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Heat Treating and Cladding Operations with High-Power Diode Lasers

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ABSTRACT

As tools for use in industrial applications, High Power Direct Diode Lasers [HPDDL], also known as semiconductor lasers, are becoming more prevalent as a heat source for industrial applications. Diode laser technology has now been used in production for a number of years. Their unique beam shape, low ownership cost, high efficiency (~60%), and compact design make them an economic alternative to traditional heat technologies for heat treating and cladding of overlay operations. The benefits of using HPDL for laser surface transformation hardening and cladding are discussed.

Keywords: HPDDL, heat treating, cladding

1. INTRODUCTION

The light emitted at the facet of the laser diode is highly divergent and astigmatic. The construction HPDDL gives it unique properties. The HPDDL is constructed from a lenslet array which 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 focusing lens will produce a concentrated line of light. This beam is very uniform, having a nearly top hat intensity profile along the long axis with a guassian profile perpendicular to the line along the short axis. The HPDDL used in this feasibility study employs 4 stacks of 21 bars, which are brought to a line by a single macro lens [Figure 1]. With dimensions of laser beam approximately 12.5 mm X <1 mm with a 125 mm focal length lens. With different macro lenses, this laser can achieve power densities from 1kw/cm^2 to 200 kW/cm^2. For Laser heat treating and cladding the power densities are approximately the same between 2 kW/cm^2 - 10kW/cm^2 .

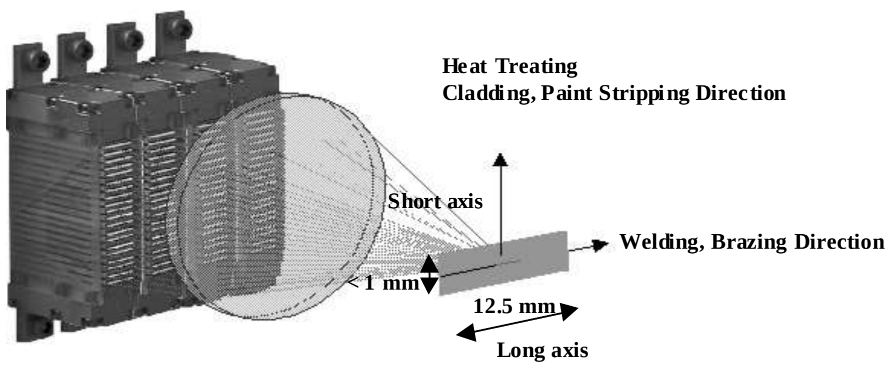

Figure 1 – HPDDL Standard Line focus configuration

2. HPDDL HEAT TREATING

2.1. HPDDL Benefits

Surface hardening is used to extend the versatility of certain metals by producing combinations of properties not readily attainable in other ways. The Benefits of HPDDL surface hardening are:

- Low or negligible distortion
- Minimal or no post processing is required
- Selective hardening in both depth and location
- Highly directional heating

- Controllable case depth
- Precision heating and control
- In-situ temperature control
- Dry process – no quench
- Environmentally friendly - Process does not require absorbent coatings
- Very high process speeds
- Hardening of larger variety of shapes
- Higher hardness
- Fatigue Life of component treated improved

For many applications, wear and the most severe stresses act only on the surface of the part. Therefore, the part may be surface hardened by a final treatment after all other processing has been accomplished including the last machining step. Laser surface hardening techniques may be used in situations where the surface of the part needs to be hardened without significantly distorting of the part. The flexibility of laser delivery systems, low distortion and high surface hardness have made lasers prevalent in applications that require selective hardening for wear and fatigue prone areas of machine and powder metal components [1].

