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Benefits of Direct Diode Lasers for Welding

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High Power Direct Diode Laser [HPDDL] systems with output powers greater than 4.0kW in a compact robust package are now available. These industrial semiconductor [diode, solid state] lasers are a new type of heat source, which are beginning to replace conventional lasers for seam welding applications. The beam shape of the HPDDL system are rectangular or a line source. This beam profile does not "key-hole", thus yielding higher quality seam welding process. Due to their high efficiency, these HPDDL are very compact and can be mounted directly on a tube mill or robot enabling high speed and high quality welding of both ferrous and nonferrous metals. These all solid state laser systems inherently provide the ability to control the output laser energy with a degree that is unmatched by conventional Nd:YAG and CO_2 lasers.

Introduction and Technical Background

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.

Laser Diodes, sometimes called injection lasers, are similar to light-emitting diodes [LEDs]. In forward bias [+ on p-side], electrons are injected across the P-N junction into the semiconductor to create light. These photons are emitted in all directions from the plane on the P-N junction. To achieve lasing, mirrors for feedback and a waveguide to confine the light distribution are provided. The mirrors of a laser diode are cleaved facets of the III-V [AlGaAs] semiconductor from which the lasers are made[4,5]. The AlGaAs lasers can be made to emit between 0.72 and 0.88 μm. The InGaAs emit photons having a characteristic wavelength of between 0.88 and 0.98 μm[6]. The HPDDL bar is composed of many individual laser cavities that are processed into a single bar. An array of laser diode on a bar can be seen in Figure 1. The light emitted from them is asymmetric.

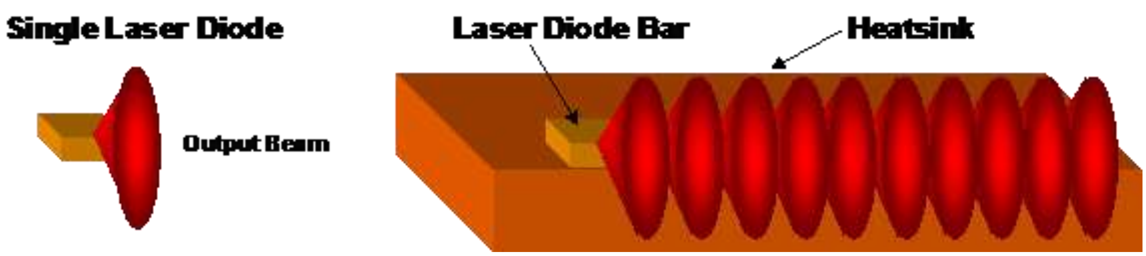

Figure 1 - Configurations of HPLLD Bar

Depending on semiconductor material used, each bar is capable of emitting many tens of 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 water-cooled heatsinks.

High Power Direct Diode Laser [HPDDL] System

The laser diodes are packaged in individual heatsink (Figure 2) assemblies in order to have continuous wave [CW] operation. These individual heatsinks are stacked to form a linear array of CW laser diodes. This two dimensional array of laser diodes (Figure 3) is capable of 1.2 kWatts of CW power.

Figure 2 - 65 Watt CW High Power Laser Diode Package

Figure 3 - 1.2 kWatt CW High Power Laser Diode Array Package

The light emitted at the facet of the laser diode is highly divergent and 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. The HPDDL used in this feasibility study used 4 stacks of 20 bars, which are brought to a line by a single macro lens [Figure 4]. This can be used to generate power densities as high as 200 kW/cm. This type of arrangement provides an ideal heat source for applications continuous seam welding. 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.

