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Surface Modification using High Power Direct Diode Lasers – Case Studies

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Abstract

High power direct diode lasers [HPDDL] laser are enabling novel surface modification processes such as laser heat treating, laser alloying, and laser cladding due to their high efficiency, unique beam shape, small size, and low installation, maintenance, operating costs. For the first time the diode laser is making laser surface modification an economically viable alternative to traditional surface modification techniques. A comparison of the advantages direct diode laser versus traditional industrial lasers such as CO2 and Nd:YAG and non-laser technologies such a vacuum carburizing, gas nitriding systems, RF induction, TIG, MIG, and plasma for each of these applications are presented. There are many installations now using diode laser for heat-treating parts ranging from thousand pound parts to small tools. The diode laser with its short wavelength and unique beam shape makes laser surface modification very easy to implement in production.

1 Summary

This paper will summarize several successful HPDDL surface modification processes along with a production installation. These are laser case hardening, laser alloying using LISI process and laser cladding using both powder and wire. We will share the savings and performance improvements for a HPDDL heat treatment production installation. These improvements are dramatic due to the high reliability and low maintenance experienced with the diode laser systems. Both the improvements helped realize a less than one-year return on investment.

2 HPDDL Heat Treatment Production Installation

2.1 Overview

A 4 kW HPDDL system was installed 2 years ago into a heavy equipment production line to provide the heat-treating for a bearing surface on large spindles. This is shown in **Figure** 1. The installation costs were recovered in less than a year because of the low installation, maintenance, operating costs, and high reliability.

2.2 Advantages

For two years the production processes had been performed by a fiber coupled lamp pumped Nd:YAG laser with a water cooled line generating terminating optic and aperture. However, the Nd:YAG laser was not well suited to this application because of the high maintenance of the system and the inability of the system to maintain power level during long processing cycles.

These problems caused significant delays in production, which increased the costs of producing the parts. It was clear that a better laser source was needed. The initial test results using the new HPDDL technology demonstrated that the HPDDL has four primary advantages over other laser systems.

The first advantage is the low installation cost for the HPPDL. The HPDDL, with its short wave length [810nm] and naturally occurring line shape beam enabled a drop in replacement for the fiber coupled Nd:YAG system. In addition, the HPDDL system is controlled by a microprocessor that can easily be programmed to mimic the input control of a Nd:YAG laser. Finally, the HPDDL is sufficiently small; that the entire unit was mounted on the robot in place of the current fiber coupled beam delivery system. The set-up, installation and checkout of the HPDDL system is straight forward compared to other more complex laser systems and was accomplished in less than one day. The HPDDL system has no special power or environmental requirements other than the existing laser safety enclosure.

The second advantage is the low operating cost of the HPDDL due to the high electrical conversion efficiency of the system. The 4 kWatt HPDDL system, complete with the water to air chiller, consumes less than 16 kW of electrical power during operation. In contrast, an equivalent lamp pumped Nd:YAG laser will consume between 350 kWatts and 400 kWatts for the same output power. This low input power requirement is one of the primary reasons for the low installation costs of the system.

The third advantage for the HPDDL is its very stable output power during operation regardless of the heat feedback to the system. The Nd:YAG laser on the other hand tended to heat up during the long heat treating cycles and slowly lost power during the process. This was causing some quality problems at the end of the process cycle where the hardness of the material would decrease due to the lower power level of the Nd:YAG laser.

The forth advantage for the HPDDL is the high reliability of the all-solid state system. Prior to this installation, the Nd:YAG laser was documented with less than 30% uptime which resulted in extra shifts, backlogs, and the eventual outsourcing of the heat treatment. However, the HPDDL proved itself to be highly reliable by posting a ~98% up time record over the last 2 years of operation.

2.3 Production Integration

The laser workstation consisted of an existing 6-axis robot for handling the laser, a large horizontal indexer for rotating the parts, a laser safety enclosure with automatic door opener and an external remote control panel. The upgrades included changing the mechanical mounts on the end of the robot, and developing software that would enable the HPPDL to mimic the control commands of the Nd:YAG laser.

