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Investigation of a Direct Diode Laser for Manufacturing Application

M.E. Marince, Rich P. Martukanitz, John M. Haake

Abstract

Direct diode laser systems are a new tool for manufacturing. In these systems, numerous laser diodes emit light that provide a highly efficient, compact, and uniform heat source for use in industrial applications. This program involved the evaluation of a 3.0 kW diode laser for its applicability in a variety of materials processing applications. This investigation included the assessment of the direct diode laser for laser welding, laser transformation hardening, laser cladding, and laser assisted forming. Results of this investigation indicate that these systems may provide a cost effective means for laser processing when a more-diffuse heat source is applicable.

1.0 Introduction and Technical Background

As tools for use in industrial applications, high-powered direct diode lasers, also known as semiconductor lasers, are becoming more prevalent.].[8,9,10] Diode laser technology has been used for a number of years in compact disks and laser printers and laser pointers.[3, 4] Their low cost, high efficiency, and compact design make them attractive and, a technology for the future.[2]

Laser Diodes, Sometimes called injection lasers, are similar to light-emitting diodes [LEDs]. In forward bias [p-side +], electrons are injected across the P-N junction into the semiconductor to create light.[1] These photons are emitted in all directions from the plane on the P-N junction.[1] To achieve lasing, mirrors for feedback and a waveguide to confine the light distribution are provided. [1] The mirrors of a laser diode are cleaved facets of the III-V [AlGaAs] semiconductor from which the laser are made. [1] AlGaAs lasers can be made to emit between 0.72 and 0.88 μm. InGaAs emit photons having a characteristic wavelength of between 0.8 and 0.98 μm. [7] High power diode lasers are composed of many individual laser cavities that are processed into a single bar. An array of laser diode bars can be seen in Figure 1. The light emitted from them being asymmetric. Each bar is capable of emitting 65 watts and having a conversion efficiency of greater than 50%. The remaining heat due to joule heating is removed by mounting the laser diodes on microchannel water-cooled heatsinks, as also seen in Figure 1.

The light emitted at the facet of the laser diode is highly divergent and to make this usable, micro-optics are precisely mounted parallel in front of each laser diode bar. Since the other axis referred to as the “slow axis,” is not collimated and is left to diverge the final focussing lens will produce a concentrated line of light during focus. This produces a beam having a nearly rectangular intensity profile along the line with a guassian profile perpendicular to the line. The 3.0kW laser used in this feasibility study used 4 stacks of 20 bars, which are brought to a line by a single macro lens. This can be used to generate power densities as high as 100 kW/cm^2. This generates an ideal processing laser for large area applications. Since the power densities are lower than that typically required to create a “key hole,” welding was performed during this investigation in ‘conduction” mode.

The particular direct diode laser used in this study generally operates with a center wavelengths of 810 nanometers, which is in the near infrared range and not visible to the human eye.[3,] Typically, Direct diode lasers operate at a shorter wavelength than the Nd: YAG [1.06 um] and CO_2 [10.6 um] lasers, which are commonly used in industrial applications.[2] This leads to an advantage of the diode laser system, since the lower operating wavelength results in a higher absorption rate with most metals.[2] The absorption rate of aluminum actually peaks near the operating wavelength of the laser used here.[2]

System efficiency is another advantage of direct diode lasers. When comparing the amount of output laser energy for a given electrical input, the efficiency of the direct diode laser is much higher than that of conventional laser systems.[2, 3,4] Table 1 represents a chart comparing the direct diode laser to other systems. The advantages of direct diode lasers are then decreased footprint, lower maintenance, and less power to operate than lasers typically used in industrial environments.[3, 4] Finally, direct diode lasers are relatively small and compact, such that the laser head can easily be mounted to a robotic arm or gantry for use. .

Another advantage of direct diode lasers is that they are solid-state lasers. This yields a highly controllable heat source. The laser used in this study has a modulation bandwidth of 20KHz on each of the 4 stacks of diodes. This makes it possible for in-situ control of heat on a part during fabrication. This is very desirable for applications such as heat treatment.

There are a wide variety of potential applications for diode lasers, a few of which have been investigated in this research. The great advantage of the direct diode laser is that all the applications described herein can be performed with the same direct laser system without the need for changing tools or optics. This could eventually provide manufacturers with tremendous flexibility.

2.0 Experimental Procedure

This investigation was conducted using a 3.0kW diode laser manufactured by NUVONYX Incorporated, Bridgeton, MO. The ISL™2500L laser system operates at a wavelength of 808±10 nanometers with the average beam spot size being approximately 12 to 14mm in length by 1mm wide. The average power density of the system is approximately 23.5 to 27.5kW/cm^2, with a peak power density of 40 to 50 kW/cm^2.