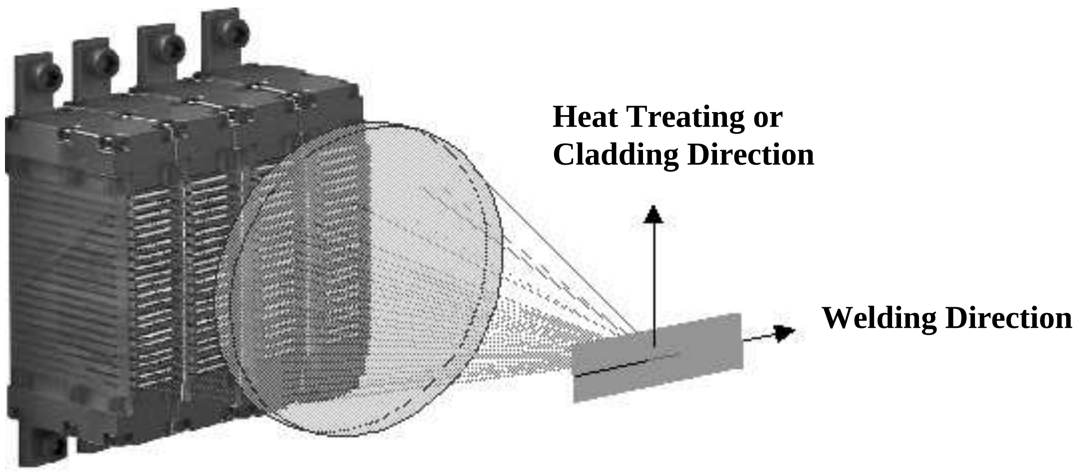

Figure 4 – Focus Configuration of Line Source HPLLD

Advantages of HPDDL

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 are very small and compact, such that the entire laser head can easily be mounted over an existing tube mill weld box or to the end of the robotic arm or gantry for use.

Wall Plug efficiency

The advantage of the laser diode is their high electrical to optical conversion efficiency. The laser diodes have demonstrated electrical to optical conversion efficiencies that vary from 30% to 60%. The net result is a diode laser system that can have a wall plug electrical to optical power conversion efficiency of >25%. Consequently, a 4,000-Watt CW laser diode system can consume less than 16,000 Watts of electrical power, including the water-cooling system. This efficiency translates into a lower cost of operation for the user. 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.[2,3,8] Table 1 is a chart comparing the direct diode laser to other systems. In Table 2 the direct diode laser is compared with the conventional laser in other areas.

Type	Wavelength μm	Wall Plug Efficiency % Laser only	System Efficiency % Chiller and power supplies included
CO_2 - Flowing Gas	10.6	12	6
Nd:YAG	1.06	1-2	0.5
Diode Pumped Nd:YAG	1.06	8-12	4-6
Direct Diode	0.8	50-60	25-30

Table 1 – Typical Industrial Laser System Efficiencies

	DIRECT DIODE ISL	CO_2 FLOWING	Nd:YAG FLASH PUMPED	Nd:YAG DIODE PUMPED
Net system efficiency, %, continuous operation at 100% power, including chiller	25%	6%	1%	6%
Hourly operating cost, $, continuous operation at 100% power	$1.50	$10.00	$30.00	$6.00
Wave Length, um	0.8	10.6	1.06	1.06
Absorbtion % - steel*	40%	12%	35%	35%
Absorbtion % - Aluminum*	13%	2%	7%	7%
Average intensity	10^3 to 10^6 constant	10^3 to 10^8 constant	10^3 to 10^7 constant	10^3 to 10^7 constant
Current maximum power (kW) commercially available	4	50	4	4
Footprint for laser, power supply, chiller, sq. ft.	8 sq. ft.	50 sq. ft.	100 sq. ft.	60 sq. ft.
Replacements, hours	Laser Arrays, 10,000 hrs	Optics-2,000hrs, Blower/Turbine - 20-30,000 hrs	Lamps - 1,000 hrs	Pumping Arrays - 10,000 hrs
Laser/Beam Mobility	High/High	Low/Medium	Low/High	Low/High
* Higher absorbtion means less reflected energy, and more efficient use of the laser beam				

Table 2– Direct Diode laser in Comparison with Conventional Lasers

Absorption Efficiency

The HPDDL used in this study generally operates with a center wavelength of 810 nm, which is in the near infrared range and not visible to the human eye. 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[7]. This leads to an advantage of the diode laser system, since the lower operating wavelength results in a higher absorption rate with most metals[8,9] [Figure 5.] This is especially true for aluminum in which the absorption peak is at the HPDDL wavelength of 810nm.

