

Welding with High Power Diode Lasers

High power diode lasers offer significant practical and cost advantages over other laser types for many welding tasks.

Laser welding with CO₂, fiber and various types of solid state lasers is a well established process currently utilized in a wide range of industries and applications. However, recent technological developments in high power diode laser technology have expanded the capabilities of laser welding, as well as changed its cost characteristics. As a result, diode lasers are poised to replace traditional laser sources in some applications, as well as expand laser welding into entirely new areas.

This article provides an introduction to high power diode laser technology and its use in welding. In particular, it compares the capabilities and characteristics of diode lasers with other welding laser technologies, reviews the applications best suited for diode welding, and provides some guidance on what materials are compatible with this process.

Laser Welding Background

Virtually all laser welding techniques can be classified into two basic categories, called “keyhole” and “conduction” welding. Both of these are typically performed autogenously, that is, no filler metal is added to the joint. Keyhole, or deep penetration welding is probably the most commonly encountered form. In keyhole welding, the laser is focused so as to achieve a very high power density (typically at least 1 MW/cm²) at the work piece. At the center of the focused beam (where the laser power density is usually highest) the metal actually vaporizes, opening up a blind hole (the keyhole) into the molten metal pool. Vapor pressure holds back the surrounding molten metal and keeps this hole open during the process. This metal vapor also re-radiates laser energy into the molten metal along the side of the keyhole, thus transferring energy through the entire depth of the keyhole and resulting in a weld with a deep aspect ratio.

The small size of keyhole region results in a relatively small fusion zone and heat affected zone. Furthermore, the highly localized application of heat means that the work piece both heats up and cools down rapidly which can minimize grain growth in high strength, low alloy steels. Even though no filler material is typically used for keyhole welding, the high temperatures of keyhole welding can vaporize volatile materials, producing a different composition in the fusion zone than in the base metal. Also with hardenable steels, the rapid cooling generates fully martensitic fusion zones and hardened heat affected zones.

In contrast, if the threshold laser power required to initiate a keyhole is not reached, then only surface melting occurs. Because laser energy is absorbed almost entirely at the surface and heat transfer into the bulk material occurs by conduction, this is called conduction welding. Conduction mode welds are typically shallow and often have a bowl shaped profile. The heat affected zone is larger than for a keyhole weld and the transition from the fusion zone to the base metal is smoother and more gradual.

In terms of material changes, the less aggressive heating cycle produced with conduction mode welding avoids the formation of martensite, and generally doesn't evaporate lighter alloying metals. Thus, changes in alloy properties between the base metal and fusion zone are minimized.

Keyhole welding requires that a high threshold power be reached to start the process, resulting in a narrow process window. Keyhole mode welding is suitable for deep penetration welds where high aspect ratios are desirable. In contrast, conduction welding works over a relatively large linear power range, resulting in greater process flexibility. Taken together, the combination of power control and shallow weld penetration result in conduction mode welding being a well accepted laser welding solution for delicate, heat sensitive parts and thin metals.

Traditional Welding Lasers

Several different laser technologies are currently employed for welding. The specific characteristics of each laser type (e.g. physical, output beam, and cost factors) determine the way in which a particular laser type can be used for welding. The most commonly encountered welding laser types are CO₂, solid state (lamp pumped or diode pumped) and fiber lasers. While high power diode lasers have also been available for a few years, they are now beginning to be utilized for appropriate welding applications. The table (next page) summarizes the primary output characteristics and practical features of the various laser types used for welding.

CO₂ lasers output at a wavelength of 10.6 μm, which is well into the infrared. Typically they produce a high power, well collimated beam of a few millimeters in diameter. While the infrared light of the CO₂ laser is not well absorbed by most metals, the combination of very high power and small beam diameter yields the power density necessary to initiate keyhole welding, albeit in a “brute force” approach. The downside of CO₂ lasers is their electrical inefficiency (the amount of input electrical energy converted into useful laser light), which translates into high operating cost. Also, their infrared light cannot be delivered by optical fiber and they are physically large. These latter two factors can present limitations in terms of how the laser is deployed in actual production settings.