A comparison with traditional transformation hardening techniques clearly show that laser surface hardening has distinct advantages. 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. A comparison with carburizing, nitriding and carbonitriding techniques also indicates advantages of laser surface processing. In pack carburizing processes it is difficult to control case depth. Whereas liquid carburizing can pose disposal problems with the salt bath and the baths often require frequent maintenance. Nitriding can be used to produce parts with high hardness and low distortion. A laser surface transformation hardened part can be produced with a deeper case and similar case hardness to that of a nitrided sample. Gas carbonitriding produces parts with less distortion than carburized parts, however gas control is critical in this process[2]. With laser beam hardening the applied light radiation instantaneously heats the surface, 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; therefore a quench is not required[3]. The major advantage of laser surface treatment is high processing speeds with precise case depths. Laser surface transformation hardening does not require a special atmosphere. 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[3]. The HPDDL is an ideal source for laser transformation hardening. The line of light, when moved across the work piece along the short axis has high edge definition without the need for special cylindrical lenses [Nd:YAG] or water cooled integrators [CO2]. The wavelength is 800nm, which is highly absorptive and does not require pre-coating of the work piece. The HPDDL systems have modulation bandwidth in excess of 10KHz, making ideal for in-situ temperature control.

There are many parameters that determine the effectiveness of a laser surface hardening treatment. The primary processing parameters used to obtain the experimental data are; laser power, processing speed, and beam profile. An increase in the laser power will result in a dramatic increase in the depth of hardening. An increase in processing speed will result in a decrease in the case depth. The energy density is a necessary criterion in the determination of the degree of surface hardening that may take place. The hardness data obtained from the experimental runs will provide information about the degree of hardening and case depth. Table 1 shows typical maximum hardnesses and case depths that can be obtained on some common industrial materials. Maximum hardness is typically obtained at the detriment of case depth and are typically inversely proportional. The microstructures produced by the heat treatment should also be considered to determine if the surface treatment is successful. The processing temperature, quench time and final temperature of the part must also be carefully monitored to ensure that the surface of the part is properly austenitized and that a proper cooling rate occurred.

Material	Maximum Hardness [Rc]	Max Depth [mm]
Carbon Steels		
1080	68	2
1075	68	2
1045	60	1.5
1030	50	0.75
1018	30	0.25
Heat treatable alloys		
4140	68	2
4340	68	2
Heat treatable Stainless Steel		
420	65	1.5
410	50	0.5
Cast Irons		
Gray	65	1
Ductile	55	0.75

Table 1 – Typical hardness and case depths obtained using HPDDL

2.2. Surface Transformation Hardening

A key application for this laser is surface transformation hardening. This laser was designed with this application in mind. The laser provides a line beam with dimensions of 12 mm X 1mm FWHM at focus. This beam, which has a top hat profile along the 12 mm direction, can be swept over the surface to produce the desired hardening. Because of the large area covered directly by the beam, this laser can quickly and uniformly treat large parts. See Figure 3.

