Presented at the ICALEO Conference October 3,2000 Dearborn, MI

High Power Direct Diode Laser Applications and Advanced Processes

Authors: Crystal M. Cook, John M. Haake, M. Cryderman

Abstract

Higher power direct diode laser [HPDDL] systems have achieved record power levels making them an economic alternative to existing heat sources and conventional lasers for many applications. These laser systems can help to create a compact, flexible manufacturing cell ideal for welding, surface cladding, heat treating, brazing and paint stripping applications. The capabilities of this direct diode laser system demonstrated here range from high-speed conduction mode welding, laser surface transformation hardening, laser cladding . Laser welding was demonstrated on ferrous, nonferrous materials, and zinc coated steels with low porosity. Therefore, making HPDDL laser ideal for tube mills and tailor welded blank applications. Laser surface claddings with very low dilution were produced using pre-placed powders yielding high corrosion and wear resistant surfaces. Laser surface transformation hardening of 4140 steel and gray cast iron produced samples with high case depths, high hardness, and low back temper percentages.

1.0 Background and Technical Overview

As tools for use in industrial applications, HPDDL, also known as semiconductor lasers, are becoming more prevalent.[1,2,3] Diode laser technology has been used for a number of years in compact disks, laser printers and laser pointers.[4] Their low cost, high efficiency, and compact design make them an attractive technology in the manufacturing environment.

The light emitted at the facet of the laser diode is highly divergent and astigmatic. To make this usable, a lenslet array is close coupled to a two dimensional array of laser diodes. 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. This produces a beam having a nearly rectangular intensity profile along the line with a guassian profile perpendicular to the line. With dimensions of approximately 12.5 mm X <1 mm with a 125 mm focal length lens. The HPDDL used in this feasibility study was the Nuvonyx ISL-4000L laser it uses 4 stacks of 20 bars, which are brought to a line by a single macro lens [Figure 4]. This laser can achieve power densities greater than 200 kW/cm. This type of arrangement provides an ideal heat source for applications continuous seam welding and large surface area applications. Since the power densities are lower than that typically required to create a key-hole and plasma, welding was performed during this investigation in the ‘conduction” mode.

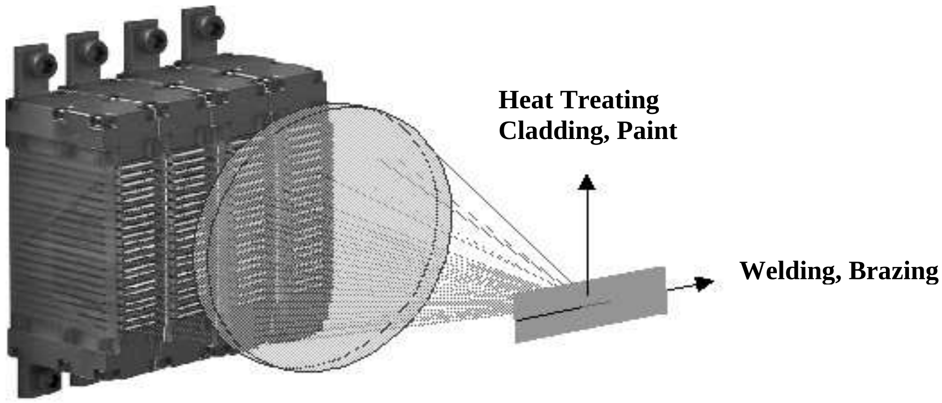


Figure 4 – Focus Configuration of Line Source HPLLD

2.0 Experimental Procedure

All the experiments, except where noted, were carried out using the ISL-4000L laser mounted to a Panasonic robot, either a model VR-16 or VR-32. The robot has active positioning accuracy of 0.1 mm.

The welding experimentation involved the study of both ferrous and non-ferrous materials. The ferrous materials examined were 304 Stainless Steel, and Galvanneal steel. The nonferrous materials included aluminum and titanium. The welding of 304 Stainless Steel on a tube mill was done through the use of a three-axis mount, which allowed for the adjustment of the laser with respect to the knit point.

The focus of the heat treatment study was on ferrous materials. The materials examined include 4340 steel and Class 40 Gray cast Iron.

