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High Power Direct Diode Lasers in Production– Case Studies

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Abstract

Direct diode laser due to their high efficiency, small size, and potential for low cost will be the future of industrial lasers. There has been many novel applications described for high power direct diode laser [HPDDL] systems but few have been implemented in extreme production environments due to diode and diode system reliability. We discuss several novel applications in which the HPDDL have been implemented and proven reliable and cost-effective in production environments. These applications are laser hardening / surface modification, laser wire feed welding and laser paint stripping. Each of these applications uniquely tests the direct diode laser and addresses their reliability in production environments. A case by case comparison of the advantages direct diode laser versus traditional industrial lasers such as CO2 and Nd:YAG and non-laser technologies such a RF induction, TIG, MIG, and plasma for each of these production application is presented, which led to the justification for using HPDDL in production..

1 Summary

This paper will summarize the results of three successful HPDDL system production installations after over one year in service. We will share the cost savings and performance improvements for two installations. These improvements are dramatic in each case due to the high reliability and low maintenance experienced with the diode laser systems. Both of these helped realize a less than one-year return on investment. In the third case, the production installation using a pulsing HPDDL for paint stripping demonstrates the pulsing reliability.

2 HPDDL Heat Treatment Production Installation

2.1 Overview

A 4 kW HPDDL system was installed into an industrial production line to provide the heat-treating required for a large steel part. This installation was a complete success by delivering high quality at a cheaper cost. The installation costs were recovered in less than a year because of the low installation, maintenance, operating costs, and high reliability.

2.2 Advantages

The production processes had been performed by a lamp pumped Nd:YAG laser for the last two years. 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 method of heat treating these parts was needed. Several technologies have been tried to date including; CO2 and Nd:YAG laser heat treating with less than adequate production results. However, the initial test results using the new HPDDL technology produced very promising results. Consequently, a HPPDL system was set up for trial testing and after several months of working with the system, it became clear that the HPDDL has four primary advantages over other laser systems.

The first advantage is the low installation cost for the HPPDL. The HPDDL system has no special power requirements, and environmental requirements other than the laser safety enclosure. 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 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 >99% up time record during the first year of operation.

2.3 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 a wavelength of 810 nm, 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 55-65 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 99% 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 water cooled aperture, the increased absorption by the part at 810 nm, the stability of the laser, and the reliability of the laser.

The absorption of the HPDDL beam by the part 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 1.

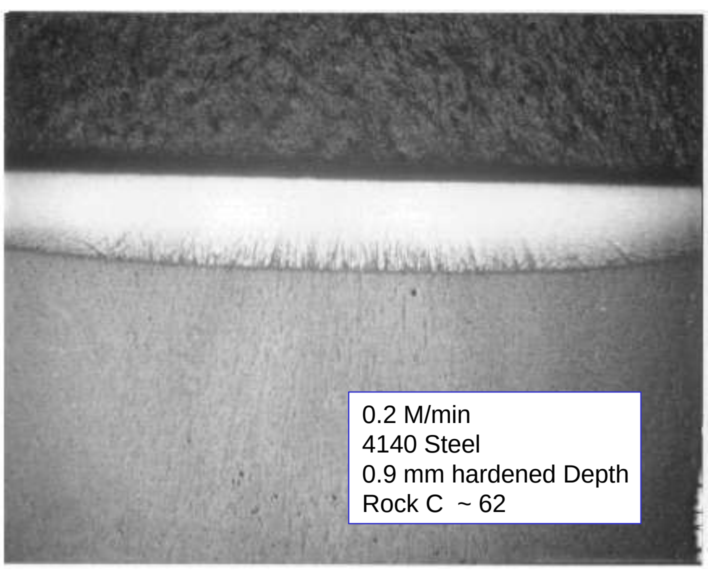

Figure 1 – Typical profile of the hardened case resulting from a HPDDL.

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. In addition, even during the processing of the part, the output power of the HPDDL is very stable indicating minimal heating in the HPDDL system. The HPDDL on the other hand, with its exceptional stability greatly improved the productivity of the laser heat treating cell.

