Laser Welding Fundamentals

Resistance Welding | Laser Welding | Laser Marking

Table of Contents

Figures

Tables

Amada Miyachi America, Inc.

Amada Miyachi America, Inc. is a leading manufacturer of equipment and systems for resistance welding, laser welding, laser marking, laser cutting, laser micromachining, and hot bar bonding. Based in Southern California, the company provides products to a wide range of markets including the medical device, battery, electric vehicle, and solar industries, as well as the global electronics, automotive, and general industrial markets.

Since 1948, Amada Miyachi America has worked to achieve one goal: to solve its customers' manufacturing challenges. Knowing there is no one solution that fits all, we strive to provide customers with innovative and reliable manufacturing technology solutions that meet their specific application and process needs. Amada Miyachi America is an ISO9001 certified company.

Amada Miyachi America also sells, distributes, services and supports the sales of all Amada Miyachi group branded products, including Miyachi Unitek, Miyachi Peco, Miyachi Eapro and Benchmark.

Contact Amada Miyachi America at its company headquarters, located at 1820 S Myrtle Ave., Monrovia, CA 91016, by phone at (626) 303-5676, or by email at info@amadamiyachi.com. Find out more about the company's products and services at www.amadamiyachi.com.

Company timeline

1948 Unitek Corporation founded in Pasadena, CA to manufacture orthodontic appliances.

1950 Weldmatic Division organized; produced a complete line of electronically operated resistance welders for missile, aircraft, electronics, and metal working industries.

1965 Moved into current Headquarters location in Monrovia, CA.

1971 Unitek Equipment Division established.

1978 Unitek Corporation acquired by Bristol Myers Squibb. Development and patent of force firing systems critical to small parts welding.

1987 Unitek Corporation acquired by 3M.

1988 Divested from 3M as Unitek Equipment Division of KVA Holdings Corp.

1991 Name changed to Unitek Equipment Inc.

1994 Acquired by Miyachi Technos and reorganized as Unitek Miyachi Corporation with merger of Miyachi America Company.

1995 Acquired Weld-Equip companies in Holland, Germany and France, and Miyachi Technos Europe in Germany.

1995 Received ISO 9001 Certification.

2000 Acquired Peco Welding Systems, GmbH.

2001 Acquired Benchmark International, Inc.

2005 Renamed Miyachi Unitek Corporation, consolidated Benchmark International to California.

2008 Reorganized European companies into single entity: Miyachi Europe Corporation.

2010 Opened applications lab in Wixom, MI.

2011 Opened sales office and applications lab in Brazil.

2013 Miyachi Corporation acquired by Amada Co., Ltd.

2014 Renamed Miyachi America Corporation.

2015 Reorganized as Amada Miyachi America, Inc.

Our Brands

Amada Miyachi America has proudly designed and manufactured its Miyachi Unitek products for the global market since 1948 and also sells, distributes, services and supports the sales of the other, Amada Miyachi Group branded products: Miyachi, Miyachi Eapro and Miyachi Peco ensuring you get the best technology solution to fit your budget and your specific application.

MIYACHI UNITEK
MIYACHI PECO
MIYACHI EAPRO
MIYACHI
BENCHMARK

1.1 Introduction

The word "LASER" is an acronym for

Light
Amplification by
Stimulated
Emission of
Radiation

A laser is made up of these elements:

Laser medium – Material in which the laser is generated. For solid state lasers the medium is typically comprised of a host material doped with the active laser element.

Pump source – Provides the necessary activation energy to the laser medium, enabling laser generation.

Laser resonator – Controls how the laser is generated in the laser medium, consists of a rear 100 percent reflector and a front partial reflector.

