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LASER IMAGING WITH A
HOLOGRAPHICALLY PRODUCED LENS

BY
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Abstract

A process is outlined by which a hologram has been produced for use as an imaging device in a laser machining apparatus. Such a hologram has been termed a hololens. The hololens was initially produced by recording the interference between a coherent plane reference wave and an object wave which was produced by passing a plane wave through a transparency. The recording film was positioned at Brewster's angle and the laser light was polarized normal to the surface of the glass plate substrate in order to reduce optical noise caused by interference between the recording beams and their reflections. This hologram was then replicated on dichromated gelatin to produce a phase hologram of low noise, and diffraction efficiency of 28%. A second hologram of a pattern of spots was produced which delivered 33% of the incident energy to the real image distributed equally to the spots in the pattern. The results appear encouraging for the use of a hololens in laser machining applications.
Introduction

The laser's potential as a welding and machining device was recognized early in its development. Early laser researchers often blasted holes in razor blades as a demonstration of the growing power output of early lasers, which was developing more rapidly than laser applications. As a result of these spectacular demonstrations, laser researchers coined a new measure of energy output of their lasers; the "Gilette". As laser technology advanced, application of this source of monochromatic coherent radiation also grew. The work outlined in this report is a study into an improvement of the process by which lasers are utilized to weld or machine.

Specifically, the project undertaken was an investigation of the feasibility of using a hologram as a focusing device in a laser machining application.

Conventional laser welding devices consist of a laser, most often a solid state, pulsed laser because of its high power output, and a lens which focuses the light to a small spot. The laser is capable of welding or machining a very small area because the beam can be focused to a spot size on the order of a few microns. This small spot size produced by laser systems offers two important advantages over many other welding and machining methods: heating is localized; and materials housed in transparent containers may be welded.
The only limitation of such a system is that the focusing lens possesses a single focal point. If a hologram were to be utilized as a focusing device instead of the lens, the laser beam could be imaged into very complicated patterns and the hologram could act as an array of lenses. The energy could then be distributed into many focal points simultaneously, thereby enabling intricate machining jobs to be performed with the single pulse of a high powered laser. (Such a holographically produced focusing device shall henceforth be referred to as a "hololens".)

There are a number of potential applications of holographic imaging of high intensity beams. A laser pulse may be imaged to a large number of spots and used to weld an array of beam lead devices or to drill an array of holes in circuit boards. Patterns may be produced in thin films. In a recent survey of the state of the art, Cohen\(^1\) described a method by which a gap capacitor was produced by cutting a 16 micrometer line through a 0.3 micron thick evaporated gold film with thousands of pulses from a YAG laser. Such a capacitor could be produced with the single pulse of a laser utilizing a hololens.

In the initial research on the subject, J.M. Moran\(^2\) was able to produce a single-spot hololens which diffracted light to a spot size of 14 micrometers with a diffraction efficiency
of 30%. He was also able to produce a hololens of two spots separated by 3.2 mm, each with a diameter of 30 micrometers. His method utilized a phase hologram recorded on dichromated gelatin due to the fact that dichromated gelatin has proven to be the optimum source of low noise, high diffraction efficiency holograms. Since the dichromated gelatin material is sensitive only to wavelengths out to 5000 Angstroms, Moran recorded the hologram with an Argon laser operating at the 4880 Angstrom line, and reconstructed with a high power ruby laser operating at 6943 Angstroms. It is necessary to reconstruct with the ruby laser because to date, it is the most powerful and is capable of a greater pulse width than other solid-state lasers.

This wavelength shift, as mentioned earlier, caused aberrations which Moran was not able to completely remove, but was able to minimize only at the expense of diffraction efficiency. His holograms of two separate spots was only able to deliver 18% of the reconstructing beam to the 1st order real image.

In this attempt to continue and improve Moran's work, the wavelength shift problem was eliminated by recording the hololens on a material which was sensitive to the ruby laser output wavelength, then copying the original hololens onto dichromated gelatin to produce a high diffraction efficiency
phase hologram. Although a ruby laser was not available for testing the hololens in an actual machining application, the utility of the hololens was determined by studies of its imaging capabilities using a low power He-Ne laser as a reconstruction source.
*5*

Theory

In 1948 Dennis Gabor proposed a novel two step, lensless imaging process which he called wavefront reconstruction. Gabor recognized that when a coherent reference wave is present simultaneously with light diffracted by an object, then information about both the phase and amplitude of the diffracted waves can be recorded even though photosensitive materials respond only to changes of intensity. This "total recording" is possible because the reference and object waves interfere constructively or destructively depending upon their relative phase. Hence, phase information is encoded in an interference pattern while amplitude information is recorded directly on the film. After the photosensitive material is properly developed it is placed back into the reference beam, and the recorded interference pattern causes light to be diffracted, thus reconstructing the original object beam. This process is now referred to as holography.