In summary, the installation of a 4 kW HPDDL system into an industrial 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 dropped to a very low level and the system has paid for itself in less than one year.

3 HPDDL Welding Production Installation

3.1 Overview

A 4 kW HPDDL system was installed into a production line to weld the sub-cell of launch canisters for the US Navy's MK 25 Vertical Launching System at United Defense [4]. The company replaced a conventional Metal Inert Gas [MIG] arc welder with a 4 kW HPDDL system. This enabled them to simultaneously reduce the manufacturing labor content for the part while increasing the quality of the welds.

3.2 Advantages

The company had been manufacturing missile launch canisters using a conventional MIG welding process. However, this new sub-cell is made of a thin corrugated skin that is reinforced with multiple braces. The heat input from the MIG process caused so much distortion that it was difficult to manufacture the sub-cell to the requisite tolerance. The company needed to develop a process that would allow them to perform the eight long welds on the container without distortion.

Each sub-cell has eight 5 meters long welds between the 2mm thick skin and the 12.5-mm thick corner braces. The distortion in the sub-cell resulted in extensive post weld activities in machining and assembly to deal with that distortion. Based on these results United Defense had to find a way to reduce the heat input to the sub-cell. Two laser techniques were studied, a Nd:YAG laser which performs a keyhole weld with a micro-wire feeder and a HPDDL which performs a conduction weld with a standard wire feeder. The criteria were for a low heat-input full penetration weld with no splatter inside the canister, no pin-holes, and a positive weld fillet geometry. All these criteria were of equal and critically important. The full penetration and positive weld fillet geometry was necessary to meet the strict strength requirements of missile launchers. The pinhole requirement is for heremeticity to prevent infiltration of the corrosive sea air. The internal splatter or contamination specification is to reduce the foreign object damage.

The final step of the evaluation was to rate the performance of the two laser technologies. At the time the reliability of the HPDDL was unproven in the production environment, so the company rated the HPDDL the same as the Nd:YAG laser with respect to maintenance and reliability. After a series of welding trials on some test article with both lasers, the HPDDL proved the only laser that could deliver a full penetration weld with no internal splatter, and no pinholes. The natural beam shape of the HPDDL, which is better suited to parts with poor fit up was much easier to feed wire creating positive weld fillet geometry. With the use of a coordinate measuring machine the measured distortion as compared to a MIG test article was 12 times less. The decision to use the HPDDL was the result of the higher rating marks received on the quality of the welds of the parts rather than any technology advantages.

3.3 Integration

The HPDDL laser was the first laser of any kind to be installed into this plant. The HPDDL was installed on the existing 10 kg robot. See Figure 2. The MIG torch was removed and the laser was installed in its place. An existing wire feeder was used with the laser to provide cold 0.8 mm diameter cold steel wire to the melt puddle. There was no special power requirement for the laser other than the 480-30 Amp, 3-phase service that was already available at the installation site. Therefore, the only installation costs for implementing the HPDDL for welding was the HPDDL itself, some simple hardware for mounting the laser to the robot, and a laser safety enclosure.

Figure 2 – HPPDL welding production installation

The process challenges were HPDDL head position/beam placement on the part since the weld joint along the corrugated part changed from a T-joint to butt joint. How to introduce the wire into the weld puddle and finally how to manipulate both the laser and wire feeder in such a way as to maintain a good, full penetration weld along a corrugated metal part. With minimal training customer developed the process capable of meeting all of these challenges. To make the process more robust, a seam tracker was integrated onto the robot to allow the system to track the seam between the thin metal sheet and the side rails. This system uses a low-power laser to measure part placement to calculate welding offsets. Because it is based on a non-contact optical technology it provides a very fast response and allows the robot to move to reference points and rapidly calculate the welding offsets. These offsets are then used as a reference for the robot to position the laser beam correctly.

The last challenge in the installation was how to keep the output window, which was only 95 mm away from the weld puddle, clean. Several techniques were tried, but the best window lifetime was achieved with a simple air-knife mounted directly on the laser itself. The weld spatter was also minimized by using mixed Argon – CO2 cover gas on the weld puddle and optimizing the wire feed into the puddle.

