27%</td>
</tr>
<tr>
<td>12</td>
<td>25%</td>
<td>32%</td>
</tr>
<tr>
<td>14</td>
<td>28%</td>
<td>36%</td>
</tr>
<tr>
<td>16</td>
<td>30%</td>
<td>40%</td>
</tr>
</tbody>
</table>

In general, this chart can be used for area reductions between 13% and 40%. Heavier or lighter area reduction can cause rapid die wear when a general-purpose die is implemented. The tendency to use standard dies in industry for processes where they are ill suited is mainly because die vendors cannot use standard die nib sizes to make smooth transitions for heavy reductions, or grind small die angles for light reductions. For these situations a double angle die, provided by Die Quip Corp. and illustrated in Figure 2.1, can be ground from a standard die nib.

On large reductions this secondary angle lessens the tendency for material to become sucked down by a sharp transition to the bearing length. On small area reductions, sometimes called finishing passes, the contact point on the approach angle is moved back away from the bearing following the previous rule of thumb. When a standard die is used in finishing passes the wire can come into contact with the approach too close to the bearing causing poor lubrication and pressure distribution, resulting in
rapid die wear and poor surface finish. This problem can be especially troublesome in
the production of fasteners and fuel injectors where accurate size and precise tolerances
of drawn wire are an absolute necessity.

Figure 2.1 – Double angle draw die

2.2 Lubricant development

In industrial settings where wire drawing is not the top priority lubrication gets
even less attention than the dies. Drawing machinery and tooling are so inexpensive
compared to other machinery and tooling that it is easy to ignore. Even in situations
where all the steps have been taken to ensure that the process is well lubricated it must be
consistently inspected. Simply ignoring a well-designed process can result in problems
like drawing ring, which is a direct result of wear at the point where the incoming wire
contacts the approach angle. In the case that this build-up is not polished out a
breakdown in lubrication will surely occur.
Generally, when wire is drawn it is best to draw at a constant speed that is high enough to provide hydrodynamic lubrication. When the speed of drawing is erratic or too slow boundary lubrication occurs. The difference between these two methods of lubrication is that in hydrodynamic lubrication the surface aspirates on the wire do not contact the die surface because of a thick layer of lubricant under high pressure. Boundary lubrication, however, allows the wire to contact the die surface and the lubrication only serves to keep the two materials from welding to each other (Tripp 1987). A number of lubricants and methods of reducing friction are being studied. In addition to new lubricants coming out on the market some individuals are trying to apply ultrasonic energy (Maropis 1991) and electrode control of lubricant to reduce the drawing force and improve surface quality (Su 1997).

In the production of fuel injectors, fasteners and other subsequently forged parts, drawing prior to the forging station occurs as it is needed. This means that the wire is almost always drawn slowly and at a non-constant speed. Cases like these require special attention because without proper lubrication metal-metal contact will take place and produce poor drawn parts. In the case of stainless steel wire, the focus material of this thesis, the best-known way to reduce friction today is through the used of calcium or aluminum stearate products. Besides providing better lubrication in the drawing process both powders, especially aluminum stearate powder, produce a hard coating that aids in the subsequent forming of the drawn wire (Tripp 1987). Proper lubricant selection, periodic inspection and record keeping will result in well-lubricated drawn wire with good surface finish and consistent diameter.
2.3 Environmental issues

A smaller but growing concern in the wire industry is environmental concerns related to wire cleaning techniques. Pickling, rinsing and bonderizing processes utilized today are based on acidic solutions that are harmful to aquatic plant and animal life when released into the environment. It has also been shown that continuous exposure to phosphates and borax, two chemicals prevalent in wire cleaning solutions, cause heart and nervous system problems (Tecnovo 1992). Because of the dangers of these chemicals new non acid-based cleaning agents are becoming more popular. New cleaning processes like the DynaPower process use mechanical descaling, electrolysis in a neutral salt solution, and ultrasonic vibration to remove scale, debris and lubrication films from wire. Compared to traditional acid cleaning this method can reduce solid wastes by as much as 76% (Stachowiak 1997).

In addition to more modern cleaning processes coatings can be applied electrostatically to a variety of different types of wire for insulation, corrosion protection, and lubrication. Thermoplastic and thermoset coatings can be applied at room temperature and then melted or cured at a higher temperature. Powder coatings, including talc and stearates can also be applied electrostatically (Reddy et al. 1998).

Finally, fluid or gas leaks that occur in wire drawing and heading machinery need to be checked regularly. Oil leaks, oil contaminated by cooling water, steam leaks or air leaks can all consume energy and/or be the cause of poor product. These leaks can be difficult to find, but ultrasonic detection can be used to find these leaks even when the
plant is at full production. In addition to checking for leaks, it is also important to maintain smooth running machinery. A poorly running machine can consume large amounts of energy. Two detection methods, namely vibration analysis and infrared thermal imaging, are gaining popularity (Rinehart and Pawlikowski 1998). With these technologies vibration and thermal signatures can be monitored and in many cases impending failures can be prevented.

2.4 Real-time intelligent drawing

Intelligent-manufacturing is the combination of engineering science, real-time control, and real-time monitoring. Intelligent drawing, therefore, would result if one could combine an adaptive drawing capability, real-time control, and real-time monitoring as shown in Figure 2.2. With the three obvious and possibly adjustable parameters in wire drawing being die angle, percentage area reduction, and coefficient of friction applying real-time control and monitoring to drawing science would seem rather straightforward. Unfortunately, however, the geometry of this process does not lend itself well to real-time monitoring or adjustment. Adjusting the die geometry in real-time could be tremendously difficult due to the large forces and mechanical complexity of an adjustable drawing die. Additionally, the friction condition in the die/workpiece interface is still not fully understood and therefore would be difficult to adjust accurately. Currently, however, there is a good understanding of drawing science and some techniques that allow us to monitor important variables in real-time. Hopefully in the future this will lead to the development of intelligent drawing processes.
In order to develop intelligent drawing processes that are able to produce high quality products, three key components must be understood. These are drawing science development, real-time monitoring, and real-time control. Up to now almost all the focus has been on theoretical, experimental and numerical modeling of drawing processes, though some experimental studies on drawing have utilized devices that are able to measure and adjust input parameters in real-time. Throughout the remainder of this chapter, accomplishments in drawing science and real-time monitoring and control are
discussed along with their related impacts on the potential for future fully intelligent manufacturing (real-time product modification).

2.4.1 Drawing science

In the past few years, numerical tools have been gaining popularity for modeling drawing processes. Prior to this, however, analytical and experimental techniques were chiefly utilized. A brief description of analytical, numerical, and experimental advancements in the field follows.

2.4.1.1 Analytical techniques

Since exact solutions are not available for drawing other techniques must be used. There are a few different analytical techniques available for this purpose. These are the slab method, uniform-deformation energy method, slip-line field theory and limit analysis. The slab method assumes homogeneous deformation and was developed in the early to mid 1900's by Von Karman, Hencky, Siebel and Sachs. The uniform-deformation energy method is used to calculate the average forming stress from work done by uniform plastic deformation. Slip-line field theory, on the other hand, can be applied to drawing when it is important to account for inhomogeneous deformation. In limit analysis two approximate solutions are developed in order to sandwich a range where the experimental data may fall. For example, to determine drawing stress an upper-bound solution that provides a result higher or equal to the actual result is found. Then a lower-bound solution that provides a result lower than or equal to the actual drawing
stress is determined. In theory the actual drawing stress is expected to lie between these two bounds. For more precise results a number of different upper and lower bounds can be generated to narrow the range where the actual results can fall. In many cases the upper-bound solution is good enough and can be used exclusively. Sample results from limit analysis for the example above are shown in Figure 2.3 (Avitzur 1983).

Figure 2.3 – Drawing stress results from limit analysis
(Adopted from (Avitzur 1983))

2.4.1.2 Finite-element and finite-difference analysis

Finite-element and finite-difference methods are being used more readily today for simulating metal forming analyses. In these analyses the workpiece is divided up into small elements and an algorithm is used to determine the deformation of the workpiece as
well as a number of other properties. When these tools are used appropriately very good results can be obtained. Many studies have been conducted this way to determine the effect of geometry, friction, and material properties on product quality.

2.4.1.3 Experimental analysis

Before computing existed numerous experimental studies were conducted. J. G. Wistreich, a well-known researcher in drawing, conducted extensive studies on copper with sodium stearate lubricant (Avitzur 1979). These popular studies, which are still used as a basis for comparison today, focused on how changes in cone angle and area reduction affected drawing stress. He also studied the coulomb coefficient of friction in the die/workpiece interface by using a novel split die. Unfortunately, while studies like those of Wistreich are useful, they are also costly and time consuming. As a result of the popularity and accuracy of finite-element and finite-difference techniques experimental studies have been used chiefly to verify numerical results.

2.4.2 Current numerical and empirical studies and the effects on product quality

Today many studies done on drawing are being carried out with the aid of the finite-element method (FEM). FEM simulation has become a powerful tool in studying drawing because with it non-uniform deformation and local stresses and strains can be accurately determined. In addition, results can be obtained quickly and easily and extensive study is possible without conducting many costly experiments. Studies on die
angle, percent reduction of area, lubrication, tool wear, and material characteristics (residual stresses and strains) have been conducted very successfully.

With this tool it has also become easier to study product quality. In drawing, product quality evolves from the characteristics of the die, material characteristics, environmental conditions, and processing parameters as shown in Figure 2.4.

![Diagram of product quality evolution]

Figure 2.4 – Product quality evolution

Numerical studies have furthered our understanding of these effects to such an extent that it is now possible to impart desired characteristics on the workpiece by varying particular parameters within these programs.

More recently studies concerning the determination of effective strain, strain rate, tensile strength, tensile elongation and hardness have been more popular than studies on
drawing stress or die pressure. This change came about due to interest in phenomena occurring in the material and new quality requirements related to manufactured wire rods. It has been proven that finite-element and empirical methods give the best results for the phenomena taking place in die deformation zone and final product by Majta et al. (Majta et al. 1992), Brethenoux et al. (Brethenoux et al. 1996) and Luksza et al. (Luksza et al. 1998). Of great significance are studies concerning the evolution of properties in wire drawing. The evolution of hardness and microstructure, effective strain distribution, and tensile strength in single and multiple pass drawing has been investigated by a number of researchers. The results of some of these important studies are discussed below.