"The term diffraction is applied to the bending of wave normals (rays) when they encounter obstacles whose optical transmission or reflection properties change significantly in distances approaching the wavelength of the illuminating light." Diffraction can be quantitatively explained by the Huygens-Fresnel principle which states
"every unobstructed point of a wavefront at a given instant in time, serves as a source of spherical secondary wavelets of the same frequency as the primary wave. The amplitude of the optical field at any point beyond is the superposition of all of these wavelets".\textsuperscript{4} Applying this idea to a simple qualitative level, refer to figure 2.1

![Figure 2.1, Diffraction at a small aperture](image)

If each unobstructed point on the incoming plane wave acts as a secondary source, the maximum optical path-length difference at an arbitrary point (P) amongst these will be \( \Delta_{\text{max}} = |\overrightarrow{AP} - \overrightarrow{BP}| \), A and B corresponding to a source point at each edge of the aperture. When \( \lambda \gg AB \) as in figure 2.1 it follows that \( \lambda \gg \Delta_{\text{max}} \)
and since the waves were initially in phase, they must all interfere constructively (to varying degrees) at the point (P). A hologram, simply stated, is a more complex deffrating aperture.

The most widely used type of hologram is the off-axis, or offset-reference hologram developed by Leith and Upatnieks at the University of Michigan. This technique of holographic recording utilizes a separate and distinct reference wave which is introduced to the recording material at an angle from the object beam, rather than being collinear with it.

One possible geometry for recording an off-axis hologram is illustrated in figure 2.2. After the coherent illumination has been split into two separate beams, one of the beams is made to strike an object, which is taken to be a transparency with a general amplitude transmittance $t_o(x_o, y_o)$. A second portion of the plane wave travels toward the recording plane such that the wave strikes the film with an angle ($\Theta$) between them. If the object beam and reference beams are represented by a phase and amplitude distribution;

\begin{align*}
A'_{\text{obj}} &= A_0(x,y) \exp \left[-j \phi(x,y)\right] \\
\text{and} \\
A'_{\text{ref}} &= A_r(x,y) \exp \left[-j \alpha(x,y)\right]
\end{align*}
then the amplitude distribution across the film plane is the sum of these two coherent beams;

\[(2.13) \quad U(x,y) = A'_\text{obj} + A'_\text{ref} = A_o(x,y) \exp [-j \varphi(x,y)] + A_r(x,y) \exp [-j \alpha(x,y)]\]

The film responds to the intensity distribution across it, which is represented by the square of the amplitude distribution;

\[(2.14) \quad I(x,y) = A_o^2 + A_r^2 + 2A_rA_o(x,y) \cos [2\pi \alpha y - \varphi(x,y)]\]

It is evident from the equation \((2.14)\) that the film will record the intensity of the reference beam, however, the intensity will be modulated by the third term of the equation, which varies from \(-2A_oA_r\) to \(2A_oA_r\). This third term may be referred to as the interference term, as it is present due to the phase difference between the object and reference beams causing them to constructively or destructively interfere. This interference is recorded as intensity variations across the film and are known as interference fringes. Hence, both the amplitude and phase of the light transmitted by the object have been
recorded, respectively, as amplitude and phase modulations of a spatial carrier (the reference beam) with frequency .