3.4 Production Results

The company has successfully welded 240 sub-cells with a total of 40 meters of welds per sub-cell using the HPDDL system this year. The laser system was capable of welding the sub-cells at the same rate as the MIG process, which is about 0.5 m/min. The labor associated with fabrication of this sub-cell dropped by 30%. This decrease in the labor was a direct result of the less thermal distortion causing less post weld processing. In addition, the HPDDL system used 1/5 of the wire to do the same job as the MIG process. The MIG process required up to 4.5 kg of wire to complete canister while the HPDDL process required only 0.9 kg of wire per canister. A cross section of the coupon of 3 mm welded to 2 mm mild steel welded with filler wire is shown in Figure 3.

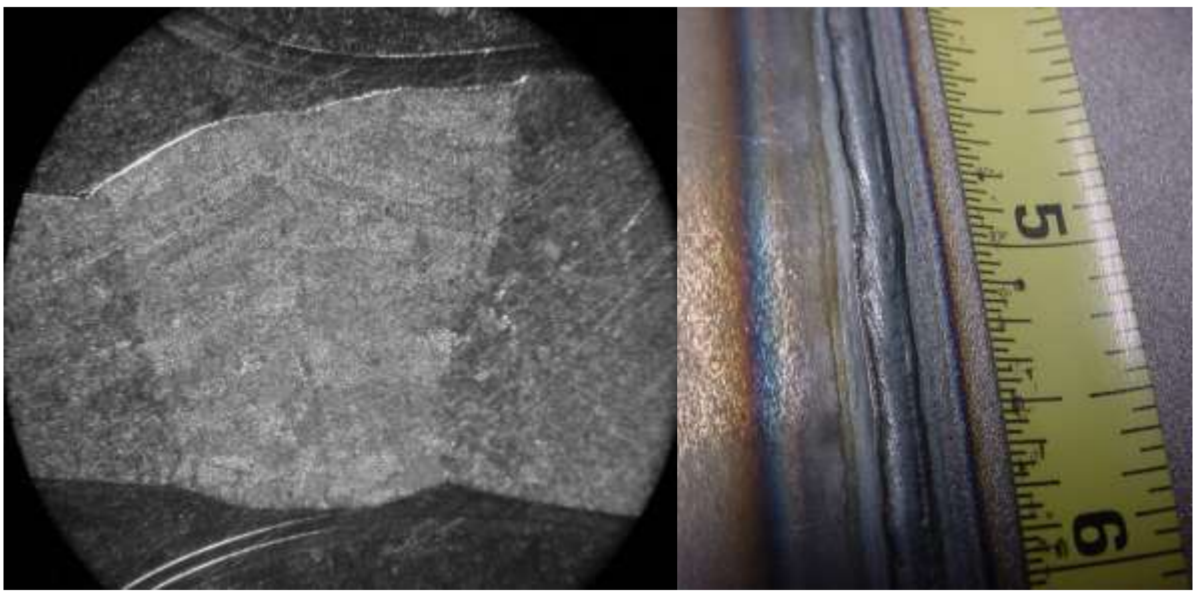

Figure 3 - Cross section of a 3 mm – 2 mm mild steel welded with HPDDL and wire feed

Even under these extreme welding condition, the laser achieved the same up-time performance as the heat treatment installation of >99%. There was however, some minor maintenance associated with the laser mainly due to spatter from the weld process. In one instance, the laser was operated without the window and the internal optic was contaminated by the spatter. Production however did not have to stop to replace the optic; the system was operated until the weekend when it was convenient for the system to be returned to HPDDL manufacturer for replacement of the optic. The laser head was shipped via overnight express on Friday arrived Saturday and was returned ready for production by Tuesday. The HPDDL is the only type of industrial laser that can be returned to the factory for service and returned to production, sometimes in less than 48 hours.