The hardness specification was easily achieved using a self-quenching heat-treating process. Like the Nd:YAG the HPDDL, which has short wavelength of 810 nm, which can case harden cleaned machined surface without the need for absorbing paints or coatings as required for CO2 lasers. [1, 2] The part is simply wiped down with an alcohol damp cloth to remove dirt and oil. The case depth achieved on the parts is approximately 1 mm with Rockwell hardness in the range of 45-55 depending on the base material.

The particular HPDDL used has focused spot that is a line that has dimensions of 12mm X <0.5 mm at a working distance from the laser head of 95 mm. A significant improvement in the process tolerance was achieved by using an optional output optic that decreased the focussing of the beam in the fast axis to 12 mm X 6 mm. This allowed the depth of focus to be expanded by over 1 cm. This allowed the part to be placed on the turntable without it having to be accurately registered and enabled the robot to be programmed without having to first access a reference point and offset its program. In addition, the optional optic also maximized the case depth, minimized the risk of surface melting and decreased the track-to-track back temper.

2.4 Production Results

The laser system was installed in June 2002 and has been operating up to three shifts a day depending on the production backlog. The maintenance cost was reduced by a factor of 300 from the previous year and the up time for the laser was better than 98% for the year. In addition, the process time for one part was reduced from 90 minutes to 30 minutes and the back-temper for each part was less than 5% which is substantially better than the parts processed with the Nd:YAG laser.

The improvements in the process speed are a result of several factors which include the natural beam shape not requiring a power reducing water cooled aperture. The absorption of the HPDDL beam is substantially higher than for the longer wavelengths of either the CO2 laser or the Nd:YAG laser. In addition, the HPPDL is highly polarized which further enhances its absorption. At elevated temperatures, the absorption rate of the highly polarized HPDDL beam can exceed 90% for incident angles from 0 to 70 degrees [3]. The net result is that the process can proceed at a faster rate when using a highly polarized beam compared to an unpolarized beam at the same power level. In addition, the process is insensitive to part geometry in which the incident angle is different within the beam or changes under the beam. The typical case obtained by using the HPDDL is seen in **Figure** 2.

The high stability of the HPDDL enables the parts to be processed open loop. Therefore, there was no need for the additional expense for an IR pyrometer and a temperature feedback system. The HPDDL output power is measured and tracked on a weekly basis. Over the last year the power level has been very stable. During the processing of the part, the output power of the HPDDL is very stable which greatly improved the productivity of the laser heat-treating cell.

In summary, the installation of a 4 kW HPDDL system into a heavy equipment production line to perform a critical heat-treating process has been a tremendous success. Part yield has been increased substantially, labor hours per part to process have been decreased substantially, maintenance has been virtually eliminated and the system has paid for itself in less than one year.

2.5 HPDDL Laser Heat Treat – Precision

The advantages of the laser heat-treating of very large parts like the example above are obvious due to the large size. However, the HPDDL is proving to be very cost competitive for small parts when compared to RF induction, vacuum carbonizing and gas nitriding. In general, the laser heat-treating has an advantage over these processes if the part has a specific surface area that needs to be case hardened. The primary cost justification is that the laser hardening process can case hardening localized areas with very little distortion, which eliminates the need for subsequent grinding or machining. Compared to induction, the laser process is typically a dry process that can produce a shallower and harder case. In addition the laser diode can heat treat areas that are difficult or impossible to access with the induction coils. The laser heat treating process is also much easier to design and maintain due to the fact that the laser heat treats only what is illuminated. There is no need for special coils, flux concentrators, shields or susceptors. When compared to vacuum carbonizing and gas nitriding the laser process typically requires a change in material to high carbon content. Therefore, the advantage of less distortion and post-machining have to be compared to cost associated with changing material. The laser diode has been successfully installed in production for heat treating, bearing slides, tools and saw blades. See **Figure** 3. The efficiency and small size of the diode laser enable multiple lasers to be powered off the same power supplies, which allow multi beam simultaneous heat-treating. The small size and the ability to illuminate the surface at a distance allow the integration of the laser into a CNC machining equipment such that the heat-treat step can be performed immediately after machining.