The experimental studies conducted by both Riendeau et al. (Riendeau et al. 1997) and Kraft et al. (Kraft et al. 1996) studied the effect of drawing schedule on the hardness and microstructure of wire. It was determined that the nature of the deformation (i.e. homogeneous or heavily redundant deformation) had a large affect on the resultant grain structure and fiber texture. They indicated that high die angles and low percent area reduction produced localized hardness at the wire surface. In addition, the larger the die angle the larger the resultant volume fraction of random oriented fiber texture, and therefore the lower annealing temperature necessary for recrystallization. From these studies a correlation between drawing schedule and microstructure can be derived, and desired surface characteristics can be designed into the wire when it is beneficial to have a specific grain structure or textural orientation. For example, in upsetting wire samples, it was shown that a finer grain structure produced less “orange peel”, a common defect.
Therefore, in this case localizing deformation to the wire surface to produce finer grains would be beneficial.

Effective strain distribution in drawn wire has also been studied numerically and experimentally. In a study by Luksza et al. (Luksza, Majta et al. 1998) the objective was to determine the relationship between the history of deformation and the quality of the final product for copper and stainless steel bars. Experimentally, it was determined that there is a significant difference in the effective strain results for wires drawn in single- and multi-pass drawing. Numerical FEM experiments were also carried out. From the results it was shown that there was good correlation with the experimental results obtained by using a visioplasticity method. Most importantly, however, was the fact that inhomogeneity in the stock wire affects the drawn mechanical properties disproportionately. Therefore it is recommended to compare relative variations in effective strain. Further work needs to be realized to determine more concretely how single- and multipass-drawing effects the final effective strain.

A numerical study, using the FEM software Eldraw, by Pilarczyk et al. (Pilarczyk et al. 1997) determined the affects of hydrodynamic friction on drawing stresses with heat generation. They compared these results to conventional wire drawing and compared both these numerical results with experiments. They found that hydrodynamic lubrication prevents the appearance of martensitic structures near the surface of the wires and increases the effective strain homogeneity along the radius of the wires.

An intensive investigation by Dixit and Dixit (Dixit and Dixit 1995) determined the effects of changing die angle, reduction, and friction on die pressure, drawing stress,
die separation force, and equivalent strain for steel, aluminum, and copper. Equivalent strain results were compared for both strain hardening and non strain-hardening materials. Their simulation utilized a mixed pressure-velocity finite-element formulation for a rigid-plastic material with a constant coefficient of friction at the die/workpiece interface.

The results of the Dixit study for copper were in good agreement with Wistreich's experimental results as well as with two other FEM analyses. However, they found that assuming a constant coefficient of friction, an assumption that is commonly made, can not be justified. Their simulation suggested that the die angle be chosen based on the maximum expected coefficient of friction. Increasing the friction-factor necessitates a larger die angle to minimize the drawing stress. Drawing stress increases more significantly with smaller die angles, so chances of significant error optimizing the drawing stress(force) is minimized by overestimating the die angle. They also observed that increasing the reduction, decreasing the die angle, or decreasing the coefficient of friction created a more homogenous product. Finally, their analysis revealed that friction and strain hardening had little effect on the strain distribution.

In other similar studies on copper by Thomsen (Thomsen 1981), Majta et al. (Majta, Luksza et al. 1992), Sadok et al. (Sadok et al. 1992), Campos and Cetlin (Campos and Cetlin 1998), and Castro et al. (Castro et al. 1996), and a study on aluminum by Aguilar et al. (Aguila et al. 1998), it was found that control of the strain path by varying processing could be of use in controlling other properties like tensile strength in drawn products.
The streamline based finite difference method (SBFDM) is another of many methods used in numerical modeling. This particular method is used when the streamline locations, rather than the direct velocities are desired. Chin and Steif (Chin and Steif 1993) used this method in their study of strain homogeneity. They confirmed that die angle and reduction in area affect redundant deformation the most. Like Dixit they also found that friction and strain hardening had little effect on the strain.

Residual stress simulations have also been carried out on drawing processes. Using the finite-element package DEFORM™ Vijayakar (Vijayakar 1997) studied residual stresses and found that low die angles, high percentage reductions, and high coefficients of friction lead to high residual stresses. Since each of these factors affects the surface temperature of the wire at the end of the die land, it was determined that the residual stresses can be controlled by adjusting the surface temperature of the wire at the exit of the die land.

All the previous discussed studies took important parameters into account in their analysis, but none of these investigations considered tool wear. In a recent article Kim et al. (Kim et al. 1997) was able to create a numerical method which predicted die wear with good accuracy. Using this simulation it is possible to predict the dimensional accuracy of the workpiece as a function of time to predict when tooling changes are necessary.

To obtain accurate results from FEM accurate input parameters are essential. In the Dixit study friction coefficients were assumed, so a method to determine this coefficient would be very helpful. To address this, Lazzarotto (Lazzarotto 1997)
conducted a test called the upsetting sliding test with which they could determine the mean Coulomb friction-factor. They found by simulation that this test accurately predicted the friction-factor. Pawelski et al. (Pawelski et al. 1998) has also suggested an asymmetric upsetting test that could be used in friction measurement. The benefit of this test is that friction-factor can be measured for different strain rates. Both Coulomb friction and friction-factor are used in a variety of modeling packages, so these tests could help produce even more realistic numerical results.

From all these studies two patterns are noticeable. The evolution of effective strain and determination of friction seem to be the main focus of research today. Numerical simulation has improved to such a level that the effects of die angle, percent reduction and lubrication on the properties of the finished product can be predicted. Research also seems to be focusing on how to measure friction accurately to improve the results of numerical simulation. Increasingly, advanced numerical studies on how parameters like temperature, die wear, material properties and residual stresses affect the workpiece are being conducted. These models are invaluable in verifying whether or not assumptions commonly made to simplify analytical methods are justified, evaluating industrial practice and further improving numerical simulation. The current need, however, is for real-time monitoring of the effect of these parameters on the effective strain path and a capability to control process parameters to produce desired product.
2.4.3 Real-time monitoring & control

It is widely known that measuring input and exit parameters is a difficult task in drawing. There are a number of industrial monitoring tools available and some experimental devices that have successfully measured and adjusted certain processing parameters. If assembled on one experimental platform, these devices could yield the first step in creating an adequate monitoring and control apparatus.

One of the most interesting studies was conducted by Su (Su 1997) on potential control of an emulsifying lubricant. In his experiments a data acquisition system continuously monitored the drawing force as a potential was applied to an emulsified lubricant during wire drawing. This potential was varied from positive to negative to evaluate the effect on friction. Up to a 35% reduction in friction was observed when a positive potential was applied (compared to conventional open-circuit wire drawing). The surface quality of the finished wire improved and power consumption was reduced as well. In his experiment copper rod was used, but theoretically this process could be used with other metals. Thus far this is the best example of an intelligent drawing process.

In another study, Hillery and Griffin (Hillery and Griffin 1994) developed a device similar to Wistreich’s split die. This particular die was made of epoxy and contained a number of strain gauges to account for strain in the axial, radial, and hoop directions. Thermocouples were also placed within the die to record the temperature adjacent to the strain gauges (to measure strain due to temperature). With this setup a lead rod was drawn and the drawing force, strain state, temperature and drawing speed
were measured. From these measurements interfacial die pressure was calculated as well. This device was successfully used to draw lead and good results were obtained. Unlike Wistreich's experiment non-constant interfacial die pressure could be measured along the longitudinal die surface. This opens the possibility that a non-uniform frictional force could be indirectly monitored within the die cavity.

The temperature of incoming and exiting wire during the drawing process has also been measured. Using an infrared pyrometer the entrance and exit temperatures were measured in real-time by Hillery and McCabe (Hillery and McCabe 1995). In this particular study they were only interested in the effects of elevated temperature on different lubricants, but it was proven that the temperature of entering and exiting wire could be monitored in real-time.

Real-time measurement tools to measure wire diameter and surface defects have also been developed. Optical measurement of wire diameter in real-time at high line speeds has been accomplished. Accuracy of 1 micron has been achieved with new technology that can remove the effects of wire vibration (Goszyk 1994; Schmald 1996). Using eddy current testing it is possible to detect cross-cracks, chevrons, inclusions, pits, seams and laps that vary along the wire (Roberts 1998). In the future, if the sensitivity of this tool is increased it could possibly be used to detect the amount of deformation in a wire.

Based on the success of these experimental studies there is potential for the implementation of real-time intelligent monitoring and control. This capability would allow process parameters to be monitored and controlled with intelligent devices.
therefore manipulating the final product. This in turn would enable the manufacture of wire products with desired product quality attributes.

2.5 Conclusions

The goal of intelligent wire drawing is to combine drawing science, real-time monitoring, and real-time control. In theory intelligent drawing processes will be able to monitor incoming material and environmental conditions and adjust process parameters accordingly to produce desired product. It was found that sufficient numerical, analytical, and experimental studies exist, but that more research needs to be conducted on how to monitor and control the wire drawing process. Despite the sparseness of literature on some issues it was shown that implementing intelligent drawing to adjust product quality attributes shows great promise and is likely to be implemented in the future.
CHAPTER 3

FUNDAMENTALS OF MODELLING DEFORMATION PROCESSES

In this chapter, quantities for stress, strain and strain-rate are introduced. The governing and constitutive equations for rigid-plastic materials used in metal deformation processes are derived from basic principles. In turn, these equations lay a basis for the application of the finite-element method to metal forming. This method is outlined in a number of textbooks, but is specifically oriented towards metal forming in Kobayashi et al. (Kobayashi et al. 1989). A more complete description of plasticity theory can be found in Johnson et al. (Johnson et al. 1982) and Johnson and Mellor (Johnson and Mellor 1973). From these sources the equilibrium equations, yield criterion, constitutive equations and compatibility conditions are presented.

In addition, the commercially available finite-element software, DEFORM, which was chosen for modeling the wire drawing process is described. Specifically, DEFORM-2D is evaluated for single-pass wire drawing.