The study was performed with the direct diode laser in two mounting configurations. The first configuration involved mounting the laser head in a small processing chamber for providing cover gas and beam containment. The laser head was rigidly mounted to allow only movement in a vertical direction. Movement along this axis permitted the user to adjust the focal point of the beam in relation to the work-piece. Thus, effectively controlling the beam spot size. A computer controlled linear stage provided work-piece movement in a single direction at various speeds. In the second configuration, the laser was mounted to the end of a six-axis robot. In both instances, the cover gas was argon when used.

3.0 Results and Discussion

3.1 Welding

Welding was conducted on various materials. During these experiments the length dimension of the focused beam, which was approximately 12 to 14 mm was directed parallel to the direction of welding.

3.1.1 Plastic Welding

The first series of experiments investigated the applicability of the laser for welding of plastic. In this experiment, welds were conducted on two sheets of plastic at the faying surfaces. A translucent piece of plastic was placed above an opaque piece of plastic, both 3.175 millimeters thick, and welded. Trials were conducted at 700 Watts, focused beam (spot size of 12-14 by 1 mm), with 33 liters per minute of argon shielding present. It was desired that the laser beam penetrate through the translucent top-piece and become absorbed in the opaque bottom-piece, thus forming the weld at the faying surfaces. The optimal results were achieved at a travel speed of 6.35 meters per minute (250 inches per minute). A travel speed of 7.62 meters per minute (300 inches per minute) provided insufficient heat input to melt the plastic and 5 meters per minute produced a visible melt on the surface of the translucent piece, which was not desired.

3.1.2 Stainless Steel 304 Welding

The welding of stainless steel 304 was also investigated with the direct diode laser using the six-axis robot. The goal of this investigation was to obtain complete penetration of the specimen, while providing little distortion, and good weld quality. The thicknesses of the stainless steel were 0.6 and 0.9 millimeters and each piece was approximately five centimeters by ten centimeters in size. The weld was made along the 10-centimeter side.

During the investigation, the power was varied from 1200 to 3150 Watts, and the maximum speed to achieve full penetration was determined. Argon shielding gas at 47.2 liters per minute was supplied through a sparger. The work-pieces were clamped down very close to the seam to minimize distortion during welding. A chart of the welding speeds versus power is shown in Table 1. The welds that resulted at all powers were aesthetically smooth, showing very little oxidation on the surface. A micrograph of two of the welds is shown in Figure 2.

3.2 Surface Transformation Hardening

Surface transformation hardening was investigated with the use of the diode laser. Laser surface transformation hardening is the heating of a surface by use of a laser and then allowing rapid quenching by conduction. This provides a hardening on the surface of the material through a solid-state transformation that results in the formation of a high-hardness microstructure, i.e. martensite. The depth of the hardened zone may be altered by varying the amount of heat input provided to the work-piece. In this evaluation, heat input was altered by varying travel speed. During these evaluations, the length dimension of the spot of focus, which was approximately 12 to14 mm, was directed perpendicular to the direction of processing. This allows very large surface areas to be hardened in a single pass. Laser surface transformation hardening is often used to harden localized areas of machine components such as gears and bearings. A flat-topped

Gaussian shaped hardened zone is obtained through a laser beam surface treatment, as seen in Figure 3.

Since the diode laser is modular in design, many stacks may be placed side by side to create an unlimited laser heat-treated width. Also, the phenomenon of superhardening occurs when multiple, overlapping passes are conducted with the diode laser. During superhardening, the formation of austenite from martensite is extremely rapid, thus, inducing imperfections that subsequently affect the strength of the martensite. Therefore, the interpass region hardness values ranging from 59 to 65 Rockwell C are obtained as seen in Figure 4.

However, in the interpass zone, backtempering can also occur because the heat generated in the second pass causes a portion of the initial pass to be raised to a temperature at which tempering occurs. Thus, the supersaturation of the quenched martensite is relieved and equilibrium mixtures of phases are approached. Tempering results in a decrease in the strength and hardness and a microstructure of tempered martensite. The back tempered region is generally 1 to 3 mm wide with a 40 to 50 Rockwell C hardness range. The effect of backtempering on the case depth of 4140 steel can be seen in Figure 5.

3.2.1 Surface Transformation Hardening of 4140 Steel

Alloy 4140 steel was evaluated for surface hardening. In this case, the 4140 steel was 25.4 millimeters thick and 50.8 millimeters by 101.6 millimeters in size. The parameters that were used were a constant power of 3150 W, a focused beam, a constant argon shield of 33 liters per minute, and speeds varying from 0.127 to 5.08 meters per minute. Figure 6 displays the Vickers hardness numbers at different depths from the top surface. The data of Figure 10 represents processing at a speed of 0.254 millimeters per minute, which was the slowest speed that was obtained before melting. Evaluation of Figure 6 reveals that the direct diode laser was able to impart surface hardening to a depth of approximately 0.5 mm. This hardened zone was found to exhibit a hardness of over 200% greater than that of the base metal. A profile of the hardened zone in 4140 steel can be seen in Figure 7.