In the usual fashion, the photosensitive material is developed to yield a transparency, in this simple case assuming the recording material is linear; i.e. the amplitude transmittance of the hologram is proportional to exposure. Thus the film transmittance may be represented by:

\[
(2.15) \quad t(x,y) = t_b + \beta [ |A_o|^2 + A'_x A_o \exp (j2\pi \alpha x) + A'_y A_o \exp (-j2\pi \alpha y) ]
\]

where \( \beta' \) is a constant of emulsion scattering determined by the product of the slope of the characteristic curve at the inertia point and the exposure time. The first term of the equation (2.15) \( (t_b) \) is the overall transmittance of the film, determined by the \( B + F \) in the unexposed areas, and by the developed density in the exposed areas. The second term \( (\beta' |A_o|^2) \) is caused by the scattering characteristics of the emulsion. The third and fourth terms are the terms of transmittance caused by the recording of the interference fringes. Note that the fringes have a frequency of \( \nu \) which is given by equation (2.12);

\[
\nu = \sin \frac{\Theta}{\lambda}
\]
If this hologram is then illuminated with a normally incident, uniform plane wave of amplitude $B$, as illustrated in figure 2.3, the field transmitted by the hologram has four distinct components, each generated by one of the transmission terms of equation (2.15):

\[
U_1 = t_b B \\
U_2 = \beta' |A_o|^2 \\
U_3 = \beta' \frac{B}{\pi} A_o \exp(j2\pi\alpha) \\
U_4 = \beta' \frac{B}{\pi} A_o^* \exp(-j2\pi\alpha) \\
\]

The field component $U_1$ is simply an attenuated version of the incident reconstruction field, and thus represents a plane wave traveling along the illumination axis. The second term $U_2$ is spatially varying and therefore has plane-wave components traveling at various angles with the optical axis. The components $U_3$ and $U_4$ are caused when the illuminating beam diffracted by the interference fringes. The component $U_3$ is proportional to the original object wavefront ($A_o'$) times a linear exponential factor. Proportionally to $A_o'$ implies that this term generates a virtual image of the object, while the linear exponential factor ($\exp(j2\pi\alpha)$) indicates that this image is deflected off the transparency axis at angle $\Theta$, as shown in figure 2.3. Similarly, the wave $U_4$ is propor-
tional to the conjugate wavefront $A'_o$, which indicates that a real image is formed on the opposite side of the hologram from the virtual image, this time at an angle $-\Theta$ from the illumination axis. It is this real image which can be formed by the hololens for use in laser machining.

Then the recording medium is silver-halide photographic emulsion, the diffraction is caused by the changes of transmission of the exposed and processed film. This type of hologram is termed an absorption hologram. If the hologram is recorded on a material such that the record is written in localized changes in the index of refraction of the emulsion, the hologram is called a phase hologram. In the absorption hologram case, an exposure and development process is chosen to make the spatial variation in the absorption constant of the hologram plate correspond to the pattern of intensity of the incident light. In the case of the phase hologram, the spatial phase modulation imposed on a wave as it passes through the hologram is made to correspond to the incident intensity pattern.

A phase hologram recorded on dichromated gelatin film is the optimum quality hologram yet to be produced.
A properly recorded and processed hologram formed on dichromated gelatin displays both high diffraction efficiency and low noise. For this reason, this material was utilized for the production of the hololens.

"It has been known since the 1830's that blue light can cause gelatin molecules to cross link when there is a small amount of dichromate present in the gelatin. Cross linking of gelatin molecules is also known as hardening or tanning of the gelatin. Sufficiently hardened gelatin is insoluble in water. Therefore, when a layer of gelatin containing a small amount of the dichromate is exposed to a light pattern for a sufficient length of time, the illuminated portion of the gelatin becomes insoluble in water while the unilluminated portion can be readily washed away in water. Thus, if the illuminating light is a holographic interference pattern, a phase hologram is produced."  

A paper written in 1969 by L.H. Lin describes an improved method of preparing dichromated gelatin phase holograms. Lin's method utilized pre-hardened emulsions in which the unexposed gelatin is not readily
washed away in water. "However, water is absorbed by the gelatin and causes the gelatin to expand. The amount of absorption, and hence the expansion, decreases with exposure. Consequently, the spatial intensity variation of the light interference-pattern during holographic exposure results in a corresponding variation in the expansion of the gelatin film. Upon subsequent rapid dehydration in isopropanol, a hologram is formed both on the surface and in the volume of the film."