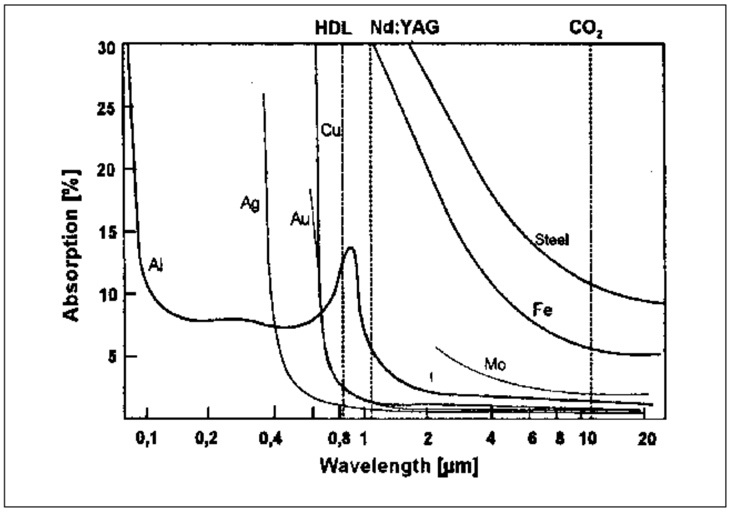

Figure 5 - Absorption vs. Wavelength for typical metals

Solid State Advantage

Another advantage of direct diode lasers is that they are solid-state lasers. This yields a highly controllable heat source. The HPDDL laser demonstrated in this study is microprocessor controlled and has a modulation bandwidth of 20KHz. This is an order of magnitude higher than conventional lasers. Unlike conventional systems, diode lasers do not require warm up time to stabilize. Power can also be turned on and off instantaneously. The instantaneous power control of the HPDDL realizes significant energy savings.

Laser Tube Mills

Conventional Lasers

CO_2 and Nd:YAG lasers are conventional lasers in which the laser beam is focused to the metal surface by mirrors or lenses. The laser light is typically focused to a spot of less than a millimeter in diameter. When the focused laser beam intensity is high [10^6 W/cm^2] it instantaneously liquefies and then vaporizes the metal surface and forms a plasma. The vapor pressure overcomes the surface tension of the liquid metal and pushes the liquid metal away from the laser beam causing the metal to form a key-hole. As the key-hole forms, the amount of laser energy absorbed by the work piece goes from the intrinsic absorption [Shown in Figure 5] to 100% at full key-hole penetration. This key-hole formation is a dynamic and chaotic process. The molten metal turbulently flows around the key-hole and resolidifies. Under very controlled conditions this can be effective method but it does have a very narrow operating windows.

The formation of the key-hole provides a deep narrow weld with minimum melted metal. This means minimum interaction time with the metal. This increases production rates and reduces the undesirable effects such as distortion and large heat-affected zones [HAZ's].

The advantages over the traditional welding methods such as Gas Tungsten Arc Welding [GTAW] are much higher welding speeds. Using a 6 kW CO_2 laser, welding speeds greater than 50 ft/min [15 M/min] have been reported for 0.040" [1mm] stainless tubing. For 0.080" [2mm] thick tube welding speeds in excess of 33ft/min [10M/min] have been reported[10].

The main fabrication disadvantages of conventional lasers are fit-up requirements and quality. Economically, there are high initial capital, installation, and operation costs.

The fit-up requirement is gap widths of < 5% of the wall thickness. To employ laser welding effectively, a tube mill has to be stable, run smoothly at the laser welding speeds, and form the tube to the fit-up requirements A seam tracking system is frequently employed to accurately track the seam[10].

The instability of the key-hole process leads to quality problems. If splatter on the inside and outside of the tube and occasional voids are acceptable than a conventional laser might be employed. Increasing the laser beam diameter will not help. In the case of the CO_2 laser the coupling efficiency of the laser light into the metal will drop off dramatically upon loss of key-hole. In the case of Nd:YAG, which has better light to metal coupling efficiency, the bigger spot means a larger HAZ and sagging.

Laser Welding with Diode lasers

The HPDDL naturally generates a beam shape that is ideal for continuous seam welding. Unlike the GTAW and the conventional laser welding, which generates a round heating spot, the diode laser generates a line of light on the metal part. This is not a key-hole/plasma generating process so it is very quiet and stable. This allows the tube fabricator to put the laser energy, independent of fabrication speed, into the part were it is needed, at the seam. This line of heat allows for a longer interaction time for the molten metal to wet together in a very controllable fashion. The line of heat also allows for the heat to penetrate deeper into the part. This is very important for low conductivity materials such as Stainless Steel [SS], titanium, and refractory metals. Therefore, the HPDDL yields high speed and high quality seam welds.

Welding Ferrous Materials

Laser diode welding of 304 Stainless Steel sheet and 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 need for special alignments. Initial results have shown similar tube fit-up requirements as the GTAW process. Tubing was successfully welded without changing the roller configuration.