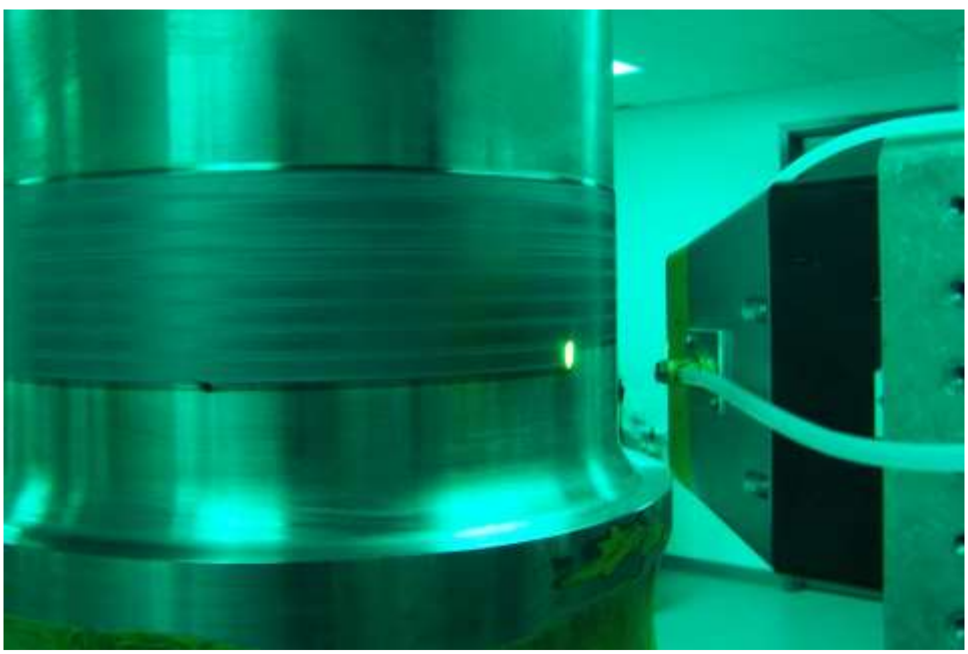

Figure 2 – HPPDL surface hardening bearing surface on large axel

2.3. 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 CO2 [10.6 um] lasers, which are commonly used in industrial applications. This leads to an advantage of the diode laser system, since the lower operating wavelength results in a higher absorption rate with most metals [4,5] [Figure 3]. Laser transformation hardening of steels is typically performed with a CO2 laser but the parts need to be coated with absorptive coatings for the otherwise reflective surface. These coatings are involve significant costs added to the laser hardening process. In addition, these coating are notoriously inconsistent during the dynamic hardening process. Users can experience significant cost savings by eliminating the absorption coating process. Additionally, the use of the HPDDL process is more environmentally friendly; disposal of waste paint, clean-up consumables, elimination of air-born particulate, VOC and air filters are eliminated. Like the HPDDL the Nd:YAG the lasers also do not require coatings but there are limits to the fiber delivery and beam shaping systems. Large components require continuous beam-on times in excess of 30 minutes at full power to cover the required surface area; thus requiring special cooling.[6] The HPDDL does not require fiber optics the beam, which is naturally a line of light, is directly applied to the work piece.

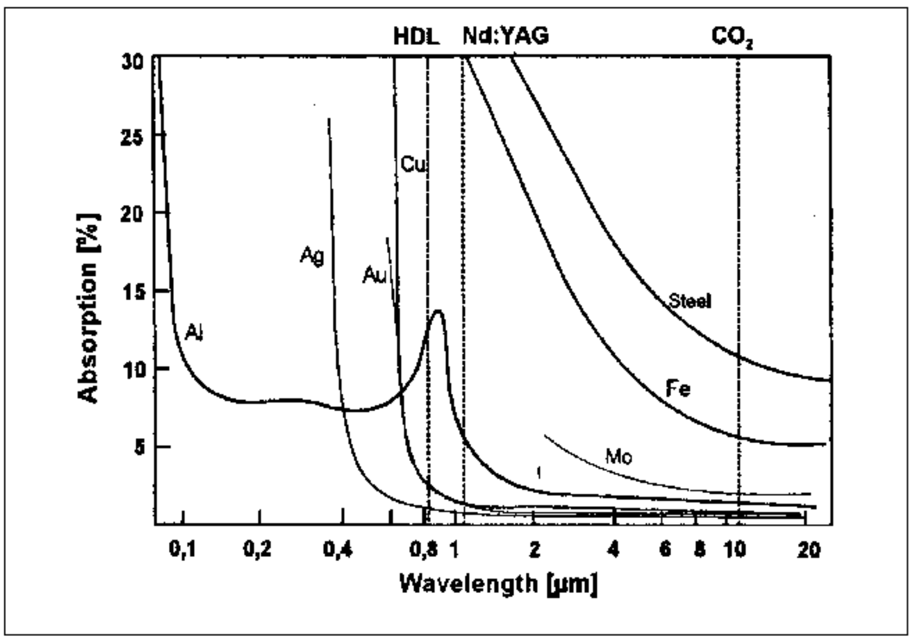

Figure 3 - Absorption vs. Wavelength for typical metals [4,5]

2.4. Operating Costs

The advantages of the HPDDL are their high electrical to optical conversion efficiency. The laser diodes used by Nuvonyx have demonstrated electrical to optical conversion efficiencies as high as 60%. The net result is a laser system [Chiller and power supplies] with a wall plug electrical to optical power conversion efficiency of ~ 30%. Consequently, a 4,000 Watt CW laser diode system consumes less than 15,000 Watts of electrical power. This efficiency translates into a lower cost of operation for the user and a much smaller footprint as shown is Table 1.