In a later study, Lin's colleagues R. Curran and L. Shankoff refuted Lin's conclusion that the dichromated gelatin hologram was both a volume and surface hologram. Volume holograms were initially described

\[ DB' + B'E = 2d \sin \Theta = \lambda \]

Figure 2.4, Volume diffraction grating
by Bragg during a study of X-ray diffraction from atomic planes in a crystal. The output of such a diffraction pattern is the in-phase addition of light scattered by successive planes within the volume of the emulsion. Bragg assumed that the diffraction was actually caused by reflections of the incident light from the planes. Maximum diffraction occurs when the angles of incidence and reflection are equal, as shown in figure 2.4. This condition is known as the Bragg condition and the angle \( \theta \) is the Bragg angle. Lin theorized that the diffraction in the dichromated gelatin hologram was due to variations of refractive index within the bulk of the gelatin, and was therefore a volume hologram. With a series of experiments, Curran and Shankoff disproved Lin's suggestion and concluded that the dichromated gelatin hologram is purely a surface grating, the diffraction being caused by the gelatin to air interface.

Curran and Shankoff theorized, then, that the mechanism of holograph formation in dichromated gelatin is as described in figure 2.5. The gelatin is exposed holographically then placed in water where the unexposed area absorbs water and expands. The rapid
Figure 2.5

IMAGE FORMATION IN DICROMATED GELATIN FILM

Exposure

Water

Develop

Isopropanol
removal of water by isopropanol in the second step of the development process creates strains in the gelatin film which are relieved by splitting. "The resultant cracks in the hologram manifest themselves in an obvious location; between the highly exposed planes of cross-linked gelatin". Under these conditions, Bragg diffraction occurs as a result of scattering from the series of air-gelatin interfaces and is purely a surface phenomenon.

In order to replicate the original hololens, which is recorded on a conventional silver-halide emulsion onto the dichromated gelatin, it is necessary only for the light source during duplication to have a coherence length greater than the distance between the original and the replication. Since the copy can be contact printed on a vacuum easel, a coherence length of only a few microns is sufficient for successful replication.
Experimental

To summarize the goals of this research, the project had four basic steps;

(1) Record a hololens onto a silver-halide emulsion
(2) Copy the original onto dichromated gelatin to produce a phase hologram
(3) Reconstruct the image
(4) Evaluate the image quality

A review of the literature on holographic recording may lead a researcher to believe that the stringent parameters on the production of a hologram make the process extremely difficult. Holographers in the past have suggested such critical restraints upon design parameters as; (1) mechanical vibrations of more than \( \lambda/8 \) make holographic recording impossible (2) although ambient temperature change tolerances have not been established, some researchers have resorted to sub-basement level "clean-rooms" with close temperature control. In a study designed to simplify the holographic process Carcel, et al.\(^\text{10}\) demonstrated that if the exposure time was kept less than a few seconds, successful holographic recording can be achieved with the following considerations; (1) a simple inexpensive experiment support can
be used to isolate the optical elements from vibrations (2) close temperature is not essential (3) extremely high quality precision optical elements and mounts are not required, and (4) long laser warm-up periods for mode stabilization are not necessary.

In order to assure successful holographic recording, all that was required was a method by which the laser, the recording material, and the optical elements could be secured in order to prevent them from vibrating. A steel surface optical table was used, which was vibration damped by placing the table on top of a partially inflated inner tube. The optical table measured 2 x 3 feet and weighed 35 pounds. The steel surface made it possible to support the optical elements on magnetic supports, or on optical benches which were magnetically held in place on the table. The entire system proved quite effective in eliminating mechanical vibration.

Figure 3.1, Holographic recording apparatus
The original recording geometry is shown in figure 3.2.

The laser, a .5 milliwatt Helium-Neon outputs at a wavelength of 632.8 nanometers with a beam diameter of 1.2 mm. The beam was expanded to approximately 8 mm with a 10X microscope objective and a positive lens. When the positive lens was placed such that the focal plane coincided with the focal plane of the microscope objective, the image formed by the lens is at infinity, hence the beam is composed of plane waves. A simple cube beam splitter, which consists of two right
angle prisms which are cemented together after the hypotenuse of one prism is coated with a semi-reflecting material, split the beam into two parts of equal intensity. The reference beam traveled down to the first of two front surface mirrors, then on to the second, and finally to the film plane. The object beam, after emerging from the beamsplitter, passed through the object transparency, then was reflected downward by a third front surface mirror and struck the film plane. The angle between the object and reference beams in this original geometry was 16°, and the film plane was adjusted such that the reference beam struck the film at approximately normal incidence. The object was a transparency produced by reducing a drawing of a dot onto KODALITH film. The result was a transparent pin-hole of approximately .8mm in diameter, surrounded by regions of opaque. The object was produced in this fashion because of the simplicity of producing similar transparencies of more complicated objects in future work.