Laser cladding deposits a clad material, in this case a pre-placed powder, onto the workpiece using the HPDDL beam to melt and fuse it. The powders used were ANVAL 410, 156 and C22. ANVAL 410 and C22 powders were chosen for their superior corrosion resistance. ANVAL 156 is a general-purpose hardfacing alloy. The powders were cladded at varying speeds in an effort to obtain the least amount of dilution. The thickness of the pre-placed powder was .050”, the substrate used for the experiments was 1018 steel. Wire feed cladding was also successfully preformed with STOODITE 190-M and 965-G wire, .045” diameter, but will not discussed here due to article length limitations.

3.0 Results and Discussion

3.1 Welding with the HPDDL system

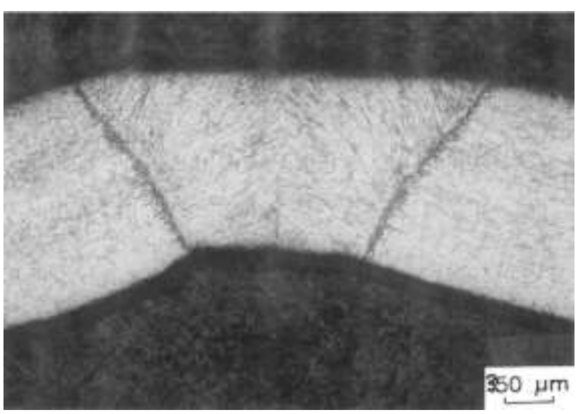
The HPDDL naturally generates a beam shape that is ideal for continuous seam welding, such as those found of tube mills. Unlike the GTAW and the conventional laser welding, which generates a round heating spot, the diode laser generates a line of light. The welding process using the HPDDL is independent of issues related to plasmas, since this line of laser light does not generate a keyhole/plasma. The line of light allows for a longer interaction time at the seam. The resulting weld pool is only at the seam, it penetrates deeper allowing molten metal to wet together in a very controllable fashion. This yields a conduction mode weld with a narrow heat affected zone [HAZ]. The welds produced are similar to those produced by a GTAW process, with no spatter, however there is less sagging and a narrower heat affected zone which results in an increase in mechanical properties such as fatigue strength and formability[10].

An application that is getting much attention is welding zinc-coated steels using the HPDDL. The HPDDL is the ideal laser source for welding zinc-coated steels. The line of light acts to preheat and vaporize the zinc such that there is no zinc present at the weld pool. This results in an excellent ductile weld.

3.1.1 304 Stainless Steel Welding of Tubing

A 4000 W CW HPDDL was used on a GTAW tube mill to weld 0.035 3/8” inch tubing. The laser diode was small enough to fit within the profile of the existing tube mill without major retrofits or seam tracking devices.

Welds produced on the tube mill exhibited exceptionally smooth surfaces on both sides, very low distortion which is consistent with the small heat affected zone, and very little oxidation on the surface as a result of the good coverage by the shielding gas. The resulting weld and HAZ are approximately 3X – 4X smaller than that resulting from a GTAW, Metallographic inspection of welds made on the tube indicated a minimal variation in hardness in the heat affected and fusion zone from the base metal (Figure 6). A micrograph of the welds is shown in Figure 7.