	DIRECT DIODE ISL	CO2 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	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- Operating costs for commonly used industrial lasers

2.5. Solid State Advantage

Another advantage of direct diode lasers is that they are solid-state lasers. This yields a highly controllable heat source. Power can also be turned on and off instantaneously. The instantaneous power control of the HPDDL realizes significant energy savings. The HPDDL laser demonstrated in this study is microprocessor controlled and has a modulation bandwidth of 6 KHz. Unlike conventional systems, diode lasers do not require warm up time to stabilize. The limitation in the feedback control is no longer the laser but the temperature monitoring systems.

Infrared temperature sensors or pyrometers can be integrated with the HPDDL in a industrial process to measure the surface temperature of objects without contact. The sensor work based on the principle that the energy emitted by an object is proportional to its temperature. Like a camera, the sensors use an optical system to collect the radiant energy emitted by the measured target. This signal is then processed by the sensor electronics to provide the desired temperature output. This temperature output can be displayed on a digital meter, or it can be in the form of a current or voltage output signal that varies linearly with temperature. These temperature output signals can then be input into a computer, controller, or other device for process monitoring and control.

3. HPDDL CLADDING

3.1. Laser cladding Benefits

The general benefits of laser cladding can be summarized.

- Low dilution
- Small heat affected zone = less distortion
- High quench rates = finer grain structure = higher corrosion potentials
- Production worthy process
- Highly controllable - Clad thickness

The laser cladding process typically involves the melting of powders which applied with a coaxial feeder, lateral injection or pre-placed. These are melted to ensure a metallurgical bond with minimal dilution, nominal substrate melting and a small heat affected zone.

3.2. HPDDL Benefits

In addition to the benefits listed above the unique beam shape and higher absorption, as described above, enable new applications that cannot be implemented with traditional lasers.

- Smaller wavelength = higher photon energy = More absorption
  - Enables wire feed cladding
  - Enables strip cladding
  - Enables spray and fuse cladding
- Small Size = portability = Enables in-field cladding
- Line source allows for wide thin and flat clads and alloy surfaces
- No scanning required
- Higher quench rates

An ideal application for the HPDDL is large surface area laser cladding, as shown in Figure 4.

Figure 4 – HPDDL clad mild steel substrate – [200 X 200 X 25 mm] 1.5 mm thick nickel chrome clad

The HPDDL line shaped beam is moved perpendicular to the long axis along the short axis. The biggest benefit of HPDDL laser cladding is that the unique line source allows the user to produce clads with a controllable width without scanning. CO_2 and Nd: YAG lasers have a smaller spot; thus, the laser must be scanned over the cladded area. The wavelength of the HPDDL is 808 nm, compared with 1060 nm for a Nd: YAG laser and 10640 nm of the CO_2 laser. The shorter wavelength of the HPDDL allows for higher absorption into the material being cladded, therefore, a higher deposition rates can be achieved. [Table 2] [7] Another advantage of the HPDDL is a solid-state laser; thus, the thermal input can be precisely controlled, yielding minimal dilution and a small heat affected zone.

Laser	Power kW	Speed m/min (inch/min)	Clad width mm(inch)	Powder feed rate kg/hr (lbs/hr)	Cladding Efficency kg/kW*hr
CO2	5	0.9 (35,4)	5 (0.197)	2.16 (4.76)	0.432
CO2	20	1.2 (47.24)	10 (0.394)	6.5 (14.33)	0.325
Diode [800/940]	3	0.9 (35,4)	5 (0.197)	2.2 (4.85)	0.733
Diode [800]*	4	0.5 (19.7)	12.5 (0.5)	2.7 (6.0)	0.675

Table 3 – Comparison between the HPDDL and the CO_2 [7]

