Moirâe interferometry analysis of laser weld induced thermal strain

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MOIRÉ INTERFEROMETRY ANALYSIS

OF LASER WELD

INDUCED THERMAL STRAIN

by

Vincent T. Kowalski

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Abstract

An experimental method is presented to study laser weld induced thermal strain using moiré interferometry. The effect of this thermal strain has significant impact on the quality and reliability of lightwave components. The goal of this investigation is to understand these thermal strains utilizing digital image analysis enhanced moiré interferometry. This technique is a full field displacement measurement tool with high sensitivity and excellent spatial resolution. The thermal strain induced by a single weld on a flat plate is investigated to establish a baseline analysis procedure. The method is then applied to study thermal strain induced from a welds applied to an interface of two separate plates. The results show that the thermal strain induced by a single weld is independent of material inhomogeneity. Principal axes of thermal strain for the laser beam are determined to be offset +30° from horizontal. Investigation of interface specimens shows that thermal strain effects vanish at distances greater than 1mm away from the center of the weld. This method provides an excellent diagnostic tool for the characterization of thermal strain induced during laser welding.
Chapter 1

Introduction

1.1 Background

The manufacturing process for most lightwave devices requires precise alignment of the optical components for optimum coupling of the light signal. An example is laser packages containing a laser diode subassembly connected to a fiber optic termination. To optimize the coupled power, the fiber endface must be at the proper location, (in the $x$, $y$ and $z$ direction), relative to the laser diode. While held fixed in the optimum location, the components are joined together creating the completed laser package. Various techniques used to join the components include adhesives, soldering and laser welding. The quality and long-term reliability of the device is greatly dependent on the joining technique. For single mode devices with a fiber core diameter of 8 microns, relative motions of the components in the order of microns could cause a large degradation in coupled power. Therefore, careful
consideration of the joining technique must be incorporated into the design phase of a lightwave device.

The use of adhesives [1] requires long curing times in which the device must be held in the alignment fixture. Near perfect stability of the assembly fixture is required throughout the entire curing process. Ultraviolet curing cements have relatively short curing times, but are impractical when the optical components are opaque. All organic adhesives present the possible occurrence of long-term outgassing or redeposition onto active elements in the package which may cause long-term reliability problems. In addition, a high degree of control on the parameters of the adhesives must be maintained in order to prevent failures due to surface cleanliness or degradation of the adhesive. Soldering methods [2] have also been used to secure aligned optical devices. The necessity of heating the entire device to high temperature is undesirable with most optical components. Also, low melting temperature solders are susceptible to creep which may impact the stability of the device. Many of the deficiencies of adhesive and solder techniques can be eliminated through the use of laser welding techniques in the manufacture of lightwave devices.
Pulsed laser welding is rapidly gaining acceptance as a highly reliable material joining technique for precision applications which demand high weld strength to weld size ratio, minimal heat affected zone size and accurate positioning of the weld zone [3]. Such requirements are necessary in the design and manufacture of lightwave packages, in which one of the primary objectives is to ensure optimal coupling between a laser diode and an optical fiber. Typically, an active alignment technique is used to adjust the relative positions of the laser and the fiber to maximize the couple power. A laser weld is formed when a beam of sufficiently high power density is focused on the interface surface of two optical components. A certain percentage of the incident light is absorbed and converted into thermal energy in the body. When the incident energy is increased to a sufficient level, the absorbed energy induces a phase change in the form of melting. The material from both substrates melt forming material intermixing. The liquid metal pool freezes very fast forming a high strength fusion bond between the components.

A phenomenon which occurs is that the final optimum coupled power will randomly change upon the completion of the laser weld process [4]. The change in power is due to a relative motion of the fiber endface with respect to the laser diode.
The factors involved in the laser welding process such as material melting and rapid cooling result in the generation of thermal stresses between the components. The alignment fixture causes a constrained thermal strain distribution to be generated. When the constraint is released, the thermal strain results in a relative motion of the components changing the optimum power level. The behavior of the thermal strain is unpredictable since the relative orientation of the optical components at the optimum coupling is random. As a result, there exists a need to analyze this phenomenon of thermal strain in order to understand the influence of material and geometry on thermal strain for a particular design. With this information, the laser welding technique can be used more effectively in the manufacture of world class lightwave devices.

A variety of techniques exist to measure deformations. However, most techniques rely on accurate determination of displacements over a certain gage length to determine strain. The sensitivity and accuracy of the technique is increased when the gage length is decreased. Two categories of deformation measurement techniques to be considered include localized region and full-field displacement techniques.
1.2 Localized Region Displacement Techniques

Local region displacement techniques measure displacements at specific points or lines of a specimen. Examples of such techniques are electrical strain gages [5] and extensometers [6]. Electric resistance strain gages experience a change in resistance with a change in strain. The measured resistance change is calibrated in terms of displacement over a known gage length on the specimen surface. The resulting measured strain is an average over the gage length. The sensitivity of the strain gage is controlled by the choice of strain gage material, length and geometry. Extensometers are used for relatively large displacements. Extensometer may use actuators that are mechanical, resistive, inductive or capacitive. Mechanical and resistive extensometers have friction effects due to contact of mechanical components. Inductive and capacitive extensometers have no friction effects and may have a resolution range in the submicron level.

The resistance strain gage and displacement transducer techniques share the limitation of measuring average displacement over a certain gage length to determine strain. No detailed information about intermediate displacements within the gage length can be obtained using these techniques. Also, the application of these techniques is limited to one fixed location on the specimen. If information is
desired at another location, the procedure will have to be repeated with the transducer or gage in another location. Strain gages can be applied at neighboring locations and monitored simultaneously, however, the proximity of information is limited by the dimensions of the strain gages. To obtain detailed information over a continuous range on a specimen, full field displacement measurement techniques must be used.

1.3 Full Field Displacement Techniques

Full field displacement techniques extract displacement information over a continuous region of a specimen. The resolution of the proximity in which information can be extracted is usually limited by distances which are in the submicron range. Methods in this category include grid method, speckle, holography and moiré. These methods may be used to monitor two in-plane orthogonal components of displacement.

With the grid method [7], a uniform pattern is etched or printed on the surface of the specimen. Distances between two discreet points on the grid are measured before and after loading to determine net displacements at grid points. Measuring and analyzing the grid is accomplished with coordinate measuring
microscopes or a digital imaging process. Sensitivity of the grid method is directly dependent on the ability of the measuring instrument to detect the new location of the grid point relative to its original location. The resolution of the grid method depends on the pitch of the grid used. Speckle [8] is an extension of the grid method in that the grid is random and identified by characteristics of the object surface rather than uniformly produced patterns. Due to the randomness of speckle images, the practical way to process images is by digital image processing. Speckle is suitable for automated measurements but like the grid method, it is limited by the ability of the viewing equipment to identify small differences in light scattered at different points on the specimen. Holography [9] utilizes images which are produced at when a reference coherent beam interferes with light diffracted by the specimen. After deformation, another hologram is superposed on the first forming fringes resulting from the interference of the two holograms. Holography is a very sensitive and accurate method for displacement measurement. An advantage of holography is that no gratings or grids are necessary to be produced on the specimen surface. However, relatively long exposure times required to record the hologram limit the used of holograms in many applications.

Another attractive approach to measure high sensitivity full field
displacements is moiré interferometry [10]. This method is based on the interference pattern generated by the interaction of a reference grating and diffraction grating applied to the surface of the specimen. The advantage of moiré interferometry is that it does not require expensive facilities and is relatively easy to apply. Moiré interferometry has been used to analyze the strain around the heat affected zone of electric arc welds. [11] This investigation demonstrated that moiré can be successfully applied to investigate a continuous traverse across a weld with a high strain gradient. Masubuchi [12] used a moiré interferometry technique to measure distortions of fillet and butt electric arc welds. Their study focused on out-of-plane distortions resulting from various loading of the specimens.

This study will focus on the application of moiré interferometry to provide an accurate method to determine full field displacement for the determination of thermal strains induced during laser welding.
Chapter 2

Moiré Interferometry

The moiré effect can be created by mechanical or optical superposition. It occurs when two similar, but not identical arrays of equally spaced lines are superposed or when one superposed array is deformed relative to the other. This relative deformation creates a series of moiré fringes. In the experimental mechanics field the moiré pattern records the full field effect of a deformation. In this study, a high sensitivity enhanced moiré interferometry method for measuring whole field in-plane displacements was used. This technique offers a unique combination of high sensitivity, excellent contrast and spatial resolution.

In 1980, Post developed moiré interferometry using high quality reference gratings with line spacing of 1200 lines/mm [13]. This effort greatly increased the capability of the technique. Since then many improvements have been added to the
technique. New experimental setup configurations and methods of optical separation have provided for more accurate V-field displacement measurements [14,15]. Further enhancements were developed in generating specimen gratings by Basehore and Post [16]. Moiré interferometry is gaining wide acceptance as one of the most accurate tools for experimental mechanics. The method generates a highly sensitive contour map of displacements which is required to determine small strains. Moiré interferometry can be used as an experimental method to validate analytical or numerical solutions to a problem. Experimental measurement provides a dependable datum to evaluate the results of complex numerically generated results, establishing a basis for hybrid experimental-computational methods.

2.1 Fundamentals of Moiré Interferometry

Moiré interferometry can be explained using the wave theory of light [17]. A parallel beam of light emitted in the \( x \) direction is depicted at a given instant as a sinusoidal or harmonic wave train, shown in Figure 2.1. The periodic amplitude fluctuations, \( A \), that vary with position \( x \) can be represented by

\[
A = A_0 \cos \left( \frac{2\pi x}{\lambda} \right)
\]  

(2.1)

where

\( A_0 \) = a constant known as the amplitude of the wave,

\( \lambda \) = wavelength of the oscillation.
The distance between peaks, $\lambda$, is very short relative to the length $x$. The wavetrain is not stationary and its velocity through free space is defined as

$$C \ (3 \times 10^8 \ m/s).$$

At any fixed point, the field strength varies with a frequency $\omega$

$$\omega = \frac{C}{\lambda} \quad (2.2)$$

The light disturbance varies with time $\tau$, at a fixed point $x = x_0$ as

$$A = A_0 \cos 2\pi \left( \frac{C}{\lambda} \right) \tau = A_0 \cos 2\pi \omega \tau \quad (2.3)$$
where the quantity $2\pi \omega t$ is called the phase of the disturbance. Any continuous surface along which the field strength, $\omega t$ equals a constant, is called a wavefront. For a parallel beam of light, wavefronts are plane cross-sections of the beam as shown in Figure 2.2.