In solid state lasers, the light from either a lamp or a series of diode lasers is focused (or pumped) into a laser rod, which then emits a small, well collimated beam of laser light in the near infrared (typically at 1.064 μm) which can be fiber delivered. A variant on this is the disk laser in which the solid state laser medium is disk shaped instead of a rod; disk lasers are all diode pumped and never lamp pumped. Solid state lasers are mostly used for conduction welding.

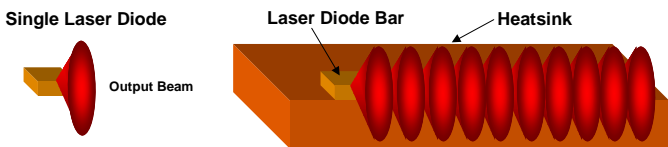
	Laser Type				
	Diode (4 kW)	DPSS (4 kW)	LPSS (4 kW)	Fiber (4 kW)	CO ₂ (6 kW)
Wavelength (µm)	0.98	1.06	1.06	1.07	10.6
Power Range	10's of watts to 10 kW	100's of watts to a few kW	100's of watts to few kW	100's of watts to 10's of kW	100's of watts to 10's of kW
Welding Mode Keyhole				•	•
Conduction	•	•	•	•	•
Size	Very Small	Large	Large	Medium	Large
Electrical Efficiency	40%	15%	5%	25%	10%
Maintenance Interval	2 years	1 year	3 months	2 years	6 months
Initial Capital Cost	Low	High	Medium	High	Medium
Cost of Ownership*	\$23/hour	\$53/hour	\$51/hour	\$43/hour	\$49/hour

The basic configuration of lamp-pumped solid state (LPSS) lasers makes them electrically inefficient; furthermore lamps must be replaced every few months, which raises operating costs and results in maintenance downtime. However, this legacy technology is well established and understood therefore some industries has been slow to move away from it. Diode-pumped solid state (DPSS) lasers offer significantly better reliability, longer maintenance intervals and lower consumables cost. However, their initial purchase price is higher putting their long term cost of ownership on a par with LPSS lasers.

Fiber lasers are conceptually like DPSS lasers, however, the laser rod is replaced with an optical fiber as the laser medium. Single mode fiber lasers (which produce light that can be focused to a small spot) deliver output in the same power and wavelength range as DPSS lasers. However, they can be focused to the small spot size needed to achieve the power density necessary for keyhole welding. Multimode fiber lasers can deliver tens of kilowatts, but in a bigger spot size, and hence lower power density, making them suited for conduction mode welding.

High Power Diode Lasers

The output characteristics and physical properties of the various traditional welding lasers lead to a number of practical and cost limitations. 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.

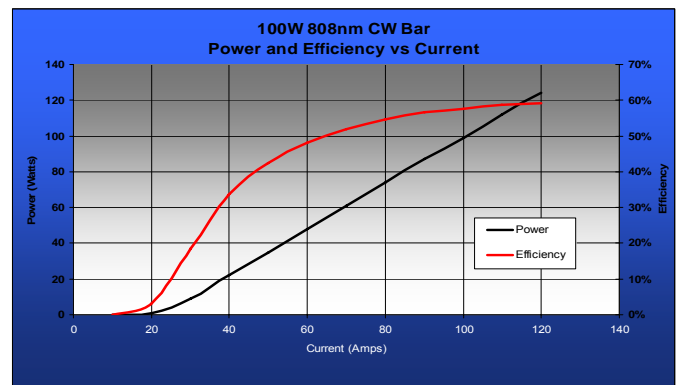


Diode laser bars consist of multiple individual emitters on a single, monolithic substrate, each producing a divergent cone of light.