Figure 1 provides a graphic illustration of the laser elements

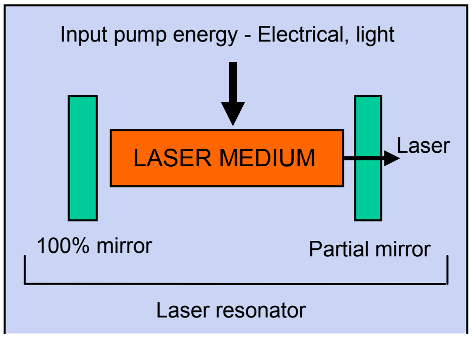


Figure 1 – Illustration of laser elements

1.2 Principle of laser generation

The generation of a laser beam is a three-step process in which steps occur almost instantaneously.

1) **Spontaneous emission –** The pump source provides energy to the medium, exciting the laser medium atoms so electrons held within the atoms are temporarily elevated to higher energy states. The electrons held in this excited state cannot remain there indefinitely and drop down to a lower energy level. In this process, the electron loses the excess energy gained from the pump energy by emitting a photon. The photons produced by this process, which is called spontaneous emission, are the seed for laser generation.

2) **Stimulated emission –** The photons emitted by spontaneous emission eventually strike other electrons in the higher energy states. This happens in a very short time due to the speed of light and density of excited atoms. The incoming photon "knocks" the electron from the excited state to a lower energy level, creating another photon. These two photons are coherent, which means they are in phase, of the same wavelength, and traveling in the same direction. This process is known as stimulated emission.

3) **Amplification –** The photons are emitted in all directions. However, some travel along the laser medium to strike the resonator mirrors to be reflected back through the medium. The resonator reflectors define the preferential amplification direction for stimulated emission. There must be a greater percentage of atoms in the excited state than the lower energy levels for the amplification to occur. This "population inversion" of more atoms in the excited state leads to the necessary conditions for laser generation.

Figure 2 is a simplified schematic representation of the three stages to laser generation.