3.2.2 Surface Transformation of Titanium 6-4

The next material that was investigated was titanium 6-4 alloy. The titanium 6-4 was 7.3 millimeters thick and each piece was 50.8 millimeters by 101.6 millimeters in size. Both a leading and a trailing shielding gas were used, each at 33 liters per minute. The power for the investigation was a constant 3150 W, the beam was focused, and speeds were varied at 0.254 to 5.08 meters per minute. Figure 8 displays the Vickers hardness number versus the distance from the top surface for titanium 6-4 that was processed at 1 meter per minute travel speed. Reviewing Figure 8 reveals that an increase hardness associated with the titanium 6-4 was negligible using these parameters. This indicates that oxygen and nitrogen pick-up was low. Additional characterization of the titanium 6-4, including fatigue and fatigue crack growth is necessary to evaluate the direct diode laser processed material.

3.3 Cladding

Laser cladding was investigated for its applicability with the direct diode laser. Loose powder of Inconel™ 625, Stellite™ 6, or stainless steel 420 was pre-placed onto a 4140 steel substrate and melted with the laser. Complete fusion of the clad material with the base material was desired. For each material, the loose powder was placed 1.20 millimeters thick and 14 millimeters wide. During each of the laser cladding evaluations, the length dimension of the spot at focus, which was approximately 12 to 14 mm, was directed perpendicular to the direction of processing. This resulted in a larger area of powder being melted. Also, for these investigations, the laser beam was at focus on the top surface of the work piece. The cladding materials were chosen based on their application in industry to provide hard, corrosion resistant, and wear-resistant surfaces. No cover gas was used during the laser cladding operation. Dilution into the substrate, which is the ratio of the intermixed zone and the clad thickness is only 0.02% when using the direct diode laser.(1) Laser cladding done with the CO_2 or Nd: YAG lasers generally yields a dilution of 1 to 10%.(1) Note also that the deposit efficiency of laser cladding with the direct diode laser is in the range of 85 to 95%.(1)

3.3.1 Inconel™ 625 Cladding

Inconel™ 625 was initially investigated. The parameters used were a constant power of 3150 Watts, no cover gas, and the speeds were varied from 0.18 to 0.5 meters per minute. The optimal speed was 0.18 meters per minute. This produced clads with good edge detail and a uniform surface. Photomicrograph of the structure of the clad is shown in Figure 9.

3.3.2 Stainless Steel 420 Cladding

Stainless steel 420 was clad under varying parameters. In this investigation, the power was a constant 3150 W, no cover gas was used, and speeds were varied at 0.18 to 0.23 meters per minute. The clad producing optimal features were at a speed of 0.20 meters per minute.

3.3.3 Stellite™ 6 Cladding

Stellite™ 6 was the final powder that was investigated for its ability to produce a wear surface. The parameters used were a constant power of 3150 Watts, no cover gas present, a focused beam, and speeds ranging from 0.18 to 0.23 meters per minute. In this case, the best clad determined, by its visual features of good edge quality and a uniform surface, was performed at a speed of 0.20 meters per minute.

The Vickers hardness number of each material that was clad as evaluated from the top of the clad into the substrate. This data is plotted in Figure 10. Investigation of Figure 10 reveals that the Stellite™ 6 and stainless steel 420 provided a significant increase in hardness, whereas, the Inconel™ 625 displayed very little increase in hardness. It should be noted that the Vickers hardness numbers of the Inconel™ 625, Stellite™6, and stainless steel 420 obtained during this investigation are very similar to hardness obtained through laser cladding using higher power CO_2 laser systems.[6]

3.4 Line Forming

A series of laser assisted forming experiments were conducted. Laser assisted forming or bending uses the laser to provide differential heating through the thickness of the material, thus causing controlled thermal distortion. The materials used in this investigation were HSLA-80 steel, which was 6.35 millimeters thick and sized at 30.5 centimeters by 30.5 centimeters, and Inconel™ 625, which was 0.165 centimeters thick and sized at 10.2 centimeters by 10.2 centimeters. The basic parameters used during the forming evaluation, in both materials, were a power of 3040 Watts with no shielding gas. During each of the laser assisted forming evaluations, the length dimension of the spot was directed perpendicular to the direction of processing resulting in a larger area being affected by the beam. Also, the beam was defocused to approximately one inch by moving the laser head away from the work-piece. This increased the beam size but decreased the intensity of the beam. The actual size of the beam with a change of one inch in the defocus direction was unable to be measured but was believed to be approximately 20mm by 2mm.

The optimal results obtained for the HSLA-80 were at a speed of 0.38 meters per minute. The results from forming at a speed of 0.5 meters per minute produced a saddle-like bending or buckling along the length of the specimen. Figure 11 shows a comparison of the deflection of HSLA-80 steel at 0.38 and 0.5 meters per minute. The optimal results with the Inconel™ 625 were at a travel speed of 0.64 meters per minute. Faster processing speeds had a negligible effect on the material and slower speeds caused the material to bend in a saddle-like fashion, or buckle. Further decreases in travel speed resulted in melting of the substrate. A comparison of the results obtained by varying travel speeds in the Inconel™625 can be seen in Figure 12. Evaluation of this plot shows that as the speed increases, the amount of average deflection decreases in a nonlinear fashion. Figure 13 displays micro hardness measurements from the surface of the HSLA-80 after forming. Notice that the hardness is unchanged at the surface and indicates negligible metallurgical alterations to the base metal after processing.