Before the initial attempt to record the interference between the two beams, a simple microscope was placed in the region of interference, at a slight angle as shown.
in figure 3.3

Reference Beam

Object Beam

Microscope

Figure 3.3, Observation of the interference fringes

In this manner, the fringe pattern could be observed and a check made of the vibration dampening of the apparatus. The fringes appeared to be stable, as long as no direct jolt was applied to the table or any of the elements. In this geometry, the fringe frequency is given by

$$U = \frac{\sin \theta}{\lambda} = \frac{\sin 16^\circ}{633 \times 10^{-6}} = 435 \text{ cyc/mm}$$

The microscope was equipped with a 40X objective and a 10X eyepiece, making the fringes easily visible.

The hololens was originally recorded on KODAK 649-F spectrographic plates, Kodak's version of a Lippmann
emulsion which is an ultra-high resolution, high contrast, panchromatic material coated on glass plates of .5mm thickness. In order to avoid wasting the costly plates, each 5x7 inch plate was cut into 12 smaller pieces on a glass cutting device which was designed and constructed according to Kodak's suggestions.  

Throughout the discussion of holographic recording, it has been assumed that the recording medium is exposed in such a way as to assure recording within the linear region of the amplitude transmission vs. exposure curve. Amplitude transmittance is determined experimentally by determining the intensity transmittance ($\mathcal{I}$), the amplitude transmittance ($t$) is then found by $t = \sqrt[3]{\mathcal{I}}$. 

The effects of non-linear recording will be discussed later in this paper, however a study of the beam intensities and the exposures the beams provide the film is important before high-quality holographic recording is undertaken. 

Using the 649-F emulsion as a radiometric device, the reference and object beams were recorded separately, then the beamsplitter was removed from the system and the total beam was recorded several times with neutral density filters in the beam. Each exposure was made for one second on 649-F plates. The series of exposures made with the ND filters in place produced the characteristic curve shown in Figure 3.4. No absolute measurements of illumination were made, however relative values will serve in the following analysis.
The recorded intensity of the reference beam was 2.4 and the object beam recorded density was .4. Using the characteristic curve in Figure 3.4, it can be seen that the relative log exposure of the reference beam is 1.4 while the object beam provided a relative log exposure of .6. Since the exposure time was one second for each beam and the beams illuminated approximately the same area on the film surface, and antilog of these numbers is an approximation to the relative intensity of each beam. Hence, the reference beam's relative intensity was 25 while the object beam's was 4, a beam ratio of 6 to 1.
Recalling equation 2.14;
\[ I(x,y) = A_o^2 + A_r^2 + 2A_o A_r \cos [2\pi \phi y - \alpha(x,y)] \]

The maximum intensity at the film plane will occur when \( \cos (U) = 1 \) and the minimum when \( \cos (U) = -1 \). Hence;
\[
\begin{align*}
I_{\text{max}} &= A_o^2 + A_r^2 + 2A_o A_r \\
I_{\text{min}} &= A_o^2 + A_r^2 - 2A_o A_r
\end{align*}
\]

Therefore, the maximum intensity of the fringes caused by the interference of those beams is given by;
\[
I_{\text{rel. max}} = 25 + 4 + 2\sqrt{(25)(4)} = 49
\]

which corresponds to a log (relative) exposure of 1.69.

The minimum intensity of these fringes;
\[
I_{\text{rel. min}} = 25 + 4 - 2\sqrt{(25)(4)} = 9
\]

Looking now to the amplitude transmission vs. exposure curve, it can be seen that care must be taken in order to assure exposure in the linear portion. The one second exposure used in this analysis caused the fringe pattern to be overexposed.
Figure 3.4, Characteristic Curve for 649-F

A 100x photomicrograph of the hologram produced by the geometry appears as Figure 3.5;

Figure 3.5, Holographic Recording (100x)
The hologram was exposed for one second and processed in D-19 for 4 minutes, followed by conventional processing steps.

Although this hololens diffracted light into real and virtual images, the diffraction efficiency was very low and duplication of this hologram was impossible. The first attempt to improve the hologram was the addition of a spatial filter.