There are large differences in the shape of laser heat source as compared to the GTAW process. These differences will require further process development to determine where the HPDDL beam should be placed with respect the "knit-point". In addition the gap dimensions at the "knit-point" will have to be established. With the GTAW process there is a gap to allow for the arc to "connect" to the thickness of the tube.

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. Metallographic inspection of welds made on the tube mill 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.

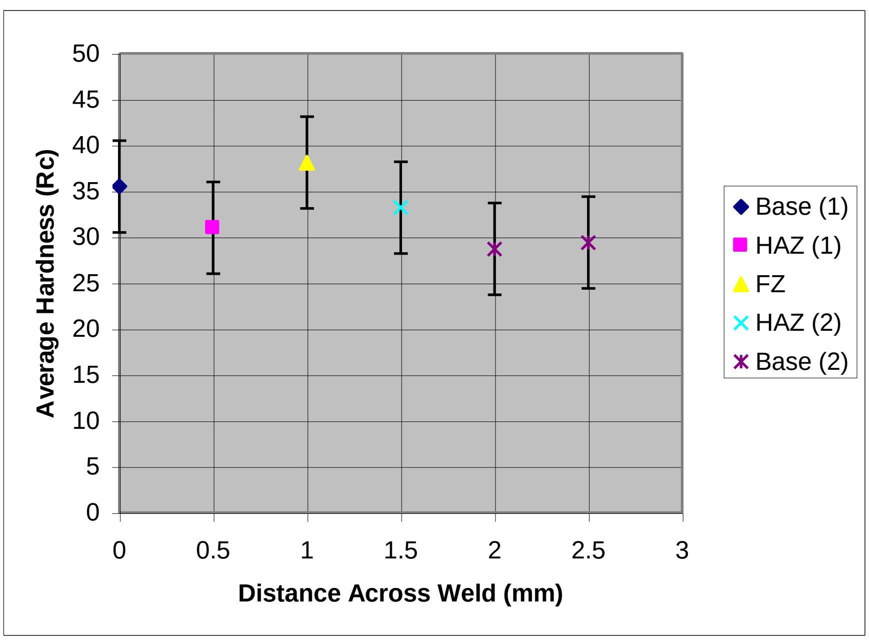

Figure 6: Average Hardness Plotted Against the Distance Across the weld for a 304 stainless steel tube.

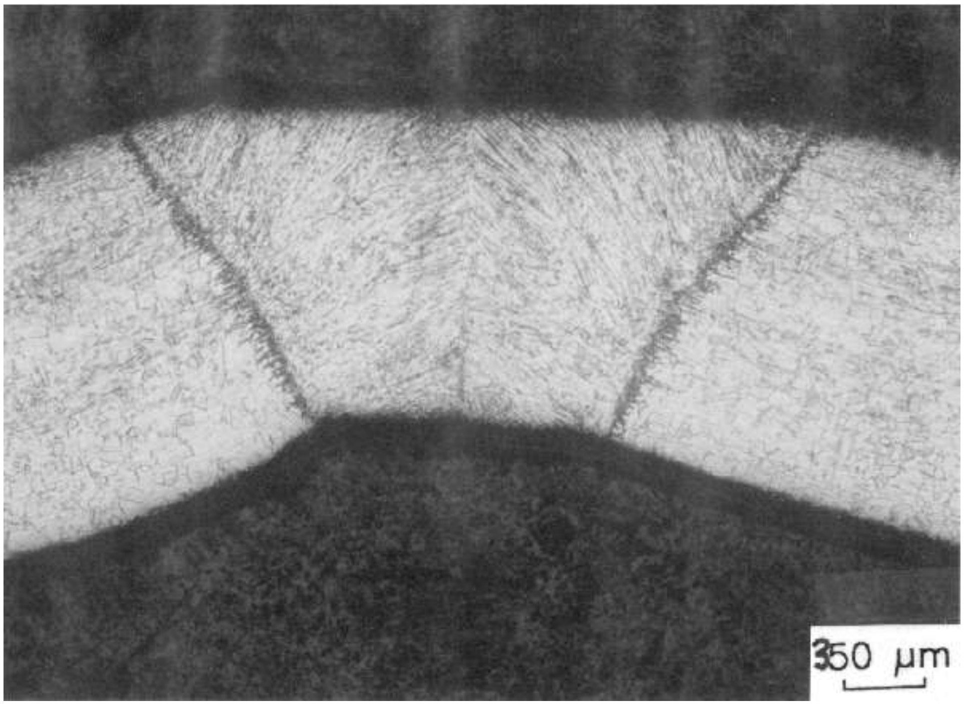

Figure 7: 304 Stainless Steel Tube Weld

The autogenous welding of 304 SS 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 coupons were 0.024" and 0.035" each piece was approximately 2" X 4" in size. The weld was made along the 4" side using an Argon shielding gas.