4.0 Summary

The objective of this investigation was to determine the applicability of a 3.0 kW direct diode laser for material processing. Several conclusions may be drawn from this investigation. Direct diode lasers are ideally suited for autogeneous seam and lap welding of stainless steel. Process speeds at 3.0 KW equal or exceed those in typical gas tungsten arc welding applications. The lasers' line source is ideally suited for large area surface transformation hardening. Laser hardening experiments involving 4140 steel and titanium 6-4 alloys resulted in a larger increase in hardness in the ferrous material when compared to the titanium 6-4. The uniform laser beam profile produces a uniform case depth of more than 0.5 mm. The back tempered zone was demonstrated to be less than 3%. Pre-placed powder of Inconel™ 625, Stellite™ 6, and stainless steel 420 was used to successfully clad a steel substrate with the direct diode laser at a power of 3040 W and speeds of seven to eight inches per minute. Laser assisted forming of HSLA-80 steel and Inconel™ 625 provided deflection with little effect on the base material. Optimal deflection occurred at 0.38 meters per minute for HSLA-80 steel and 0.64 meters per minute for Inconel™ 625, both being at 3150 Watts.

5.0 References

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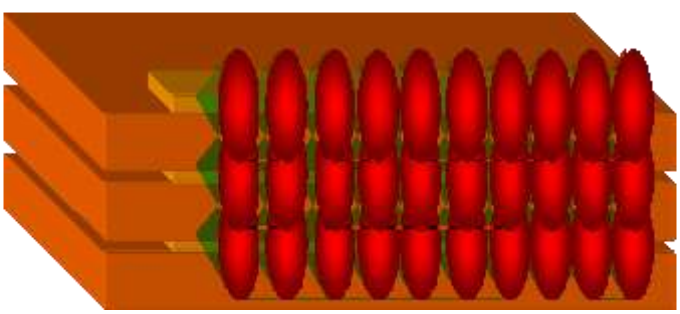

Figure 1: Light Emission From a Diode Array (Courtesy of NUVONYX Inc.)

Table 1: Diode Lasers in comparison with other conventional lasers

	Direct Diode	Nd:YAG {DP}	CO_2
Wall Plug Efficiency [%]	50 - 60	3- 5 {8 –12}	8 - 10
Wavelength [um]	0.8 – 0.98	1.06	9.4 – 10.8
Avg. Intensity	10^3 - 10^6	10^5 - 10^7	10^3 - 10^8
Max power [kW]	expandable	5	50
Size [head only] [cm^3/w]	1-2	20 -50	200
Service [h]	Very little	1000 {2000}	2000
Relacement [hours]	Laser arrays [10,000]	NO Lamps {8,000}	NO
Beam forming/guiding	Lenses,fibers	Lens, fibers	mirrors
Mobility	high	Very low High with fiber	none
Investment [$/W]	65	180 {250}	70
Replacement/rebuild costs [$/W]	20 - 25	no	no

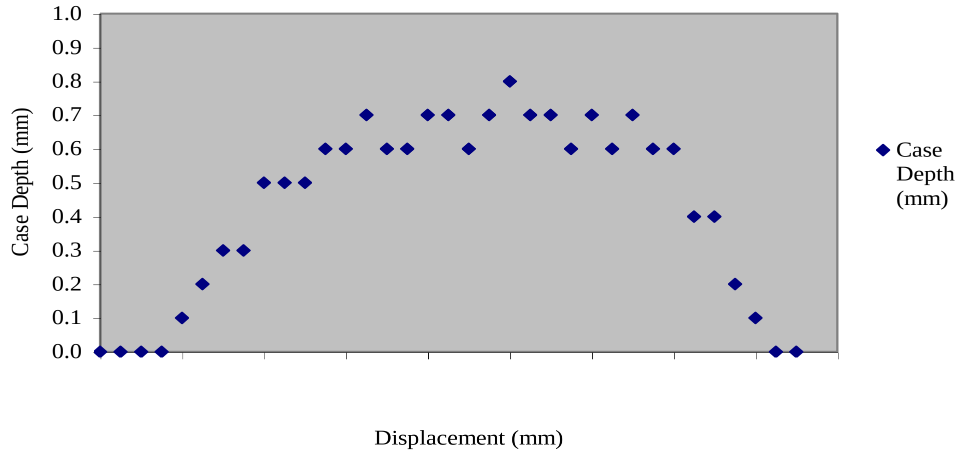

Figure 3: The hardened zone produced from a single pass, laser beam surface treatment. The beam profile is typically Gaussian as shown in the above graph.