The diode laser is a semiconductor device that directly converts electrical energy into laser light. Typically, higher power diode lasers output in the near infrared, most commonly at either 808 nm or 980 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 as high as 100 W. 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.

As shown in the graph, the maximum conversion efficiency of transforming input electrical energy into light in diode laser bars is about 59%, which translates into a total electrical efficiency of about 40% for a high power diode laser system. This is many times higher than for any other laser type, as can be seen in the previous table. 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.

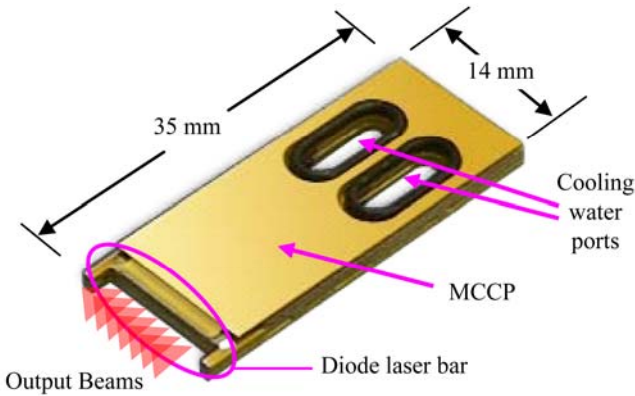


This graph of conversion efficiency and power vs. input electrical current shows that diode laser bars are far more efficient than any other laser type

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 chiller.

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 individual MCCP mounted diode laser through assembled stack to an integrated, multi-stack assembly that can deliver as much as 4 kW of power.