The coupons were butted tightly together and then clamped in a fixture and blanketed by Argon using a large area sparger. Argon flow rates were as high as 47 liters per minute, which provided complete coverage of the coupons over their entire length. The laser power was varied from 1200 watts to 3,150 Watts and the optimum welding speeds were recorded [Figure 8]. In Figure 8 there are two different curves for the 0.024" SS. In Series I the backside weld width was measured to be between 0.030" and 0.050". In Series II the backside weld width was less than 0.030". This results in a higher travel speed.

All of the welds exhibited exceptionally smooth surfaces on both sides, very low distortion of the plates 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 speeds for the flat sheets are approximately 30% lower than those achieved in a tube mill. This is due to better tooling and fit-up in the tube mill. The gap in the tubing being welded also allows for better absorption into the material being welded. Also, the direct diode laser is a line source, which allows for a slight preheat on the area to be welded. During the flat sheet welding process a heat sink was used, whereas on a tube mill the material being welded is not heat sunk. A micrograph for a lap weld is shown in Figure 9.

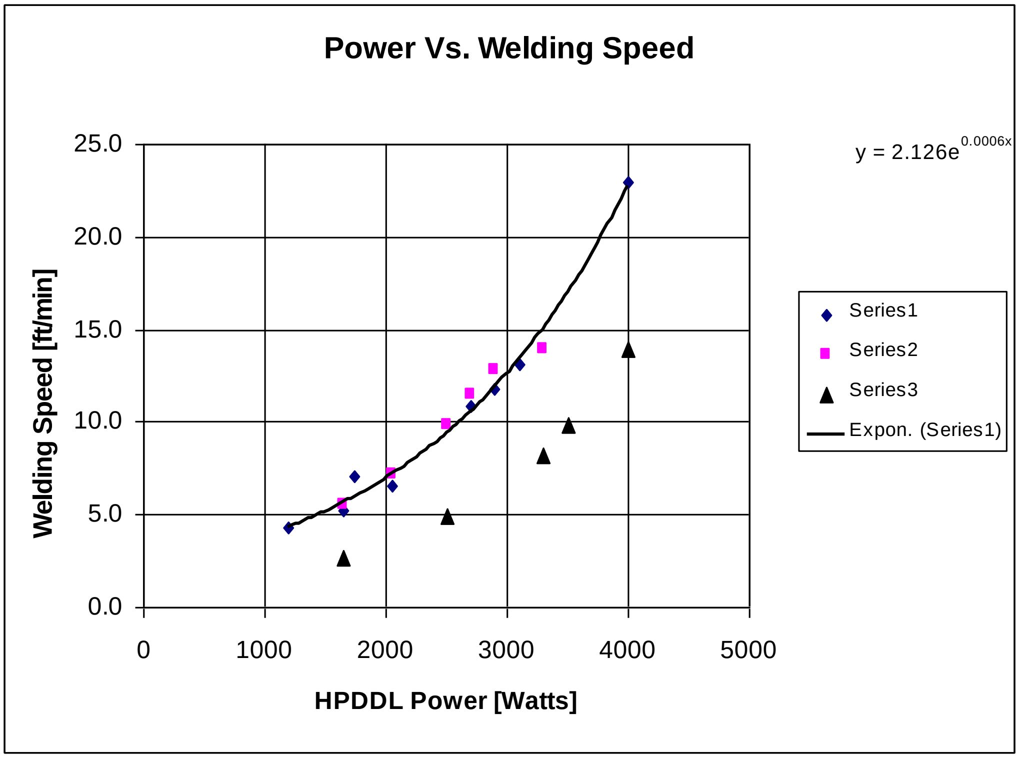

Figure 8 – Seam Welding of flat 304 SS sheets - speed vs. laser power.