![Figure 2.2 Parallel wavefront of light](image)

When two collimated beams of the same phase intersect with a relative angle $2\beta$, their wavefronts are perpendicular to the beams and they too intersect at $2\beta$. Interference of two beams at a given instant in time is shown in Figure 2.3.
Figure 2.3 Interference of two planar beams of light [18].
The wavefronts are separated by a distance equal to the wavelength $\lambda$. At point $a$, the field strength equals the summation of the individual field strengths from both beams 1 and 2. This gives constructive interference along every point of $a\,b$ and $c\,f$. At point $c$ and along every point of $c\,d$ the resultant strength is zero and the result is destructive interference. These lines of constructive and destructive interference cause fringes to be formed. From Figure 2.3, it can be determined that

$$\sin \beta = \frac{(\lambda/2)}{p}$$

(2.4)

where $p$ is the distance between constructive fringes. The frequency $F$ of the fringes formed is given by

$$F = \frac{1}{p} = \left(\frac{2}{\lambda}\right) \sin \beta$$

(2.5)

In moiré interferometry, two beam interference is used to create high frequency reference gratings where the frequency $F$ is determined by the wavelength of the laser, $\lambda$. A wide range of frequencies may be obtained changing the parameters of equation (2.5). The wavelength $\lambda$ is determined by the particular light source chosen. The angle $\beta$ has a theoretical limit of $90^\circ$, however $\beta$ should not be too large or too small to provide a practical experimental setup.
2.2 Diffraction Grating

Moiré interferometry incorporates the diffraction of light in addition to interference in the formation of fringes. High frequency phase diffraction gratings, have regularly spaced furrowed surfaces with symmetric furrow profiles. Figure 2.4 shows a cross-sectional view of a phase type grating. Typically, the cross-gratings are used to measure two perpendicular displacement components. The period or pitch of the grating is the distance $p$ between corresponding points of adjacent furrows. A diffraction grating divides every incident wave train into a multiplicity of wave trains of smaller intensities. When a beam is cast incident at an angle $\phi$ onto a reflective diffraction grating, the incident beam is reflected back into a set of beams emerging at diffraction angles $\beta_n$ defined by

$$\sin \beta_n = n\lambda F_g + \sin \phi$$

(2.6)

where $n$ is the diffraction order and $F_g$ is the frequency of the grating. The diffracted beams emerge at diffraction orders numbered in sequence, $...\beta_{-1}, \beta_0, \beta_1, \beta_2, ...$ in which the zero order diffraction is reflection of the incident beam. The number of diffraction orders which emerge within the range $\pm 90^\circ$ is large when $F$ is small and the maximum number of diffraction orders is large when $F$ is large. The first
Figure 2.4  Phase type diffraction grating

\[ F_g = \frac{1}{p_g} \]

Figure 2.5  Diffraction of incident beam into separate orders
order diffraction beams \((n = \pm 1)\) have the strongest intensity of the diffraction orders and are primarily used for data collection. Using equation (2.6), one can solve for the incident angle which would cause the +1 diffraction order of an incident beam and the -1 diffraction order of another symmetric incident beam to emerge perpendicular to the grating. This condition is shown in Figure 2.5. In this case, \(\beta_x, \beta_y = 0\) and the angle \(\phi_n\) is determined by

\[
\lambda F = \sin \phi_n
\]  

(2.7)

Figure 2.6 shows this condition in which \(\beta_x, \beta_y\) are perpendicular to the grating surface and are parallel to each other. This condition is generally the unloaded, null state in which no interference is taking place. When a diffraction grating frequency is changed, (by a loading condition), the first order diffraction beams will no longer emerge parallel to each other. This condition is shown in Figure 2.7 in which interference of the first order is occurring. This interference phenomenon is the basis of fringe formation used for displacement measurement in moiré interferometry.

2.3 Moiré Interferometry

In experimental strain analysis, moiré fringes are produced by the interaction of a grating applied to the surface of a specimen and a reference grating. The two
Figure 2.6 Interference of first order diffraction - undeformed

Figure 2.7 Fringe formation due to Interference of first order diffraction
gratings must have the center to center distance between adjacent lines, (the pitch of the grating) that are equal or a multiple of one another. A schematic of the configuration of the two gratings is shown in Figure 2.8. A diffraction grating is produced on the specimen. Usually a cross-line grating is used in order to measure displacement in two directions simultaneously. This diffraction grating is a high reflecting symmetric phase-type grating of the type shown in Figure 2.4. The diffraction grating is firmly attached to the specimen. When a load is applied to the specimen, the grating moves and deforms together with the specimen surface. The reference grating is formed by the interaction of two parallel laser beams as shown in Figure 2.8. Before deformation, typically the specimen and the reference gratings align such that the opaque bars of one grating coincide with the opaque bars of the other grating as shown in Figure 2.9. Light will be transmitted as a series of bands having a width equal to one-half the pitch of the gratings. However, diffraction effects and resolution capabilities of the eye will cause this series of bands to appear as a uniform gray field with an intensity, $I_{\text{ave}}$, equal to approximately one-half the intensity of the incident beam, $I_o$.

When the specimen is subjected to a uniform deformation the specimen grating will exhibit a deformed pitch as shown in Figure 2.10. The transmission of
Figure 2.8  Schematic of moiré interferometer
Figure 2.9 Light transmission through matched reference and specimen grating

Viewed as a uniform gray field
light will now appear as a series of bands of different width. When the transparent interspaces of the two gratings are aligned, a light band will be perceived. When an opaque bar of one grating is aligned with the transparent interspace of the other grating, a dark band known as a *moiré fringe* is formed. In this application, deformations of the specimen in the direction normal to the grating do not contribute to moiré fringe formation [19]. The displacement of the specimen over a given interval is

$$\Delta L = np$$  \hspace{1cm} (2.8)

or

$$\Delta L = \frac{n}{f}$$  \hspace{1cm} (2.9)

where

- $n =$ the number of moiré fringes in the gage length,
- $p =$ the pitch of the reference grating,
- $f =$ the frequency of the reference grating.

The engineering strain of the specimen under tensile loading, $\varepsilon_i$, over the given interval, $L_0$, is

$$\varepsilon_i = \frac{\Delta L}{L_0} = \frac{np}{1 - np}$$  \hspace{1cm} (2.10)
Figure 2.10 Light transmission through unmatched gratings - formation of moiré fringe.
For compressive strains, the engineering strain, $\varepsilon_c$, over the arbitrary interval, $L_o$, is given by

$$\varepsilon_c = \frac{\Delta L}{L_o} = \frac{np}{1 + np} \quad (2.11)$$

### 2.3.1 Geometry of Moiré Fringes

Moiré fringes are produced by either changes in the pitch or rotation of the specimen grating with respect to the master grating. In a general point in a stressed specimen, the effects of rotation and deformation may occur simultaneously. Figure 2.11 shows the geometry of moiré fringes in terms of differential fringe spacing. From Figure 2.11 it follows that [20]

$$p_r = d \sin \theta \quad (2.12)$$

$$\delta = d \sin (\phi - \theta) \quad (2.13)$$

$$\frac{p_r}{\sin \delta} = \frac{\delta}{\sin (\phi - \theta)} = \frac{\delta}{\sin \phi \cos \theta - \cos \phi \sin \theta} \quad (2.14)$$
Figure 2.11 Geometry of moiré fringe - pitch analysis

Figure 2.12 Geometry of moiré fringe - angle of inclination analysis
where $p_s$ = the pitch of the reference grating,

$\delta$ = the distance between fringes,

$\theta$ = the rotation angle of the specimen grating with respect to the reference grating,

$\phi$ = the angle of the moiré fringe with respect to the reference grating.

Using the geometry of moiré fringe generation based on inclination angle, Figure 2.12, it is observed that

\[ p_s = d^* \sin (\phi - \theta) \]  \hspace{1cm} (2.16)

\[ p_r = d^* \sin (\pi - \theta) \]  \hspace{1cm} (2.17)

\[ \frac{p_s}{\sin (\phi - \theta)} = \frac{p_r}{\sin (\pi - \theta)} \]  \hspace{1cm} (2.18)

Substituting equation (2.14) into (2.18), it follows that
\[ P_s = \frac{\delta \sin \theta}{\sin \phi} \quad (2.19) \]

In order to eliminate \( \theta \) from equation (2.19), use the trigonometric identity:

\[ \sin \theta = \frac{\tan \theta}{\sqrt{1 + \tan^2 \theta}} \quad (2.20) \]

Substitute equation (2.15) into equation (2.20) to obtain

\[ \sqrt{1 + \tan^2 \theta} = \frac{(\delta/p_r + \cos \phi)^2 + \sin^2 \phi}{(\delta/p_r + \cos \phi)^2} \quad (2.21) \]

or

\[ \sqrt{1 + \tan^2 \theta} = \frac{1 + ((\delta/p_r)^2 + 2(\delta/p_r) + \cos \phi)}{(\delta/p_r + \cos \phi)} \quad (2.22) \]

Therefore, using the deformed specimen pitch, \( P_s \), can be expressed in terms of the pitch of the reference grating \( p_r \), in terms of \( \delta \) and \( \phi \) which can be determined from the moiré fringe pattern

\[ P_s = \frac{\delta \sin \theta}{\sin \phi} = \frac{\tan \theta}{\delta \sqrt{1 + \tan^2 \theta}} = \frac{\delta}{\sqrt{1 + (\delta/p_r)^2 + 2(\delta/p_r) \cos \phi}} \quad (2.23) \]
In many cases, the rotational effect on moiré fringe formation are small. Therefore, \( \phi = 0 \) or \( \pi \). Thus one can obtain the pitch of the deformed specimen grating from the distance between moiré fringe centers, \( \delta \) is as follows:

\[
p_s = \frac{\delta p_r}{p_r \pm \delta} \tag{2.24}
\]