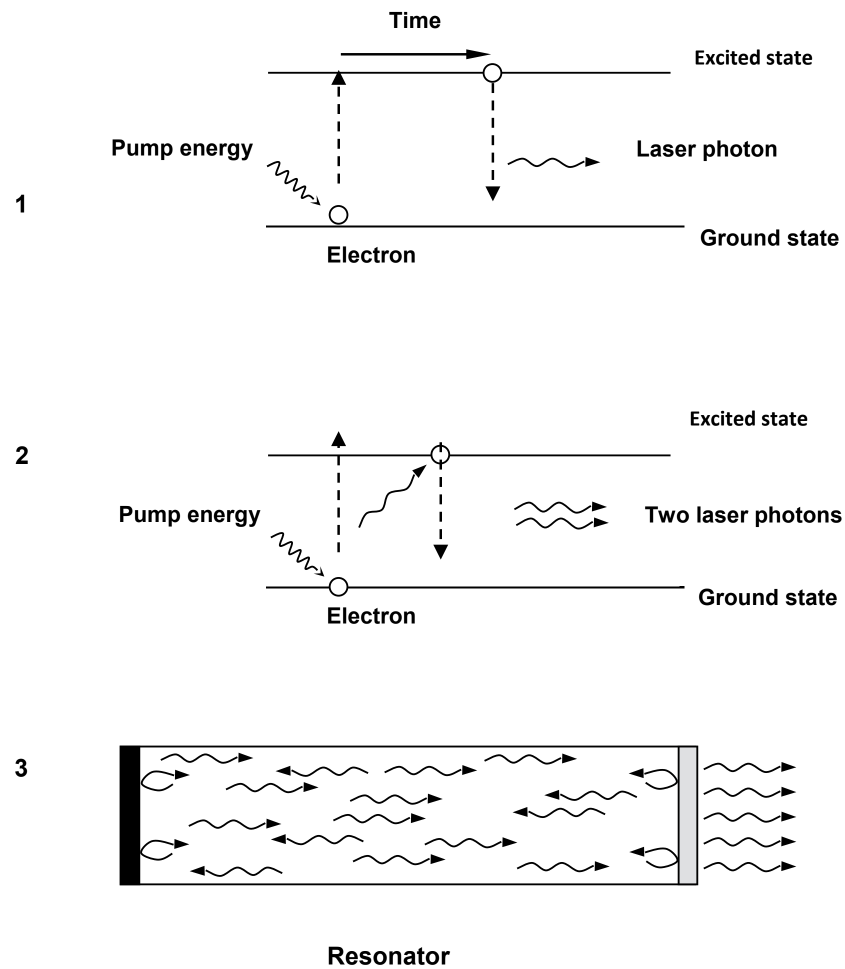


Figure 2 – Stages to laser generation

1.3 Welding lasers

Lasers suitable for welding include pulsed neodymium-doped yttrium aluminum garnet (Nd:YAG), fiber, and diode. Each offers unique features that align to specific applications.

The pulsed Nd:YAG laser has by far the largest install base with peak powers and pulse widths designed for micro welding. For example, 25-50 W pulsed Nd:YAG lasers are routinely used for seam welding 0.015-inch thick titanium cases for implantable devices.

More recently developed fiber lasers offer excellent flexibility in tailoring weld dimensions and the best penetration per watt performance, which enables high speed seam welding. A 300 W fiber laser can seam weld 0.01-inch thick airbag detonator casings at 2 inches per second, while a 20 W pulsed fiber laser can produce a 0.001-inch diameter spot welds in 0.001-inch thick foil. The architecture of the fiber laser is scalable, with laser powers available at multi kilowatt levels used for penetration welding applications up to and beyond 0.25-inch thickness.

The diode laser is a well-established laser technology that been used for many plastic welding applications, notably in the automotive industry for welding the rear light housing. Welding of plastics with lasers is a current growth area, particularly with the development of laser-friendly plastics and lasers that can weld visually clear plastics. More recently, the diode laser has become available at multi kilowatt levels suited to metal welding.

1.3.1 Nd:YAG laser

The laser rod used in Nd:YAG laser welders is a synthetic crystal of yttrium aluminum garnet (YAG). The YAG material is the "host" material, containing a small fraction of neodymium, the active element. The YAG crystal is an ideal host for the lasing material Nd^{3+}, because it is physically hard, stable, optically isotropic, and has good thermal conductivity, which permits laser operation at high average power levels. Neodymium is an excellent lasing material because it produces a higher level of peak powers than any other doping element. The laser rod dimensions are selected for power and optical quality. The maximum rod size is limited to a diameter of around 15 millimeters (mm) and a length of 200 mm, to ensure crystal quality and thermal management.

1.3.1.1 Nd:YAG pump source

Light energy, provided by flash lamps, is used to pump the Nd:YAG crystal. The flash lamp is an operational consumable that requires changing according to usage. Flash lamp lifetime ranges from 200,000 to 150 million + shots, depending upon manufactured quality, pulse parameters, and duty cycle. Increased lamp lifetime generally results from keeping the lamps at temperature; therefore, seam welding applications and multi-shift operation will offer the longest lifetimes.

1.3.1.2 Nd:YAG resonator

The resonator has a pump cavity that houses the flash lamp and laser rod. This is usually an elliptical shaped clamshell design with gold plated internal surfaces to reflect all the light from of the lamp into the rod. Cooling is provided to both the flash lamp and the laser rod by flooding the entire pump cavity with flowing water. **Figure 3** shows the major components of a Nd:YAG welding laser optically pumped with a flash lamp.