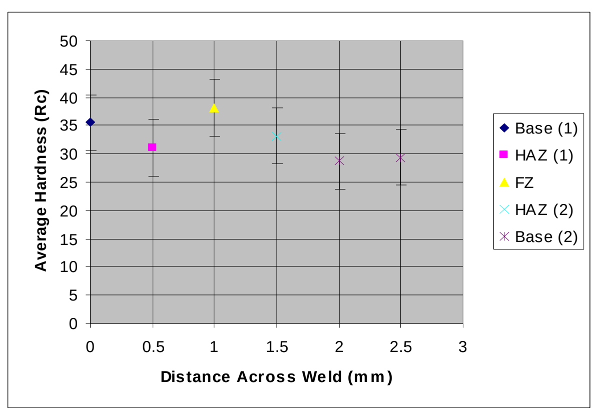
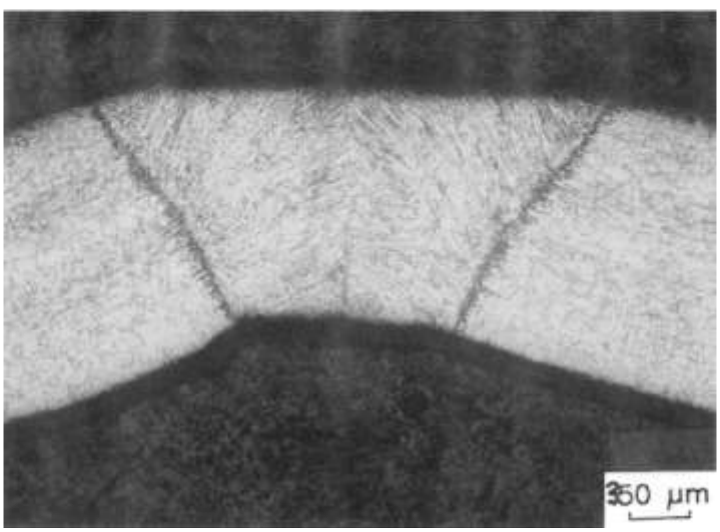


Figure 6: Average Hardness Plotted Against the Distance Across the weld for a 304 stainless steel tube.

3.1.3 Seam Welding of Galvanneal Steel

A seam weld was made on two sheets of galvanneal steel in 100% argon atmosphere. The two sheets varied in thickness, one having a thickness of 0.7 mm, the other 1.4 mm. There was a pre-set 500 μm gap between the two sheets being welded. The welds were exceptionally smooth and exhibited low distortion and were not embrittled due to good gas coverage. During the welding process the line source allowed for the zinc to vaporize first out of the area to be welded, yielding a full penetration high quality steel weldment.

Figure 7: 304 Stainless Steel Tube Weld



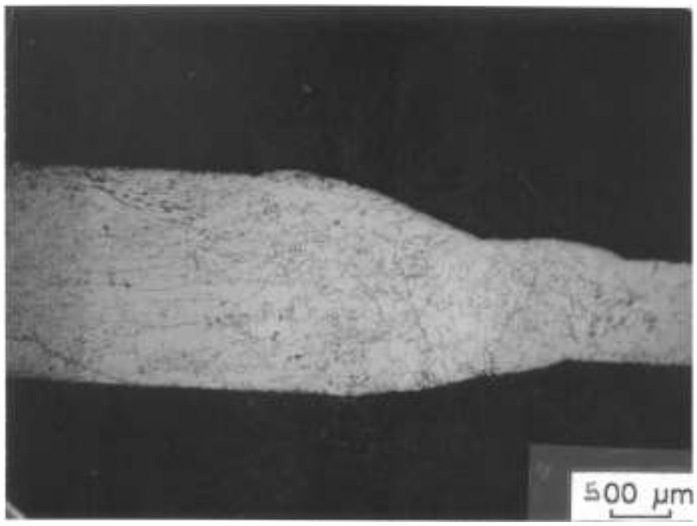


Figure 10: Micrograph of galvanized steel lap weld, 18.5 X magnification, 2% Nital etch.

Microhardness was also taken across the welded area of a galvanized steel lap weld. It was found that the hardness slightly decreases in the fusion and heat affected zones. This is an indication that the weld does not experience embrittlement due to oxides or zinc impurities. Therefore, a weld is produced with uniform strength and ductility. The heat-affected zone is also minimal for the weld as seen in Figures10 and 11.