The component of normal strain perpendicular to the reference grating is

\[
\varepsilon = \frac{p_s - p_r}{p_r} \tag{2.25}
\]

### 2.3.2 Full Field Strain Determination

In the determination of strain using moiré interferometry, the fringe pattern depicts the in-plane displacements of every point on the specimen surface as contour maps of equal displacement fringes. For each point in the fringe pattern, the components of displacement in the \( x \) and \( y \) directions, \( U \) and \( V \), respectively are

\[
U = \frac{N_z}{F} \tag{2.26}
\]

\[
V = \frac{N_y}{F} \tag{2.27}
\]
where $N_x$ and $N_y$ are fringe orders when lines of the reference grating are perpendicular to the $x$ and $y$ directions, respectively and $F$ is the frequency of the reference grating. Strain is calculated by taking the derivative of the displacement curve at each point

$$
\varepsilon_x = \frac{\partial u}{\partial x} \quad (2.28a)
$$

$$
\varepsilon_y = \frac{\partial u}{\partial y} \quad (2.28b)
$$

$$
\gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \quad (2.28c)
$$

Figure 2.13 shows the displacement plots used to determine the displacement gradients $\partial u / \partial x$ and $\partial u / \partial y$. Alternatively, Figure 2.14 shows the displacement plots used to determine the displacement gradients $\partial v / \partial x$ and $\partial v / \partial y$. The derivatives in the right hand side of equation (2.28a,b,c) may be determined from measured displacements and the equations become

$$
\varepsilon_x = \frac{\Delta U}{\Delta x} \quad (2.29a)
$$
\[ \varepsilon_y = \frac{\Delta V}{\Delta y} \quad (2.29b) \]

\[ \gamma_{xy} = \frac{\Delta U}{\Delta y} + \frac{\Delta V}{\Delta x} \quad (2.29c) \]

The use of equations (2.29a,b,c) require that \( \Delta x \) and \( \Delta y \) are sufficiently small to accurately represent the derivative of the displacement curve. In order to have small increments, \( \Delta x \) and \( \Delta y \), it is necessary to collect displacement data from points that are very closely spaced. A factor that has to be taken into account when using the moiré method for displacement and strain analysis is the existence of a null field. In general, the specimen grating lines will not be perfectly straight and uniformly spaced. Also the optical components used to form the reference grating may cause slight deviations in the uniformity of the reference grating. The result is that a small amount of carrier fringes will appear on the view of the specimen prior to loading. These effect of these carrier fringes can be accounted for by subtracting their effect from the final displacement curves.
Orientation of specimen grating

Moiré fringe pattern

\[ \varepsilon_{xx} = \frac{\partial u}{\partial x} = \frac{\Delta u}{\Delta x} \]

Position along AB

\[ \frac{\partial u}{\partial y} = \frac{\Delta u}{\Delta y} \]

Position along CD

Figure 2.13 Displacement distributions to evaluate \( \partial u/\partial x \) and \( \partial u/\partial y \).
Figure 2.14  Displacement distributions to evaluate $\partial v/\partial x$ and $\partial v/\partial y$. 

$$
\epsilon_{xy} = \frac{\partial v}{\partial y} = \frac{\Delta v}{\Delta y}
$$
2.4 Moiré Interferometer

There are many optical arrangements that can be contrived to produce the interference of two collimated laser beams as shown in Figure 2.8. A schematic of a typical two-beam interferometer is shown in Figure 2.15. A narrow collimated beam emerging from the laser head is directed by mirrors into a small decollimating lens. The lens converges the light into the spatial filter. The function of the spatial filter is to eliminate any extraneous rays contained in the beam. The diverging light beam leaving the spatial filter is focused onto a parabolic mirror. The spatial filter is located at the focal point of the parabolic mirror. The light reflects from the parabolic mirror as a clean wide collimated beam. Half of the collimated beam is projected at the proper angle, $\beta$, directly onto the specimen surface. The other half of the collimated beam reflects from plane mirror and is incident onto the specimen surface at an angle $-\beta$. The two beams interact with the corresponding lines on the specimen cross-grating to form the moiré pattern. The light emerging normal to the specimen surface (forming the moiré fringe pattern), is collected by the camera lens objective. The camera lens focuses the moiré fringe pattern onto the camera sensor. The recorded image is sent to the image processor for storage.

Ideally, the optical components (decollimating lens, spatial filter, parabolic
Figure 2.15  Schematic for a two-beam interferometer
mirror and plane mirror) should be of sufficient optical quality to produce wavefronts that are plane to within a fraction of a wavelength. Lower quality optics may result in an unavoidable fringe pattern which cause a null field to be formed.

This arrangement allows measurement of one component of the displacement field. To obtain the orthogonal component of the displacement field the specimen can be rotated in the holding fixture 90° about the axis of the beam emerging from the specimen. In this manner the two beams interact with corresponding lines of the specimen cross-grating to provide displacement information in the orthogonal direction. This is a simple method to record two orthogonal displacement fields on the same specimen using two collimated beams. If the size of weight of the specimen holding fixture limits the ability to rotate the specimen, another method that can be used to obtain the orthogonal component is a four-beam interferometer.

A four-beam interferometer illuminates the specimen from four directions. Two directions are used to measure each component of the displacement field. This arrangement is shown in Figure 2.16, where two adjustable mirrors, A and B are added to the basic two-beam system. The collimated beam should be wide enough to illuminate all three plane mirrors and the specimen simultaneously. If sections
Figure 2.16 Schematic for a four-beam interferometer
A' and B' of the incoming beam are blocked, the setup measures the component of the displacement field in the x-direction similar to the two-beam interferometer arrangement discussed earlier. Alternatively, if sections C' and D' of the incoming beam are blocked, light from sections A' and B' are incident on mirrors A and B respectively. Light is reflected from mirror A upward in a plane normal to the y-z plane forming an included angle of $+\beta$ between the specimen and the z axis. Also, light is reflected from mirror B downward forming an included angle of $-\beta$ between the specimen and the z axis. The two beams from mirrors A and B combine to form a second virtual reference grating with lines of interference perpendicular to the y axis. This second reference grating interacts with corresponding lines on the specimen grating to provide displacement information in the y-direction.

The basic moiré interferometry technique is enhanced by using fractional fringe analysis to compute the displacement field at every point in the field (in addition to fringe centers). Also, digital image processing is used to collect light intensity information needed for computations. The enhanced technique enables automated analysis of moiré fringe patterns while increasing the sensitivity of the method.
Chapter 3

Fractional Fringe Analysis

3.1 Moiré Fringe Formation

In moiré fringe formation, displacements may be represented by continuous functions of the light intensity distribution. As discussed in section 2.2, before a specimen is loaded, the corresponding pairs of diffraction orders reflecting from the grating will be parallel. The two parallel beams of a given diffraction order cannot interfere to form constructive and destructive interference fringes. This diffraction state is shown in Figure 2.6. A recording instrument receives uniform wavefronts from all pairs of diffraction orders. When a specimen is deformed, the specimen grating deforms with it. The grating will experience local changes in frequency depending on the load. This will introduce rotational separations between beams that were originally parallel creating the conditions of two beam interference as shown in Figure 2.7. A fringe pattern of constructive and destructive interference will be formed by each pair of intersecting beams. This fringe pattern will not be uniform but will follow the deformation
distribution of the specimen. From Figure 2.7, it can be seen that many fringe patterns are formed simultaneously by the various pairs of diffraction orders. A recording instrument receives the sum of all the patterns superposed together. Sciammarella in 1965 [21] developed the following summation law of diffracted light intensity, $I(x)$, from all of the $n$ orders as

$$I(x) = I_o + I_1 \cos 2\pi FU(x)$$
$$+ I_2 \cos 4\pi FU(x)$$
$$+ I_3 \cos 6\pi FU(x)$$
$$+ \ldots \ldots$$
$$+ I_n \cos 2n\pi FU(x)$$

(3.1)

where

$F$ = the reference grating frequency,

$U(x)$ = the displacement at point $x$ perpendicular to grating lines,

$I_o$ = the background light intensity

$I_n$ = the harmonic components corresponding to the diffraction orders contributing to the moiré pattern, ($n = 1,2,3,\ldots$)

In moiré interferometry, the interference fringe pattern is due to one diffraction order only as shown in Figure 3.1. Only the $\pm 1$ diffraction orders emerge perpendicular to the specimen surface. These two orders are recorded to provide
Figure 3.1 Diffraction arrangement in moiré interferometry.
the moiré image used in strain analysis. Since only one diffraction order is used in moiré analysis, equation (3.1) is simplified to include only one term. The simplified optical law becomes

\[ I(x) = I_0 + I_1 \cos 2\pi F U(x) \]  

(3.2)

### 3.2 Fractional Moiré Fringe Analysis

The optical law described by equation (3.2) provides a powerful tool for representing displacements as continuous functions of light intensity. The quantities \( I(x), I_0 \) and \( I_1 \) must be determined for the analysis of displacement. The application of the moiré method to the analysis of strain is limited by the precision of the instruments recording the light intensity of the displacement fringe patterns.

In fractional fringe analysis, the continuous fringe order, \( \phi(x) \) is used rather than displacements \( U(x) \). The optical law, equation (3.2) can be expressed in terms of the continuous fringe order, \( \phi(x) \) as follows

\[ I(x) = I_0 + I_1 \cos 2\pi \phi(x) \]  

(3.3)
The light intensity will be a maximum at the center of a bright fringe for

\[ \phi(x) = n, \quad n = 0, 1, 2, 3, \ldots \]  \hspace{1cm} (3.4)

Also, the light intensity will be a minimum at the center of a dark fringe for

\[ \phi(x) = \frac{1}{2}(2n + 1), \quad n = 0, 1, 2, 3, \ldots \]  \hspace{1cm} (3.5)

Figure 3.2 illustrates this relations between light intensity and position given by equation (3.4) and (3.5). The bright fringes are the loci of points where the displacements in the x-direction of the specimen grating are equal to an integer multiplied by the pitch of the reference grating. The dark fringes are the loci of points where the displacements in the x-direction of the specimen grating are equal to an integer multiplied by the half pitch of the reference grating.