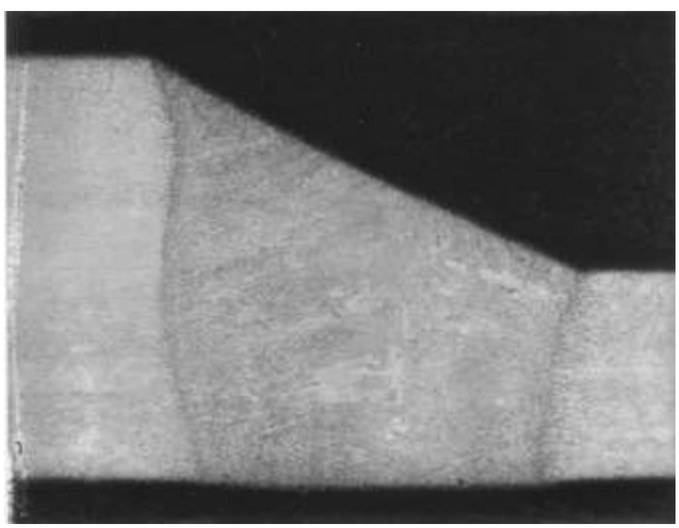

Figure 9: Micrograph of 304 SS lap weld showing excellent penetration and grain structure.

Tests with carbon steel coupons produced similar results, although at somewhat slower speeds. The carbon steel coupons that were lap welded were 2” x 4” in size and 0.06” in thickness. The welds were again exceptionally smooth and exhibited low distortion, but the heat-affected zone was somewhat larger than for the stainless steel materials.

Welding Galvanized Steel

Seam welds were produced with sheets of galvanized steel. The galvanized steel coupons were 4” X 13” in size and ranged in thickness from .028” to .064”. Using a 4 kW laser, an argon sparager and air knife the samples were welded at high speeds. A six axis robot allowed the laser to be tilted at a 70° angle to successfully produce the lap weld. The thinner steel was welded at speeds in excess of 9 ft/min, while the thicker steel produced quality welds at 3 ft/min. The welds were exceptionally smooth and exhibited low distortion. During the welding process the zinc boiled out of the weld, leaving a full penetration steel weldment. The crossection of the weld zone is seen in Figure 10.

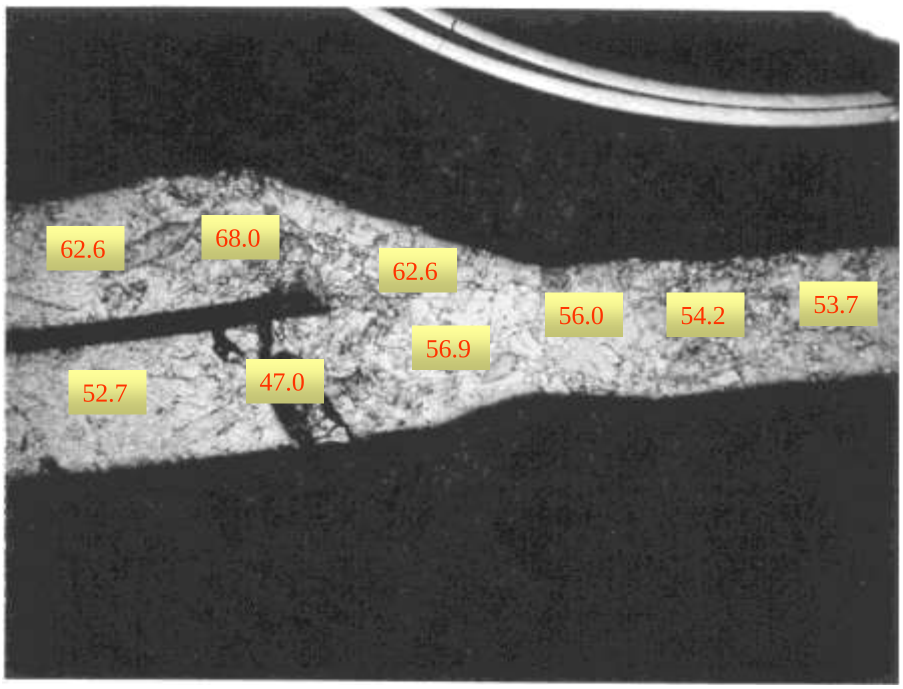

Figure 10: Micrograph of galvanized steel lap weld, 18.5 X magnification, 2% Nital etch.