3.1 Stress, strain and strain rate

The mechanics of deformation in elasticity can be described from three main properties. These are stress, strain and strain-rate. These properties can be described
mathematically most clearly by looking at a simple uniaxial tension test. The following formulation is based on infinitesimal deformation theory. When the deformation is small no distinction needs to be made between Lagrangian or Eulerian formulations because the product of the displacements are small and can be neglected. Based on infinitesimal deformation theory the stresses, strains and strain-rates are given for a specific time with respect to a fixed cartesian coordinate system.

\begin{align}
\text{stress} &= \sigma = \frac{\text{load}}{\text{Area}} = \frac{P}{A} \\
\text{strain} &= \varepsilon = \frac{dl}{l} \\
\text{strain-rate} &= \dot{\varepsilon} = \frac{i}{l} \\
\text{total strain} &= \varepsilon = \int \frac{dl}{l_0} = \ln \frac{l}{l_0}
\end{align}

In three dimensions the strain-rate tensor and stress tensor can be written in index notation:

\begin{align}
\dot{\varepsilon}_{ij} &= \frac{1}{2} (u_{ij} + u_{ji}) \\
\sigma_{ij} &= \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}
\end{align}

where \( u_{ij} \) are the velocity components. The stress tensor may also be defined by three principal stresses. These components are the roots of the following equation.

\[ \sigma^3 - I_1 \sigma^2 - I_2 \sigma - I_3 = 0 \]
The roots are shown below.

\[
I_1 = \sigma_1 + \sigma_2 + \sigma_3 \tag{3.8}
\]

\[
I_2 = - (\sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1) \tag{3.9}
\]

\[
I_3 = \sigma_1 \sigma_2 \sigma_3 \tag{3.10}
\]

3.2 Yield criterion selection

Next a yield criterion must be established to define the limit of elasticity under any combination of stresses. The yield function is

\[
f(\sigma_{ij}) = C(\text{constant}) \tag{3.11}
\]

or

\[
f(I_1, I_2, I_3) = C \tag{3.12}
\]

where only the magnitude (and not direction) of principle stresses affects the yield criterion for isotropic materials.

Since moderate tension or other forces do not affect yielding of a particular material, yielding is only dependent on the principal components of the deviatoric stress tensor. In index notation the deviatoric stress tensor is defined as

\[
\sigma'_{ij} = \sigma_{ij} - \delta_{ij} \sigma_m, \quad \text{where} \quad \delta_{ij} = 1, \quad i = j
\]

\[
\delta_{ij} = 0, \quad i \neq j
\]

(3.13)

and \(\sigma_m\) is the mean or "hydrostatic" stress. The components of the deviatoric stress tensor are not independent, since

\[
\sigma'_1 + \sigma'_2 + \sigma'_3 = 0. \tag{3.14}
\]

Therefore, the yield criterion becomes...
According to the Von Mises yielding criterion yielding occurs when \( J_2 \) reaches a critical value, which means Equation 3.15 doesn’t depend on \( J_3 \). Then \( J_2 \) becomes

\[
J_2 = \frac{1}{2} (\sigma'_{ij} \sigma'^{ij}) = k^2
\]

(3.16)

The material parameter, \( k \), can be determined from a uniaxial tension test and is \( \bar{\sigma}/\sqrt{3} \), where \( \bar{\sigma} \) is the flow stress. It follows from Equation 3.16 that,

\[
\bar{\sigma} = \sqrt{\frac{3}{2} (\sigma'_{ij} \sigma'^{ij})}
\]

(3.17)

3.3 Equilibrium conditions and surface tractions

The equilibrium conditions for Cartesian coordinate system expressed in index notation is

\[
\frac{\partial \sigma_{ij}}{\partial x_i} = 0
\]

(3.18)

Applied surface tractions, \( F_i \), are in equilibrium with stresses along the boundary of a given part. These surface tractions are characterized by, \( F_i = \sigma_{ij} n_j \), where \( n_j \) is the unit normal vector. In two dimensions the equilibrium of surface tractions are

\[
F_i = \sigma_1 \left( \frac{dx_2}{dl} \right) + \sigma_{12} \left( \frac{dx_1}{dl} \right), \quad F_2 = \sigma_{12} \left( \frac{dx_2}{dl} \right) + \sigma_2 \left( \frac{dx_1}{dl} \right)
\]

(3.19)

Graphically, the surface tractions in two dimensions are shown in Figure 3.1.
3.4 Virtual work-rate principle

Next the virtual work-rate principle needs to be applied. This principle states that for the stress field the work-rate inside the deforming body equals the work-rate from the surface tractions. This applies to all velocity fields that are continuously differentiable. This definition is represented by

\[ \int_V \sigma_{ij} \frac{\partial w_j}{\partial x_i} dV = \int_S F_j w_j dS \]

(3.20)

or \[ \int_V \sigma_{ij} \dot{\varepsilon}_{ij} dV = \int_S F_j w_j dS \], where \[ \dot{\varepsilon}_{ij} = \frac{1}{2}(w_{ij} + w_{ji}) \]

(3.21)

When deformation extends to the plastic range, the stress and plastic strain relationships are defined by the plastic strain-rate or infinitesimal plastic strain

\[ \dot{\varepsilon}^p_{ij} = h \frac{\partial g}{\partial \sigma_{ij}} \dot{f} \quad \text{or} \quad \dot{d} \varepsilon^p_{ij} = h \frac{\partial g}{\partial \sigma_{ij}} df \]

(3.22)

where \( g(\sigma_{ij}) \) is the plastic potential and \( f \) is the yield function. \( h \) and \( g \) are also scalar functions of the invariants of deviatoric stresses. Assuming that \( g = f \),
Eqs. 3.22 can be transformed by

\[ \frac{\partial f}{\partial \sigma_y} = \frac{\partial f}{\partial \sigma_{yy}'} \frac{\partial \sigma_{yy}'}{\partial \sigma_y} = \sigma_{yy}' \]

(3.24)

to become in the rate form,

\[ \dot{\epsilon}_{yy} = \sigma_{yy}' \dot{\lambda} \]

(3.25)

when \( f(\sigma_{ij}) = J_2 = \frac{1}{2} \sigma_{ij}' \sigma_{ij}' \) (Equation 3.16). For rigid-plastic materials the \( p \) superscript may be dropped (because elastic strains are neglected) and the result is the Levy-Mises equations which are represented by three equations of the kind

\[ \dot{\epsilon}_1 = \left\{ \sigma_1 - \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \right\} \dot{\lambda} = \frac{2}{3} \left\{ \sigma_1 - \frac{1}{2} (\sigma_2 + \sigma_3) \right\} \dot{\lambda} \]

(3.26)

and three of the kind

\[ \dot{\epsilon}_{12} = \sigma_{12} \dot{\lambda} \]

(3.27)

3.5 Work hardening

Finally total plastic work per unit volume during deformation is

\[ W_p = \int \sigma_y d\epsilon_{yy} \]

(3.28)

over the strain-path. It follows that

\[ \bar{\sigma} = \sqrt{\frac{1}{2} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right)} = \sqrt{\frac{3}{2} \left\{ \sigma_{ij}' \sigma_{ij}' \right\}} = f(W_p) \]

(3.29)
where $\bar{\sigma}$ is the flow stress. In metal forming process analysis the following equation is frequently used to model the strain-hardening characteristics.

$$\bar{\sigma} = H\left(\int d\bar{\varepsilon}\right) = H(\bar{\varepsilon})$$  \hspace{1cm} (3.30)

This quantity is related to the plastic work by

$$dW_p = \sigma_y \, d\varepsilon_y = \bar{\sigma} \, d\bar{\varepsilon}$$  \hspace{1cm} (3.31)

Using the flow rule, Equation 3.22,

$$\dot{W}_p = \sigma_y \dot{\varepsilon}_y = \sigma_y \frac{\partial f}{\partial \sigma_y} \dot{\lambda}$$  \hspace{1cm} (3.32)

Since $f(\sigma_y)$ is a homogeneous function of degree 2

$$\dot{W}_p = \sigma_y \frac{\partial f}{\partial \sigma_y} \dot{\lambda} = 2f(\sigma_y) \dot{\lambda} = \bar{\sigma} \dot{\bar{\varepsilon}}$$  \hspace{1cm} (3.33)

and since $f(\sigma_y) = \bar{\sigma}^2 / 3$, the proportionality factor $\dot{\lambda}$ is

$$\dot{\lambda} = \frac{3 \dot{\bar{\varepsilon}}}{2 \bar{\sigma}}$$  \hspace{1cm} (3.34)

Then $\dot{\bar{\varepsilon}}$ can be determined by considering

$$\dot{W}_p = \sigma_y \dot{\varepsilon}_y = \sigma_y' = \frac{1}{\dot{\lambda}} \dot{\varepsilon}_y \dot{\varepsilon}_y = \frac{2\bar{\sigma}}{3\dot{\bar{\varepsilon}}} \dot{\varepsilon}_y \dot{\varepsilon}_y = \bar{\sigma} \dot{\bar{\varepsilon}}$$  \hspace{1cm} (3.35)

From this it can be seen that

$$\dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}} \dot{\varepsilon}_y \dot{\varepsilon}_y$$  \hspace{1cm} (3.36)
3.6 Governing equations and finite-element formulation

The governing equations follow from the plasticity theory. These equations consist of three equilibrium equations, the yield criterion, constitutive equations and compatibility conditions. In summary these equations are:

**Equilibrium Equations:** \[ \frac{\partial \sigma_{ij}}{\partial x_j} = 0 \]

**Yield Criterion:** \[ \sigma = \sqrt{\frac{3}{2} (\sigma'_i \sigma'_j)} \]

**Constitutive Equations:** \[ \dot{\varepsilon}_{ij} = \sigma_{ij} \lambda, \text{ where } \dot{\lambda} = \frac{3 \dot{\varepsilon}}{2\sigma} \text{ and } \dot{\varepsilon} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij}} \]

**Compatibility Conditions:** \[ \dot{\varepsilon}_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}) \]

With these equations it is possible to solve rigid-plastic deformation problems. The boundary conditions are prescribed with velocity and surface tractions. In wire drawing the direction of material flow with respect to the die is known, so this allows the magnitude of the frictional stress to be given by Coulomb law, \( F_s = \mu F_n \), or by the shear factor law, \( F_s = m k \). In bulk deformation processes like wire drawing the shear factor is used.