In a simple fringe counting analysis is used, \( \phi(x) \) has only discrete values of multiples of \( 1/2 \). To obtain additional information available for other points in the field, equation (3.3) must be used. Knowledge of the light intensity at an arbitrary point, \( I(a) \), with the values of \( I_0 \) and \( I_x \) known, leads to a determination of \( \phi(a) \). The value of \( \phi(a) \) will be a fraction between 0 and 1/2 and will yield the displacement at point \( a \) when multiplied by the pitch of the reference grating.
Figure 3.2 Light intensity distribution in moiré interferometry
The same argument holds for any intermediate point between any two fringes. This technique is known as fractional fringe analysis [22]. Therefore, the fringe orders need not be multiples of \(1/2\), they may be any fractional number.

Equation (3.3) can be rearranged to determine displacements as a function of light intensity as

\[
U(x) = \frac{1}{2\pi F} \cos^{-1} \left[ \frac{(I(x) - I_0)}{I_1} \right]
\]  

(3.6)

Equation (3.6) may be applied over each half fringe separately, determining the displacements relative to the starting point. The cumulative displacements are found by adding each successive displacement to the displacement of the starting point as follows

\[
U(x) = U_0 + \frac{1}{2\pi F} \cos^{-1} \left[ \frac{(I(x) - I_0)}{I_1} \right]
\]  

(3.7)

where \(U_0\) is the displacement at the starting point, \((x = 0)\). \(U_0\) is the reference grating pitch multiplied by either an integer or an odd multiple of \(1/2\), depending upon whether the starting point is a center of a bright or dark fringe respectively.
$I_0$ and $I_1$ are determined from known values of maximum and minimum light intensity, $I_{\text{max}}$ and $I_{\text{min}}$ as

\begin{align*}
I_0 &= \frac{1}{2} (I_{\text{max}} + I_{\text{min}}) \\
I_1 &= \frac{1}{2} (I_{\text{max}} - I_{\text{min}})
\end{align*} \quad (3.8)

The task of determining the displacement field has become that of determining the light intensity field. This can be accomplished using video cameras in conjunction with digital image processing systems. Recent advances in the field of digital image analysis by Voloshin [23,24] have led to significant progress in automated measurements of light intensity for photoelasticity and geometric moiré applications.

3.3 Digital Image Processing

Digital image processing is the technique used in this work to record and analyze a moiré fringe pattern in order to determine the light intensity values required in equation (3.6) to compute displacements. Since the moiré image contains a large amount of data over the full field, it is necessary to capture the data by an automatic method [25]. Digital image processing is capable of
acquiring data over a wide range of shades of gray. In this manner, a digital image can be recorded which will contain a large amount of information about an image in a relatively compact format. The digital image can be processed and manipulated by a digital computer using methods that cannot be duplicated by non-digital technology. The two main components of the digital image processing system are the image acquisition device and the image processor.

The digital image acquisition device generates a sampled digital representation of a moiré fringe pattern image. Examples include scanners, facsimile systems, and video cameras. Among all image acquisition systems, video cameras are the only devices capable of sensing all points in an image simultaneously. In this work, a charged coupled device (CCD) camera is used as the sensor to receive the projected image. The field lens of the camera forms an image of the desired scene on the image sensor of the camera. The image sensor, when exposed to light accumulates a charge at each point that is proportional to the incident light intensity. The output signal from the CCD camera is in an analog format which is downloaded to an image processor where signal is digitized. The CCD camera has the advantage of an extremely linear radiometric
response and broad spectral response than other sensing systems. The device is small and lightweight giving versatility to experimental measurements.

The second main component of the digital image processing system is the image processor. This is a computer based system that receives image information from the acquisition device, changes the information to a digital format, and stores the information in an image buffer. The digitized image is available to be accessed to perform mathematical analysis on the image. Analog video signals are transmitted from the image acquisition device in standard NTSC (National Television System Committee) format. A high speed analog-to-digital converter digitizes the data and enters them into a buffer memory which is large enough to hold one complete digitized video image. The digitized data are transferred by the host computer from the frame buffer to other peripheral storage.

Initialization and acquisition are accomplished using a FORTRAN code which controls the different devices to perform the desired function. The main sequence of the initialization and acquisition phase is as follows:

1. Open a channel to the data processor driver. The driver verifies
the current devices and their configurations.

2. Clear the two image buffers to assign one as input frame buffer and the other as an output frame buffer.

3. Trigger the camera and frame acquisition buffer to be properly synchronized to ensure that the image will be digitized and acquired at the beginning of the frame.

4. On-line previewing of the image to ensure that the camera is properly focused and that the quality of the light is optimum.

5. In response to user input: freeze, digitize and save the image in a file in the host computer.

This is the procedure to acquire and save an moiré pattern image from the CCD video camera source. The digitized image is ready for analysis in the determination of strain.

3.4 Digital Image Analysis System

Digitizing the image enables a greater number of points to be analyzed in full field moiré interferometry. With an accurate method of measuring the light intensity in moiré fringe pattern, the optical law can be utilized to relate light intensity measurements into displacements. In moiré interferometry, the light
distribution is required along cross-sections where strain information is of interest. The image analysis system retrieves light intensity along user selected lines, applies the optical law and determines the displacement along the line. The sequence of operations is as follows:

1. The range of points to be used in strain analysis is selected by input of beginning and ending coordinates.

2. The code determines the position coordinates of all pixels on the line, records the light intensity values and stores them in arrays.

3. Digital filtering of the data is performed using Fast Fourier Transformation [26] to reduce the effect of optical noise or image imperfections.

4. Locations of the fringe centers are determined by a comparison of light intensities at each point on the line with neighboring values until the maximum and minimum values, $I_{\text{max}}$ and $I_{\text{min}}$, are evaluated.

5. Fringe centers are assigned the proper order throughout the region of monotonicity.

6. For each half-fringe, fractional fringe analysis is performed. First $I_0$ and $I_1$ are determined from $I_{\text{max}}$ and $I_{\text{min}}$ for each half fringe.

Equation (3.7) is then used to compute displacement $U(x)$ where $x$ is
the length coordinate of the line.

7. The final displacements are stored in an array for strain analysis. The above sequence may be repeated for any number of lines throughout the entire digitized moiré image. As noted in step 3 of the procedure, the signal may include imperfections or noise which will effect the accuracy of the displacement calculation and corresponding strains. To minimize this effect, digital filtering is used.

3.5 Digital Filtering

The presence of optical noise in moiré patterns requires the use of techniques to eliminate their effect without affecting the accuracy of the data. Noise could be generated from dirt or scratches in the specimen grating. Noise can also be attributed to unavoidable reflections or imperfections of the optical components. Since moiré interferometric fringes are formed from one diffraction order only, the ideal light intensity distribution should exhibit a smooth continuous distribution. The presence of optical noise causes local spikes or irregular changes in the light intensity. Figure 3.3 shows the effect of optical noise on a typical distribution. The irregularities of light intensity are not related to displacement of the specimen, therefore they are eliminated using a Fourier
Transformation. The original distribution shown in Figure 3.3 is represented by a Fourier series. The resulting Fourier coefficients representing the distribution are computed using a Discrete Fourier transform computation [27]. The higher order coefficients are eliminated and the distribution is reconstructed using and inverse Fourier Transform based on the remaining coefficients. In the analysis of an image, first a high number of coefficients is used to reconstruct the distribution which is examined for the effects of optical noise. If the effect of optical noise still exists, the number of terms in the inverse Fourier is reduced until an optimum distribution is reached. The filtered light intensity distribution is shown in Figure 3.4. Since one can assume that the displacement field does not have high gradients, the elimination of noise from the signal gives a reliable determination of light intensity [28].

3.6 Enhanced Moiré Interferometry

The use of digital image enhancement coupled with fractional fringe analysis greatly increase the power of moiré interferometry in the analysis of displacements. The sensitivity is greatly increased by the ability to evaluate intermediate displacements between fringe centers using fractional fringe analysis. Digital imaging techniques assure geometric accuracy of the data. The
Figure 3.3 Unfiltered light intensity distribution.
Figure 3.4 Light intensity distribution with filtered curve.
positions of data points correspond to fixed pixel positions that are referenced. Displacement analysis studies involving small loads or studies of stiff specimens will generate a small number of fringes. The resulting patterns can be accurately analyzed using fractional fringe enhancement techniques.

Another important fact is that the null field can be properly handled in the analysis of displacements. The null field displacements are determined by fractional fringe analysis at each point in the region being analyzed. The null field displacements are subtracted from the final displacement values at each point. The ability to account for the null field improves the accuracy of the final data and overcomes difficulty in obtaining a perfect null field before loading a specimen.

In summary, the use of digital image processing combined with fractional fringe analysis increases the versatility and sensitivity of the method. Many new applications are possible with more precise data acquisition and analysis.
Facility and Experimental Procedure

4.1 Facility

The system used to produce and record moiré images for this study consists of the moiré interferometer and the image acquisition system. The moiré interferometer is an optical system used to produce the moiré fringe pattern. Any method to bring two coherent beams onto a specimen grating as shown in Figure 2.8 would suffice. Several optical designs can be developed to form the reference grating [29]. A two-beam interferometer provides information along one axis of the displacement field. A four-beam interferometer is capable of providing two orthogonal axes of the displacement field. As described in Chapter 3, the image acquisition and storage system includes high quality video equipment, and a computer based image processor. All of these components are required for the
fractional fringe enhanced displacement analysis. This section describes these components and systems and includes pertinent specifications and requirements.