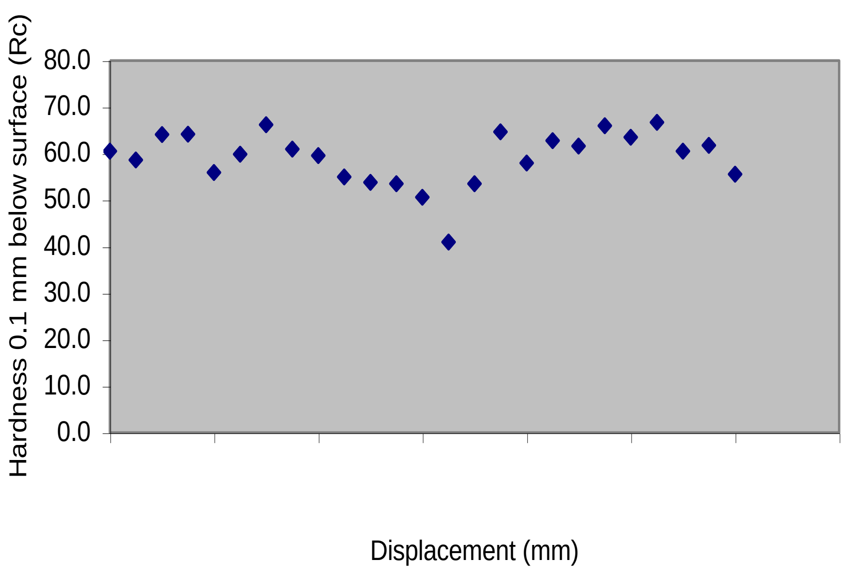

Figure 4: Superhardening has occurred in this sample as seen in the high hardness values obtained 0.1 mm below the surface.

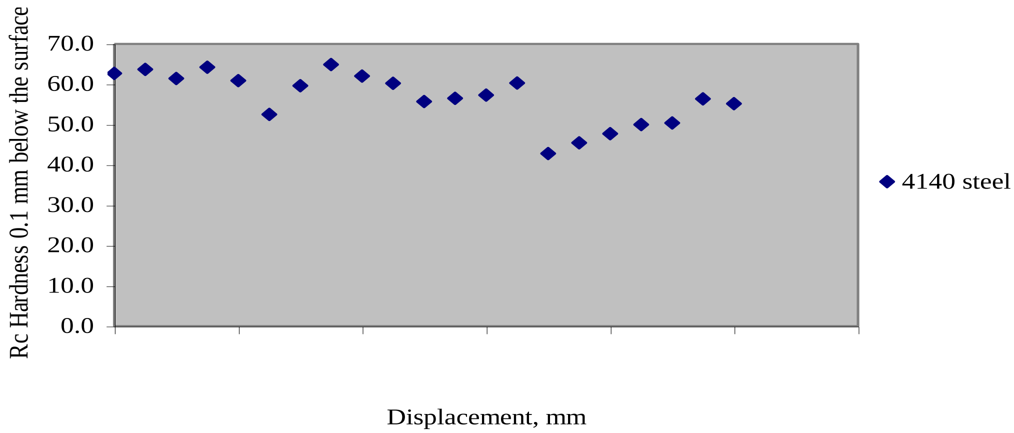

Figure 5 : This figure demonstrates the effect of backtempering on hardness of a sample. The second beam was moved over 13mm after the first pass. Note, that the superhardened zone is immediately followed by the back tempered zone.