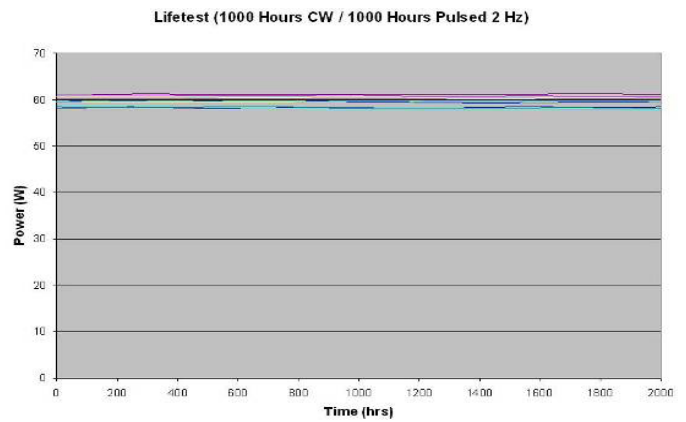


A single diode laser bar mounted on a MCCP

Coherent HighLight Diode Laser Systems

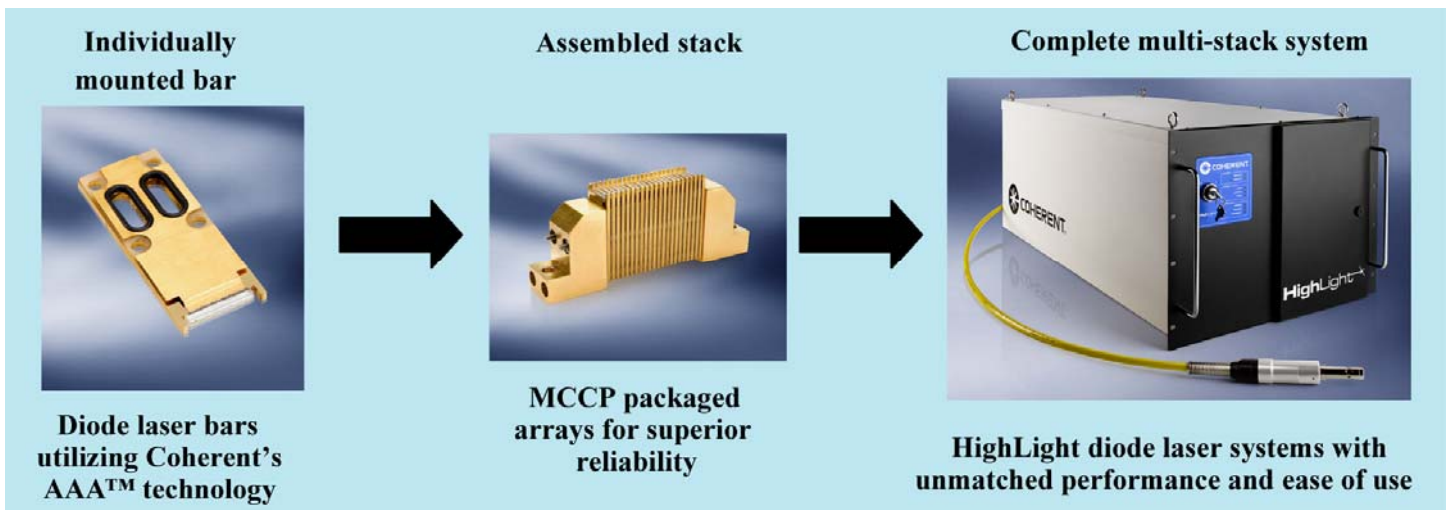
The Coherent HighLight diode laser system was specifically designed for industrial processing applications, such as welding, heat treating and cladding. The Coherent HighLight diode laser product line currently consists of two models. The first is the HighLight 4000L which offers 4 kW of output at 808 nm. The nominal beam size from this laser is 1 mm x 12 mm at a 90 mm working distance. However, a variety of optical accessories are available so that the output can be well matched to the needs of specific applications. The second model is the HighLight 1000F which is a high brightness, fiber-coupled system that delivers 1 kW at 975 nm from a 600 μm core optical fiber. The combination of small size and fiber delivery (fiber lengths from 5 m to 50 m) make the 1000F particularly easy to deploy in industrial environments where space and access to electrical and water service are an issue. Furthermore, its small spot size makes it particularly well matched to the requirements of many welding applications.

Coherent HighLight systems deliver an ideal combination of reliability and ease of use thanks to the use of advanced technology in diode construction, process control and packaging, as well as practical systems convenience factors. We've also carefully engineered our MCCP technology to make it exceptionally robust and reliable as confirmed by both field data and on-going life-testing. For example, the next graph shows output power from 10 different laser bars as they are on/off cycled over 20,000,000 times, at a cycling frequency of 2 Hz. These particular testing conditions were chosen to mirror the pulsed (on/off) demands of many real world materials processing applications. Note that there is no significant drop off in output power over the 2,000 hour test period in any of the devices, and these results can be extrapolated mathematically to indicate a projected array lifetime of at least 20,000 hours. Furthermore, we've seen no diode array failures due to corrosion or erosion in our MCCP architecture in 10 years of actual industrial operation.



Testing indicates 20,000 hours MTBF for Coherent MCCP diode lasers with on/off cycling

As mentioned previously, the primary advantage of HighLight lasers for welding are the substantial cost of ownership savings derived from their electrical efficiency. Additionally, the HighLight has instant "on" capability so there is no standby power consumption.



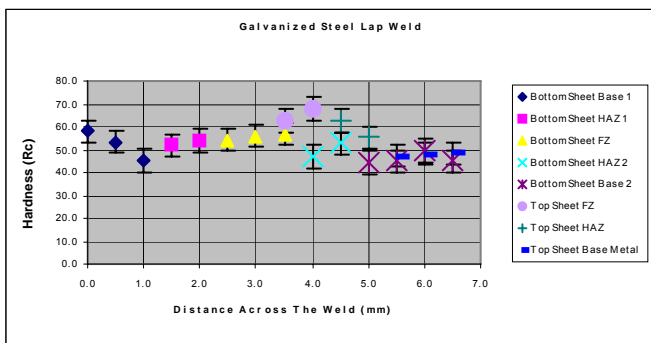
Coherent is the only vertically integrated supplier of high power diode lasers, producing everything from the wafer level through to finished systems

Even larger savings result from reduced maintenance costs which are orders of magnitude smaller for the HighLight as compared to other welding lasers. Maintenance downtime is also minimized because the physically compact HighLight laser can be more rapidly replaced than bulkier lasers and if required, replacements can even be shipped via overnight courier services.

