Heat Treating with High Power Diode Lasers

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Carbon dioxide (CO_2) lasers have been used in heat treating for over 30 years, as an alternative for induction or other traditional heat treating techniques. However, limitations in CO_2 laser reliability and cost of ownership have made their use as a heat treating source less than ideal. Over the past few years, a new approach for heat treating based on the high-power, direct diode laser has emerged. Direct diode lasers utilize a very different technology than CO_2 lasers to produce light and in this way overcome the most significant disadvantages of CO_2 lasers. While direct diode lasers are by no means a panacea for all applications they do offer some compelling advantages in certain distinct applications. This article reviews the basics of laser heat treating, its optimum uses, and compares CO_2 with diode laser technology.

Benefits of Laser Hardening

In laser heat treating or case hardening, a spatially well defined beam of intense laser light is used to illuminate a work piece. This light is readily absorbed near the surface and causes rapid heating that is highly localized to the illuminated area and which does not penetrate very deep into the bulk material. Depending upon the particulars of the part size, shape and material; the bulk heat capacity of the material typically acts as a heat sink for the extraction of heat from the surface therefore enabling self-quenching.

The ability to precisely control the physical extent of the illuminated region, together with the short timescale of energy transfer into the material, gives rise to the main benefits of laser surface modification over other techniques. Several key benefits include rapid processing, precise localized control over case depth/hardness and minimal part distortion. In some cases, part distortion is minimized to the extent that post heat treat machining is very limited or eliminated entirely. Furthermore, in many instances, the laser induced surface transformation creates a finer grain structure due to the rapid air/part mass quench process resulting in superior wear and corrosion resistance. In addition, laser heat treating can yield increased fatigue strength due to the compressive stresses induced on the surface of the component.

The effectiveness of case hardening depends on the hardness of the transformed surface layer as well as the case depth. Typical case depths and hardness that can be achieved using direct diode laser technology are listed for a variety of metals in the following table. Part geometry and carbon content significantly influence the results that can be achieved with a laser heat treat process.

Material	Typical Hardness (HRc)	Typical Case Depth (mm)
Carbon Steels		
1080	68	2
1075	68	2
1045	60	1.5
1030	50	0.75
Heat Treatable Alloys		
4140	68	2
4340	68	2
Heat Treatable Stainless Steel		
420	65	1.6
410	50	0.5
Cast Irons		
Gray	65	1
Ductile	55	0.75

These characteristics of laser hardening contrast significantly and compare favorably to flame hardening and induction hardening techniques. For example, flame hardening is limited by poor reproducibility, poor quench characteristics and environmental issues. Induction hardening typically produces deeper thermal part penetration thus requiring an active quench process, both of which can lead to undesirable and/or difficult to control part distortion. The laser heat treating process is generally simpler to implement and maintain than induction hardening due to the ability to easily limit heating to the irradiated area. This avoids the need for special coils, flux concentrators or shields.

In most cases laser processing is more easily integrated into manufacturing flow than traditional hardening technologies. In industries that have moved heavily towards Lean Manufacturing, this action has sometimes forced traditional heat treating to be an outsourced process since the majority of these methods are batch in nature. In contrast, laser heat treating is inherently a "one piece" flow making it well suited for the Lean Manufacturing environment.

Of course, laser heat treating is by no means the optimum approach for all applications. In general, laser heat treating has an advantage over other processes if the part has a specific, limited surface area that needs to be case hardened or if the part is so large that it is cost prohibitive to transport and heat treat with conventional means. Clearly, the laser is at a disadvantage for bulk heat treating of thick parts or for applications requiring large batch processing. The photograph below shows a saw tooth tip selectively hardened by a direct diode laser and represents an ideal use of laser hardening.

A saw tooth tip selectively hardened by a direct diode laser

In addition, obtaining optimum results and maximizing the cost savings from laser heat treating may require changes to the part design and/or process flow. For example, when compared to vacuum carbonizing and gas nitriding, the laser heat treat process may require a change in work piece material to one higher in carbon content to achieve the desired results. In these instances, the advantage of reduced distortion and elimination of post-machining have to be compared to the cost associated with changing material.

Process specifics also have to be carefully considered in order to reap the maximum benefit from laser processing. For example, back tempering can occur when the scanning laser beam overlaps an area previously processed causing it to again reach the tempering temperature range. The result is that the overlapped area can have lower hardness than the rest of the hardened zone. The solution is to either design the laser scan pattern so as to minimize the extent or degree of back tempering to an acceptable range or to make sure that back tempering is localized to non-critical or low stress areas. For example, on a camshaft lobe, the overlap region would be localized to the non-lift area opposite the apex of the lobe.