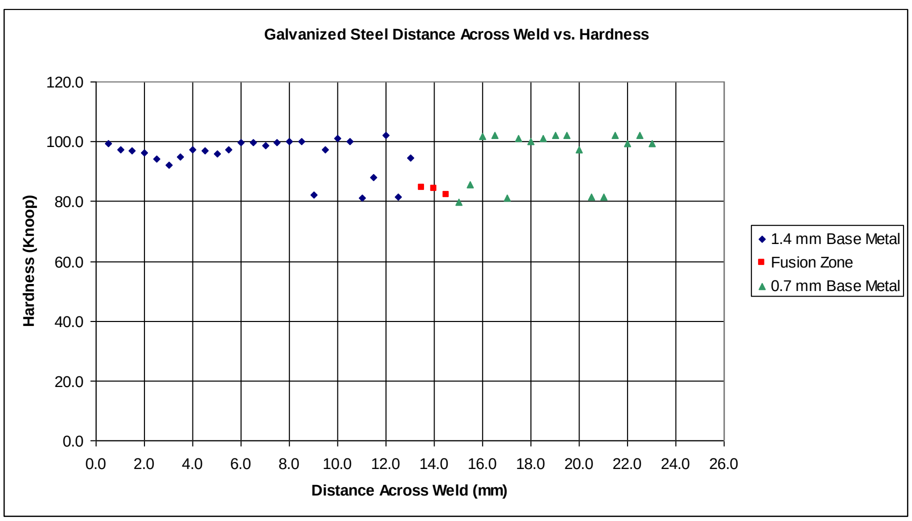


Figure 11: Average hardness plotted against distance across the weld for galvanized steel lap weld.

3.1.4 Aluminum Welding

Seam welds were produced on 0.040" thick 5182, 5754, and 6061 aluminum. The welds produced were all similar in quality and weld speed. Shown here is the 5754 aluminum seam weld with minimal porosity, a smooth surface and minimal distortion.

Microhardness measurements across the welds as well as tensile tests indicate that there is not a loss of volatiles in the fusion zone. The loss of strength in the weld and HAZ is expected to be similar to other process. References here . The heat-affected zone is also negligible for this material. The thickness of the material was 1 mm and the weld was produced at 3.6 kW of power at 6 m/min [Figure 12]

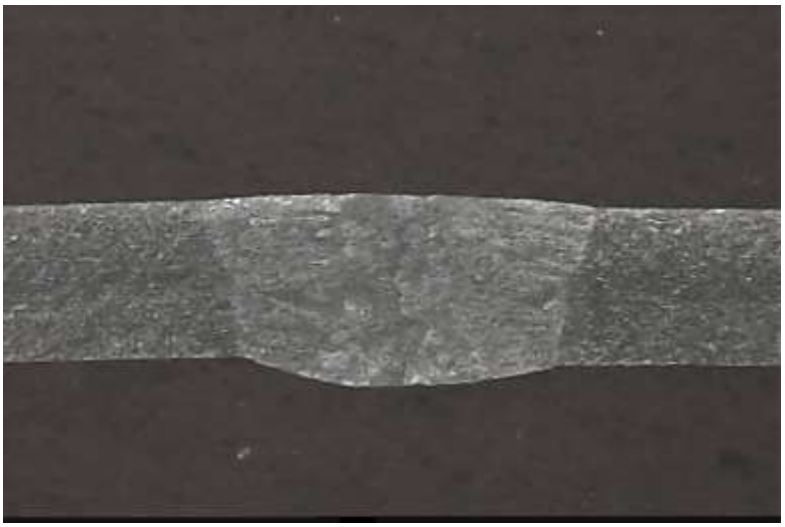


Figure 12: The fusion zone and heat affected zone of a 5754 aluminum laser weld.

3.1.5 Commercially Pure Titanium Welding

Tests were also conducted on a commercially pure titanium tube, but not on a tube mill. The welds were produced at speeds of 13.5 ft/min at 3.4 kW in 100% argon atmosphere. Throughout the weld there was minimal variation in the hardness in the fusion and heat affected zone from the base metal. The weld exhibited a smooth surface, very little deformation, and no splatter on the inside as seen in Figure 12.

Microhardness was also taken across the tube weld. Minimal variation in hardness from the base material was observed in the heat affected and fusion zone. The lack of variance in hardness is an indication that there is minimal oxidation within the weld due to good coverage by the shielding gas. This is also an indication that the weld has a tensile strength similar to that of the base material. Figure 13 shows the hardness across the weld.