In summary, the installation of a 4 kW HPDDL at United Defense is significant on several levels each contributing to the rapid recovery of the investment in the HPDDL laser system. The installation costs were significantly minimized by the utilization of the existing welding cell, power, and floor space. The HPDDL was effectively a drop in replacement of a MIG weld torch. The upstream manufacturing processes used to prepare the canister parts and pre-assemble them for MIG welding was not changed. The low distortions leading to significant labor savings in the fabrication each sub-cell. The low operating, consumables, and maintenance costs of the system also contributed to the rapid recovery of the investment in the laser system.

5 Pulsed Operation of Laser Diodes

It has been recently written that laser diodes have significantly shorter lifetimes if they are cycled on and off as required by most automotive welding and heat-treating applications. [5] One of the primary reasons why HPDDL systems are much more efficient than standard industrial lasers is that they can be instantly turned on without a warm-up time.

Nuvonyx, Inc has extensively tested its laser diodes for the industrial applications, using test procedures, which thermally cycle the laser diodes. A 1200 W laser diode array (21 bars) was cycled on and off [10 millisecond pulses] for 2,210 hours. After 498 Million cycles the output power of the laser diode actually improved. The PI curves at measured throughout the life test are shown in Figure 4.

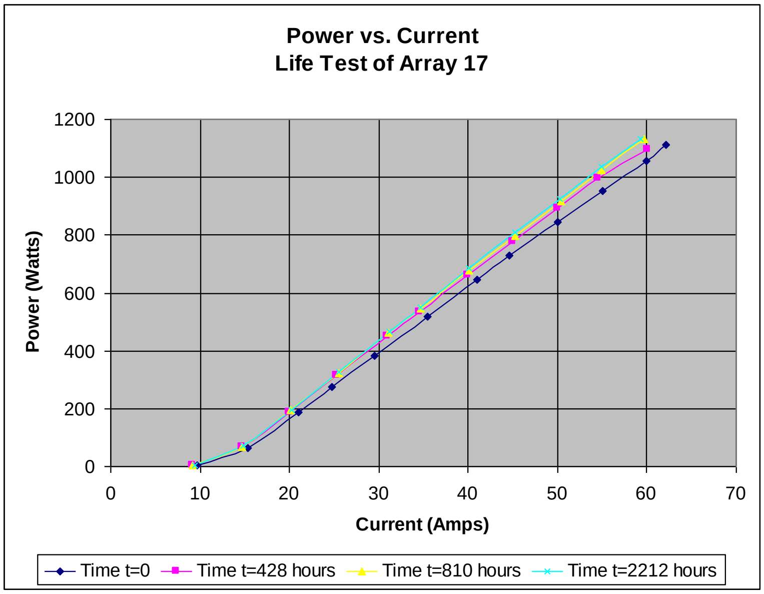

Figure 4 - After 2210 hours of pulsed operation the output power of the laser performs the same as in the CW life tests

A second test of our laser diodes that was performed by a third party evaluator operated a Nuvonyx laser diode high power array pulsed to 120 amps, with 500 microsecond pulses at a duty cycle of 20%. In this test the output power of each bar is 100 Watts during the long pulse. After 70 Million cycles, the Nuvonyx laser diode arrays showed no measurable degradation in power [6] after. A third test is currently being performed by an independent test group; here the laser diode arrays have been continuous cycled for the last year with no degradation in performance [7, 8]. A fourth test performed by Nuvonyx using two primary suppliers of laser diode bars. The laser diode bars that were mounted with the Nuvonyx packaging process and both bar types show no degradation any differently than CW operation, when pulsed at the thermal cycle time constant of the package, Figure 5. This test is still in progress and by the time of the conference, the laser diodes should exceed 3,000 hours of continuous pulse testing.