Welding with HighLight Lasers, When and Where

HighLight lasers are best employed for conduction mode welding of thin metals for applications in which cost is a prominent factor (both purchase price and operating costs) and in which practical considerations such as floor space and part access are important. Indeed, their small size and low weight mean that these laser systems can be mounted directly on robot arms and moved relatively quickly. Alternatively, the ability to deliver the output through long lengths of optical fiber allows a high level of flexibility in terms of where the laser system is located. It also enables beam delivery into tight or hard to access spaces. Typical uses would therefore be under-hood welding of components in automobile manufacturing and welding of heat-sensitive medical devices such as pacemakers.

More importantly, HighLight lasers can be utilized with existing process recipes, meaning that there is no significant learning curve in a transition. Specifically, they can be employed with the same materials and alloys which are currently processed with conduction mode welding. Typical examples are medium and high carbon steels which tend to form an undesirable martensitic fusion zone when subjected to the high temperatures and fast temperature cycling experienced with keyhole welding. The galvanized (zinc coated) steels commonly used in automotive applications can also be welded with HighLight lasers. Again, these are problematic with keyhole welding because the zinc melts rapidly, whereas the lower temperatures of conduction welding result in a fusion zone which has a uniform dilution of zinc and steel with no porosity. The graph shows the average hardness versus distance across the weld for a galvanized steel lap weld, and demonstrates that conduction mode welding with HighLight lasers does not significantly change material properties in the fusion and heat affected zones.

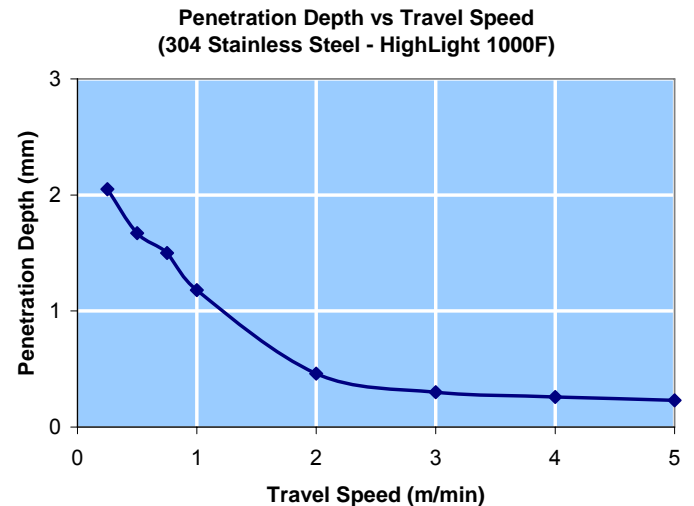


Average hardness vs. distance across a lap weld in galvanized steel

Stainless steel is also well-suited to conduction mode welding with diode lasers, particularly in applications where the corrosion resistance of the weld is critical. Typical examples are in medical devices, reactors and aerospace components. Again, this is because the lower process temperature doesn't cause removal of more volatile alloying elements from the fusion zone. Additionally, stainless steels are generally increasingly reflective at longer wavelengths so the shorter wavelength of the diode laser results in incrementally better light absorption and thus higher efficiency than with older laser types.