The following functional represents the basic configuration of the finite-element formulation prior to discretization.

\[ \delta \pi = \int_{\Omega} \sigma : \dot{\varepsilon} \; dV + \int_{\Gamma} \lambda \delta \varepsilon_{ij} \; dV + \int_{\Gamma} \dot{\varepsilon}_{ij} \delta \lambda \; dV - \int_{\Gamma} F_i \delta u_i \; dS = 0 \quad (3.37) \]
λ is the LaGrange multiplier, \( \bar{\sigma} = \sigma(\bar{\varepsilon}) \) for rigid-plastic materials, and \( \dot{\varepsilon}_v = \dot{\varepsilon}_{ii} \) is the volumetric strain-rate. This formulation is based on the variational approach that requires that the velocity field satisfy the compatibility and incompressibility conditions.

3.7 DEFORM finite-element software

In lieu of creating a finite-element code at Lehigh University it was decided that a commercial code would be used. The software chosen was DEFORM-2D from Scientific Forming Technologies Corporation (SFTC). The FEM engine is based on the finite-element formulation described above. In addition, SFTC offers DEFORM-HT which includes micro-structure and diffusion modules for DEFORM-2D to simulate heat-treatment processes. A three-dimensional finite-element program, DEFORM-3D, is also available for non-axisymmetric simulations. SFTC is well known throughout the metal forming community and it has been proven by their many customers that DEFORM-2D produces reliable and accurate results.

DEFORM-2D is used to model a variety of metal forming operations. These processes include drawing, extrusion, forging, swaging, blanking and coupled die stress analysis. The software provides a pre-processor, simulation program, post-processor, a multiple operations tool, and a process monitor. A snapshot of the front-end is shown in Figure 3.2.

With the pre-processor, shown in Figure 3.3, geometry can be created or imported from design/drafting software for each object. Processes can be simulated isothermally or with heat transfer, and with the DEFORM – HT transformation of the grain structure
or diffusion of the dominant atom can be calculated. Various methods of applying
friction, force, temperature, pressure and velocity boundary conditions are available. An
example of the application of velocity boundary conditions is shown in Figure 3.4. Once
the process is fully designed a database can be generated for running simulations.

Simulations can be run in batch or interactive mode. In interactive mode the
details of the simulation can be viewed to troubleshoot any problems. In either batch or
interactive mode the simulation can be viewed through simulation graphics. In
simulation graphics stress, strain, damage and other variables can be viewed. Data is
displayed per a given time step in a contour animation.

Once simulations are complete, the results can be viewed in the post-processor as
shown in Figure 3.5. Like the other modules, it is easy to view stress and strain results,
plot load/stroke data, or to extract data for specific points on the workpiece. The most
important applications in the post-processor are the point-tracking and flow-net features.
Point-tracking allows you to pick points on the workpiece and extract data for any of the
state variables. Flow-net allows the user to see how a control volume deforms during
processing. Figure 3.6 shows an example of point tracking and Figure 3.7 shows an
example of a deforming grid (flow-net feature) in the drawing process. For either feature
the points of interest may be chosen with the mouse or an imported text file.
Figure 3.2 – DEFORM front-end
Figure 3.2 – DEFORM front-end
Figure 3.3 – DEFORM pre-processor
Figure 3.4 – Application of velocity boundary conditions
Figure 3.4 – Application of velocity boundary conditions
Figure 3.5 – DEFORM post-processor
Figure 3.5 – DEFORM post-processor
Figure 3.7 – Flow-net option in the post-processor
3.7.1 DEFORM-2D evaluation description

Despite the reputation of SFTC, an evaluation of the software was performed for the wire drawing process. In general DEFORM-2D is widely used for other bulk deformation processes like forging and blanking, so evaluating the package's affinity for drawing processes was necessary. In order to properly evaluate the accuracy of the results DEFORM-2D produces it was absolutely necessary to enter the proper material, geometry and processing conditions. Die profiles and hole diameter as well as the processing conditions were measured accurately. In addition, the use of an isothermal simulation or one that accounts for heat transfer was considered.

The die shape was measured on a coordinate-measuring machine. The profile of the die was measured along the length of the die. It was then measured again approximately 180 degrees from the previous measurement to verify the consistency of the die. Single profile measurements of two separate dies from the experimental investigation are represented in Figure 3.8. The two profiles in this figure are offset to show the similarity between them. The maximum difference between any point along the contour of these profiles is 0.03 mm. The profile from the second die was chosen for the evaluation.

The processing conditions that were considered important were the material properties, draw speed and friction condition. Material properties of the 302 stainless steel wire were determined by tensile testing specimens. From this extensive study the flow stress data was extracted for a material with average performance. Draw speed was recorded by determining the amount of time needed for a set length of material to pass
through the end of the die. This rudimentary method was necessary due to the lack of any means to dial-in a given draw speed. Finally the friction condition was estimated. This estimate was mainly taken from friction conditions used in the literature and DEFORM-2D information.

In the literature single-pass drawing of 302 stainless steels with about 10% reduction in area is considered an isothermal process. In our case this is especially true because the drawing speeds are low and the local strains are not large. In a study by Riendeau et al. (Riendeau, Mataya et al. 1997) it was shown that drawing wire at slow speeds with light reductions does not raise the temperature of the material significantly enough to cause changes in the flow stress for strains less than 0.2. In another study El-
Domiaty et al. (El-Domiaty and Kassab 1998) designed a chart that can be used to identify the degree of temperature rise that can be expected from a given die-angle, reduction, and material based on an analytical technique. This chart is shown in Figure 3.9.

![Drawing process evaluation chart](image)

Figure 3.9 – Drawing process evaluation chart
Furthermore, simulations run at Lehigh University accounting for temperature effects and heat transfer showed no differences in the resulting effective strain gradient for wire drawing under the same conditions. Therefore, the effect of temperature rise on the effective strain distribution in the final drawn wire was negligible.

Effective strain distribution is the most important result of this verification simulation. Through a micro-hardness conversion, which will be explained in Chapter 4, the effective strain distribution was converted to micro-hardness. Obtaining this micro-hardness distribution was of paramount importance. Knowing this distribution within the drawn wire was extremely important to consider for subsequent forming operations. Furthermore, the capability to produce the same micro-hardness distribution from two coils of wire with slightly different material properties, solely by varying the processing conditions, was desired. This capability is discussed further in Chapter 4.

3.7.2 DEFORM-2D evaluation results

DEFORM-2D was used to create the axisymmetric wire drawing simulation displayed in some of the previous screenshots of the software. The evaluation simulation utilized two objects. These two objects were a 1.55 mm x 12.70 mm billet and a draw die profile measured with the coordinate measuring machine. The mesh consisted of approximately 3200 elements, which translates into 20 elements across the radius of the wire. A draw speed of 0.127 m/s was applied through velocity boundary conditions at the leading edge of the wire. A constant shear factor of 0.15 was applied at any point of
contact between the two objects. The billet was drawn a total distance of 10.3 mm utilizing 2160 time steps each $3.75 \times 10^{-5}$ s long.

The results of the evaluation were promising. By using the conversion the effective strain in the wire was converted to Knoop micro-hardness. Figure 3.10 shows the effective strain contours superimposed on the wire specimen.

Figure 3.10 – Strain contours
contact between the two objects. The billet was drawn a total distance of 10.3 mm utilizing 2160 time steps each 3.75 x 10^{-5} s long.

The results of the evaluation were promising. By using the conversion the effective strain in the wire was converted to Knoop micro-hardness. Figure 3.10 shows the effective strain contours superimposed on the wire specimen.

Figure 3.10 – Strain contours
As expected the center of the wire is softer than the edge. There was an unexpected small decrease in micro-hardness at the very edge, however, it was discovered that this behavior is not as strange as first thought since it has been documented in the literature (Riendeau, Mataya et al. 1997) and turned up in the experimental results. The differences between the experimental and simulation results were small. The correlation from the center of the wire to approximately 1 mm was very good. The experimental micro-hardnesses were slightly greater than the simulation up to this point, but the distribution shape matched the simulation remarkably well. From 1 mm to the wire’s edge the simulated micro-hardness distribution does not seem to vary as severely as experiment.

Figure 3.11 shows both these distributions.

![Figure 3.11 – Micro-hardness distribution results](image-url)
3.8 Conclusions

In this chapter the governing equations used in DEFORM-2D and the evaluation of the software were presented. The governing equations were derived from basic plasticity theory and, in addition, the finite-element formulation before discretization for rigid–plastic deformation problems was shown. Then, an evaluation of the software was performed to verify the accuracy of the program for modeling wire drawing. A two-dimensional axisymmetric model was used and the results for the effective strain were collected. By using a micro-hardness conversion the effective strain results were converted to micro-hardness and compared to experimental micro-hardness data. The correlation between the simulation and experimental results was good and it was decided that DEFORM-2D could be used effectively to model wire drawing problems. In the following chapters it is used to determine the influence of die angle, bearing length, lubrication condition and draw speed on the micro-hardness distribution of drawn wire. These results become the basis for a numerical model that can be used to achieve desired properties in this wire.
CHAPTER 4

NUMERICAL TESTING AND RESULTS

The process parameters in wire drawing are still not fully understood. Gaining a better understanding of the effects of and interactions between parameters such as die angle, bearing length, lubrication and draw speed is the only way to enable the improved control of outgoing material properties. For the present study a specific emphasis was placed on attempting to control the hardness distribution in drawn wire. During the study a numerical investigation of the total effect and interdependence of die angle, bearing length, lubrication and draw speed on the micro-hardness distribution within drawn stainless steel wire was performed. The analyses were based on the utilization of DEFORM-2D, a commercially available finite-element software package.

Two numerical models were developed to determine how to properly adjust the process parameters to obtain desired outgoing material properties for this wire. Using a factorial design the effects of these parameters on the micro-hardness distribution of outgoing drawn material was determined. Possible interactions between the processing variables were also investigated.
4.1 Research goals

There were two main goals to accomplish in this study. The most obvious one was to understand the total effect of the process parameters on the micro-hardness distribution in a drawn wire. The next goal was to determine if it was possible to obtain the same micro-hardness distribution in a drawn wire if the material strength of the stock or incoming wire was not uniform. A detailed experimental study was conducted on an existing single-pass wire drawing setup to determine the differences in the performance of stock and drawn wire and how it varied heat to heat (a heat represents a coil of wire processed from a different batch of stainless steel). A numerical study was also conducted to determine if adjustments in the process parameters could be made to effectively tailor outgoing material properties with a desired range. Conclusions were then drawn from these two results.