3.3. Laser Cladding

During a laser cladding process, dilution is expected to be minimized. In cladding operations dilution, is often defined as the amount of intermixing of the clad and substrate with current cladding techniques. Dilution is measured by visual analysis or through a SEM elemental line scan. Visual analysis allows the user to get a quick estimate of the dilution of the clad, however, with the HPDDL this method of measurement was found not to be very accurate. Through visual analysis, dilution is defined as the distance the clad layer extends below the substrate. SEM analysis is a true, accurate measure of the dilution, or intermixing of the clad and substrate. Laser alloying is a process that is often grouped with laser cladding operations. Laser cladding and alloying are traditionally distinguished by the relative amounts of the consumable material added and substrate melted. Generally the two categories are arbitrarily separated by their relative amount of dilution, laser alloying being classified as having greater than 10% dilution, laser cladding having less than 10% dilution[8]. In laser alloying it is generally desired to mix portions of the coating with the substrate to produce an alloyed layer, thus a high dilution and high intermixing is expected. It should also be noted that laser alloying requires convection in the weld pool and laser cladding does not. In many laser alloying processes, the cooling rate is often monitored to ensure intermixing and the formation of unique metallurgical compounds. Ultrafast quench rates of the order of 10^{11} Ks^{-1} are often required[8] as well as a high solubility of the clad material in the parent material.

The clad material deposited with the HPDDL does not intermix with the substrate in many applications; therefore, the dense, uniform microstructures of the clad layer allows for enhanced single pass corrosion or wear resistance. The denser microstructure and better bonding of laser clads allows for enhanced corrosion and wear resistance with a single pass. Laser cladding is a viable alternative to plasma spraying and TIG or MIG processes. It is difficult to produce a thin clads with a TIG, MIG or plasma spray system without having less than 5% dilution, therefore, as many as 15 overlapping passes may be required to obtain an undiluted clad layer[9]. Conventional arc welding processes generally impart a significant amount of heat into the part resulting in a large heat affected zone and distortion. Post-weld treatment can improve the properties of the joint, but can also lead to distortion of the component[10]. The surface finish of overlapping passes produced with the HPDDL are relatively flat as compared to TIG cladding, which produces distinct ridges and valleys, which lead to cracking when bent [11]. In addition, the arc welding processes often are also responsible for the losses of alloying elements[12]. A direct comparison of a laser clad layer with an arc-welded layer indicates that the HPDDL clad has significant grain refinement, which in some cases lead to an increased wear resistance [13]. Laser cladding also has advantages over plasma clad processes. The sharp intermetallic boundary of the plasma clad layer with the substrate also often leads to pores and cracking [13]. The interface between the clad and substrate of a HPDDL clad is smooth with minimal dilution and no boundary layer. The HPDDL also surpasses flame spray technology, since flame spray produces a more porous coating with limited adhesion [14]. The HPDDL has been used to subsequently clad flame sprayed coatings. This is shown to significantly reduce the pores and create a true alloy bond with the substrate.

Property	Oxyacetylene Welding (OAW)	Gas Metal Arc Welding (GMAW)	Gas Tungsten Arc Welding (GTAW)	Plasma Arc Welding (PAW)	HPDDL Cladding
Mode	Manual	Automatic	Automatic	Automatic	Automatic
Hardfacing alloy	All	All	All	All	All
Layer Depth (in.)	.0625 to .0938	.0625 to .0938	.0625 to .0938	.0625 to .0938	.0625 to .669
Number of Passes	---	5	15	5	1
Clad Width (in.)	---	0.875	0.250	0.875	0.475
Surface Speed (m/min)	2.25 to 2.50 sq. in/min	18 to 20 ipm	36 ipm	18 to 20 ipm	7 to 32 ipm
Preheat	400 to 600 F	600 to 800 F	600 to 800 F	600 to 800 F	None
Dilution (%)	1 to 10 %	15 to 25 %	1 to 8 %	5 to 30 %	Negligible
Costs For Hard-Facing 100 6 in. OD Tool Joints					
Shielding Gas	---	$24	$105	$48	$100
Oxygen	$6	---	---	---	---
Acetylene	$25	---	---	---	---
Tungsten Carbide	$485	$615	$550	$615	---
Wire or Powder	---	$22		$198	$200
Total	$516	$661	$655	$861	$300
Hardfacing Time (min)	2500	450	750	450	67

Table 4. Economic comparison of traditional overlay process vs. HPDDL cladding

3.4. Standard Visual Examination

In order to obtain the visual dilution the clads are crossectioned. The portion of the clad that is above the substrate is measured at the highest point as well as the entire length of the clad layer. The portion of the clad below the substrate is divided by the length of the total clad layer to produce a percentage visual dilution [Figure 5]. The drawback to this method of measuring dilution is the lack of accuracy in measurements, due to the fact that the amount of alloying cannot be determined with this method. However, visual dilution measurements are a straightforward approach to determining the approximate dilution of a sample while processing.