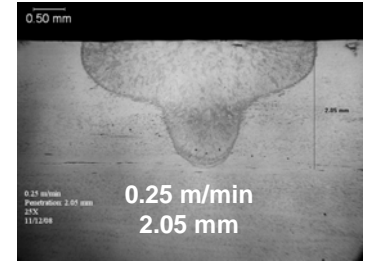
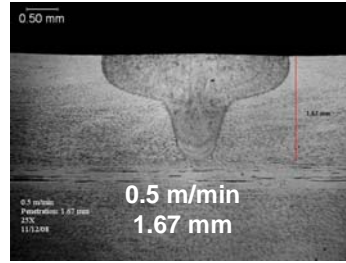
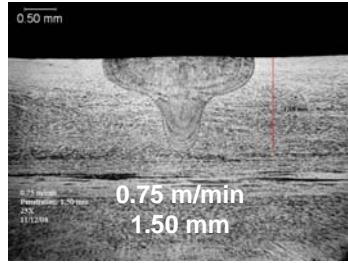
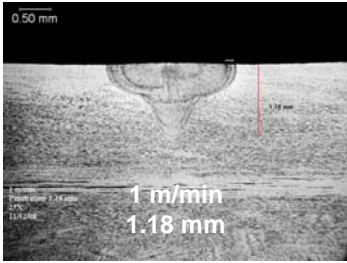
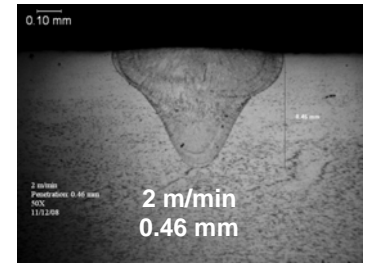
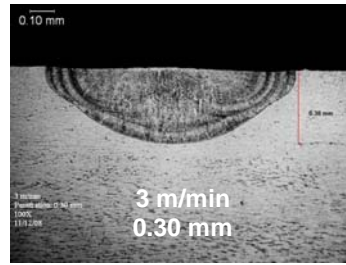
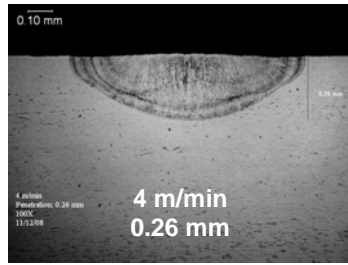
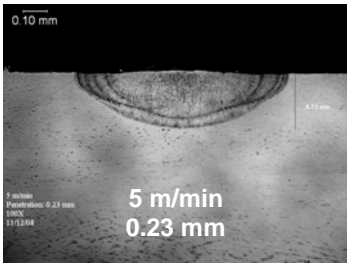
The higher absorption of shorter wavelength light is even more pronounced in aluminum which has a very significant dip in its reflectivity in the near infrared. Aluminum alloys containing volatile alloying materials such as magnesium, which are difficult to keyhole weld can thus be successfully conduction welded with diode lasers.

The photos show a series of bead-on-plate welds on 304 stainless steel performed with the HighLight 1000F (1 kW). A Precitec laser process head fitted with f/100 focusing optics was attached to the fiber end of the HighLight 1000F producing a 600 μm spot size at the work surface. Argon was used as the assist gas. In each case, the travel speed and penetration depth of the weld are listed. These images clearly demonstrate that the HighLight laser produces good quality welds up to depths of 2 mm. These welds don't suffer from porosity and exhibit a minimal HAZ. The penetration depth as a function of travel speed is summarized in the following graph.



Penetration depth vs. Travel speed for the HighLight 1000F laser performing bead on plate welds on 304 stainless steel.

In conclusion, the Coherent HighLight laser is an innovative tool for many conduction mode welding applications that delivers a number of advantages over other laser sources. In particular, the HighLight laser offers attractive cost of ownership characteristics and its small size and fiber delivery capability make it easy to integrate directly with existing production equipment.



Process Speed & Penetration Depth: 304 Stainless Steel