**4.1.1 Moiré Interferometer Specifications**

The optical arrangement of the interferometer used in this investigation is the two-beam system shown in Figure 2.15. The laser source is a Spectra-Physics Helium-Neon laser, model SP127-25 which delivers 25 mW of 632.8 nm wavelength light. The laser beam has 1.25 mm beam diameter and is polarized. With the setup used, \( \lambda \) is 632.8 nm and \( \beta \) is 49.4'. Using equation 2.5, the frequency of the reference grating, \( F_s \) is 2400 lines/mm. The decollimating lens is a 6 mm diameter double convex lens with a 12.5 mm focal length. The decollimating lens focuses the laser beam to a spatial filter with a 50 \( \mu \)m diameter pinhole. A K&S X-Y-Z positioning stage retrofitted with 5 micron resolution Newport Differential Micrometers is used to adjust the location of the spatial filter. The parabolic mirror has a 108 mm diameter and a 867 mm focal length. Front surface coated plane mirrors are used to redirect the beam. All optical components used in the system are of high optical quality \((\lambda/20)\).

Due to lightweight nature of the specimens used for this work, the
specimen and holding fixture are readily rotated to investigate two components of the in-plane displacement field. Figure 4.1 shows the arrangement of the specimen holding fixture and rotation stages used in conjunction with the two-beam interferometer. The rotation stage used to adjust the angle $\psi$ of the holding fixture is a Newport Precision Rotary Stage, model 481 with a 15 arc-second resolution. This stage has a quick-release design to allow course and fine adjustment of angle $\psi$. To enable critical alignment of the interferometer, the planar mirror mount must have the capability to enable incremental rotation of the mirror about two perpendicular axes of the mirror. The high precision mirror mounts used are manufactured by Edmund Scientific Co. and allow fine angular rotations of the mirrors with a resolution of 2 arc-seconds. The rotation stage used to adjust the angle $\theta$ of the entire holding fixture and mirror mount assembly uses a Newport Micrometer No. 63 with a resolution of 0.001 mm for precise control of the angle of incidence $\beta$ of the collimated beam.

The quality of a fringe pattern obtained using a moiré interferometer is extremely sensitive to mechanical disturbances. To obtain accurate and reliable measurements, the interferometer is mounted on a Barry Controls, model 40694 vibration isolating air table which minimizes the possibility of any vibration in
Figure 4.1  Experimental work holder arrangement.
the laboratory (or in the laboratory building) from affecting the accuracy and repeatability of displacement measurement using the interferometer.

4.1.2 Image Processing System

The digital image processing system used is a PC-based system. The host computer is a Zenith ZBF-2526 work station with a 80387 coprocessor running at 12 MHz. The frame buffer is a Data Translation board DT-2851 which accepts a single analog video input that may be either NTSC or RS-170 format. The geometric resolution of the frame buffer is 480 lines by 512 pixels and the grey resolution scale is 256 grey levels. The board has the capability of storing 256 Kbytes. External and programmed frame acquisition are possible. The frame processor is a Data Translation board DT-2858 Auxiliary Processor reduces the time required to perform arithmetic intensive operations on the image buffers. This allows the computer to perform control functions only which usually do not require high-speed data transmission.

In addition to the hardware mentioned above, the system includes a Microsoft FORTRAN Complier, Version 4 to manipulate the developed FORTRAN source codes used in image manipulation.
A video camera is used to acquire the pattern and send it in standard analog video signal to the image processor for analysis. The camera used is a CCD video module that accepts interchangeable lens. The camera is manufactured by SONY, model XC-57 and has a CCD image sensor of 510 by 492 pixels. The minimum light intensity of the camera is 3 lux at F1.4, which is adequate for the laser power used in the system. Several interchangeable lenses of focal lengths ranging from 50 mm to 1000 mm are also available for viewing field sizes ranging from 50 by 50 mm down to 2 by 2 mm. An Olympus OM-2S photographic camera is used for producing hard copies of fringe patterns. A set of objective lenses is available to cover the same range of field size as the video camera system. Other auxiliaries include a video recorder to store video images of an experiment and a dark room to produce photographs of moiré patterns.

4.2 Alignment of Interferometer

To obtain the moiré fringe pattern using the interferometer for a particular specimen, an alignment procedure is performed. The configuration of the interferometer is designed to permit fine adjustments of the optical components using selected diffraction orders emerging from the specimen grating [30]. Before starting any alignment, the location of the spatial filter with respect
to the decollimating lens is adjusted to provide the maximize the intensity of the beam emerging to the parabolic mirror. This is accomplished by placing a screen across the mirror to view the profile of the cross-section of the beam while fine adjusting the position of the spatial filter using high precision differential micrometers. The position of the spatial filter is optimum when the beam exhibits the brightest symmetric profile possible. This adjustment guarantees a high quality moiré pattern with the maximum contrast between bright and dark fringes.

The first step in the alignment procedure is adjusting the specimen grating to be parallel with the reference grating by properly orienting the planar mirror with respect to the specimen. In this alignment state, the +2 and -2 diffraction orders (shown in Figure 3.1) emerging from the specimen retrace the incident beams back to their source at the pinhole of the spatial filter. Prior to alignment, the +2 and -2 diffraction orders appear as two distinct dots located at the spatial filter. By adjusting the two precision lead screws on the planar mirror mount, the two diffraction orders form one single bright dot and the two gratings are perfectly aligned.
The next step in the alignment process is to adjust the angle $\beta$ to the proper value. In this alignment state, the $+1$ and $-1$ diffraction orders emerging from the specimen (shown in Figure 3.1) will be perfectly parallel. To perform this alignment, a convex lens is placed in the path of the light beam emerging from the specimen. The convex lens focuses the $+1$ and $-1$ diffraction order beams to converge. The converging beams appear as two distinct dots on a screen placed across the focal plane of the lens. By adjusting the angles $\psi$ and $\theta$ (shown in Figure 4.1, the two diffraction orders form one bright dot on the screen. Adjustment of the $\psi$-rotary stage aligns the two diffraction orders vertically while the $\theta$-rotary stage aligns the two diffraction orders horizontally.

With the alignment procedure performed adequately, the camera is placed in the path of the light emerging from the specimen. The camera is focused on the specimen using ambient light while blocking the laser beam light. At this camera focus setting, the moiré pattern of the specimen can be recorded. To obtain the orthogonal component of displacement for the specimen, the locking mechanism for the $\psi$-rotary stage is released for a coarse manual adjustment of $90^\circ$. Then, the stage is locked and the alignment process is repeated from the beginning.
4.3 Replication of Specimen Grating

Specimen diffraction gratings are produced by a two-stage replication process from a high quality master grating. The master consists of a thin acrylic layer with perpendicular corrugations mounted on a glass substrate. The frequency of the cross grating is \(1200 \text{ lines/mm}\) over a \(60 \text{ mm} \times 60 \text{ mm}\) active area. The master grating is used to produce single-use submasters which are used to produce grating replicas on specimens. The submasters are fabricated from a silicon rubber layer mounted on a glass substrate. Before the silicone rubber submasters are used to replication of gratings, the surfaces must be made reflective. This is accomplished using vacuum deposition of a metallic layer onto the grating surface of the submaster. A metal layer thickness of approximately 40 Å is deposited on the submaster to make the grating surface highly reflective.

To reproduce the grating onto the specimen surface, the grating lines of the submaster are first aligned to a reference edge of the specimen. A low power optical laser beam is used to optically align the specimen and grating as shown in Figure 4.2. The laser is a 5mW Helium-Neon type manufactured by Oriel, model 79270. A high quality glass reference plate is aligned to the submaster using the ±1 diffraction order formed by the interaction of laser with the grating.
Figure 4.2 Optical alignment of reference plate to submaster
Figure 4.3 Replication of grating onto specimen.
The plate is attached to the submaster with an adhesive using the base of the alignment fixture as a reference.

The procedure for reproducing the grating onto the specimen is shown schematically in Figure 4.3. The specimen surface is first cleaned using an alcohol moistened wipe. A small drop of adhesive is applied to the metallized submaster surface. The specimen is carefully brought into contact with the adhesive and aligned against the edge of the glass reference plate. The adhesive is Norland UV Cure Optical Adhesive number 81. The adhesive is cured using a UV light source. When the specimen is removed from the submaster, the metallized layer adheres to the specimen grating providing a reflective surface.

4.4 Experimental Procedure

The purpose of this study is to characterize the thermal strain induced during the laser welding process of lightwave packages. In the assembly of packages, two components are first aligned such that the coupled light is in the desired range. A high power laser beam is focused on the interface of the two components. The uneven heating and cooling of the components causes thermal strain to be generated between the two components. The thermal strain causes
relative motion of the two components which changes the coupled power. After welding the final power of the device can change in a random manner as a result of thermal strain from sequential welds. The random nature of the thermal strain has serious implications on the yield of the process and the reliability of the final product.

In this study, moiré interferometry is used to establish an understanding of the random phenomena of thermal strain induced during laser welding. The first stage of the project is to establish an accurate and repeatable method for measuring thermal strain. For this purpose, single laser welds are applied to flat specimens to isolate the complex effects of welding an interface. The method of measuring thermal strain is developed by studying the symmetry of the laser weld on the flat plate. Once the accuracy and repeatability of the measurement technique is established, a study of the thermal strain is conducted for the case of welding on an interface of two plates.

The specimens are welded with a 1.06 µm wavelength YAG laser welding facility at a power of 3.50 J. The welding experimentation requires recording the initial moiré pattern, removal of the specimen for welding and replacement into
Figure 4.4 Clamp arrangement for specimen

Figure 4.5 Orientation of single weld specimen with respect to material axes
the interferometer to obtain the final pattern. This requires an accurate clamping fixture to provide precise repositioning of the specimen. The fixture consists of a clamping arrangement with three pins accurately located to secure the specimen as shown in Figure 4.4. The clamp is spring-loaded to provide uniform clamping force for different specimens. The samples are held in the plane of the fixture (z-direction) using two 2 mm diameter Alnico (Aluminum-Nickel-Cobalt) magnets. A preliminary investigation of the repeatability of strain calculation is performed to verify the integrity of the holding fixture. Details of this repeatability investigation are given in Appendix A.