Microhardness was also taken across the welded area of a galvanized steel lap weld. It was found that the hardness does not vary from the base material in the heat affected zone and fusion zone. This is an indication that the weld does not experience embrittlement and that the weld has uniform strength. The heat affected zone is also minimal for the weld as seen in Figure 11.

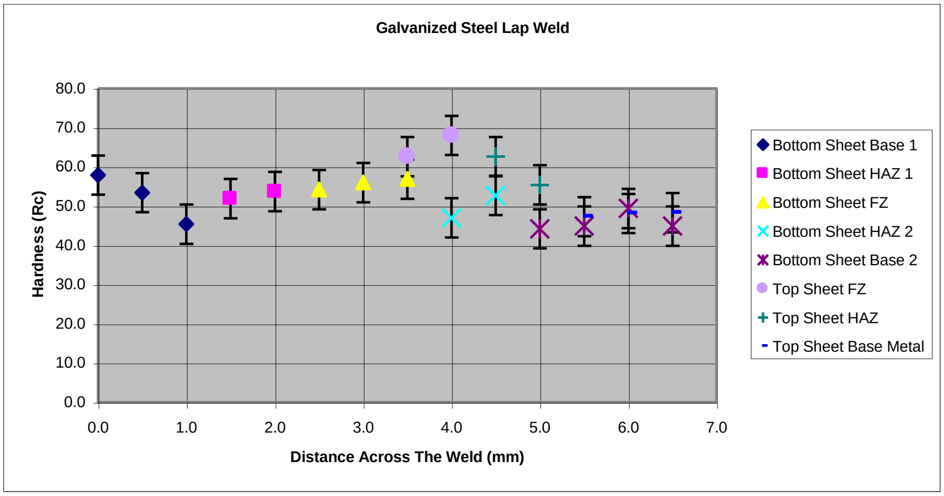

Figure 11: Average hardness plotted against distance across the weld for galvanized steel lap weld.

Welding Non-Ferrous Materials

Commercially Pure Titanium Welding

Tests were also conducted on a commercially pure titanium tube. Welds were produced at speeds of 13.5 ft/min at 3.4 kW. 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.

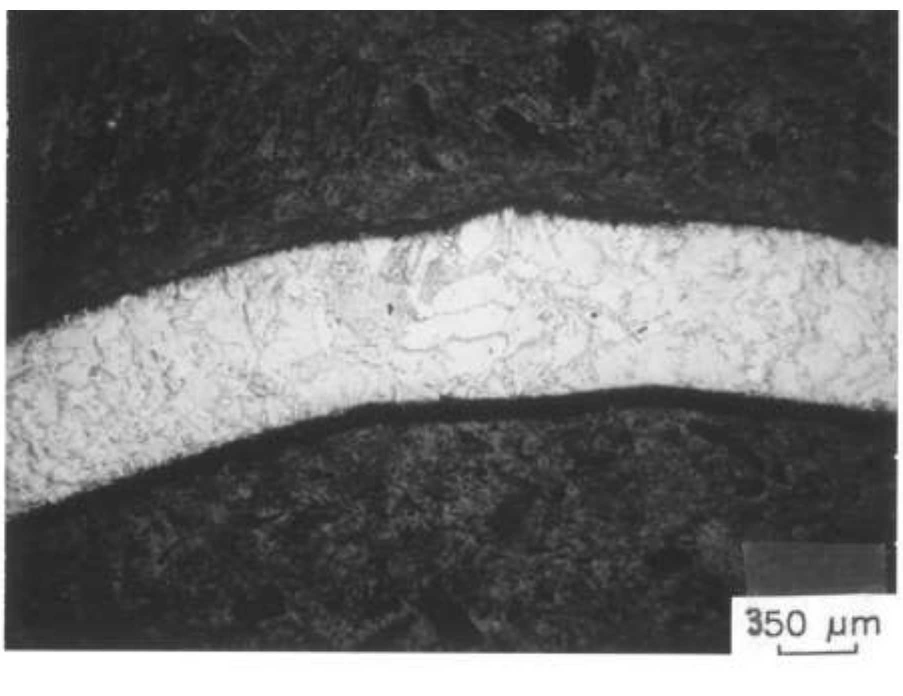

Figure 12: The fusion zone and heat affected zone of a titanium tube weld.

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.