In this chapter only the numerical results are presented and discussed. A discussion of the experimental studies and how well they correlated with the numerical results is saved for Chapter 5. In the end, a simplified process chart was designed in order to tailor outgoing material properties to certain levels from stock stainless steel wire conditions at a specific reduction in area. The potential for expanding this process chart to many materials and area reductions is also discussed.

4.2 DEFORM-2D model configuration

The finite-element package DEFORM-2D was selected for this study. Since the wire cross-section was circular the two-dimensional modeling package was sufficient. To perform simulations in two-dimensions the process was considered to be
axisymmetric. The process of drawing 302 stainless was assumed to be a rigid (die) – plastic (wire) problem. Temperature effects were neglected due to the low drawing speeds (< 0.127 m/s) and an area reduction of only 11% as discussed in chapter 3. At the die/wire interface friction was modeled by assuming a constant shear factor. Draw speed was applied by utilizing a constant velocity boundary condition at the leading edge of the wire.

4.2.1 Die geometry

Four die geometries were developed. These dies consisted of 6° and 16° dies combined with bearing lengths of 1.24 mm and 1.86 mm. These profiles were modeled after several actual state-of-the-art dies that were measured on a Brown & Sharpe, MicroVal Pfx coordinate-measuring machine. Adjustments to the die profile were limited to the approach angle and bearing length.

4.2.2 Wire model geometry

In this study the wire under examination had a circular cross-section. Therefore, it was only necessary to create a small rectangular object to represent the wire in two-dimensions. Every simulation utilized the same model which was 12.1 mm long and 1.55 mm in width.

4.2.3 Material description

The true stress – true strain data input into DEFORM-2D was determined by performing physical tensile tests with actual stock stainless steel material.
Conventionally, flow stress data for this material would be collected by a uniform compression test. Under compression, data for the flow stress vs. strain at a constant strain-rate can be obtained for all strains. It is also possible to run a compression test to determine the effects of strain-rate on the material, especially if the material is deformed at a high temperature. Unfortunately, since the wire under examination had such a small diameter a compression test could not be easily accomplished. So instead the flow stress behavior was determined from a tensile test. Since tensile testing is not compatible with a determination of flow stress at strains past failure the true stress – true strain data was fit with the power law curve

\[ \sigma = K\varepsilon^n \]  

(4.1)

where \( K \) is the strength coefficient, \( \varepsilon \) is the true strain, and \( n \) is the strain-hardening exponent. ASTM standard test method E646-93 was used to calculate this equation. This fit allows the data to be extrapolated for strains up to 1.

Three points were extracted from the true stress – true strain curve for each of six heats. A composite true stress – true strain curve was created by averaging the strength coefficient and strain-hardening coefficient. The composite true stress – true strain curve is shown below in Figure 4.1. The true stress at strains of 0.1, 0.3 and 0.7 were then used as material property input for DEFORM-2D. True stress – true strain curves for the hardest and softest materials were used in simulations where the stock or incoming material was considered to have non-constant properties.
4.2.4 Mesh generation

The proper mesh for the wire geometry needed to be determined. Simulations were performed to evaluate how many elements along the radial direction were necessary to obtain convergence of the effective strain data. The convergence simulation utilized the 6° die with a 1.24 mm bearing length. The lubrication shear factor and draw speed was kept at 0.15 and 0.025 m/s, respectively. Tests were run for meshes with 7, 12, 16, 20 and 24 elements across the radius of the wire.

It was apparent from the results that 16 elements were necessary to obtain convergence. To ensure that convergence was obtained with other die geometries and
processing parameters 20 elements was chosen to allow for a factor of safety. The
effective strain curves in Figure 4.1 show that the simulations with 16, 20 and 24
elements across the wire’s radius were all virtually equivalent.

![Figure 4.2 - Evaluation of mesh size on effective strain](image)

4.3 Numerical experiments

Three numerical experiments were performed to determine the effect of specific
parameters on the wire drawing process. These experiments were designed using full
factorial designs. The parameters for the first experiment were die angle, bearing length,
lubrication and draw speed. The second experiment was conducted to refine the results
of the first set of simulations based on the analysis. The third set of simulations was
conducted somewhat independently of the first two to determine the importance of stock material properties. The objective of all these studies was to determine the effect of these parameters on the effective strain response (later converted to hardness) in a drawn specimen. Effective strain in DEFORM-2D is defined as

\[
\bar{\varepsilon} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 - (\varepsilon_2 - \varepsilon_3)^2 - (\varepsilon_3 - \varepsilon_1)^2}
\]  

(4.2)

The effective strain distribution and the effective strain at the edge and center of the wire were of primary interest in this study.

4.3.1 Micro-hardness / effective strain conversion

In Chapter 5 the numerical results that are described later in this chapter are compared to experimental test results. Since the experimental data was taken by measuring micro-hardness, a micro-hardness to effective strain conversion was needed. To determine the relationship between these two quantities a number of compression tests and corresponding hardness measurements are necessary. Fortunately in a study by Rendeau et al. (Rendeau, Mataya et al. 1997) a similar 302 stainless steel was used. A comparison of the composition of the Shinsho 302 stainless steel used during the current study with the material used by Rendeau is shown below in Table 4.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Cu</th>
<th>Mo</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shinsho</td>
<td>0.010</td>
<td>0.21</td>
<td>0.81</td>
<td>0.032</td>
<td>0.001</td>
<td>9.46</td>
<td>17.71</td>
<td>3.08</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Rendeau</td>
<td>0.013</td>
<td>0.52</td>
<td>1.64</td>
<td>0.029</td>
<td>0.006</td>
<td>9.71</td>
<td>18.48</td>
<td>3.63</td>
<td>0.53</td>
<td>0.018</td>
</tr>
</tbody>
</table>
As is evident the compositions are reasonably similar. In light of this, the hardness to effective strain conversion employed by Riendeau was considered appropriate for use during the current study.

The 200g Knoop hardness scale was utilized by Riendeau, and found to be appropriate for the present project. This is based on the fact that the indents are small enough to allow for enough measurements across the diameter of the wire in the metallographic samples. The relationship between 200g Knoop hardness and true stress (MPa) established by Riendeau is represented in Figure 4.3.

![Graph](image-url)

Figure 4.3 – KHN to true stress conversion
The equation for Knoop hardness number that corresponds to Figure 4.3 is

\[ KHN = -0.0004\sigma^2 + 0.6775\sigma - 0.75 \] (4.3)

where \( \sigma \) is true stress. Since true stress is a function of strength coefficient and strain-hardening exponent the equation for KHN becomes

\[ KHN = -0.0004K^2\varepsilon^n + 0.6775K\varepsilon^n - 0.75 \] (4.4)

where \( \varepsilon \) is the effective strain. If Equation 4.4 is applied to the numerically calculated effective strain, associated Knoop micro-hardness results can be obtained. This conversion was utilized throughout the present study to both produce micro-hardness predictions and compare numerical and experimental results.

4.3.2 Design of the \( 2^4 \) full factorial experiment

During the first phase of numerical testing a \( 2^4 \) full factorial was considered. All of the parameters, which were die angle, bearing length, lubrication and draw speed were assumed to be two level variables. For these simulations the dies discussed in the die geometry section were used. The lubrication shear factor was set at 0.15 or 0.4 and the low and high draw speed was 0.0254 m/s and 0.127 m/s, respectively. Since this was a full factorial 16 individual simulations were run. The 16 combinations are shown in Table 4.2.

4.3.3 Numerical results for the \( 2^4 \) factorial experiment

The effective strain distribution of this experiment was measured by recording 17 equally spaced points from the edge of the wire model to the line of symmetry (center of
Table 4.2 – $2^4$ factorial design

<table>
<thead>
<tr>
<th>Test #</th>
<th>Die Angle</th>
<th>Bearing Length, mm</th>
<th>Shear Factor</th>
<th>Draw Speed, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>1.24</td>
<td>0.15</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>1.24</td>
<td>0.15</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>1.86</td>
<td>0.15</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>1.86</td>
<td>0.15</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>1.24</td>
<td>0.40</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
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<td>0.40</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>1.86</td>
<td>0.40</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>1.86</td>
<td>0.40</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>1.24</td>
<td>0.15</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
<td>1.24</td>
<td>0.15</td>
<td>5</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>1.86</td>
<td>0.15</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>1.86</td>
<td>0.15</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>1.24</td>
<td>0.40</td>
<td>5</td>
</tr>
<tr>
<td>14</td>
<td>16</td>
<td>1.24</td>
<td>0.40</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>1.86</td>
<td>0.40</td>
<td>5</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>1.86</td>
<td>0.40</td>
<td>5</td>
</tr>
</tbody>
</table>

wire) using the point tracking feature in DEFORM-2D. A regression analysis was then performed on these results using the software Statgraphics. For this analysis the effective strain just inside the outside edge of the wire (second data point) was considered. The numerical model representing the effective strain at this point is shown below.

$$\text{Effective Strain} = 0.00259 + 0.01355\alpha + 0.00001L - 0.00111m - 0.00029V$$

$$- 2.5 \cdot 10^{-7} \alpha \cdot L + 0.00516\alpha \cdot m + 0.00002\alpha \cdot V$$

$$- 0.00004L \cdot m + 2.5 \cdot 10^{-6} L \cdot V - 0.00055m \cdot V$$

(4.5)

where $\alpha$ is die angle, $L$ is bearing length, $m$ is shear factor and $V$ is draw speed. The model clearly showed that die angle was the main contributor to changes in the effective strain in the wire. Lubrication effects were second to the effects of die angle, but were
less significant. Changes in both bearing length and draw speed had very little effect on the effective strain distribution. A comparison between die angle and shear factor can be more easily seen when the effective strain response is shown graphically for constant bearing length and draw speed as in Figure 4.4.