3 HPDDL laser surface alloying and cladding

Laser surface alloy and cladding offer industry great promise in that they permit the modification of the surface of functional parts without a significant amount of distortion or heat effect zone. Some of the biggest application are for anti-galling for metal on metal surfaces, the cylinder kit area is a prime example. There are also many anti-erosion application for surface areas in which steel is in contact with silica containing material [dirt and sand]. There are several overviews of the literature surround laser surface alloying and cladding [4]. The common thread for laser surface alloying and cladding is the addition of material onto the surface of the part to be modified. This material can even be a gas, like nitrogen. The processing parameters necessary for alloying and cladding are different due to surface intermixing and turbulent requirements. As the name implies alloying uses base material as a major constituent of the resulting alloy. Cladding typically requires little or no intermixing with substrate material. Typically, the alloying is much thinner than the clads, on the order of 10 –100 microns where cladding is from 100's – 1000's of microns thick. Since the amount of materials melted for laser alloys is smaller one can travel at greater speeds at a given power and power density distribution. The beam shape is critical for both laser alloying and cladding. The diode laser has a naturally occurring beam shape that is very close to a "top hat" profile that many have found to be close to the ideal for laser cladding an alloying. However, others have shown that the optimum beam shape is not a top but a "Bat-Ear" profile. The molten pool convection driven by the marangoni flow proceeds from the molten regions of lower surface tension to those of higher surface tension, and is dependent on the material and the physical characteristics of the heat source. [5, 6] This flow determines the final shape and flatness of the resulting modified surface. The construction of the HPDDL allows for the customization of beam shape to achieve the desired heating profile.

3.1 Laser Alloying

As with any industrial process economics is the final arbiter of is adoption by industry. The heat source [laser] and the application of the secondary alloying material must be low cost. The Laser Induced Surface Improvement [LISI] process that has been patented by University of Tennessee has a potential for low production cost [7]. This process involves the application of an environmentally friendly precursor mixture to the surface using a paint spraying technical. This allows one to apply a very uniform but thin precursor layer due to the self leveling characteristics of paint. In addition, this allows one to perform out of position alloying on complex irregular shaped substrates without the concern of feeding materials in-situ into the beam. This process has been demonstrated commercially on the wheel lock mechanisms for the "fifth wheel" or the heavy vehicles coupler using a fiber coupled Nd:YAG 3kW laser with a line generating optic as the heat source and a Cr/CrB precursor [8]. The ISL-4000L HPDDL which is 25 – 30 X more efficient than the Nd:YAG produces a natural line shape at 4000W. Therefore, we set out to compare the HPDDL to that of Nd:YAG so as to demonstrate that a low cost HPDDL laser source will produce the same quality coatings thus enabling similar process for many other application requiring large amount of surface areas be processed .

3.1.1 Laser Alloying Process

We have demonstrated the LISI with two different HPDDL lasers using a Cr/CrB precursor coating. The ISL-4000L, which is only lensed in one axis producing a profile, is shown in **Figure** 4. The beam has dimensions of 12 mm X 0.4 mm FWHM with a 125 mm focal length lens. Since this laser is only lensed in the fast direction and not the slow the beam has large "wings" in the beam profile, which contain approximately 60 watts of power. This power is not enough to melt the precursor into the surface, but leads to thermal delamination of the precursor approximately 2 mm outside the alloy region. This exposed substrate becomes a defect for a subsequent alloying track. This problem was over come by a water-cooled aperture that blocks the wings from illuminating the surface. The result of LISI with the ISL-4000L with the beam block is shown in **Figure** 5.