The laser was operating in the TEM_{oo} mode, so that it provided a Gaussian distribution output. An amount of optical noise was also present in the emitted light. The noise can arise from several causes including reflections from the walls of the laser tube, to dirt and imperfections on the exit mirror of the laser and the beam expanding microscope objective. The spatial filter used was designed to eliminate such optical noise without altering the output mode of the light. This was possible due to the fact that when the beam is focused by the microscope objective, the noise and the central spot are not imaged at the same position. The Gaussian distribution of light can be focused and passed through the pinhole. The optimum size pinhole is large enough to permit nearly all of the Gaussian
light to pass, yet small enough to block the optical noise. A pinhole of 35 μm is recommended for use with lasers of the beam diameter output of the He-Ne laser which was utilized.

![Figure 3.5, Spatial Filtering](image)

Alignment of the pinhole is a difficult task, requiring some type of X,Y, and Z controls on the position of the pinhole, so that it can be properly placed at the focal point of the imaged beam. For this purpose, a holder was designed, using a 90° angle iron with screws on either side allowing motion in a horizontal or vertical direction of both the laser and the spatial filter/beam expander.
Figure 3.7, Spatial filter and alignment apparatus

Once the pinhole was adjusted so that it was in the focal plane of the lens, it was then placed in the holder with the laser, and the necessary adjustments were made to allow the focused beam to pass through the pinhole. This particular spatial filter arrangement also had a positive lens which collimated the filtered beam.

Figure 3.8 is a micro-densitometer trace of the hologram produced by this recording geometry.

(see following page)
The noise has been eliminated by the addition of the spatial filter, however, the low contrast of the fringes made replication difficult as well as delivering less than optimum diffracted energy to the real and virtual images. Once again returning to equation 2.14, it can be seen that maximum fringe modulation is obtained when the object and reference beams are balanced, i.e. the beam ratio is 1 to 1. In order to reduce the intensity of the reference beam, .9 neutral density was placed in the beam as shown in figure 3.9. (see following page)
Figure 3.9, Recording Beam Paths

A micro-densitometer trace of the hologram produced by the geometry of figure 3.9 appears as figure 3.10. The hologram was recorded with an increased exposure time of four seconds, and processed again in D-19 for four minutes. It can be seen that the addition of the neutral density did increase the modulation in the recorded fringes, however, the scattering of light by the filters (three KODAK WRATTAN .3 neutral density filters were used) caused a great deal of noise in the recorded fringes, which appears as the low frequency irregular modulation of the fringe pattern. (see following page)
Figure 3.10, Micro-d trace of hologram

A simple way to eliminate optical noise has already been described, the use of a spatial filter.

In order to put neutral density into the reference beam without attenuating the object beam, it was necessary to spatially filter each beam separately, making a change in the recording geometry necessary. The final arrangement of optical elements used to record the hololens appears as figure 3.9.

(see following page)
The 649-F emulsion was exposed in this geometry for four seconds, then developed in D-19 for four minutes. The resulting hologram was a high contrast low noise recording of the interference fringes, as shown in the photomicrograph and micro-densitometer trace of figure 3.10.

(see following page)
It was now possible to attempt to replicate this hologram of a point source onto the dichromated gelatin material. The dichromated gelatin emulsion was prepared on glass plates by first fixing out all of the silver of a 649-F spectrographic plate, then soaking the emulsion in methanol for a few minutes to remove the sensitizing dye and other impurities in the gelatin. The result was an approximately 12-15 μm thick layer of hardened gelatin on the glass plate. The gelatin was sensitized by soaking for five minutes in a 5% solution of potassium dichromate, then allowed to dry. Once again, each large plate was cut into 12 smaller pieces.

Lin\textsuperscript{12} reported a maximum diffraction efficiency of 80% for a holographic recording of the interference of
two plane waves. The maximum diffraction efficiency decreases as the interference pattern becomes more complicated. Diffraction efficiency of the developed hologram is dependent upon the exposure. Lin found maximum diffraction efficiency at an exposure of 30m Joules.

The exposing device used for replication was a diazo contact printer equipped with a high pressure mercury arc lamp and a vacuum easel. Since no absolute measure of the illumination provided by the printer was made, an exposure series was made. The original hololens was placed in contact, emulsion to emulsion, on the vacuum frame. Exposure times ran from 2 to 20 minutes. The holograms were developed by placing them in running water for 5 minutes followed by a 2 minute wash in isopropanol. The hologram exposed for nine minutes had the maximum diffraction efficiency with 28% of the energy striking the hologram being diffracted into the first order real image.