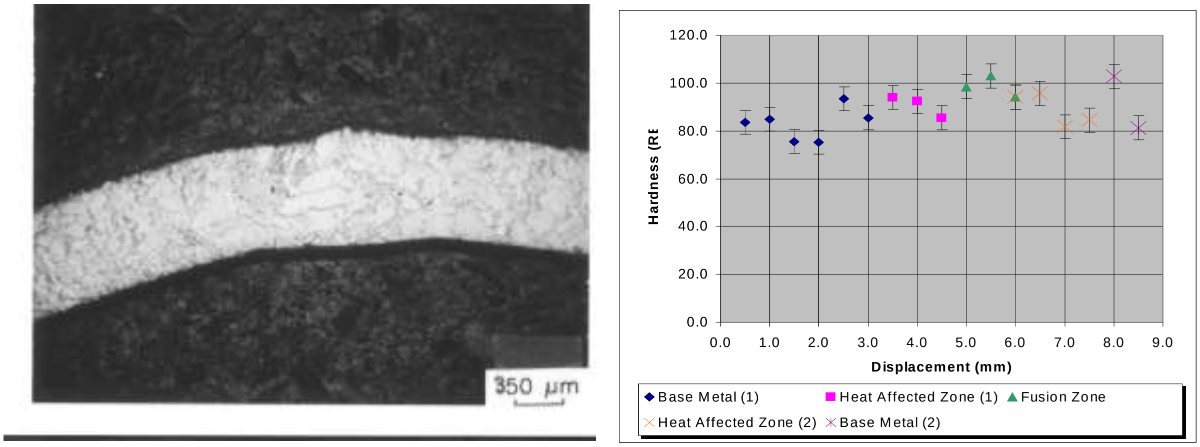


Figure 13: Hardness measurements taken across the fusion zone and heat affected zone of a titanium tube weld.

3.2 Heat Treating with the HPDDL system

Through laser transformation hardening a material can be case hardened with negligible distortion. A comparison with flame hardening and induction hardening techniques clearly show that laser surface hardening is the most advantageous process. Flame hardening has poor reproducibility, poor quench and environmental issues. In induction hardening a quench is required, distortion of the part occurs and there is large thermal penetration. With laser beam hardening the applied energy is concentrated on the surface only, there is no radiation spillage outside the optically defined area. The bulk of the material acts as a heat sink for the extraction of heat from the surface. The major advantage of laser surface treatment is high processing speeds can be achieved because light radiation instantaneously heats the surface of the part. Laser surface transformation hardening not only increases the wear resistance, but also under certain conditions the fatigue strength is also increased due to the compressive stresses induced on the surface of the component[11].

The HPDDL is an ideal source for laser transformation hardening. The line of light, which when moved across the work piece as shown in Figure 4, has high edge definition with out the need to special cylindrical lenses [Nd:YAG] or water cooled integrators [CO_2]. The wavelength is 800nm requires no pre-coating of the work piece to get absorption. The ISL-4000L has a modulation bandwidth of 20KHz, making ideal for in-situ temperature control.

3.2.1 Surface Transformation Hardening of 4340 Steel

Experiments were done relating the degree of back-temper, case depth and case hardness on 4140 steel. The minimum back-temper reading for two passes at a given displacement was found to be 15 mm. The hardness within the case was found to be in the range of 50 to 65 R_c, while the case depth was generally between 0.7 and 1.5 mm. The hardness and case depth can be controlled by the input power, travel speed and beam intensity. Through experimental data, the width of the laser beam is approximated at 14 mm.

At a displacement of 15 mm between passes, a very low degree of back-temper is present. The region that is back tempered has a width of only 1.5 mm [3- 5%], demonstrating very high laser beam edge definition. Figure 18 shows the interpass zone for the sample in which the beam was shifted 15 mm from its original position to produce the second pass. The hardness in the back-tempered region is generally 30 to 40 Rockwell C.

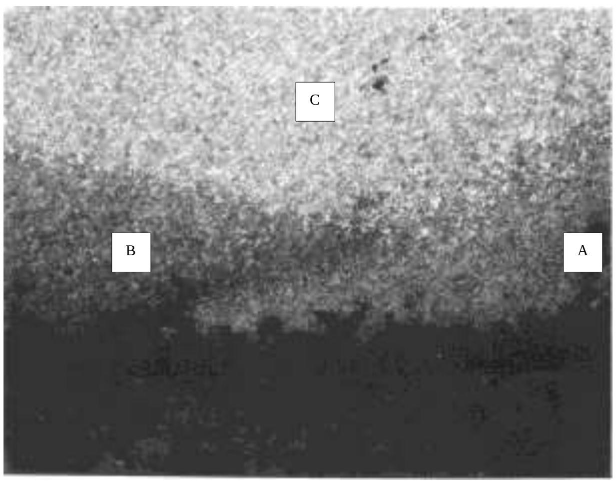


Figure 15: This sample was produced by shifting the beam 15 mm from the initial pass to produce the second pass. The region marked A is untempered martensite. B marks the region in which the martensite is tempered. C indicates the base metal (2% Nital etch, 50X magnification).