With proper HPDDL laser design, this aperture can be eliminated. This is demonstrated using a fast and slow lensed HPDDL [9] producing a 500 W beam as shown in **Figure** 6. This beam has dimensions of 1.7 mm X 0.3 mm. As can be seen from these profiles the fast and slow-lensed laser has the sharper profiles due to the aperaturing effect of the slow lenses. This laser does not require a water-cooled mask to protect the precursor coating form thermal degradation for pass to pass application. The LISI resulting from the fast and slow lensed HPDDL is shown in **Figure** 7.

3.1.2 Laser alloying Conclusion

The Direct diode laser has demonstrated that it can be used to produce the same quality as the inefficient fiber coupled Nd:YAG laser. Therefore, industry now has an inexpensive laser alloy process for erosion and corrosion improvement that combines an inexpensive HPDDL laser source with a inexpensive precursor process. Further improvement in diode laser technology with respect to beam power and beam shape will make this even more affordable for many surface alloy applications. Currently this process is being explored for cylinder liners, lubrication free applications, and ground and rock engagement surfaces.

3.2 Laser Cladding

As with laser alloying, laser cladding allows one to modify the surface properties without significantly affecting the base structure. The properties of the clad layer are critically important and are dependent on chemical composition and microstructure. This is closely linked to the degree of mixing with the substrate. It is well know that the laser cladding has the potential for much less chemical dilution that any other thermal process such as TIG, MIG and PTA [plasma]. The high solidification rates result is a finer grain structures which lead to high oxidation and corrosion resistance.

Since the clad materials and subsequent machining processes are additional expense one desires to clad with the highest degree of efficiency. There are two efficiency numbers that have to be considered. One is material efficiency and the other is energy efficiency. The material efficiency is defined by the total amount of clad material required by the specification to that used during the cladding process. Typically clad efficiency is defined as the amount of material actually clad to the substrate divided by the amount applied at the work piece. This assumes the unincorporated material is waste. A better definition would be the final amount of clad material divided by the waste and that removed during the subsequent machining steps. The energy efficiency encompasses the laser efficiency, absorption at the surface and any post heating processes required. Distortion is directly related to the amount of heat/clad material applied to the work piece. In the case of high nickel materials that are difficult to machine more heat is applied by TIG "washing" the surface to decrease the macro roughness. This adds even more distortion.

The objective is to put down only the amount of clad material required with the highest efficiency and no post machining. Many applications may only require a thin layer of clad material with the desired properties. The problem is that many cladding application process cannot deliver thin and flat clads with low chemical dilution. The bead geometry, which is a direct result of the heating profile, is the primary driver of the final bead shape. The bead geometry determines the final thickness and roughness of the clad due to subsequent side-by-side clads. These processes typically use TIG, MIG or plasma overlay processes that have very large surface roughnesses with a large degree of dilution. They are limited to a minimum of 0.80" or more. This is also typical of a gaussian shape laser beams that produce high dilution or clads with large height to width ratios. This requires multiple cladding /overlay passes have to be performed to get the low dilution chemistry at the surface or the interpass regions. The HPDDL with its line shape top-hat beam is a new cladding heat source that allows one to achieve thin wide and flat clads with low dilution. This allows the user to achieve the most efficient material process for those applications only requiring clads as thin a 0.010".

In addition to the benefits of the beam shape the HPDDL has a benefit of having a much shorter wavelength, 800 nm as compared to CO2 laser wavelength of 10600 nm. This shorter wavelength [higher photon energies] has increased absorption on all metal surfaces. The diode laser has been document to be almost twice as efficient as a CO2 laser in melting powder [10]. This more absorbing wavelength makes wire feed cladding easy implemented. This benefit is in addition to the electrical efficiencies, which are 4 – 6 times that of CO lasers. Therefore, there is a 10X- 12X advantage for the HPDDL over CO2.