![Figure 4.4](image)

**Figure 4.4 – Effective strain response surface for L = 1.55mm and V = 0.076 m/s**

This response surface clearly shows that shear factor only slightly affects effective strain as compared to die angle. However, if the capability existed to adjust shear factor accurately the effective strain at the edge of the wire could be finely adjusted. At all other data points except the very edge these affects become even less pronounced. The distribution in Figure 4.5, which displays the individual test results, shows this behavior.
At the center of the wire the effective strain was nearly identical for all of the simulations. Since die angle was clearly the most significant factor, a more focused and refined second factorial design was run with die angle as the only variable. This is described in the following section.

4.3.4 The $3^1$ full factorial experiment

As a result of the first numerical experiment no further consideration was given to realizing control over final product hardness by changing bearing length, lubrication, or draw speed. Three more simulations were run holding bearing length, lubrication and draw speed constant at 1.549 mm, 0.15, and 0.127 m/s, respectively. One die angle of
10° was added to account for any non-linear effects, therefore the die angles under examination were 6°, 10° and 16°.

### 4.3.5 Numerical results for the $3^1$ factorial experiment

The result of each simulation is shown in Figure 4.6. Once again 17 points across the radius of the wire in DEFORM-2D were recorded.

![Figure 4.6 - Effective strain results](image)

Recalling the first goal of this research, which was to understand the total effect of the process parameters on the effective strain distribution (and perhaps hardness) in a drawn wire, it was necessary to determine how effective strain depends on the significant variables. It happened that die angle was the only variable that had a significant effect on
the effective strain, so its dependence on die angle was calculated. The effective strain distribution in the wire as a function of die angle for all 17 points was calculated. The results for 5 of the 17 points are displayed in Figure 4.7.

![Graph of effective strain vs. die angle](image)

Figure 4.7 – Graph of effective strain vs. die angle

With this data the effective strain at any included die angle from $6^\circ - 18^\circ$ can be predicted by interpolation. These results indicate that the surface’s effective strain increased dramatically with die angle. However, the effective strain at the center of the wire was almost completely unaffected by a change in die angle. This was due to the small percentage area reduction and relatively low die angles.
The results for a number of different die angles, which are important for later use in chapter 5, are shown in Figure 4.8.

Figure 4.8 – Numerically calculated effective strain for various die angles

4.4 Numerical study of material variation

At this point the capability to control the effective strain in a drawn wire with the same incoming material properties was developed. However, how this would be affected by small variations in material properties was not understood. Therefore, a $2^2$ full factorial experiment was conducted to see how significant an effect incoming material strength would have. Since the material variations being considered here were small the assumptions of negligible effects from bearing length and draw speed and only a minor effect from lubrication were considered to remain valid. The two extremes of material
flow stress data that was input into DEFORM-2D were shown previously in Figure 4.2. The geometry from the $2^4$ full factorial, a shear factor of 0.15 and a draw speed 0.127 m/s were all used in the four simulations. Table 4.3 shows the layout of the third factorial design. Figure 4.9 shows the effective strain results.

Table 4.3 – $2^2$ factorial design

<table>
<thead>
<tr>
<th>Test #</th>
<th>Die Angle</th>
<th>Strength Coefficient, K</th>
<th>Strain Hardening Coefficient, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>0.19</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>0.19</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>0.22</td>
<td>139</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>0.22</td>
<td>139</td>
</tr>
</tbody>
</table>

Figure 4.9 – Effective strain results for die angle and material properties
Examining the results of Figure 4.9 shows that there is a small interaction between material strength and die angle. At low die angles, an increase in material strength decreases the effective strain at the surface of the wire, but at high die angles the opposite is true.

Unlike the previous analysis where material strength was constant, the conversion to Knoop micro-hardness was not proportional for these simulations. Therefore, before regression analysis was performed the effective strain results were transformed to micro-hardness using Equation 4.4. The results are shown below in Figure 4.10.
Using these results a regression analysis was performed on each of the 17 points across the radius of the wire. For this regression analysis, a material performance index, MPI, was developed to simplify the resulting equation. Zero represents the lowest stock material strength and ten represents the highest incoming material strength. The equation for MPI is

\[ MPI = 0.2564 K + 2 \cdot 10^2 n - 68.89 \]  

The resulting equation for point 2 is shown below.

\[ KHN = 232.5 + 1.900 \alpha + 0.894 MPI + 0.014 \alpha \cdot MPI \]  

The response surface described by this model is shown in Figure 4.11.

Figure 4.11 – Response surface for die angle vs. material

This response surface correlates with the behavior in the micro-hardness plot. It showed that a small change in material properties caused a significant variation in the final micro-
hardness. Subsequently, it is possible to account for material variation (by adjusting die angle) to obtain product with desired micro-hardness. Since incoming material strength can be measured the die angle can be manipulated to account for this variation to obtain uniform product. From the previous experiments it was also found that shear factor affects micro-hardness, but shear factor cannot be easily measured and traditional lubrication techniques cannot be set up to achieve a desired shear factor. Therefore, it was not considered for countering varying stock material properties.

4.5 Numerical testing summary

All the testing performed revealed that die angle and material strength were the only variables that cause appreciable differences in the final effective strain distribution. These results are not entirely surprising. The material's low strain-rate sensitive behavior and information in the literature, especially comments from Dixit and Dixit (Dixit and Dixit 1995) about small effects of friction on strain distribution, correlate well with the present results. There is very little information on the effects of bearing length on effective strain, but it is not surprising that it has a very small effect on micro-hardness. It is important to remember, however, that these results do not apply to other dependent variables like drawing force, temperature rise and surface finish where the variables that were eliminated here may be important.

Since die angles and material strength can be adjusted to affect the micro-hardness distribution a capability to obtain uniform drawn wire was developed. An overview of this capability is shown in Figure 4.12. With this system in place the ability to produce uniform and optimized drawn product from stock wire of various strength can
be accomplished. In the figure only two input parameters need to be known. These are the desired hardness at any point in the wire and the stock wire's incoming material strength. These two inputs must satisfy the DEFORM-2D model. If this is true the model will produce the most suitable die angle for the process. In chapter 5 this capability is tested against two sets of experimental data.

Figure 4.12 – Desired micro-hardness capability
be accomplished. In the figure only two input parameters need to be known. These are the desired hardness at any point in the wire and the stock wire’s incoming material strength. These two inputs must satisfy the DEFORM-2D model. If this is true the model will produce the most suitable die angle for the process. In chapter 5 this capability is tested against two sets of experimental data.

Figure 4.12 – Desired micro-hardness capability
CHAPTER 5
EXPERIMENTAL VERIFICATION

In this chapter the numerical results of chapter 4 are compared to a number of experimental tests. There were two different types of samples. The first set of testing was done using a single heat of material for different die angles in order to evaluate the accuracy of the numerical micro-hardness model to changes in only die angle. The second set of samples explored the variation in drawn wire micro-hardness and ultimate tensile strength. This experiment was performed on five different coils of 302 stainless steel wire each from a different material heat, so that the effects of material variation could be determined.

5.1 Experimental test setup

Ultimate tensile strength and micro-hardness data were collected for stock and drawn wire from six different heats of material. Descriptions of the material, draw die geometry, and process parameter values selected for drawing this wire follow.
5.1.1 Material description

The wire was high quality (high tolerance) stainless steel wire. Six different heats of wire were obtained. In this specific case it was uncoated (no copper coating) 302 stainless steel. The wire had an initial diameter of 3.099 +0 / -0.005 mm. Each coil was provided with a vendor certificate indicating its average as-tested tensile strength as well as its chemical composition.

5.1.2 Draw die geometry

Tungsten carbide dies were used in this study. Each die consisted of a tungsten carbide die insert placed in a tool steel casing. The inserts were roughed out by machine (Ballofet 78M410) and then hand polished with various polishing pastes. Samples from each heat were drawn with their own new die. Two dies of the five dies, all made to the same specifications, were measured on a Brown & Sharpe, MicroVal Pfx coordinate-measuring machine. This equipment was running MMIV software and had a linear accuracy, repeatability and resolution of 0.005 mm, 0.003 mm, and 0.001 mm, respectively. The average measurements were included die angle of 6.61°, a 1.549 mm bearing length, and an orifice diameter of 2.921 mm. The geometry of the two die profiles is shown in Figure 5.1.

The sixth heat of wire was processed differently for determining the effect of die angle on the micro-hardness distribution. This material was drawn through six different dies. The geometry of these dies is given in Table 5.1.
5.1.3 Processing parameters

Experimental data for all the experimental testing was collected keeping lubrication, and draw speed constant. The wire was lubricated with machine oil in a draw box. Draw speed was kept constant at approximately 0.127 m/s.
5.2 Tensile and micro-hardness data collection

The tensile tests were performed on a 44.5 N MTI Phoenix testing machine connected to an IBM compatible personal computer. Before testing each specimen was cut to approximately 250 mm in length and was marked in 25 mm increments for tensile elongation measurement. Each stock and drawn wire specimen was placed 25 – 38 mm inside each of the V-grips, so the gauge length was approximately 180 mm. Each specimen was pulled at 19 mm/s until failure occurred. For the first five heat numbers five stock and five drawn samples from each heat were tested. For the sixth heat of material three stock and eighteen drawn samples were tested. The drawn samples from heat six resulted from drawing the stock wire through the six different dies in Table 5.1.

Micro-hardness measurements were obtained via a Leco micro-hardness tester with a Knoop diamond indenter.

5.2.1 Load selection for micro-hardness testing

Although not a standard load for micro-hardness tests, 200 g was used for two reasons. First, 500 g, a more standard load, would have resulted in too large an indentation. Since the region around a micro-hardness indentation work hardens, subsequent tests taken next to it would not indicate the true properties of the untested material. Hence, the standard rule of thumb that subsequent indentations should be made at a distance of 2.5 times the width of the previous indentation was implemented.
Secondly, by using a smaller load, the width of the indentations were smaller, and therefore multiple micro-hardness tests could be performed closer together.

5.2.2 Indentation locations

The indentation locations were selected to maximize the information content of the hardness of the samples while minimizing the number of tests required. For samples from the first five heats, it was concluded that only the micro-hardness at the edge of the sample and at the center of the sample was needed. Point 1 was taken as close to the edge as possible. Point two was then taken according to the method discussed above. A schematic of the location of the indentation tests for the stock and drawn samples from these five heats is presented in Figure 5.2.