Traditional CO_2 Laser Heat Treating

In the past, the CO_2 laser was the most commonly used source for laser heat treating. However, this technology has several significant drawbacks when applied to hardening. The first of these is that CO_2 lasers output at a wavelength of 10.6 µm which is well into the infrared. This long wavelength light is not readily absorbed by most metals which typically require a heat treat process. As a result, surfaces for heat treating with a CO_2 laser must first be "painted" with an absorptive coating, generally a black oxide. The use of direct diode technology can eliminate this time consuming, costly and environmentally unfriendly process step.

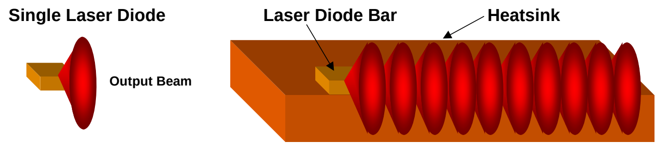
The second drawback is the shape of the CO_2 laser output which is a well collimated "pencil beam" of a few millimeters in diameter. Since this is much smaller than the area typically to be treated the beam must be expanded or scanned to match the processing area and homogenized to eliminate inherent brightness variations.

Another limitation of CO_2 laser technology is the conversion of input electrical energy to useful light output is relatively low. Higher electricity consumption translates directly into increased operating cost.

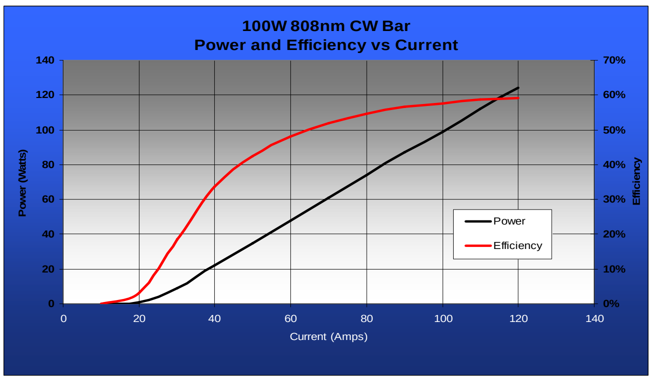
High Power Diode Lasers

The inherent characteristics of CO_2 lasers have limited their ability to fulfill the true potential of laser hardening. In response to the need for a more optimal source for this application, Coherent has developed the HighLight™ series of products based on high-power diode laser technology.

The diode laser is a semiconductor device that directly converts electrical energy into laser light. High-power diode lasers output in the near infrared, commonly at either 808 or 975 nm. A typical individual diode laser emitter might produce at most, a few Watts of output power. However, numerous emitters can be fabricated on a single, monolithic semiconductor substrate or bar with a total output of 100W or more. These linear bars can, in turn, be combined in horizontal and vertical stacks to produce high-power direct diode laser systems with total output power in the multi-kilowatt range.



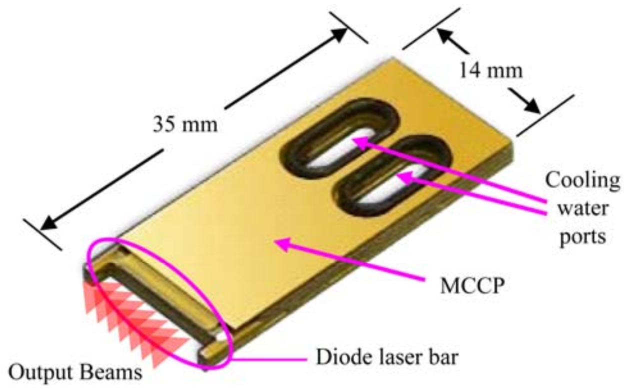
Diode laser bars consist of multiple individual emitters on a single, monolithic substrate, each producing a divergent cone of light.



This graph of conversion efficiency and power vs. input electrical current shows that diode laser bars are far more efficient than any other laser type

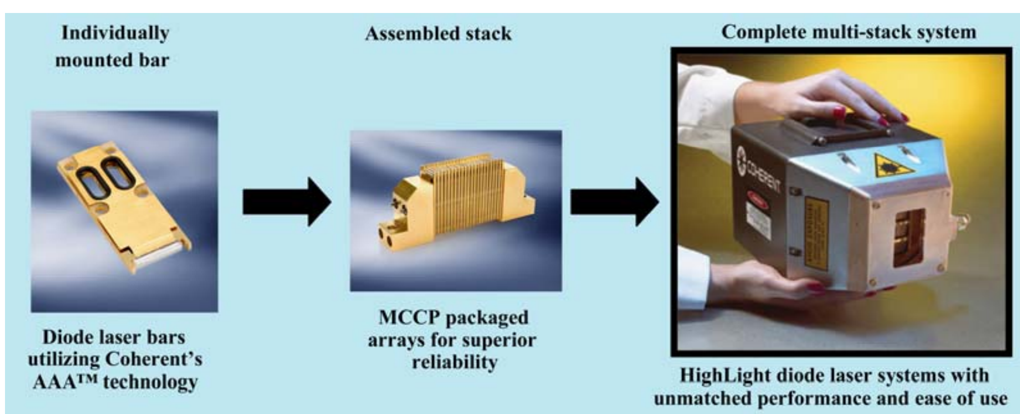
As shown in the graph above, the maximum conversion efficiency of transforming input electrical energy into light in diode laser bars is about 59% which is many times higher than for any other laser type and approximately 3 – 4 times higher than that of the CO_2 laser in particular. The primary benefit of this high efficiency is that it lowers the operating cost of the system since less electricity is required to produce a given amount of output power. Of course, this reduced power consumption also decreases the carbon footprint of the laser's operation thereby qualifying direct diode laser technology as "green" technology which in some cases may result in federal, state, and/or local subsidies being available to assist with the implementation of direct diode laser technology.