3.2.1 HPDDL Laser cladding – powder

As shown in **Figure** 8, the ISL-4000L HPDDL can achieve very flat clad at rates of up to 5.5 pounds per hour for a 4 kw laser. The resulting clad is low dilution [<1%] very smooth and flat and require minimal post machining. The dilution as pictured, In **Figure** 9, by the crossection of the clad shows very little melting of the surface under the clad.

3.2.2 HPDDL Portable Laser Cladding

In addition to the advantages described above the diode laser is 100 times smaller than conventional lasers. This is enabling a whole new industry, portable or in field laser cladding- repair. The portability of the diode laser and its ability to use wire is enabling in field repair and cladding.

We report for the first time the use of a laser to produce a wide clads vertically. Which opens up the possibility for portable in-field cladding. The process used a robot mounted ISL-4000L integrated with a wire feeder and wire oscillator. The results of this clad are shown in **Figure** 10-11. The dilution is higher than powder due to the exposure of the substrate, slower process speed [more energy], and the stirring action of the feeding a solid wire into the melt pool. Preheating the wire before it enter the laser beam and melt pool can minimize this dilution.

4 Conclusion

We have discussed laser heat-treating production applications in which the HPDDL have been implemented and demonstrate, high reliability, and fast paybacks in harsh production environments. The HPDDL has been shown that it has distinct and quantifiable advantages over traditional industrial lasers such as CO2 and Nd:YAG and non-laser technologies such a induction TIG, MIG, and PTA [plasma] for laser case hardening, alloying and cladding. We have demonstrated vertical [out of position] wire feed cladding using the HPDDL. The low operating cost and small size of the HPDDL will enable portable in-field laser heat treating, alloying and cladding

5 References

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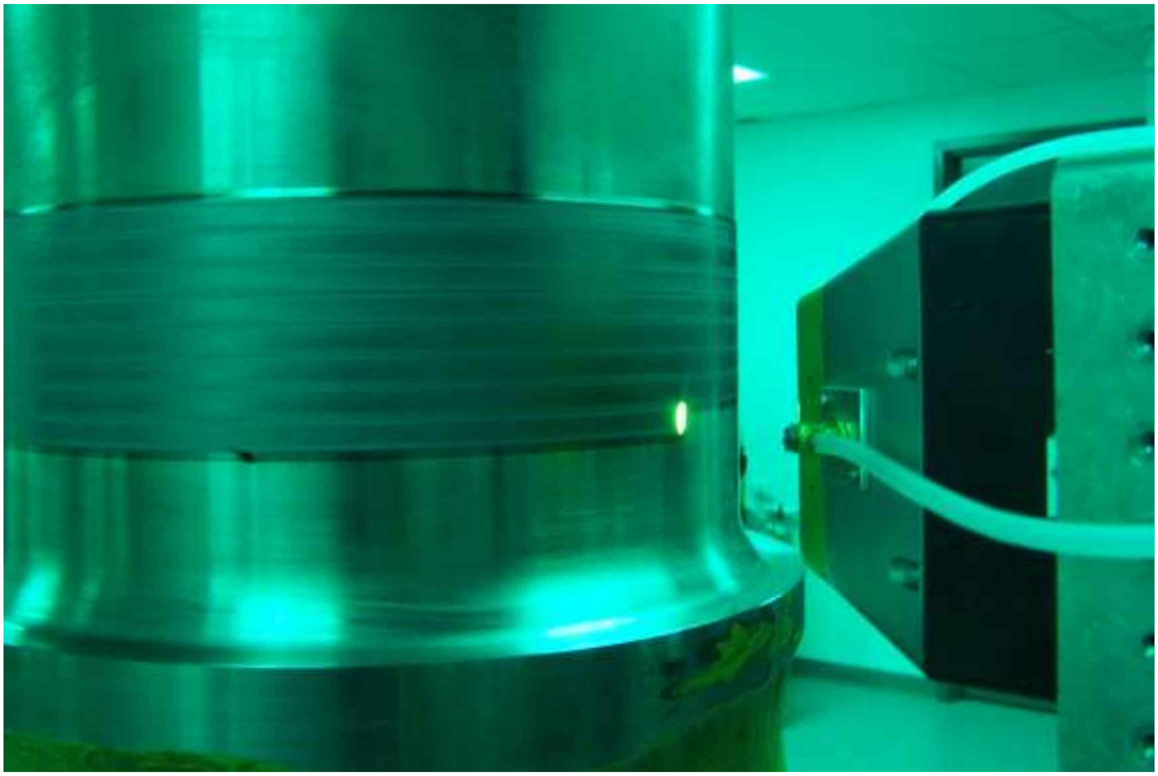