The reconstructed real image of a pinhole produced by this dichromated gelatin hologram contained two aberrations which made it unacceptable for laser welding purposes. Firstly, the energy was diffracted into several orders of images beyond the first; causing a
reduction in diffraction efficiency. Secondly, the image of the pinhole which was produced was a spot with two smaller spots on opposite sides. Since the dichromated gelatin hologram is a phase hologram, it has no optical density. Hence, it was necessary to study the fringes with the aid of a differential interference microscope.

A diagram of the optical system of a differential interference microscope appears as in figure 3.11.

![Diagram of optical system of a differential interference microscope](image-url)

Figure 3.11, Differential interference microscope
This microscope utilizes polarized light which is sheared by the Savart plate \((Q_1)\) into two coherent rays which vibrate perpendicular to each other, and at the same time are laterally displaced from each other. The rays are passed through the specimen and then are made to interfere, so a phase difference imparted by the specimen appears as an amplitude difference in the eyepiece. When the lateral displacement caused by the Savart plate is smaller than the resolution limit of the microscope, the image will show no double contours. It is also possible, by tilting the second Savart plate \((Q_2)\) to cause the background, and other flat areas of the specimen to show an interference color. A photomicrograph of the dichromated gelatin hologram made by a differential interference is shown in figure 3.12.

![Photomicrograph(100X) of hologram](image)
It can be seen that the dichromated gelatin hologram fringe pattern consists of sharply defined edges between the exposed and unexposed areas, whereas the original hologram consisted of sinusoidal varying fringes. The result of these fringes, a cross section of which appears in figure 3.12, is the forming of higher order images upon reconstruction of the hologram, and a resulting loss of diffraction efficiency to the first order image.

Figure 3.12, Cross-section of fringes produced in dichromated gelatin film
Initially, it was though that the sharp edges were caused by overmodulation of the dichromated material, in other words, the fringes were being recorded on a non-linear portion of the material. However, reducing the input modulation by lowering the contrast of the fringes on the original did not cause the reduction of the amount of energy being diffracted into the higher order images, it merely reduced the overall diffraction efficiency of the dichromated gelatin.hologram. It was concluded, therefore, that this was not a tone-reproduction problem.

Researchers in the past who have recorded directly onto dichromated gelatin report that the material is linear over a large range, hence the formation of the "hard" edges must be caused during the replication process. It is believed that although the contact between the original and the copy during replication is kept as close as possible, light which is diffracted by the original does effect the exposure present over the film surface. (see figure 3.12) The problem is further amplified by the mechanism of the dichromated gelatin development in which large exposure differences across an edge are manifested by a crack in the emulsion along the edge. This effect results in the formation of the
higher order images upon reconstruction.

Since the effect was caused by diffraction in the copying process, and by the mechanism of development of the dichromated gelatin, no solution to the problem could be found. The result was a hologram of lower diffraction efficiency than hoped for, due to the energy being diffracted into higher order images.

The second aberration which effected image quality was the appearance of two "ghost" images on opposite sides of the desired image. The images appeared at a distance of a few millimeters from the actual image, and were much lower in intensity than the actual. These second images were caused by a low frequency modulation in the recorded fring pattern.

Because the ghost images appeared in exactly the same position in the reconstruction of each hologram in the exposure time series, it was evident that the low frequency modulation was present in the original, however, since the efficiency of the original hologram was low, the ghost images were not visible.

Figure 3.13 is a photomicrograph of a hologram recorded exactly as the original hologram, however the development in D-19 was allowed to continue for six minutes. In this photo, the low frequency fringes are clearly evident. (see following page)
Recalling equation 2.14, the angle between the two beams interfering to cause this low modulation is given by:

\[ \sin \theta = \frac{n-\lambda}{\lambda} \]

the measured frequency of the fringes was 2.73 cyc/mm hence;

\[ \theta < 0.1^\circ \]

The angle between the interfering beams was less than one tenth of a degree, which indicates that the interference was between the recording beams and reflections of these beams off of the front and back glass surfaces of the recording plate. (see figure 3.14b)

It is possible to eliminate surface reflections by recalling the condition established by Brewster for
FIGURE 3.4b, Reflections from air-glass interface.
reflection of polarized light. The condition's explanation is beyond the scope of this work, however, the law can be stated; "If an incoming unpolarized wave which can be considered to be made up of two incoherent orthogonal waves, is made incident upon a medium of different index of refraction than the one its traveling through such that $\theta_r + \theta_t = 90^\circ$, only the component polarized normal to the incident plane will be reflected."\(^{13}\)