4.4.1 Single Weld - Flat Plate

For this phase of the experimentation, 6.1 mm by 12.2 mm specimens are fabricated from 1.27 mm thick cobalt-nickel alloy (Kovar). A wire EDM (electrostatic discharge machine) is used to prepare the samples to avoid generating any residual stresses within the specimens during machining. To investigate the influence of the raw material inhomogeneity on thermal strain, all specimens are cut from a Kovar sheet in an identical orientation with respect to raw material. In order to isolate raw material effects, a rolling direction used by the manufacturer in fabrication of the Kovar sheet is identified. Then specimens
Weld locations

(a) Material axis, $a$, parallel with $x$-axis.

(b) Material axis, $a$, perpendicular to $x$-axis.

Figure 4.6 Single weld specimen orientations.
were all cut in the identical orientation with respect to the rolling axis. The physical dimensions of the samples are shown in Figure 4.5 along with the direction of raw material. Before grating replication, it is necessary to lap the surface of the specimen using 600 grit silicon carbide paper and water. To ensure that the specimen surface is perfectly flat, the lapping paper is placed on an glass lapping plate. A cross-grating with line spacing of 1200 lines/mm is then applied to each specimen using the procedure outlined in Section 4.3.

Each specimen is mounted in the workholder and the initial moiré pattern of each sample recorded. The weld beam axes and interferometer coordinate axes are coincident in the orientation shown in Figure 4.1. The specimens are welded with raw material axis \( a \) oriented to the \( x - y \) reference frame axes as shown in Figure 4.6. In Figure 4.6a, the test weld is applied to the specimen with material \( a \)-axis parallel with the reference \( x \)-axis. Then, the test weld is applied to the specimen with the \( a \)-axis perpendicular to the reference \( x \)-axis, Figure 4.6b. Two test welds are applied to each specimen to separate the effects raw material anisotropy from laser welder beam asymmetry. Test welds are applied to the specimens (through the grating) at the locations shown in Figure 4.6. The welded specimens are placed into the moiré interferometer setup and the final moiré
pattern was recorded. A moiré pattern of an unaffected region away from the weld zone is recorded for each specimen to be used as the null pattern in strain calculations.

4.4.2 Interface Laser Weld

With the foundation of an accurate and repeatable laser weld strain analysis technique, an investigation of the thermal strain is performed for the case of welding on an interface of two Kovar plates. This study is designed to simulate the actual phenomena of thermal strain induced by laser welding two lightwave package components. For this investigation, 6.1 mm by 12.2 mm Kovar plates were divided into two sections and pre-welded as shown in Figure 4.7. The pre-welding technique is used to fix the specimens together to facilitate the application of the grating. The pre-welds are applied to the ends of the specimen to eliminate assymetry bending stresses induced by the pre-welds. Welding on an interface presents several obstacles which must be overcome to successfully record a moiré pattern across two separate pieces. First, the grating transfer process requires the specimen to be perfectly planar since the submaster grating is mounted on a precision glass plate. In the single weld analysis, applying a test weld through the grating did not present a problem since the grating layer is thin.
Figure 4.7 Pre-welded Kovar specimen.

Figure 4.8 Geometry of test welds for interface weld analysis.
In this case, the weld beam vaporizes the grating on the surface and melts the metal underneath forming a weld pool. However, applying the grating to interface weld specimens, shown in Figure 4.7, presents a different problem.

After the Kovar plates are divided into two sections, it is necessary to ensure that the interfaces surfaces are smooth and perfectly flat. Matching interface surfaces are ground smooth and flat on a surface grinder. When the two sections are pre-welded together, the interface is barely visible under high power magnification. The first grating transfer procedure attempted in this phase of the experiment was to apply the grating to the lapped specimen surface after pre-welding. When a test weld is applied to the specimen, the result was inconsistent weld quality over many trials. Some weld pools would form an uniform circular distribution across the interface, while others formed a hollow pit which penetrated into the interface. It was determined that the epoxy being drawn into the region between the two pre-welded sections of the specimen during the curing process was the main reason for development of the hollow pit. This failure mechanism was not immediately obvious since the interface of the pre-welded specimen is barely visible under high power magnification. However any minute separation is enough to allow the UV cure adhesive used for the grating to enter.
the interface. The presence of the adhesive presents an organic contaminant which interferes with the quality of the weld. The failure mode would not consistently appear if the test weld happened to encounter a portion of the interface where no adhesive entered the interface. Therefore a modified grating transfer technique is implemented.

The final method used to prepare the interface weld specimens is to apply the grating to both half sections of a specimen together, then pre-weld the specimens. In this procedure the interface surfaces were ground and deburred as described above. The grating is applied to both specimens secured together using a magnet. The interface surfaces are cleaned and pre-welds applied to the ends as shown in Figure 4.7. Two test welds are applied to the specimen along the interface using three weld spacing intervals as shown in Figure 4.8. Only one of the spacing intervals, 1 mm, 3 mm, or 5 mm, is used on a particular specimen.
Chapter 5

Results and Discussion

The main phases of the experimental investigation of laser weld induced thermal strain include:

1. determine the influence of the raw material inhomogeneity on thermal strain for a laser weld applied to a single flat plate,

2. based on the results of phase 1, evaluate the existence of principal axes of the weld laser beam,

3. analyze the effect of weld spacing on thermal strain for welds applied to an interface of two plates.

The first phase of the experimental investigation provides a reliable procedure to analyze the laser weld induced thermal strain. The results of the first phase motivated the second phase of work to investigate the symmetry of the weld laser beam. The experimental method was then applied to the interface weld experiment which is designed to simulate the complex case of welding an actual lightwave
An analytic solution to the thermal strain problem for a single weld on a plate is first presented.

### 5.1 Analytic Formulation for a Single Weld

The weld process involves non-uniform heating of the substrate metal, followed by melting with plastic deformation and then rapid non-uniform cooling resulting in thermal strain [31]. The formulation used here models the rapid non-uniform cooling of the laser weld resulting in thermal strain. For a thin circular disk with a temperature distribution \( T \) (which is a function of \( r \)), the thermal strain is given as [32]:

\[
\varepsilon_r = \varepsilon_r = \frac{1}{E} (\sigma_r - \nu \sigma_0) + \alpha T 
\]  

(5.1)

In this case, the temperature is assumed to be uniform throughout the thickness of the plate. If \( T_o \) is the temperature at the center and \( T_1 \) is the temperature at the edge (radius = \( b \)), the temperature \( T \), as a function of \( r \) is given by

\[
T = (T_o - T_1) \left(1 - \frac{r^2}{b^2}\right) + T_1 
\]  

(5.2)
The radial and tangential stress components obtained from the temperature distribution of equation (5.2) are given by

\[
\sigma_r = -\frac{1}{4} \alpha E (T_o - T_1) \left( 1 - \frac{r^2}{b^2} \right) \quad (5.3)
\]

\[
\sigma_\theta = -\frac{1}{4} \alpha E (T_o - T_1) \left( 1 - \frac{3r^2}{b^2} \right) \quad (5.4)
\]

Thermal strain given by equation (5.1) is computed using equation (5.3) and (5.4) with the following parameter values

\[
\alpha = 5.86 \times 10^{-6} \quad \frac{1}{\circ C}
\]

\[
T_1 = 1450\circ C
\]

\[
v = 0.30
\]

\[
b = 1 \text{ mm}
\]

\[
T_o = 22\circ C
\]

\[
E = 138 \times 10^3 \text{ MPa}
\]

The calculated results for the thermal strain induced by a non-uniform temperature distribution are shown in Figure 5.1. The results indicate a maximum value of thermal tensile strain at the center of the plate. Thermal strain decreases with increasing distance from the weld center. These analytic values will be compared with thermal strain values obtained experimentally from single plate data.
Figure 5.1 Analytic values of thermal strain
5.2 Laser weld - single plate analysis

The thermal strain resulting from a laser weld is analyzed using procedures and specimen geometry outlined in Section 4.4.1. Since the specimen surface is prepared to be extremely flat, the moiré fringe pattern before welding is adjusted to be a close approximation of a null field. This eliminates the need to subtract carrier fringes from the final fringe pattern in subsequent displacement analysis. A photograph of a typical laser weld on a single plate is shown in Figure 5.2. The extremely high thermal energy generated in the plate by the weld beam causes local destruction of the grating in the vicinity of the weld pool. A certain amount of grating destruction is expected since the maximum rated temperature of the grating material is 150 °C while the Kovar melting temperature is 1450 °C. Typically, the radius of the laser weld heat affected zone is 0.40 mm. The corresponding radius of the destroyed grating is approximately 0.50 mm. The unavoidable grating destruction allows displacement information to be obtained 0.10 mm from the heat affected zone of the laser weld (or 0.50 mm from actual laser weld center).

The final moiré fringe pattern obtained after welding is shown in Figure 5.3. The black circular region is due to grating destruction in the area surrounding the laser weld. The fringes (dark lines) depict contour lines of constant displacement.
Figure 5.2 Typical laser weld - single plate
in the $x$-direction. The fringe pattern image in Figure 5.3 includes the minimum number of displacement fringes generated by the thermal effect of the laser weld. The minimum fringe pattern is the result of the specimen grating and reference grating being aligned horizontally by adjusting angle $\theta$, using the procedure outlined in section 4.2.

Post [33] showed that the number of added carrier fringes does not affect strain analysis using moiré interferometry. By adjusting the rotation angle $\theta$ of the stage shown in Figure 4.1, the number of carrier fringes for a particular specimen can be increased as shown in Figure 5.4. The regions at the ends of the specimen (away from the weld) exhibit a uniformly spaced fringe pattern. The grating lines in this region have not been distorted by welding and can be realigned with the reference grating. The unaffected regions retain the same fringe order before and after welding and are the null fields used for strain analysis.

As shown by the density of fringes adjacent to the weld in Figures 5.3 and 5.4, there is a high concentration of strain adjacent to the laser weld pool. Using the fractional fringe relation given by equation 3.7, a scan of light intensity in the region local to the weld yields the displacement distribution shown in Figure 5.5.
Figure 5.3 Single weld moiré pattern - minimum fringe density

Figure 5.4 Single weld moiré pattern - with carrier fringes
Figure 5.5 Displacement distribution versus position.