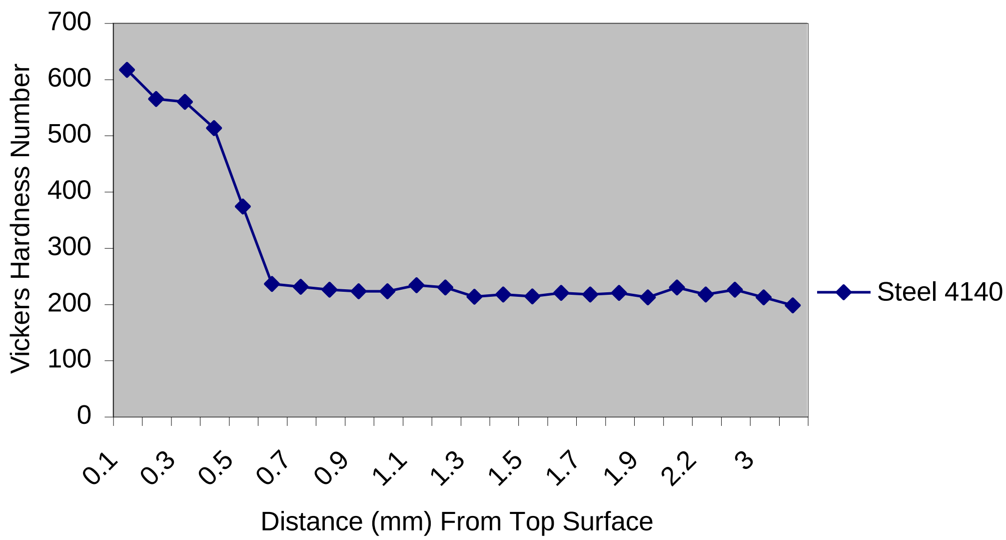

Figure 6: Vickers Hardness Number Versus Distance From Top Surface of 4140 Steel

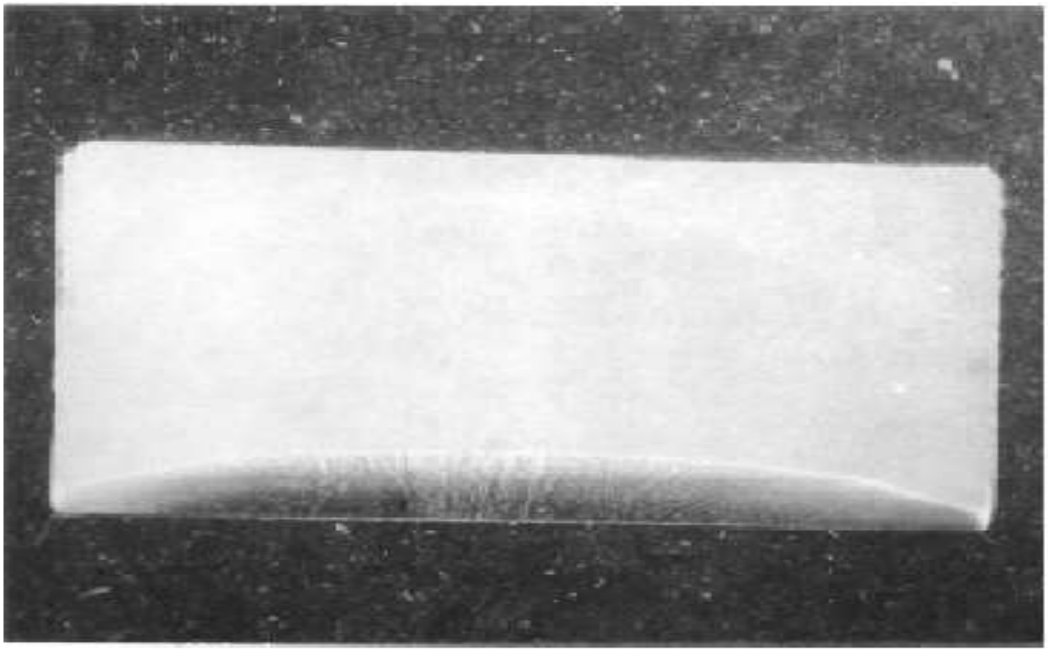

Figure 7: This photograph demonstrates the surface hardening in a 4140 steel. This picture was taken at a magnification of 6X.

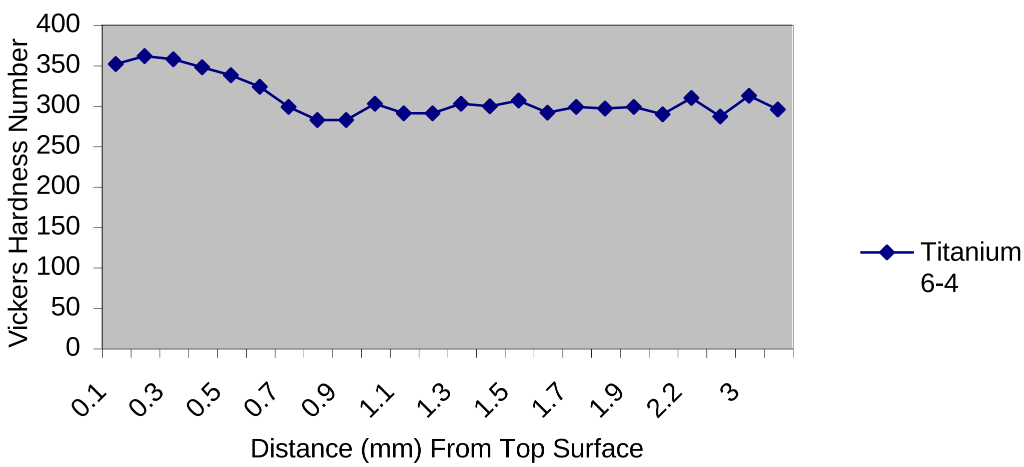

Figure 8: Vickers Hardness Number Versus Distance From Top Surface in Titanium 6-4