![Figure 5.2 - Schematic location of indentation tests](image)

For the sixth heat the micro-hardness tests were performed to determine the hardness distribution across the entire cross-section of the wire. Twenty-one equally spaced
indentations were taken on the stock sample and twenty indentations were recorded on the drawn samples due to the diameter reduction.

5.2.3 Verification of Knoop hardness number conversion

The equation for the Knoop Hardness Number (KHN) is as follows:

\[ KHN = \frac{P}{A} = \frac{P}{CI^2} \]  

\( P \) = load (kilograms)  
\( A \) = area (mm)  
\( C = 0.07028; \) a constant relating the length of the indentation shape to its area  
\( I \) = length of indentation (mm)

Note, however, that Equation 5.1 holds for loads equal to or greater than 500 g. To verify that these numbers would still be accurate for 200 g loads double sets of measurements were carried out on some of the samples. Micro-hardness indentations of 200 g loads and of 500 g loads were taken next to each other (but still separated by the 2.5 diameter distance rule). These measurements were taken at the center of the stock and drawn samples. Thus, 200 g and 500 g indentations were measured at different hardness regions of the stock and drawn samples. The KHN’s for the 500 g indentation measurements were then calculated using equation (5.1). These KHN calculations were considered correct. The same equation was then used to calculate the KHN’s of the 200 g indentations. These data were then plotted in Figure 5.3, and the difference between the
two data sets was observed. The difference in the two data sets was minimal, as tabulated in Table 5.2.

![Graph showing KHN comparison for 200g and 500g loads](image)

**Figure 5.3 – KHN comparison for 200g and 500g loads**

**Table 5.2 – Error induced by utilizing 500g load KHN equation for 200g load indentations**

<table>
<thead>
<tr>
<th>Load</th>
<th>KHN 200 g</th>
<th>KHN 500 g</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>190.37</td>
<td>191.75</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>241.42</td>
<td>235.36</td>
<td>-2.6</td>
</tr>
</tbody>
</table>

The percent difference represents how much one would have to alter the KHN from a 200 g load to equate the correct KHN calculated from a 500 g load. The two sets are very
close, so the hardness of the harder material is exaggerated by at most 3%. Since the difference was minimal it was decided to use the 200 g load measurements.

5.3 Experimental tensile and micro-hardness results

Micro-hardness data was collected at the points indicated in Figure 5.2 for heat 1 through heat 5. Tensile tests were also performed on the stock and drawn wire for these heats. This information is tabulated in Table 5.3.

Table 5.3 – Experimental drawn micro-hardness (according to Figure 5.2) and stock and drawn wire ultimate tensile strength measurements

<table>
<thead>
<tr>
<th>Heat #</th>
<th>KHN point 1</th>
<th>KHN point 2</th>
<th>KHN avg. of pts. 3 &amp; 4</th>
<th>UTS, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>208</td>
<td>225</td>
<td>189</td>
<td>547</td>
</tr>
<tr>
<td>2</td>
<td>192</td>
<td>198</td>
<td>173</td>
<td>560</td>
</tr>
<tr>
<td>3</td>
<td>202</td>
<td>203</td>
<td>191</td>
<td>516</td>
</tr>
<tr>
<td>4</td>
<td>205</td>
<td>208</td>
<td>195</td>
<td>521</td>
</tr>
<tr>
<td>5</td>
<td>194</td>
<td>196</td>
<td>185</td>
<td>525</td>
</tr>
<tr>
<td>Drawn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>252</td>
<td>279</td>
<td>249</td>
<td>645</td>
</tr>
<tr>
<td>2</td>
<td>256</td>
<td>265</td>
<td>233</td>
<td>668</td>
</tr>
<tr>
<td>3</td>
<td>269</td>
<td>269</td>
<td>245</td>
<td>603</td>
</tr>
<tr>
<td>4</td>
<td>203</td>
<td>196</td>
<td>195</td>
<td>621</td>
</tr>
<tr>
<td>5</td>
<td>195</td>
<td>193</td>
<td>191</td>
<td>621</td>
</tr>
</tbody>
</table>

In addition, the micro-hardness distribution and the stock and drawn tensile strength were measured for the material drawn in heat 6. Since micro-hardness was taken across the entire cross-section, the two points equidistant from the line of symmetry were averaged. The stock and drawn micro-hardness distributions are shown in Figure 5.4a & 5.4b show
the micro-hardness results of drawing the stock wire through the six draw dies discussed earlier. Tensile testing measurements for the stock and drawn wire are shown in Table 5.4.

![Graph of micro-hardness results for different draw dies.](image)

Figure 5.4 – Hardness distribution for dies a) 1, 2 & 3 and b) 4, 5 & 6 from heat 6
Table 5.4 - Heat 6 ultimate tensile strength measurements

<table>
<thead>
<tr>
<th>Heat #</th>
<th>Wire Description</th>
<th>UTS, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat 6</td>
<td>Stock Wire</td>
<td>522</td>
</tr>
<tr>
<td>Heat 6 drawn by</td>
<td>Die 1</td>
<td>610</td>
</tr>
<tr>
<td></td>
<td>Die 2</td>
<td>633</td>
</tr>
<tr>
<td></td>
<td>Die 3</td>
<td>666</td>
</tr>
<tr>
<td></td>
<td>Die 4</td>
<td>616</td>
</tr>
<tr>
<td></td>
<td>Die 5</td>
<td>607</td>
</tr>
<tr>
<td></td>
<td>Die 6</td>
<td>662</td>
</tr>
</tbody>
</table>

5.4 Comparison between numerical and experimental hardness results

At this point the numerical and experimental data was compared. The comparisons made were done to find answers to the two goals discussed at the beginning of chapter 4. The first goal, which was to see if the main effects and interactions between the variables could be determined, is discussed first. Then the more challenging task of determining how to adjust the processing parameters to obtain consistent drawn product from different incoming material conditions is discussed later.

5.4.1 Process parameter adjustment results

The numerical model that was developed in chapter 4 from the $3^1$ numerical testing was used to calculate the micro-hardness distribution for heat 6. Effective strain distributions from the numerical model were collected for all 17 points for each die angle in Table 5.1. A comparison between numerical hardness and experimental micro-hardness distribution (from Figure 5.4) is shown in Figure 5.5 (a)-(f).
Figure 5.5 (a)-(b) – Simulation vs. experimental hardness distribution for dies 1 & 2
Figure 5.5 (c)-(d) – Simulation vs. experimental hardness distribution for dies 3 & 4
Figure 5.5 (e)-(f) – Simulation vs. experimental hardness distribution for dies 5 & 6
Examining these graphs more closely we can see that the numerical predictions related well to the experimental data with the exception of die 3 and die 5. The explanation for this behavior may lie in Table 2. Upon closer examination die 3 and 5 have slightly different orifice diameters than die 1, 2, 4 and 6. Die 3 is approximately 0.009 mm smaller and die 5 is approximately 0.007 mm larger than average. These differences affect the percent reduction in area and affect the resulting micro-hardness distribution. Subsequently, the numerical simulation did not accurately predict the micro-hardness distribution for either die. The experimental micro-hardness distribution for die 3 was steeper and larger than predicted. For die 5 the distribution followed the same pattern but was lower than predicted.

The experimental hardness measurements were also backed up by the drawn tensile strength. The material from die 3 was the strongest of the group and that correlated well with the fact that die 3 had the greatest experimental micro-hardness. Material drawn from die 5 on the other hand proved to be even weaker than the material from die 4, which had a smaller die angle. Again the fact that the area reduction was smaller seems to account for this variation.

The goal was to prove if the DEFORM-2D model could accurately predict the micro-hardness distribution in drawn 302 stainless steel wire by controlling die angle. The results showed that there was a very good correlation between the numerical and experimental distribution. However, the data were sensitive to small differences between the numerical and experimental reduction in area. The similarity between the simulated and experimental results also proved that the exclusion of bearing length, lubrication and
draw speed in the numerical model had little affect, and that the Knoop hardness – true stress conversion was effective.

Using this approach the desired micro-hardness distribution can be predicted by only knowing the true stress – true strain behavior of the material. The only limitation of this numerical model was that it assumes that the incoming material is completely uniform. Developing a capability to correct this model for the incoming material variation would be extremely beneficial. It could even be expanded to other metals or materials entirely. Area reduction could also be added into the numerical model, so that the model would be not limited to one operation (or exact orifice diameter) and therefore could be expanded to many conventional wire sizes.

5.4.2 Material variation results

As-received stock 302 stainless steel wire is not perfectly uniform. If the wire is drawn a number of times before it is sent to the customer the chemical composition, material strength, strain history and diameter are all slightly different. Since this is the case, the optimum die angle necessary to produce uniform drawn product is slightly different from heat to heat, coil to coil and perhaps even within a particular coil. The model that was developed in chapter 4 can account for these differences in as-received stock wire by adjusting die angle. Here this model is compared to the experimental results. The data for heats 1-5 is shown in Table 5.3 and was used to determine the effectiveness of this numerical model. Specifically, the stock ultimate tensile strength was used to determine the incoming wire strength condition. Then the drawn ultimate tensile strength was used to get an experimental micro-hardness number that was
compared to the numerical micro-hardness. Then after this verification a simple process chart that allows the user to choose an appropriate die angle to obtain a specific outgoing tensile strength or micro-hardness was developed (as depicted in Figure 4.12).

The stock wire strength was used as input for the numerical model flow stress database. The high and low strength material was from heat 2 and 3, respectively. The incoming strength condition for the other heats was then based on a point scale. Zero represented the weakest and 10 represented the hardest material. For example heat 2 was a 10, heat 3 was a 0, and heat 1 was a 7. This scaled number was then used in the numerical model developed in chapter 4. This point scale system allows this model to be used more easily. This point scale, which was based on true stress – true strain behavior, could easily be converted to ultimate tensile strength (engineering stress) because it is supplied with each coil of wire by the manufacturer. Converting the scale would eliminate the need to test as-received material.