The particular angle of reflectance for which the situation occurs is designated by $\theta_p$ and referred to as Brewster's angle. Hence, from Snell's law;

$$n_t \sin \theta_p = n_i \sin \theta$$

and the fact that;

$$\theta_t = 90^\circ - \theta_p$$

it follows that;

$$n_i \sin \theta_p = n_t \cos \theta_p$$

and;

$$\tan \theta_p = n_t / n_i$$

hence, when the incident beam is in air and the transmitting medium is glass, Brewster's angle is $56^\circ$. Thus, if light is polarized such that the plane of polarization is parallel to the glass/air interface, and the angle of incidence is made $56^\circ$, no light will
be reflected from the front surface of the glass. Also, since the light is bent toward the normal upon entering the glass, it strikes the second glass/air interface at an angle such that reflections are reduced to zero. Figure 3.14 graphically represents Brewster's Law.

![Figure 3.14, Reflectance vs. incident angle](image)

Figure 3.15 represents an alternative holographic reconstructing geometry in which the holograms were recorded at some angle $\theta$. Upon reconstruction, the hologram is illuminated by the conjugate of the original reference wave, producing the real image in proper perspective.
Thus, if the laser source is polarized, and the geometry is arranged such that the plane of polarization is parallel to the glass plate holding the emulsion, a hologram which is free of noise caused by reflections can be produced without sacrificing diffraction efficiency or image quality.

A final hologram was recorded, using an array of four pinholes arranged in a square pattern as an object. The hologram was recorded at the Brewster angle, the angle being determined simply by rotating the film holder until the reflections from a sample plate were no longer visible.

The diffraction efficiency of this hologram was measured by recording the diffracted light on KODAK PANATOMIC X film. A sample of the film was then exposed on a KODAK 101 sensitometer with a KODAK WRATTAN FILTER (Q6) in place in order to stimulate the spectral quality of the laser illumination. From the characteristic curve produced by this spectrometric exposure, it was possible to determine the illumination provided by the diffracted laser light by measuring the densities of the recorded reconstruction.

The final hololens delivered 33% of the illumination incident upon it to the first order real image.
The total energy in each of the spots could be altered by changing the position of the hololens in the illuminating reconstruction beam. By proper positioning of the hololens, it is possible to assure equal energy to each spot.

If a positive lens is placed in the path of the real image forming rays, the image can be reduced in the overall area. Figure 3.15 A & B are photomicrographs of the reconstructed real images made by placing a piece of 649-F in the real image beam after the beam has been reduced by a positive lens. Figure 3.15A is the spot pattern, each spot having a diameter of approximately 140 μm, while figure 3.15B is the pattern further reduced to a diameter of 80 μm per each spot.

Figure 3.15, Photomicrograph of recorded real image
Conclusion

Cohen\(^\text{14}\) reports that the amount of energy required to accomplish a weld varies depending upon the materials to be welded, however, the average power required is about one Joule. The studies made by Moran\(^\text{15}\) indicate that the dichromate gelatin can withstand an energy density of 20 Joules per \(\text{cm}^2\). Since the area of the recorded holograms was approximately \(0.5 \text{ cm}^2\) and their diffraction efficiency was around 30\%, the hologram of the single spot could easily be used for welding applications, delivering a maximum of 3 Joules to the area to be welded without damaging the hologram. The hologram of four spots, however, will not be able to deliver enough power to each spot to allow welding. On the other hand, if the overall area of the recorded hologram were increased, the hololens could easily diffract enough energy into each spot.

It is unfortunate that the hololens was untested in actual laser welding applications. The next step in this work need be an actual weld performed by the hololens, in order to test the hololens' durability and the ability of the real image to be aligned to allow multiple welds with a single laser pulse. A laser with enough power to enable such tests was not available and therefore
was left for further research.

The process described here is a two-step process, involving the replication of a hologram onto another, and the procedure naturally leads to loss of resolution in the final hologram, and causes loss of maximum diffraction efficiency due to non-linear recording. This two-step process, however, does produce high quality images with a diffraction efficiency high enough to make it feasible for a laser machining application. I believe the project has successfully proven the utility of a holographically produced imaging device as an improvement in a laser welding apparatus.
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