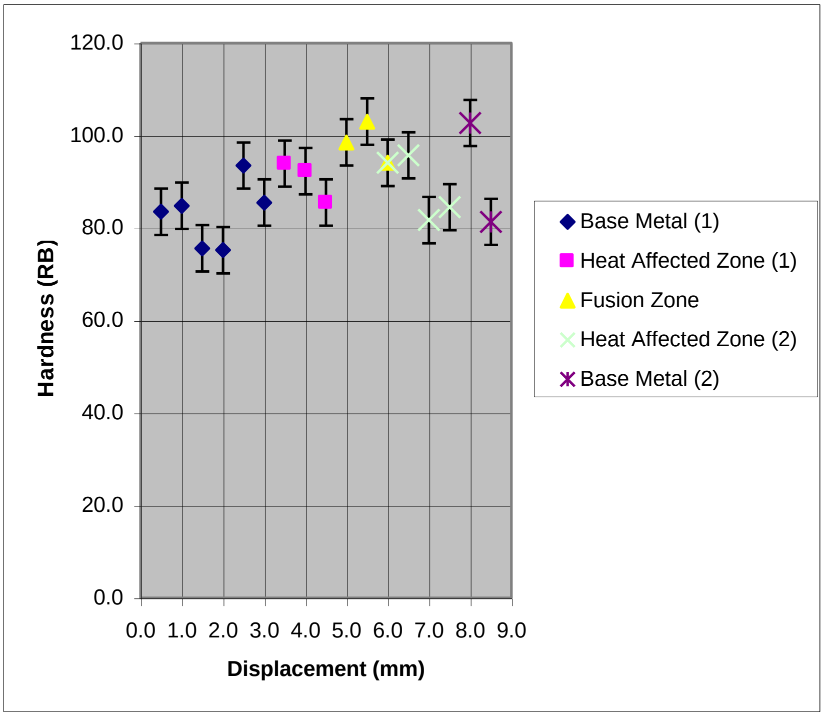

Figure 13: Hardness measurements taken across a titanium tube weld.

Welding Aluminum Plates

Welds were produced on 6000 and 5000 series aluminum coupons using the cover gas that impinged on both top and bottom. The aluminum coupons that were seam welded at 3.6kW, with welding speed of up to 8 m/min. At the time of the writing this article the weld strength and hardness have yet to be measured. An crossection of a weld is shown in Figure 14

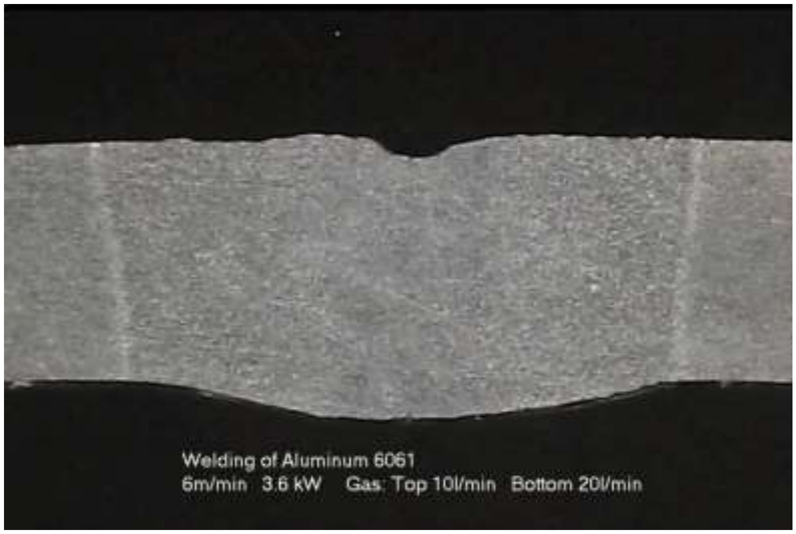

Figure 14: Micrograph of Aluminum 6061 weld at 6M/min.

Conclusion

The HPDDL system is a new type of heat source capable of meeting the autogenous welding needs of the tube mill and white goods industry. The beam shape of the high power laser diode system is rectangular or line source, which does not "key-hole", thus yielding higher quality autogenous seam welds than conventional lasers. Due to their high efficiency, HPDDL have low operation cost and are very compact. The HPDDL can mount directly on a tube mill or end of a robot with very little modification. These all solid state laser systems 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 zone. The HPDDL will eliminate costly mill down times for tip changes. These systems need virtually no maintenance, therefore enabling around the clock seam welding and tube fabrication.

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