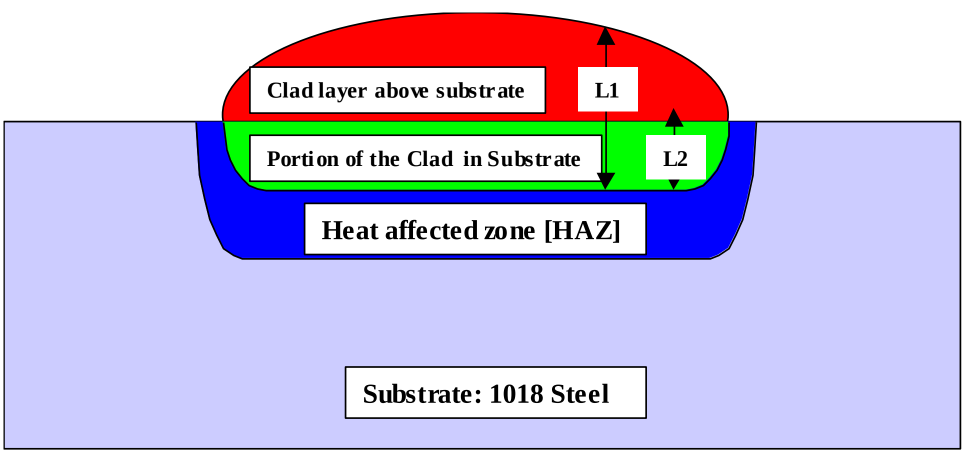

Figure 5: Standard visual measurement of dilution was performed through the equation L2/L1.

3.5. SEM Analysis

In order to get a better picture of the amount of alloying/dilution that a clad has a Scanning Electron Microscope [SEM] with elemental trace can used on each of the samples to determine the dilution of the clad layer. This dilution defined by the amount of intermixing of the clad layer and substrate. Each powder has a reasonable amount of Chromium; therefore, this element was traced in the clad layer for each powder. Iron was traced in the substrate.

At both a low and high process speed the dilution of the clad into the substrate is minimized. This can be seen in Figure 6.

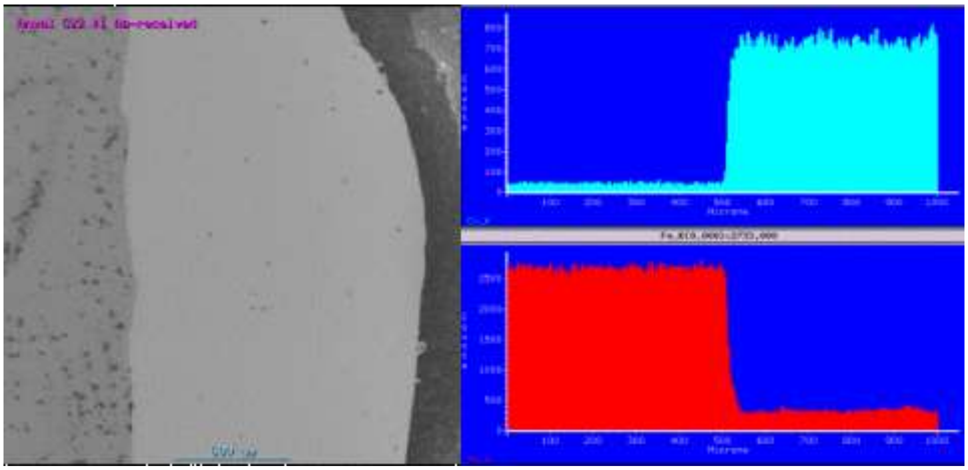

Figure 6: A SEM line trace of a NiCrMo clad produced at 0.45 m/min, 4 kW.