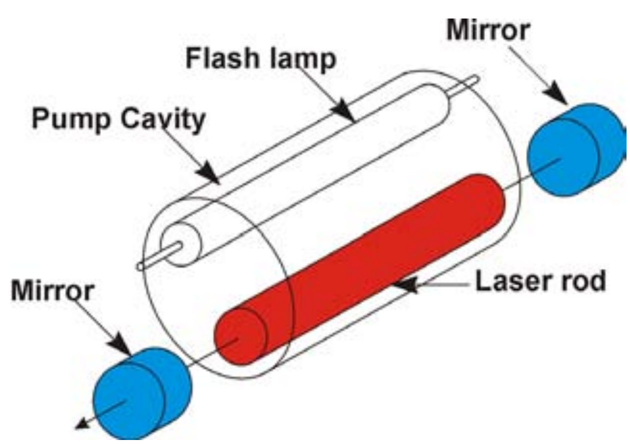


Figure 3 – Major Nd:YAG components

1.3.2 Fiber laser medium

As the name suggests, a fiber laser is generated within a flexible doped glass fiber that is typically 10 to 30 feet long and between 9 and 50 microns diameter, as shown on **Figure 4**. For most industrial lasers Ytterbium is used as the doping element because it provides sufficient conversion efficiency and a near 1 micron wavelength, which aligns to standard optical delivery components. Thulium can also be used and tuned between a 1-2 micron wavelength, which is often used for low power plastic welding applications. The central core is surrounded by an additional layer that enables the pump energy to be delivered to the inner core along its length.

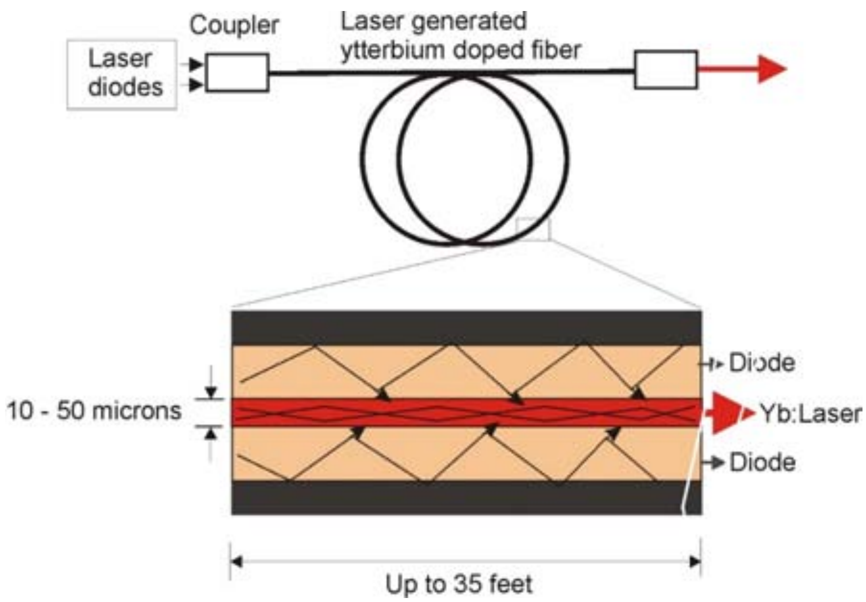


Figure 4 – Fiber laser with flexible doped glass fiber

1.3.2.1 Fiber laser pump source

The fiber core medium is pumped by diodes that output a specific wavelength, which is efficiently absorbed by the doping element. This enables excellent conversion of pump to laser energy, providing up to 50 percent conversion of input electricity to laser light, also known as wall plug efficiency. The pump diodes have long lifetimes, typically more than 50,000 hours, and so are not considered a consumable. In certain fiber laser architectures, the diodes can be replaced in the field.

1.3.2.2 Fiber laser resonator

In a fiber laser, the lasing takes place within a small core optical fiber. The resonator is formed between fiber Bragg gratings that are etched into the fiber, which act as the full and partial reflectors. The laser is contained within the fiber, so there is essentially an auto-alignment within the resonator – with no need for external adjustment.