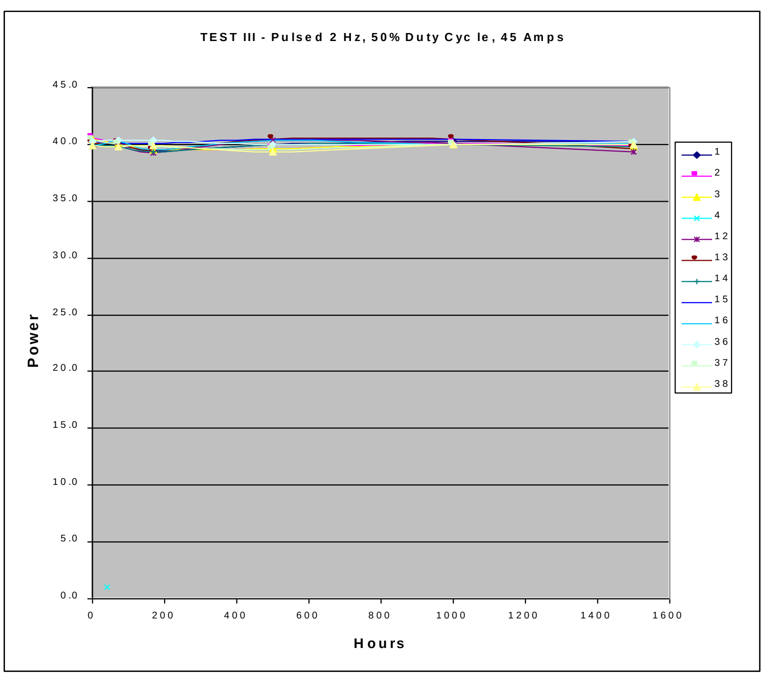

Figure 5 - Thermal cycle testing of laser diode bars with no degradation in performance after 1500 hours

6 HPDDL Paint Stripping Industrial Installation

The HPDDL paint stripping operation is where the laser is pulsed at rates up to 10 kHz to allow the paint to be thermal-mechanically ablated from the surface without burning. This is performed with-in a Class 1 enclosure that also acts as a containment room with vacuum recovery units to pick up the ablated paint dust and organic fumes. HPDDL system has been successfully installed in a pulsed production polyvinylidene difluoride (PVDF) stripping application since last April 2002. This system has accumulated over 50 million cycles at ~ 1 msec pulses during the last year for a total on time of 1100 hours with no degradation in performance. The up time has been > 99% with very minimal maintenance cost.

7 Conclusion

We have discuss several production applications in which the HPDDL have been implemented and demonstrate, high reliability, and fast paybacks in harsh production environments. The typical disadvantages of associated with new technology such as short production lifetimes or unpredictable maintenance have not been seen in at least three production installations. Specifically the degradation of the HPDDL laser bars and laser heads have not been seen in all three of the above installations. These three production applications address three primary concerns associated with HPDDL reliability: long cycle time stability, extreme thermal feedback, and on-off cycle fatigue. The HPDDL has shown that it is a reliable and robust laser under all these conditions. In addition, laboratory results have shown that the HPDDL arrays have not degraded over thousands of hours of both CW and pulses operation. In production, 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 TIG, MIG, and plasma for each of these production application. These production applications are laser hardening, laser wire-feed welding, laser paint stripping.

8 References

[1] J. Koch and L. Maass, “ Hitting Paydirt with Lasers”, Industrial Laser Solutions, August 2000.

[2] O. Sandven, “Laser Surface Transformation Hardening,” Metal handbook, 9th ed., Vol. 4: Surface Engineering ASM, p 507-517.

[3] K. Minamida, Nippon Steel Corporation , Personal Communication.

[4] B.D. Johnson,.; Diode Laser Improves Canister Welding. Photonics Spectra (2003) 4,37

[5] OPTECH Consulting AG, March 2003, High Power Laser Diodes and Diode Based Lasers, Market Analysis and Forecast, p 84.

[6] J.T. Schriempf, “Evaluating High Power Diode Arrays” Solid State and Diode Laser Technology Review, SSDLTR 2003, Albuquerque, New Mexico, May 2003

[7] D. Gallant and J. Boeckl, “High power Diode Array Reliability Experiment”, LASE’ 2003, San Jose CA, Jan. 2003

[8] D. Gallant, The Boeing Company, Personal Communication, Kirtland AFB, April 2003.