Figure 5.6 Thermal strain $\varepsilon_r$ versus position.
The straight line in Figure 5.5 depicts the null field displacement curve which is subtracted from the final displacement curve at each location to give the actual displacement at each point. The thermal strain component in the x-direction, $\varepsilon_x$, is obtained by numerically calculating the derivative $\partial u/\partial x$, at each point of the scan. The experimental and analytic values of thermal strain versus position are shown in Figure 5.6. The experimental strain distribution curve reflects the fact that information in the weld region ($0 - 0.48$ mm) is lost due to grating destruction by the laser weld. The analytic strain values show a trend of decreasing strain from the weld center similar to the experimental strain values. This technique for strain analysis is applied in each phase of the experimental work. The first case involves analyzing the effect of material orientation on laser weld induced thermal strain.

The final moiré pattern images for specimens with test weld applied with material $a$-axis parallel to the reference $x$-axis is shown in Figure 5.7. Figure 5.8, shows the resulting patterns with the test weld applied with material $a$-axis perpendicular to reference $x$-axis.

Since there a fringe concentration adjacent to the weld as shown in Figure 5.7 and 5.8, thermal strain is computed in this region to analyze material effects on
Figure 5.7 Fringe pattern after test weld applied with material a-axis parallel to reference x-axis.
Figure 5.8 Fringe pattern after test weld applied with material a-axis perpendicular to reference x-axis.
laser weld induced thermal strain. The \( x \) and \( y \) components of thermal strain for both orientations of material axis \( a \), are shown in Figures 5.9 and 5.10 respectively. The \( t \)-test of significance [34] for the \( x \) and \( y \) strain data gives a value of greater than 0.15 throughout the entire weld affected region. The significance value indicates that all \( x \)-component strain data are from the same population (regardless of orientation of material axis \( a \)). The same idea is true for the \( y \) component of strain. Thus, one may conclude that the raw material inhomogeneity due to machining processes in manufacture does not significantly effect the magnitude of thermal strain generated from a laser weld.

A comparison of the \( x \) and \( y \) component of thermal strain is shown in Figure 5.11. The \( y \)-component of thermal strain is significantly larger than the \( x \)-component (within a 0.06 mm radius from the weld center) at a \( t \)-test value of 0.012. Since the magnitude of thermal strain is independent of material direction, the differential between the \( x \) and \( y \) component indicates an asymmetric laser weld beam.

Analysis of the weld pool shape and pattern of the destroyed grating suggests the existence of principal strain axes of the laser weld beam. The principal axes of
Figure 5.9 Single plate, x-component of thermal strain

both weld orientations.
Figure 5.10 Single plate $y$-component of thermal strain

both weld orientations.
Figure 5.11 Comparison of x and y component of thermal strain.
the laser beam will yield a maximum strain along one direction and a minimum strain along the orthogonal axis. To investigate the symmetry of the weld laser beam, the following series of experiments were designed and performed.

5.3 Laser Weld Beam - Principal Axis Investigation

A photograph of a typical weld and subsequent grating damage is shown in Figure 5.2. Since the weld beam is focused to a concentrated area from a collimated beam, the power intensity distribution along any cross-section approaches a Gaussian distribution [35]. The specimen grating surrounding the weld pool shown in Figure 5.2 undergoes catastrophic destruction without any visible change to the substrate metal underneath. The phenomenon is attributed to the grating maximum tolerable temperature of $150^\circ C$ while the melting point of the Kovar substrate is approximately $1450^\circ C$. The power density at the periphery of the weld beam is sufficient to cause damage to the grating without affecting the substrate metal. Consequently, the grating damage zone consistently exhibits an elliptical profile. Detailed analysis of grating damage zone and weld pool using a high magnification coordinate measuring microscope indicates a principal axis orientation of $+30^\circ$ from the horizontal axis of the laser beam.
An experiment is performed using the identical specimen preparation and displacement measurement technique outlined in section 5.2. Test welds are applied with the specimen rotated $+30^\circ$ about the center axis of the weld beam. Figure 5.12 shows the strain distribution along the $x'$ and $y'$ axes. Similar to the results of the single weld results in section 5.2, the resulting strain in the $y'$ direction has a greater magnitude than the strain obtained in the $x'$ direction. The $y'$-component of thermal strain is significantly larger than the $x'$-component (within a $0.06 \text{ mm}$ radius from the weld center) at a t-test value of $0.010$. This value indicates a higher significant difference between the $x'$-$y'$ strain components than exists between the $x$-$y$ strain components.

A comparison of the $x$ and $x'$ strain distributions is shown in Figure 5.13. A similar comparison for $y$ and $y'$ is shown in Figure 5.14. T-test values of greater than $0.10$, (throughout weld affected range) indicates that there is not a significant difference between the $x$ and $x'$ strain distributions. A similar analysis indicated no significant difference between the $y$ and $y'$ strain distributions.

The results suggest that thermal strain values for the $+30^\circ$ coordinate axes approach the principal values for the laser weld. A higher significant difference is
Figure 5.12  $x'$ and $y'$ component of thermal strain -

(oriented $+30^\circ$ from the reference $x$-$y$ axes).
Figure 5.13 Comparison of $x$ and $x'$ component of thermal strain.
Figure 5.14 Comparison of $y$ and $y'$ component of thermal strain.
obtained in a comparison of the $x'$- $y'$ strain components. These results show that although material orientation does not affect the magnitude of thermal strain, the laser weld beam itself introduces asymmetry. The effect of the asymmetry of the weld beam allows a determination of principal axes through the rotation of the axes of welding.

5.4 Interface Laser Weld Analysis

The thermal strain resulting from a laser weld applied to the interface of two plates is analyzed using procedures and specimen geometry outlined in section 4.4.2. A photograph of a poor quality contaminated weld and a high quality weld is shown in Figure 5.15. The contaminated weld is a hollow pit with very little substrate material intermixing to produce the weld pool. Using the modified pre-welding procedures of section 4.4.2, the resulting welds exhibit a uniformly round weld pool with no cracks throughout the surface of the weld. Intermixing of the two substrate materials is very symmetric on both sides of the weld.

The region used for strain analysis for each interface weld specimen is shown in Figure 5.16. The $x$-component of strain is determined along scan lines located at each $y/s$ location for all weld separation cases: $1\text{mm}$, $3\text{mm}$ and $5\text{mm}$.
a. Poor quality contaminated laser weld

b. High quality laser weld

Figure 5.15 Comparison of interface laser weld results.
Figure 5.16 Interface weld specimen - region of strain analysis
The final moiré pattern images of Region A (Figure 5.16) are shown for the 1mm, 3mm and 5mm cases in Figures 5.17, 5.18 and 5.19. Typical displacement distributions at all $y/s$ locations for each weld separation case are also shown in Figures 5.17, 5.18 and 5.19. For the 1mm weld separation case, the displacement distributions at $y/s$ values greater than 0.14 are linear. This suggests that at locations greater than $y/s = 0.14$, the null pattern of zero displacement is obtained. This situation indicates that no weld induced thermal strain is evident at these locations which are relatively far removed from the laser weld center. Similarly in the 3mm and 5mm case, thermal strain is evident only at $y/s$ locations adjacent to the weld (0.43 and 0.71, respectively). For this study, thermal strain is analyzed for each weld separation case at $y/s$ locations where the displacement distributions are non-linear: 1mm ($y/s = 0.00, 0.14$); 3mm ($y/s = 0.43$ mm) and 5mm ($y/s = 0.71$ mm).

For the 1mm case, the $x$-component of thermal strain at $y/s = 0.00$ and 0.14 are shown in Figure 5.20 and 5.21, respectively. Results for 3mm separation, ($y/s = 0.43$) and 5mm separation ($y/s = 0.71$) are shown in Figure 5.22 and 5.23. Figure 5.24 shows a comparison of thermal strain at locations adjacent to the laser weld (see Figure 5.16): 1mm ($y/s=0.14$), 3mm ($y/s=0.43$) and 5mm ($y/s=0.71$).
Figure 5.17 1mm weld separation - final image and displacement curves.
Figure 5.18 3mm weld separation - final image and displacement curves.
1.0 mm

Weld 1

a. Final moiré image

b. Displacement distribution.

Figure 5.19 5mm weld separation - final image and displacement curves.
Figure 5.20 Thermal strain, 1mm separation, $y/s=0.14$.

Figure 5.21 Thermal strain, 1mm separation, $y/s=0.14$. 

105
Figure 5.22 Thermal strain, 3mm separation, $y/s=0.43$.

Figure 5.23 Thermal strain, 5mm separation, $y/s=0.71$. 

106
Figure 5.24  Comparison of thermal strain adjacent to laser weld:

1mm (y/s=0.14), 3mm (y/s=0.43) and 5mm (y/s=0.71).
The t-test values of greater than 0.10 indicate that there is no significant difference of thermal strain adjacent to the laser weld for the 1mm, 3mm and 5mm weld separation cases. The results indicate that laser weld induced thermal strain adjacent to the weld is independent of the distance between neighboring welds.

The 1mm weld separation case exhibits non-zero strain along the centerline of the interval between welds (y/s=0.00). Thermal strain along the centerline is zero in the 3mm and 5mm cases. This indicates that thermal strain at the center of two welds is not affected by welds that are greater than 1mm apart.

The results of all interface weld experimentation show that thermal strain on a weld interface is approximately 30\% of the strain level induced by the same laser weld at similar locations of the single plate case (see section 5.2). One can conclude that excess energy may be absorbed by the two plates in the form of bending stresses or the energy may be absorbed in intermixing of the two substrate materials during the weld process. Also, the pre-welds on the end of the specimen may constrain the level of thermal strain induced on an interface.
Chapter 6

Conclusions

In the assembly procedure of lightwave devices, light power coupling tolerances require the components to be precisely aligned and fixed in position. Laser welding offers an excellent means to fix the components with a high weld strength to size ratio. A serious impact on long term reliability may occur if the coupled power changes during or after completion of the weld process. Coupled power changes can be the result of motions generated by laser weld induced thermal strain. The goal of this investigation is to perform a baseline study in the parameters affecting thermal strain. Digital image analysis enhanced moiré interferometry is employed to provide a representation of the full-field displacement field. Fractional fringe analysis is applied to determine the actual laser weld induced thermal strain.