A displacement of 15 mm produces an unacceptable region that is less than 5% of the pass. The interpass region is comprised of a slight degree of tempering. Measurements began in the middle of the first pass and extended to the center of the second pass. Also, note that the slope of the tail of the second pass is steep, allowing for a decrease in the amount of backtemper. The degree of back-temper can be directly related to the case depth of the sample. As the case depth decreases the amount of back-temper increases and vice versa. The shaded portion of the graph indicates an acceptable case depth (Figure 19). The hardness within the case of the sample is between 55 and 65 R_C.

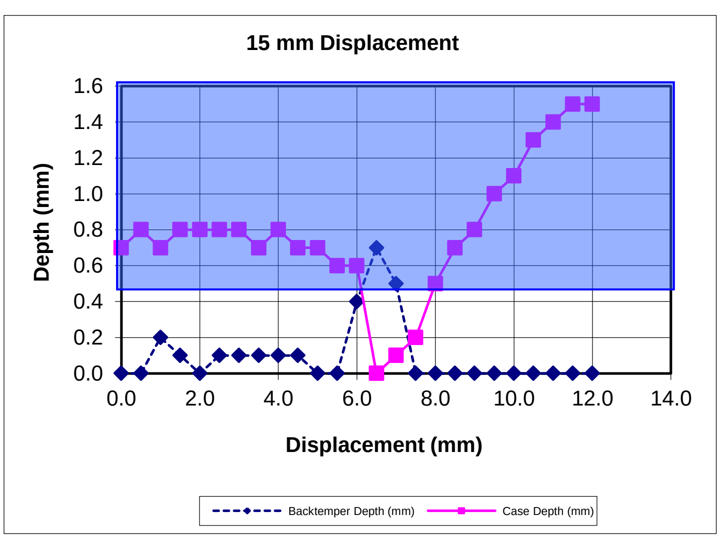
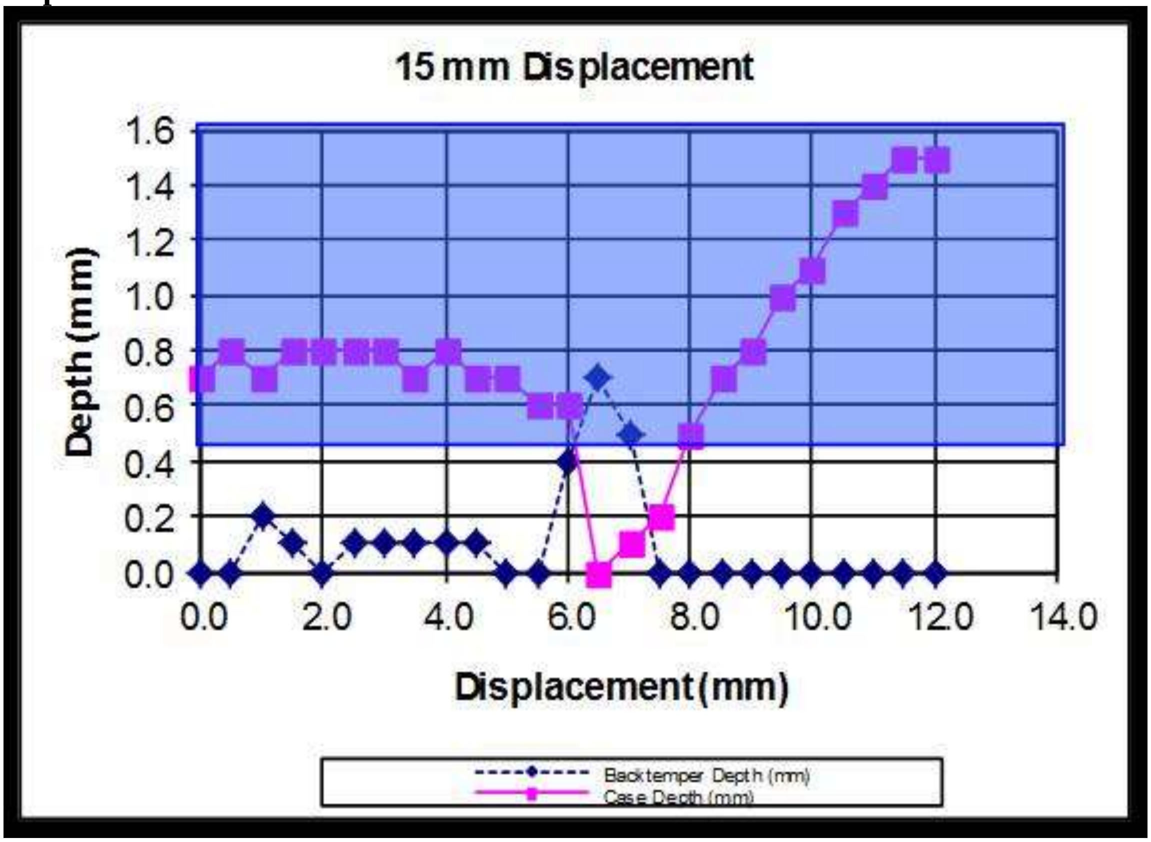