Fiber lasers use power modules that are made up of individual modules ranging from 200 to 2000 watts (W). For example, a 4 kilowatt (kW) laser is made up of multiple modules, with the option of adding an additional module for redundancy. Fiber lasers are very compact, with power up to 1kW offered in rack-sized formats. They can be air-cooled up to 500 W. **Figure 5** and **Figure 6** show the power scaling of fiber laser, with a single module and then with a number of single modules combined into a higher power laser.

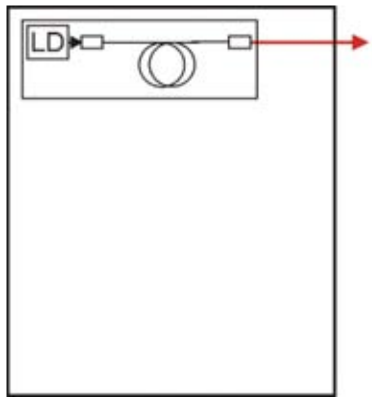


Figure 5 – Single module

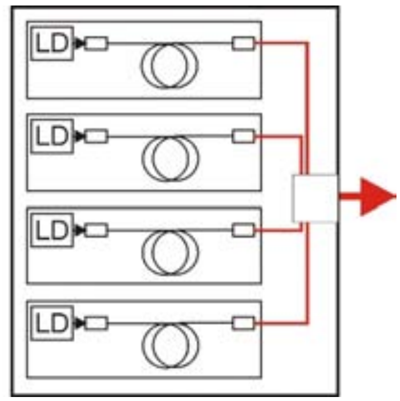


Figure 6 – Modules combined

1.3.2.3 Single mode and multi-mode fiber lasers

Two fiber laser configurations are available, depending upon the size of the lasing fiber's core diameter. A single mode fiber laser refers to small core diameter fibers, between 10-20 microns. As the name suggests, this laser is restricted to a single transverse mode that results in a power density cross section through the laser that has a high central maximum that falls off sharply. This is known as a Gaussian mode. The multi-mode fibers have core diameters equal or greater than 50 microns. This larger diameter allows more transverse modes to propagate, leading to a mode shape known as a "flat top." The term refers to the even power density through the laser's cross section. See **Figure 7**.

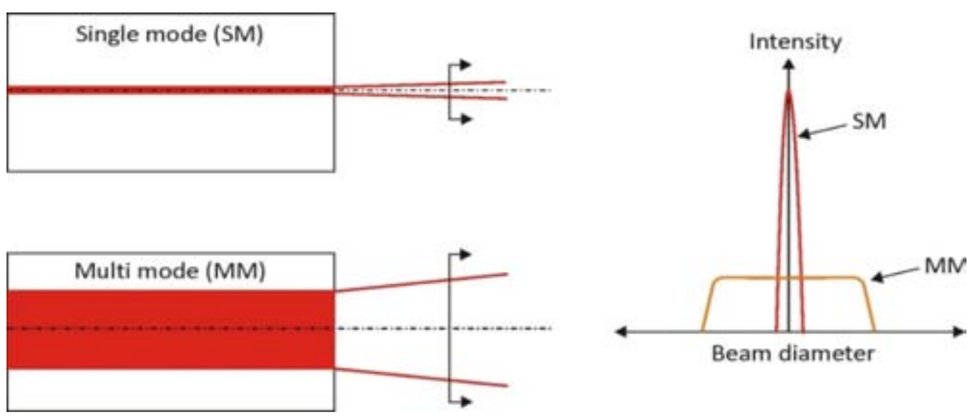


Figure 7 – Single mode and multi-mode lasers

1.3.3 Diode laser medium

A wide variety of semiconductor materials can be used as the diode laser medium to produce wavelengths between 750-980 nanometers (nm). The medium most commonly selected for laser materials processing is gallium arsenide (GaAs). This medium converts power efficiently, producing a wavelength of between 900-980nm.