The first phase of the investigation is to establish a procedure to accurately measure thermal strain using the moiré interferometer. Digital image processing
allows high magnification of the region local to the laser weld to measure strain. The experimental procedure is applied to an investigation of thermal strain induced on a flat plate by a single laser weld. The results show that thermal strain is constant regardless of the orientation of the raw material with respect to the laser weld beam. Therefore, one can conclude that raw material inhomogeneity does not contribute to thermal strain induced in a lightwave component. The results also reveal that one component of thermal strain along an axis of the weld is greater than the orthogonal strain component. The result prompts an investigation of the symmetry of the laser weld beam.

A study is conducted by applying the test weld with the specimen rotated +30° with respect to original x-y coordinate frame. Strain measurements along the axes of the rotated frame indicate a higher significant difference of the $x'$ and $y'$ components of thermal strain. The maximum $x'$ component of strain is approximately 67% of the corresponding maximum $y'$ component. The results indicate the existence of principal axes within the power distribution of the laser weld beam at the weld focus point. The 67% asymmetric nature of the weld beam may induce unbalanced thermal strain within a welded lightwave package assembly.
causing distortion of precisely aligned components. This may be a factor which could cause a power coupling degradation after laser welding.

The final phase of this investigation is to study thermal strain induced from a laser weld applied to an interface. The experiment is designed to simulate the process of welding an actual lightwave component. Interactions of the two substrate materials during welding presents conditions which are more complex than the single plate investigation. Two test welds are applied at 1mm, 3mm and 5mm weld spacing intervals to specimens which consist of two pre-welded plates. The results show that the magnitude of thermal strain induced from welding on an interface is approximately 30% of the thermal strain level obtained for the single plate case. This fact suggests that much of the beam energy is absorbed in the intermixing of the two substrate materials. Only the 1mm weld separation case produced thermal strain along the centerline of the interval between welds. This indicates that thermal strain at the center of two welds is not affected by welds that are greater than 1mm apart. Also, thermal strain levels at locations adjacent to the weld are not significantly affected by weld separation distance.
This investigation has successfully demonstrated that digital image analysis enhanced moiré interferometry can be used in the study of thermal strain induced by a laser weld. Digital image processing, fractional fringe analysis and high frequency specimen gratings increase sensitivity levels to enable the technique to be an invaluable diagnostic tool in the manufacture of lightwave devices. This study has opened up the potential for many applications in the study of laser weld induced thermal strain. Future experimentation can be designed using cylindrical type specimens to simulate highly complex thermal strain problems. Also the method can be used to study the effects of welding offset surfaces. This would simulate the offset of aligned optical components experienced in the manufacturing process. Finally, the results of this investigation can be used to verify the output of numerical models of the laser weld induced thermal strain. The use of this diagnostic technique can help improve the design of high quality and reliability lightwave devices.
References


In the investigation of laser weld induced thermal strain, it is necessary to record the initial pattern and then remove the specimen to apply the test laser weld. The specimen is then replaced into the interferometer system and the final moiré pattern is recorded. The clamping fixture is designed to provide highly repeatable placement of the specimen to provide an accurate calculation of strain. To verify the degree of repeatability for the clamping fixture, the following experiment is performed with a single plate.

A specimen grating is applied to the specimen and an initial moiré image is recorded. Since no external load is applied to the plate, the initial moiré image exhibits the behavior of a null pattern. Since the resulting carrier fringes are equally spaced, a calculation of displacement along any line will result in a linear distribution. The specimen is removed from the holding fixture and replaced. A second moiré image is then recorded. This removal and replacement procedure is
repeated and the moiré image is recorded for each trial. Displacement is calculated at various scan lines on the specimen in the x and y direction for each trial.

The sample estimate of mean is given by [36]

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{N}$$ (A.1)

The sample estimate of variance is calculated as follows

$$s^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{N - 1}$$ (A.2)

The displacement data yield the following values of mean and variance

<table>
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<tr>
<th>Line</th>
<th>Mean (Slope)</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
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<td>x-direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>9.58E-06</td>
<td>4.08E-08</td>
</tr>
<tr>
<td>2</td>
<td>9.35E-06</td>
<td>5.95E-08</td>
</tr>
<tr>
<td>3</td>
<td>9.46E-06</td>
<td>2.81E-08</td>
</tr>
<tr>
<td>y-direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.03E-05</td>
<td>6.78E-08</td>
</tr>
<tr>
<td>2</td>
<td>9.71E-06</td>
<td>6.79E-08</td>
</tr>
<tr>
<td>3</td>
<td>9.95E-06</td>
<td>9.39E-08</td>
</tr>
</tbody>
</table>
The results indicate a high degree of repeatability in strain calculation using the outlined experimental method and word holder. A very high degree of repeatability verifies the assumption that a specimen can be removed from the interferometer and retain a high degree of accuracy in strain calculation.
Appendix B

Uncertainty Analysis

For a general result $Q(q_1, q_2, q_3 ..., q_n)$, the uncertainty interval for each of the measured parameters $S_i$ is given as [37]:

$$S_i = \left[ \sum_{i=1}^{n} \left( \frac{\partial Q}{\partial q_i} S_i \right)^2 \right]^{0.5} \tag{B.1}$$

In fractional fringe analysis, the displacement $U(x)$ is related to light intensity by the relation

$$U(x) = \frac{1}{2\pi F} \cos^{-1} \left[ \frac{I(x) - I_0}{I_1} \right] \tag{B.2}$$

where $F = 2400$ lines/mm.

The determination of displacement requires measurement of the quantities $I(x)$, $I_0$, and $I_1$. The equation can be written as
\[ U(x) = \frac{1}{2\pi F} \cos^{-1} L(x) \]  

(B.3)

\( L(x) \) varies over the interval (-1,1) for any half fringe. It is necessary to know the uncertainty of \( L(x) \) to determine the uncertainty in \( U(x) \). \( S_L \) can be computed using equation (B.1) knowing the errors in \( I(x), I_0 \), and \( I_1 \). The error interval in \( I(x) \) is \( \pm 0.5 \) gray level since discrete gray levels are used in analysis. \( I_0 \) and \( I_1 \) are computed from \( I_{\text{min}} \) and \( I_{\text{max}} \) in the field. Their error intervals are estimated from (B.1) knowing that \( I_{\text{min}} \) and \( I_{\text{max}} \) each have an error interval of \( \pm 0.5 \) gray level. This leads to an error interval of \( \pm 1/(2\sqrt{2}) \) gray levels for each of \( I_0 \) and \( I_1 \). The uncertainty in \( L(x) \), \( S_L \), is determined using (B.1)

\[ S_L = \frac{1}{2L_1} \left[ \frac{3 + L(x)^2}{2} \right]^{0.5} \]  

(B.4)

This is used in equation (B.1) to obtain the uncertainty interval in \( U(x) \) as

\[ -S_U = \frac{1}{2\pi F I_1} \left[ \frac{3 + L(x)^2}{2(1 - L(x)^2)} \right]^{0.5} \]  

(B.5)

In fractional fringe analysis, the derivative of the displacement curve is used to compute strain. The derivative of the displacement equation (B.3) gives
\[ U'(x) = \frac{1}{2\pi F} \frac{1}{\sqrt{1 - L(x)^2}} L'(x) \]

where \( L'(x) = \frac{dL(x)}{dx} \)

Using equation (B.1), \( S_U \) is determined as

\[
S_U' = \left[ \left( \frac{L(x)'}{2\pi F} \frac{2L(x)}{(1 - L(x)^2)^{1.5}} S_L \right)^2 + \left( \frac{1}{2\pi F \sqrt{1 - L(x)^2}} S_L' \right)^2 \right]^{0.5} \tag{B.7}
\]

The derivative of the normalized light intensity with respect to \( x \) yields the following expression

\[
L(x)' = \frac{I(x)'}{I_1} \tag{B.8}
\]

Using equation (B.1), the \( S_L \) is given by

\[
S_L' = \frac{1}{2I_1} \left[ 4S_{L_1}^2 + L(x)' \right]^{0.5} \tag{B.9}
\]

The error in \( U(x) \) varies at each point across any half fringe. The level of error is dependent on the value of \( L(x) \) and the derivative \( L'(x) \). In equation (B.8), the error of the derivative of displacement increases to infinity as \( L(x) \) approaches ±1.0. At
the fringe centers where \( L(x) = \pm 1.0 \), displacements are determined by searching for maximum and minimum light intensity values, not by fractional fringe analysis.

This allows the infinite error interval at \( L(x) = \pm 1.0 \) to be avoided.

Along a scanline, the magnitude of light intensity at a point \( b \), immediately following a minimum peak at point \( a \) (where \( L(x) = -1 \)) will have a value which is higher by at least one gray level relative to the minimum. The light intensity at point \( b \) is given by

\[
I(b) = I(a) + 1
\]

\[
= I_0 - I_1 + 1
\]  \hspace{1cm} (B.10)

The corresponding value of light intensity is given by

\[
L(x)_{\text{min}} = L(c) = \frac{1}{I_1} - 1
\]  \hspace{1cm} (B.11)

In fractional fringe analysis, the practical range for parameters in equation (B.7) are as are as follows
\[ 50 \leq I_1 \leq 100 \]
\[ \frac{341.3}{I_1} \leq \frac{L'(x)}{I_1} \leq \frac{86016}{I_1} \]
\[ \frac{11.38}{I_1} \leq \frac{S'}{I_1} \leq \frac{2867}{I_1} \]
\[ .003026 \leq U' \leq .005000 \]

Substituting values of \( S_L \) and \( S' \) into the uncertainty equation for the derived displacement, with light intensity \( L(x) = 100 \), the calculated result of the relative uncertainty is

\[ \frac{S_{U'}}{U'} = \left[ (1.09 \times 10^{-4})^2 + (3.68 \times 10^{-5})^2 \right]^{0.5} / .003026 \]
\[ = 3.80\% \]
Vita

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OF
TITLE