Figure 16: The relationship between back-temper and case depth at a 15mm displacement.



3.2.2 Surface Transformation Hardening of Gray Cast Iron

Surface transformation hardening of Class 40 Gray Cast Iron was also performed without the use of an absorptive coating or inert gas shielding using a HPDDL. The beam was defocused 4 to 8 mm and moved at various speeds over the workpiece. The gray cast iron was much more sensitive than the 4340 due to the very narrow process widow between melting, producing surface carbides, and desirable hardening. It was determined that at a 6 mm defocus a case would be produced with a higher hardness value than the case produced at 8 mm defocus. The 4 mm defocus produced suface melting and carbides At a higher degree of defocusing the case depth would increase. This will occur up to a critical amount of defocusing. This application will benefit greatly from temperature control which it completely within the means of the HPDDL.

3.3 Cladding with the HPDDL

Another ideal application for the HPDDL is large surface area laser cladding. As shown in Figure 4 the line of laser light is scanned perpendicular to the long axis. Wire feed hard facing can also be performed such that the wire is feed into the laser beam parallel to the long axis.
Rapid heating and solidification characterize laser surface cladding. This allows for the production of metastable, non-equilibrium phases that cannot be produced by traditional

cladding methods. The denser microstructure and better bonding allows for better corrosion resistance. The thermal input can also be controlled thus yielding minimal dilution and a small heat affected zone. Laser cladding is also chemically clean and environmentally friendly. Multiple pass samples were prepared which demonstrated uniform cladding thickness

3.3.1 Cladding with Pre-Placed Powders

The thickness of the pre-placed powder was .050”; the substrate used for the experiments was 1018 steel.

ANVAL 156, a general-purpose wear resistant material produced superior clads with minimal dilution. A SEM line trace was used to determine the amount of intermixing of the clad and substrate. The ANVAL 156 powder has a composition that includes 29% Chromium therefore Chromium was the traced element in the clad layer. Iron was traced in the substrate. The SEM analysis indicates that the dilution and intermixing of the clad into the substrate is minimal [Figure 20]. The area that was traced was 1001.53 μm and starts in the substrate and continues throughout the clad [Figure 21]. The lack of intermixing allows for the entire clad pass to have superior wear resistance.