The small size of diode lasers makes them easier to integrate into workstations. It also means that they produce their waste heat in a relatively small physical area. As a result, they can be effectively cooled with a small volume of circulating water and a DI chiller.



A single diode laser bar mounted on a MCCP

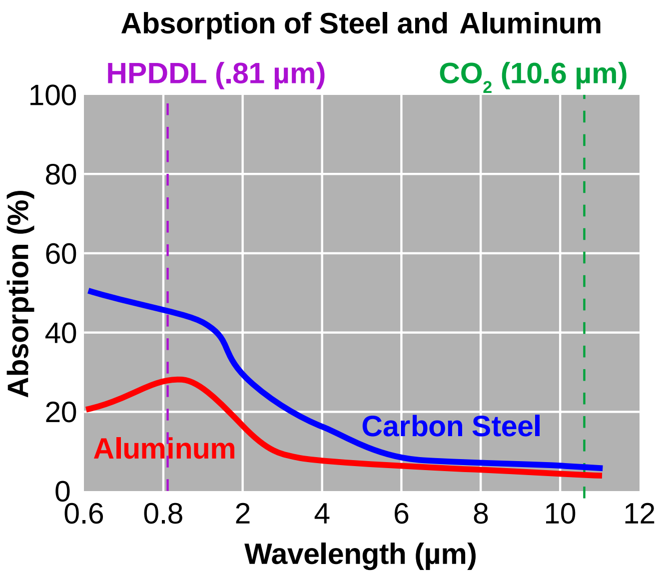
The photo shows a mounting configuration for diode laser bars called a Micro-Channel Cooled Package (MCCP). Here, the diode laser bar is mounted on to a plate that contains internal channels for water circulation. The MCCP contains two large water ports, one for input and one for output, which each have an o-ring at their edge. These o-rings provide a water tight seal when two MCCPs are placed against each other face-to-face. This enables multiple MCCPs to be stacked together and water circulated through the entire assembly. The next photo shows the power scaling progression from an individual MCCP mounted diode laser, to an assembled array, to a fully integrated, multi-array assembly which in this case delivers 4 kW of CW laser power.



Coherent is the only vertically integrated supplier of high power diode lasers, producing everything from the diode bar at the wafer level to fully integrated laser systems

Diode Laser Advantages

High power direct diode laser (HPDDL) systems address all the previously mentioned disadvantages of CO_2 lasers for heat treating. Specifically, the shorter output wavelength of the diode laser is very well absorbed by most metal requiring heat treating, as shown in the following graph. This eliminates the need for surface preparation as well as the environmental compliance costs associated with emissions, clean up and disposal of the chemicals utilized in the painting process.



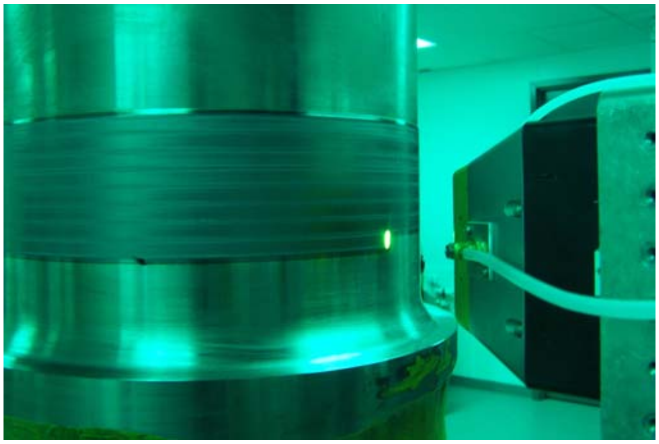
Absorption as a function of wavelength for carbon steel and aluminum

The shape of the output beam from a HPDDL is also well matched to the needs of many heat treating tasks. Specifically, HPDDLs incorporate optics that integrate all the individual laser "beamlets" into a single beam; a typical nominal cross-section would be 1 mm x 12 mm. This extended beam shape has a relatively uniform intensity over most of its area. This native beam shape is often more useful for laser heat treating large areas than the small, non-uniform output beam from a CO_2 laser.