In Table 5.3 data for micro-hardness at point 1 and 2 are shown. These data were to be used in the comparison between the numerical model and experimental results. Unfortunately these results had a standard deviation greater than the “fine tuning” of the drawn micro-hardness that was being optimized. Unlike the results for adjusting die angle, where the entire distribution across the wire was sampled, these four data points (as shown in Figure 5.2) were not strong enough to make a comparison, but they do give some quantitative insight as to where these measurements should lie. Fortunately, the tensile testing for all five heats that accompanied the micro-hardness measurements was within 5% of the manufacturer’s data and it was possible to make a conversion to an “overall” micro-hardness. This conversion was accomplished by calculating the true
stress from the engineering stress, and then using a tensile strength - Knoop microhardness conversion chart (Leco Form No. 200-971). As was shown at the beginning of the chapter the difference between 500 g and 200 g Knoop micro-hardness measurements was small. The ultimate tensile strength – Knoop micro-hardness chart is shown in Figure 5.6. A line was fit to this data and then used to calculate the “overall” micro-hardness from the experimental tensile data. The numerical micro-hardness was calculated using Equation 4.7.

![Graph showing the ultimate tensile strength - Knoop micro-hardness chart](image)

Figure 5.6 – Ultimate tensile strength – Knoop micro-hardness chart

\[
KHN = 0.3219 \sigma + 1.7803
\]
Equation 4.7 corresponds to point 2 of 17 from the numerical micro-hardness distribution and also point 2 in the micro-hardness mapping in Figure 5.2. All these results are shown in Table 5.5.

<table>
<thead>
<tr>
<th>Heat #</th>
<th>True Stress, Mpa (drawn material)</th>
<th>Experimental Micro-hardness</th>
<th>Numerical Micro-hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>838</td>
<td>266</td>
<td>267</td>
</tr>
<tr>
<td>2</td>
<td>869</td>
<td>272</td>
<td>268</td>
</tr>
<tr>
<td>3</td>
<td>784</td>
<td>251</td>
<td>258</td>
</tr>
<tr>
<td>4</td>
<td>808</td>
<td>253</td>
<td>259</td>
</tr>
<tr>
<td>5</td>
<td>807</td>
<td>255</td>
<td>260</td>
</tr>
</tbody>
</table>

The conversion of the true ultimate tensile strength of the drawn wire to an “overall” micro-hardness seemed to represent the numerical micro-hardness from point 2 well and for this reason it was selected. The numerical and experimental calculations seemed to be proportional to each other. However, the high end of the numerical results fit better than the low end of these results. One possible reason that can explain this problem is the way the Leco micro-hardness chart, which was used for the experimental conversion, is laid out. This chart is split into two different sections, soft metal and hard metal. Unfortunately, these two curves do not coincide in the region they overlap (750 – 820 MPa). In addition, the choice to represent drawn tensile strength by a single point from the numerical results may not be the best way to represent ultimate tensile strength of a wire. Another method that has been proposed was to take concentric shells of different hardness and tensile strength. These results would then be weighted by an area-weighting scheme.
Details of the comparison aside the numerical model seemed to predict the relative change in hardness with respect to known stock material differences rather well. The order of change was also consistent with the experimental results. With this initial success a capability to account for the differences in stainless steel wire can be realistically achieved. Therefore, a simple process chart, presented in Figure 5.7, was created for use in a wire drawing setup.

![Process Chart for Manually Intelligent Wire Drawing](image)

**Figure 5.7 – Process chart for manually intelligent wire drawing**

A capability to account for material differences from coil to coil was briefly discussed in chapter 1. This capability was called intelligent wire drawing. In this situation this chart enables the user to implement a manually intelligent wire drawing system. That is, if a uniform micro-hardness is desired in the drawn product the die angle
can be chosen for the stock material condition. The only tools necessary for applying this capability are number of wire drawing dies with different included die angles. In practice a micro-hardness would be chosen, the chart would be consulted to find the best die angle for a given coil of wire and then the die with the closest die angle would be chosen.

5.5 Conclusions

This study was focused on stainless steel wire, but by no means is this capability limited to this material. Intelligent drawing technology in a manual adjustable format can be applied to a wide variety of metals and processing conditions. In addition to developing an understanding of this wire drawing process a methodology to examine the behavior of other materials and processes was laid out. By using DEFORM-2D and experimentally determined material data a numerical model can be developed and this information can be collected, processed and quickly implemented into any drawing operation.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR
FUTURE WORK

A capacity to apply intelligent wire drawing in the field has been developed. Through the use of the finite-element code, DEFORM-2D, a process chart for controlling the Knoop micro-hardness distribution across a stainless steel wire was created. This process chart was based on the results of a number of factorial experiments. The dependence of this micro-hardness distribution on material properties and die angle was confirmed by two groups of experimental testing. With this capability the ability to account for as-received stock wire property variation can be achieved. In addition to the creation of this capability a novel micro-hardness mapping method was developed and used to compare the simulation and experimental results.

6.1 Conclusions

DEFORM-2D was used successfully to simulate the wire drawing process. Before it was used to examine the two research goals its accuracy was evaluated. It was
evaluated quantitatively and the results showed good correlation to experiment. With this success other axisymmetric simulations were created. Effective strain measurements, output from DEFORM-2D, were gathered from the post-processing tools and then transformed to 200 g load Knoop micro-hardness using an experimental correlation. Using this process two technical goals were achieved.

The first goal was to use numerical simulations to evaluate the main effects between die angle, bearing length, lubrication condition and draw speed on the micro-hardness distribution of drawn wire. The possibility of interactions between these variables was also explored. From the numerical testing it was found that bearing length and draw speed have a negligible effect on the micro-hardness distribution. The lubrication condition in the die had a very small effect, but capitalizing on this effect to control hardness was ruled out because of the difficulties that would arise from attempting to control this condition experimentally. Die angle had the largest effect and was selected as the parameter to control. Experimental tests were run on a number of die angles and then compared to the numerical results. As a result of this, the numerical predictions were calculated to be accurate.

The second project goal was to evaluate the capability to produce uniform drawn wire from stock wire with slightly varying material properties. From the results of goal 1 it was determined that die angle was the most important process parameter, so a numerical model based on die angle and material strength was developed for predicting the micro-hardness distribution. It was used as a “steering wheel” to correct for the differences in stock wire properties. The magnitude of the changes in the micro-hardness distribution that could be achieved by adjusting die angle was significant enough to steer
stock wire hardness towards a desired drawn micro-hardness. Five different batches of material representing different stock wire conditions were drawn experimentally and the resulting "overall" micro-hardness (converted from tensile test results) was compared to the model's prediction. The results were good, but more evaluation of this prediction tool against full micro-hardness distributions (rather than an "overall" micro-hardness) for a significant number samples needs to be conducted.

The results of the second research goal were used to create a process chart intended to be used in the field. The user would choose a desired micro-hardness for the drawn wire, gather the manufacturer's supplied ultimate tensile strength data and then use this process chart to find the most appropriate die angle from the available dies for that batch of wire. When a new batch of wire would be delivered the process would be repeated.

Initially this capability for intelligent wire drawing could be deployed in a manually adjustable sense. Without this capability the stock wire property variation can not be counteracted. However, if this technology is applied the gains could be significant. Two of these include reduced property variation in the drawn wire, and dramatically increased tool life in subsequent forming operations. In the least this capability will increase the attention wire drawing operations usually get in practice. Next to cold forging, machining and other forming processes wire drawing is much less costly and in many cases neglected except when obvious problems occur, such as a wire break. This capability will bring attention to the importance wire drawing operations play in metal forming, especially because such operations often exist as a first step in the manufacture of a variety of more complex products.
6.2 Recommendations for future work

A number of improvements can be made in the future. These include expanding the use of the DEFORM-2D finite-element tool to include the heat treatment package, expanding the research to include area reduction and more materials, and converting the manually adjustable system to a real-time automatically adjustable wire drawing system.

Currently the output from the finite-element simulations is the effective strain distribution across the wire. Then a conversion based on experimental testing is used to convert these numbers to Knoop micro-hardness. Recently, however, an additional module available with DEFORM-2D has been developed that allows the user to obtain predicted hardness measurements using post-processing tools. If in the future this module is proven reliable the conversion that was used in this thesis could be evaluated further. Expanding this system to study other materials and operations would certainly be made easier to accomplish with this added feature.

In this thesis not only was one wire drawing operation studied, but a basic methodology for studying different wire drawing configurations was documented. This same procedure can be used to study many different wire drawing processes in the field. To do this though the model would have to be expanded to include other area reductions and wire diameters, and many different materials. If this were to be done an initial fractional factorial design would have to be created to screen out the negligible parameters. The full set of parameters to evaluate would include die angle, area reduction, bearing length, lubrication condition, draw speed, material strength coefficient and strain-hardening coefficient. Then another smaller full or fractional factorial design
would be created for only those parameters that cause significant change when they are varied. With these results a new process chart could be used to diagnose many wire drawing configurations.

Finally, the most important undertaking for the future will be to expand this system to a fully-automated real-time intelligent wire drawing system. In theory this system would not only be able to monitor and steer the drawn hardness in a wire to those that are desired from one coil to the next, it would be able to do it as the wire is drawn. Small variations in the as-received stock material would be able to be determined quickly and then proper adjustments would be implemented via a control system to obtain the desired results.

All of the above mentioned research extensions, as well as a number of others, have been made possible as a result of the fundamental wire drawing science-base enhancements resulting from the current work. The continuation of the effort in an appropriate fashion will likely lead to significant improvements that could be implemented throughout the metal forming industry, and enable the manufacture of continuously better products at reduced costs. The present investigation, therefore, will hopefully serve as a major contribution to the overall field of manufacturing science.
REFERENCES


VITA

Robert Gifford was born in Waltham, MA. In 1994 he graduated salutatorian from Nashua Senior High School in Nashua, NH. He then continued his education at the University of Delaware in Newark, DE where he received a Bachelor’s of Science degree with honors in Mechanical Engineering and a minor in Japanese in 1998. While at the University he completed two years of undergraduate research in composite braiding under the supervision of Dr. Tsu-Wei Chou and Dr. Tim Kostar. He also placed second with his group in their senior design class competition for designing and building a supersonic rocket sled prototype for Aberdeen Proving Grounds. Then, he continued his education in the Mechanical Engineering and Mechanics Department at Lehigh University. Once at the university he became part of the Intelligent Materials and Manufacturing Laboratory (IMML) lead by Dr. John P. Coulter. While working in the IMML he studied metal deformation and specifically wire drawing processes. In June 2000 he received his Master’s of Science degree in Mechanical Engineering from Lehigh University in Bethlehem, Pennsylvania.
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