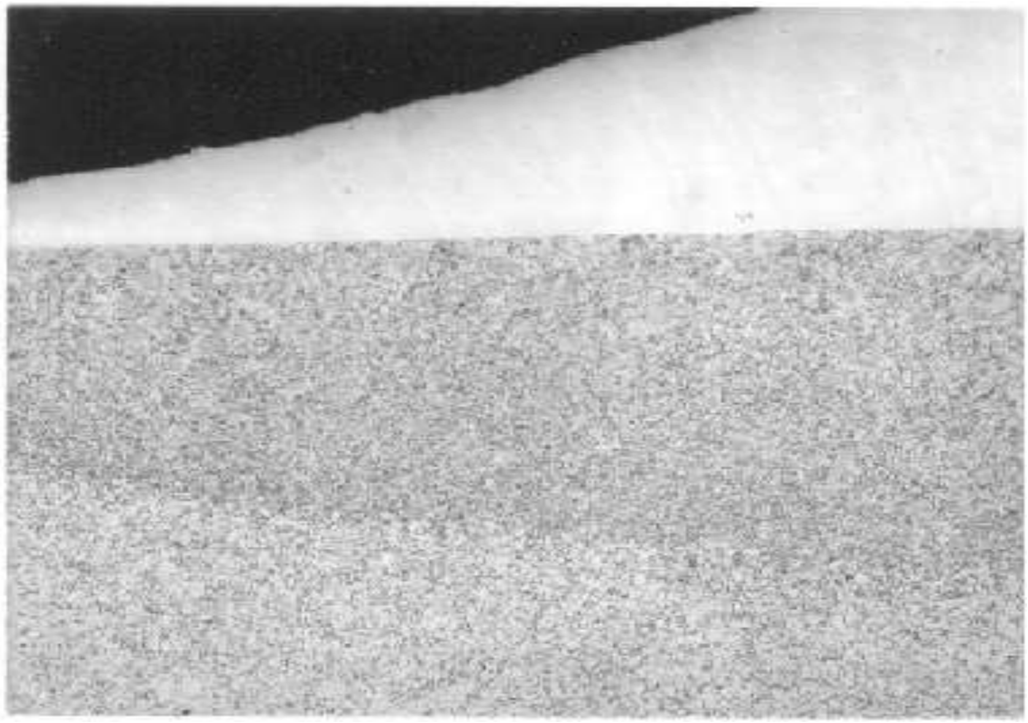

Figure 9: Inconel 625 clad taken at a magnification of 50X.