Figure 1 – HPDDL heat treating bearing surface on a large truck spindle

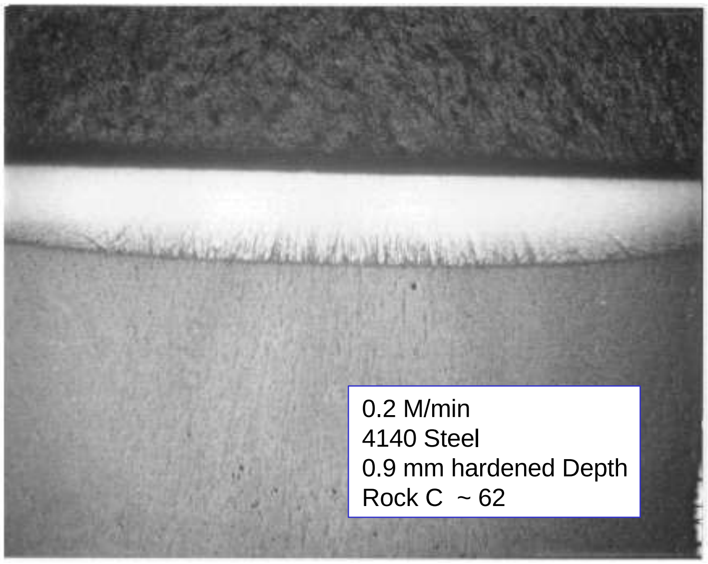

Figure 2 – Typical profile of the hardened case resulting from a HPDDL.