HPDDLs offer a substantial cost advantage over CO_2 lasers. One reason for this is that their electrical efficiency (conversion of input electrical energy to useful light output) is about 3 – 4 times higher than that of the CO_2 laser. This translates directly into lower operating cost. Additionally, the HPDDL has "instant on" capability so there is no standby power consumption. Even larger savings results from reduced maintenance costs which are orders of magnitude less for the HPDDL as compared to a CO_2 laser. Maintenance downtime is also minimized because the physically compact HPDDL can be more rapidly replaced than bulkier CO_2 lasers and replacements can even be shipped via overnight courier services. The table (next page) details the total cost of owning and operating the two laser types, and shows that the HPDDL costs just over $100K less to operate over a five year period, that, in addition to all the other process advantages it provides in a laser heat treat application. The HPDDL also offers simplified integration over CO_2 lasers. The small size and the ability to focus on the surface at a reasonable working distance facilitate the integration of the laser into CNC machining equipment. This allows the heat treat step to be performed immediately after machining which has given rise to laser-based combi-machines.

Heat Treating with Diodes Lasers

For the majority of laser hardening applications, the HPDDL output beam illuminates an area that is smaller than the total area to be processed. Thus, either the work piece or the beam is moved in order to achieve total coverage. A typical implementation of this approach, in this case for a large construction vehicle spindle, is shown in the photograph.

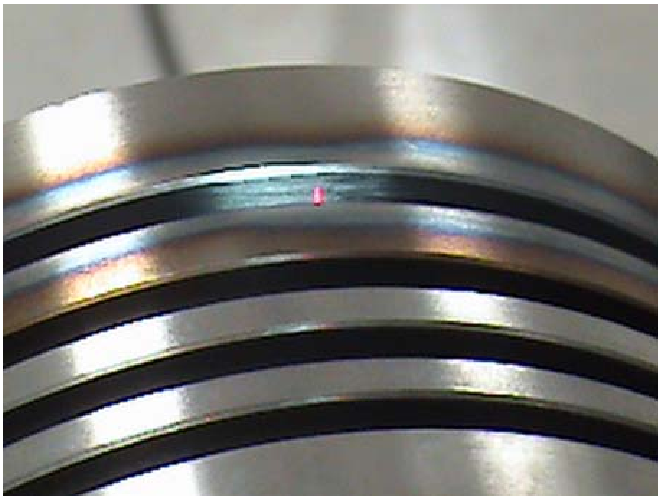


The laser beam is moved across the part in order to heat treat large areas

The next two photos show how diode laser hardening delivers very localized results that are uniform and consistent. On the left, the top and bottom surface of an upper ring land groove have been selectively heat treated to enhance wear resistance. On the right is a typical serrated tool jaw (material SAE 1075) heat treated with the Coherent HighLight HPDDL.

In conclusion, the HPDDL is a unique source for laser heat treating that delivers a number of advantages over traditional technology as well as other laser sources. In particular, the

HPDDL laser offers attractive cost of ownership characteristics, provides many advantageous laser heat treat process options along with its small size and output characteristics make it easy to integrate directly with existing production equipment.



The top and bottom surface of an upper ring land groove have been selectively heat treated to enhance wear resistance

A typical serrated tool jaw (material SAE 1075) heat treated with the Coherent HighLight HPDDL

	Year 1	Year 2	Year 3	Year 4	Year 5	$/hr
FreeSpace Diode Laser (Coherent 4000L)[1]						
Capital cost[2]	$53,350	$53,350	$53,350	$53,350	$53,350	
Refurb cost					$80,000	
Electric Consumption ($)3	$1,665	$1,665	$1,665	$1,665	$1,665	
PM	$3,500	$3,500	$3,500	$3,500	$3,500	
Total	$58,515	$58,515	$58,515	$58,515	$138,515	$35.82
CO_2 Laser (6kW Flowing Gas) [1]						
Capital cost[1]	$60,000	$60,000	$60,000	$60,000	$60,000	
Refurb cost	$20,000	$20,000	$20,000	$20,000	$20,000	
Electric Consumption ($)[2]	$6,240	$6,240	$6,240	$6,240	$6,240	
PM	$10,000	$10,000	$10,000	$10,000	$10,000	
Total	$96,240	$96,240	$96,240	$96,240	$96,240	$46.27

1. Coherent estimates. Subject to change without notice.
2. 5 year straight line depreciation.
3. Based on electricity cost of $0.05/kW/hr for 8 hours/day, 5 days/week.