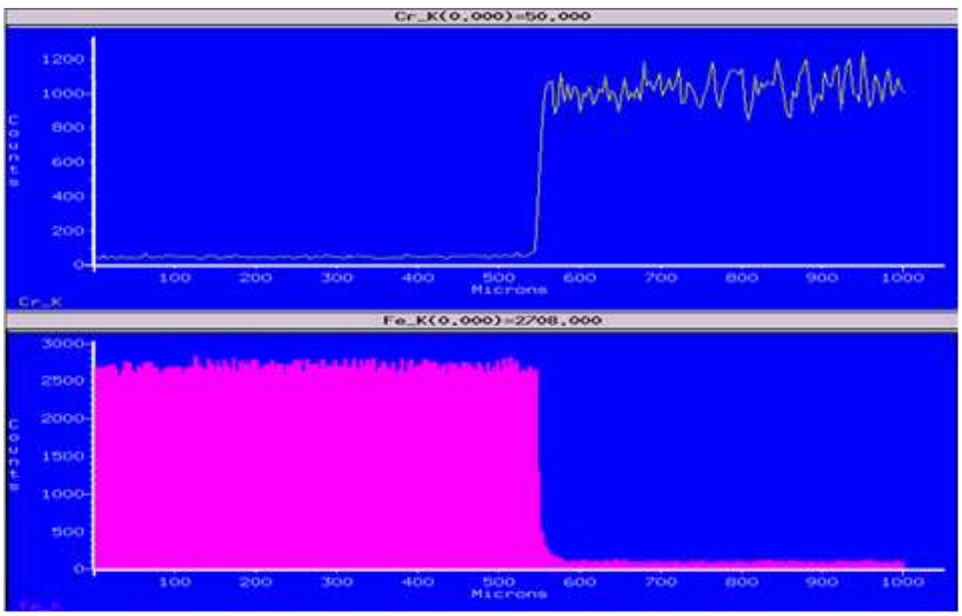


Figure 20: SEM trace of clad and substrate.

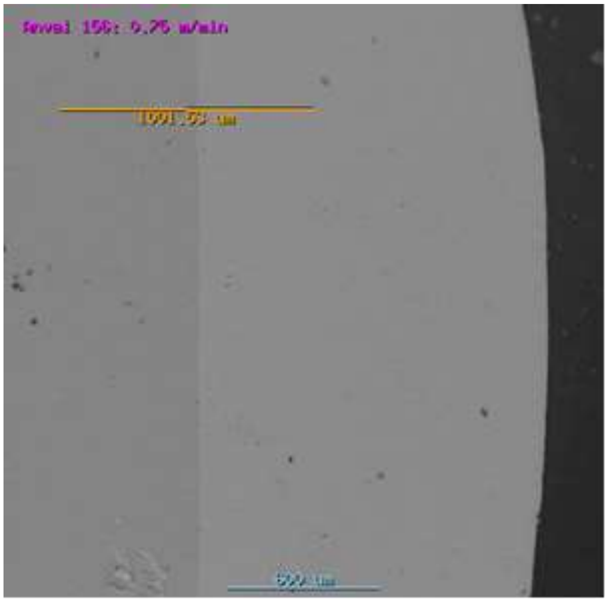


Figure 21: Anval 156 clad on 1018 steel produced at 4 kW, 0.75 m/min.

4.0 Conclusions

The ISL-4000L system is a versatile laser system capable of meeting the needs of many current industrial applications and enabling future applications. The advantages of direct diode lasers are the high wall plug efficiency, order of magnitude smaller footprint, lower maintenance, high absorption in work piece, and high control bandwidth. The HPDDL can mount directly on a tube mill or end of a robot with very little modification. The benefits of the unique beam properties and 800nm wavelength of the ISL-4000L HPDDL have been demonstrated. The applications demonstrated that make use of this line source are; high quality and high speed seam welding as required for tube and pipe manufacturing; Welding of zinc coated steels yielding pore free ductile welds. Further taking advantage of the line source and processing along the short axis, large area heat treating, cladding, and paint stripping are possible. Laser hardening experiments were successfully conducted on 4140 steel without the need for pre-cating. The uniform laser beam profile produces a uniform case depth of more than 0.5 mm. Large area laser cladding was also demonstrated with very low dilution making it the optimum laser source . It is clear that this laser system is capable of economically meeting the needs of many exisitng applications. Future work will take advantage of fact that HPDDL inherently provide the ability to control the output laser energy with a degree that is unmatched by conventional Nd:YAG and CO_2 lasers, allowing for in-situ control of the weld, heat treat, and clad zones.

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