Figure 3 – HPDDL heat treated tool jaws - Material SAE 1075

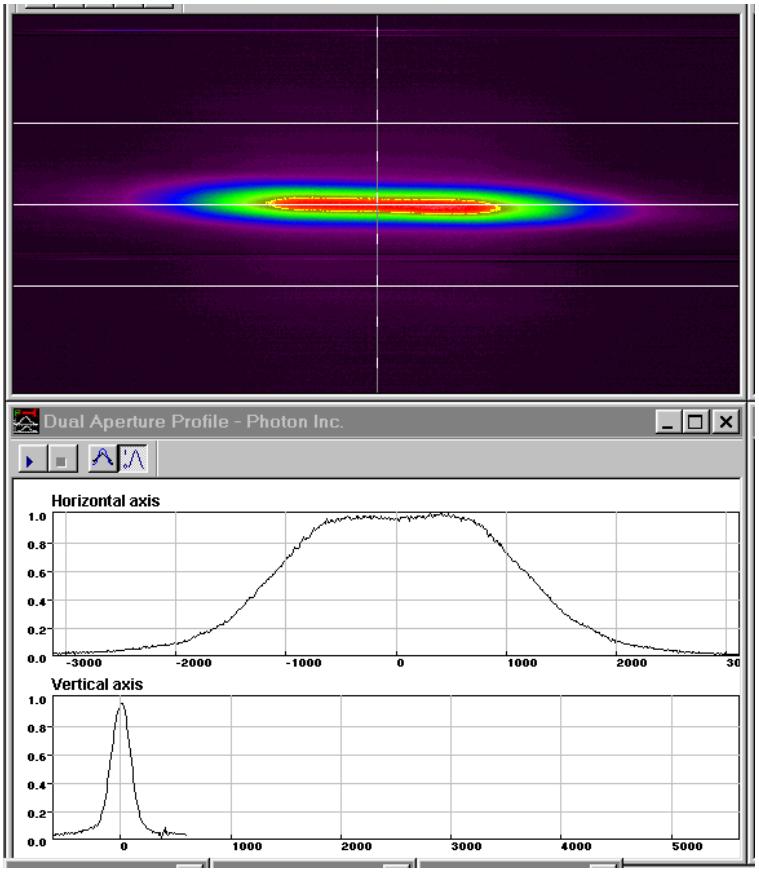

Figure 4 – Profile of laser beam at focus from ISL-4000L - 5.7X demagnification

Figure 5 – Resulting LISI surface from ISL-4000L HPDDL – Process speed 1.0 m/min @ 4000W

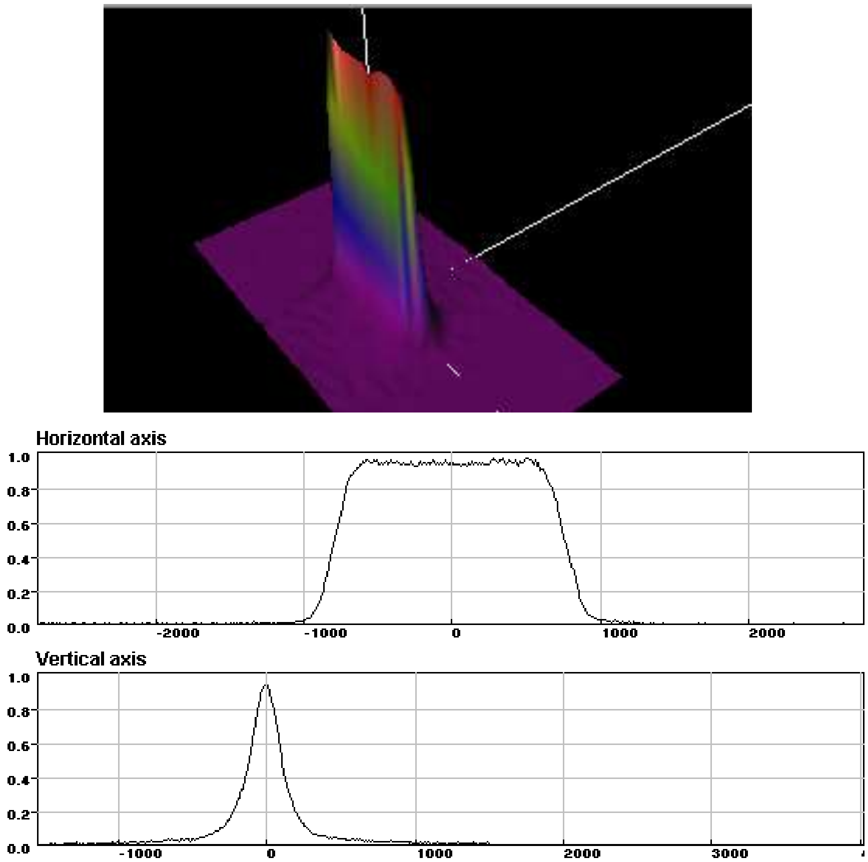

Figure 6 - 21 bar HPDDL array fast and slow lensed array followed by a 5.75x horizontal axis telescope (to compress the spot so it would fit in the CCD camera) and an f=125mm lens

Figure 7 – Resulting LISI surface from a fast-slow lensed HPDDL process speed 1.0 m/min @ 500 watts

Figure 8 – Result of powder feed clad with ISL-4000L 0.5 m/min, 60 cm^2/min @ 1.1 mm thick @ 4000 W of laser power

Figure 9 Crossection of powder feed clad

Figure 10 - Result of HPDDL wire feed cladding. 4 layers of overlapping Inconel 625 wire 0.2 m/min @ 4000 w

Figure 11 – Crossection of HPDDL wire feed cladding