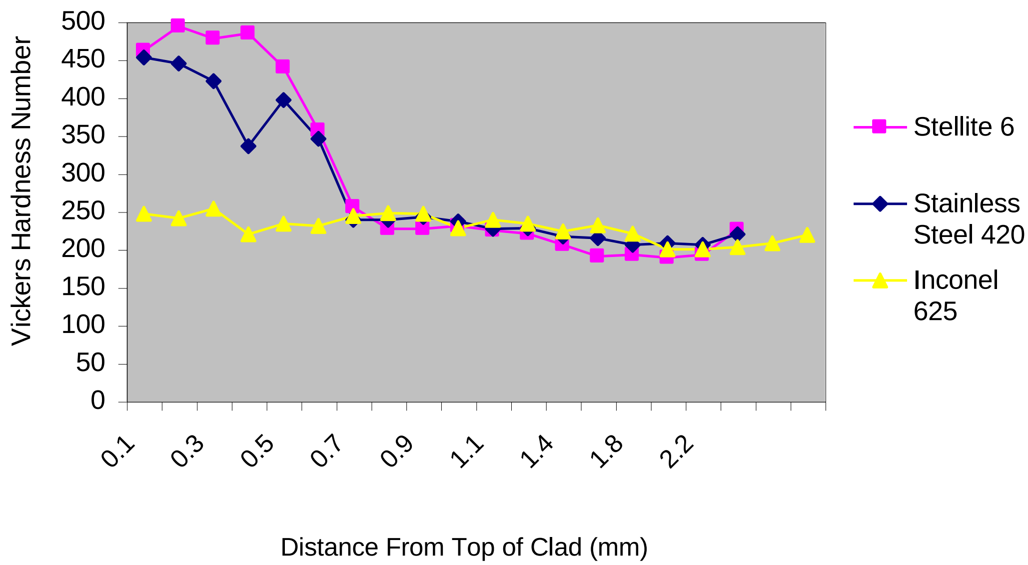

Figure 10: Vickers Hardness Number Versus Distance From Top of Clad

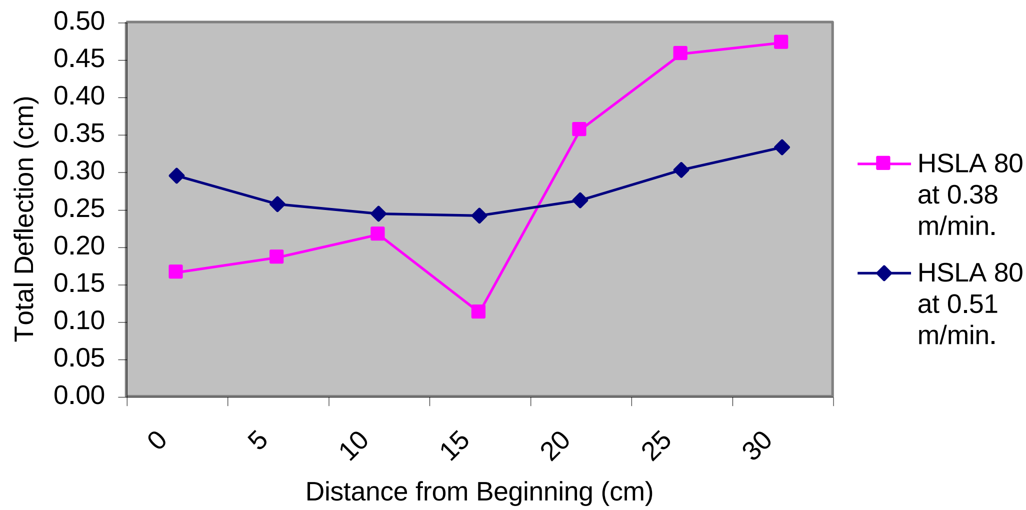

Figure 11: Comparison of Deflection Versus Distance From Beginning in HSLA 80 Steel Laser Assisted Forming

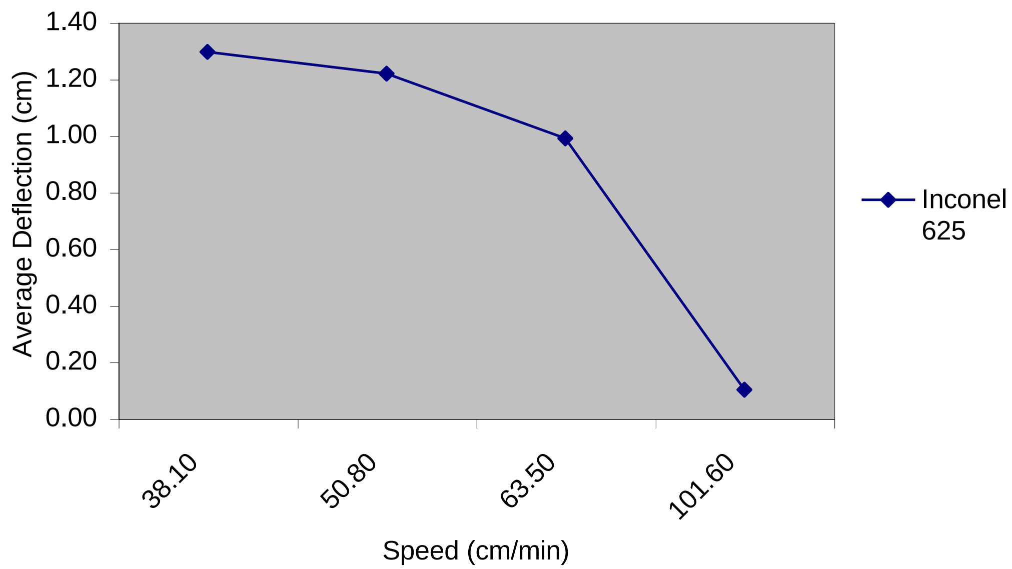

Figure 12: Average Deflection Versus speed in Inconel™625 Laser Assisted Forming

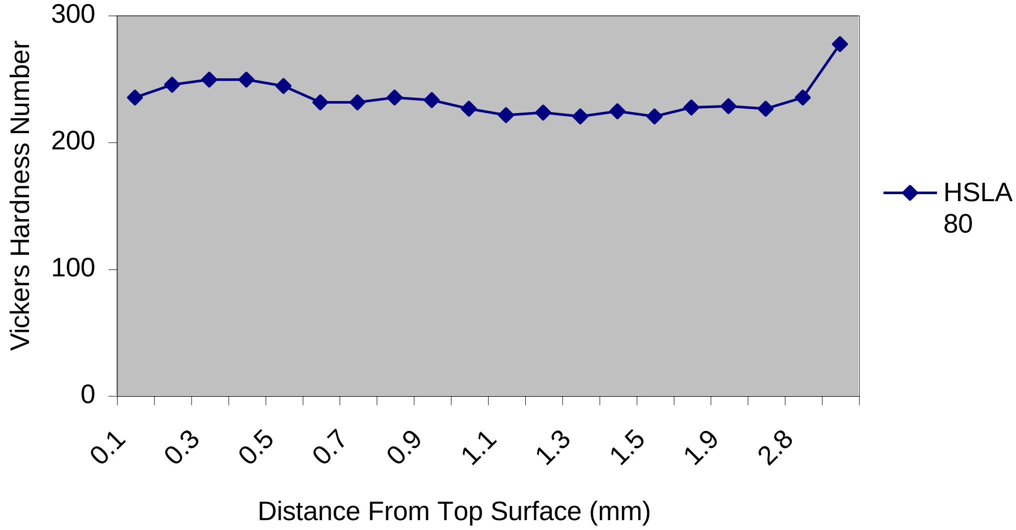

Figure 13: Vickers Hardness Number Versus Distance From Top Surface in HSLA 80 Laser Assisted Forming