The properties of overlapping passes with regard to dilution and amount of intermixing are similar to those of a single pass.

3.6. Microstructural Characterization

To bring out the microstructure, the 410T stainless material was electrolytically etched in oxalic acid, while the NiCrMo and cobalt based alloys were etched electrolytically in a solution containing equal amounts of CrO3 and potassium permanganate, and 8% sodium hydroxide. The microstructures indicate thorough melting of the colbalt based powder. [Figure 7]. Grain growth is seen in the heat-affected zone of the clad, however, there is no evidence of the melting of the substrate. The 410 T SS powder shows also shows grain growth in the heat-affected zone, but the microstructure of the clad show is primarily martensitic due to the rapid quench rate of the powder. The microstructures present indicate that the dilution of the clad into the substrate is minimal and that changes in process speed do not reflect changes in dilution.

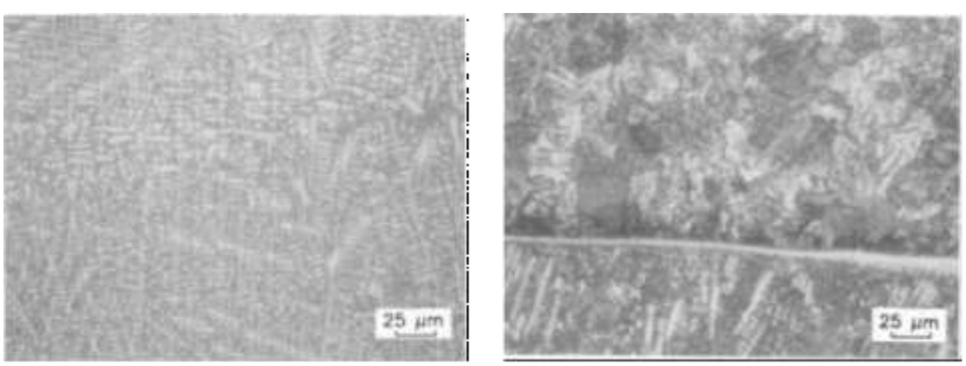

Figure 7: Dendritic formation in the Cobalt based clad layer, also the interface between the clad and substrate is shown on the left.

3.7. Wire feed cladding

One of the benefits of HPDDL laser is the ability to feed standards welding wire into the laser beam. This cladding has been demonstrated using :

- Standard wire feeder
- Standard MIG welding wire
- Standard Hardfacing wire
- SiB brazing wire

Using standard welding wire and wire feeders the HPDDL was used to produce clads . This can be done either in a horizontally or normal position [Figure 8] or in vertical or out of position [Figure 9]. The dilutions have been measured to be higher that the powder cladding process, however they are within the dilution specs for standard overlay processes such a MIG and PTA. The allows for remote laser cladding and out of position cladding.

Figure 8 –HPDDL wire feed clad – performed in the horizontal position using standard 0.8 mm diameter wire.

Figure 9 - HPDDL wire feed clad – performed in the vertical position using standard 0.8 mm diameter wire

4. CONCLUSION

HPDDL systems are versatile laser systems capable of cost effectively meeting the needs of industry for laser heat treating and laser cladding applications. The advantages of direct diode lasers are the high wall plug efficiency, unique beam properties, high absorption on the work piece, order of magnitude smaller footprint, lower maintenance costs, , and high control bandwidth. All these lead to a dramatic reduction in production ownership costs.

When the same HPDDL used for laser cladding it allows the user to produce thin wide single pass clads with minimal dilution. This cannot be accomplished by traditional arc welding processes, which require multiple passes to achieve a wide clad layer. The low dilution clads with controllable thickness are beneficial because much lower distortion and the end user can save the expense of purchasing excessive amounts of cladding wire and powder. Laser cladding is highly advantageous over TIG and MIG processes because the amount of dilution and distortion is minimized. The primary advantage of the HPDDL in comparison to CO_2 and Nd:YAG lasers is lower ownership costs, higher deposition rates, elimination of scanning optics, thin clads with low dilution, and the ability to use wire or strip form clad material.

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