Figure 8 is a schematic representation of the material sandwich that makes up the diode laser medium. The red ellipse represents the laser coming out of the page. The p and n materials provide the necessary electrons and "holes" needed for lasing to occur. The double layering of the material ensures greater efficiency of this process. As noted earlier, the lasing process occurs when a free electron and a hole recombine to create photons by spontaneous emission. The resonator is formed by the coated and uncoated facet ends.

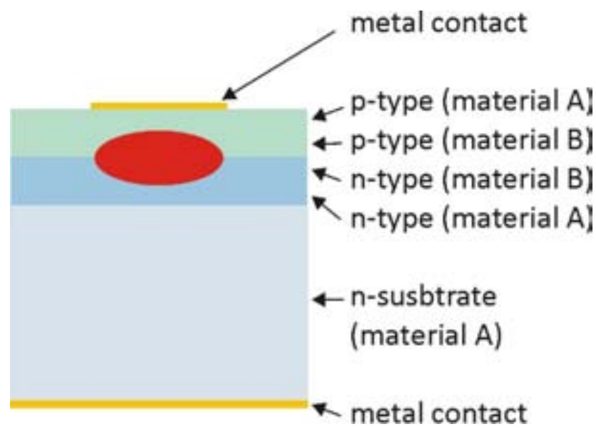


Figure 8 – Material sandwich for diode laser medium

1.3.3.1 Diode laser pump source

A voltage potential across the diode stack provides the pumping energy that creates the conditions of electrons and holes in the medium that enables lasing.

1.3.3.2 Diode laser combining

Individual diodes or diode arrays must be combined to produce the hundreds of watts and kilowatts of output power needed. The methods used to combine diodes take advantage of the fact that a laser diode can emit slightly different wavelengths by orders of nanometers and that the arrays can have different polarizations. This means that many diodes or diode arrays can be combined to produce a single output laser with high power.

1.4 Laser safety

In the United States, the FDA's Center for Device Radiation Hazards (CDRH) has jurisdiction over laser safety issues regulated under ANSI 136.1. In addition, the Laser Institute of America offers guidelines and practices for laser safety. The main hazard associated with using Nd:YAG fiber and diode lasers operating around 1 micron wavelength is the effect on the eyes of direct or indirect exposure to the laser radiation. (This is of course aside from the nominal hazards associated with operating any piece of equipment.)

Since the human eye actually focuses the laser beam directly back to the retina, laser operators, and all other persons in the proximity of the laser, must always work in what is known as a Class 1 eye safe environment, the safest of the four laser classes. The Class 1 eye safety level is achieved by either wearing the appropriate safety goggles or containing all the laser radiation in a light-sealed Class 1 enclosure/workstation. CDRH provides laser manufacturers and users with specific rules, standards, and exposure limits for each type of laser and power level. To comply with regulations, one must file a CDRH report for each laser and each laser system. When a laser or laser system is brought in-house, a member of staff should undergo training to become a certified Laser Safety Officer.

To create sufficient heat at the part for welding, the laser is focused by a lens, such that all the light is focused at the same point. This creates a very high concentration of power (more correctly termed power density) that rapidly heats up metals. The process by which laser light is absorbed by metals is complex and not covered here. Rather, this document focuses on the overall heating effect that enables the laser to heat, melt metal, and serve as a laser welding source.

2.1 The laser as a heating source

Laser welding requires that the laser raise the temperature of the material to be welded. The laser must be absorbed by the material to induce a temperature rise. In effect, the laser is focused onto the material similar to the way the sun can be focused by a magnifying glass. The difference is that the laser's power density is many orders of magnitude higher, around 106 watts per cubic centimeter (watts/cm^2).

Figure 9 illustrates the mechanism of laser absorption into the part and the part's subsequent heating. Laser light photons, packets of light energy that make up the laser, impinge onto the material and are partly or wholly absorbed. The energy of the photon is absorbed in the material lattice and causes phonons or heat waves within the lattice. Repeated absorption of photons eventually leads to lattice breakup and melting.

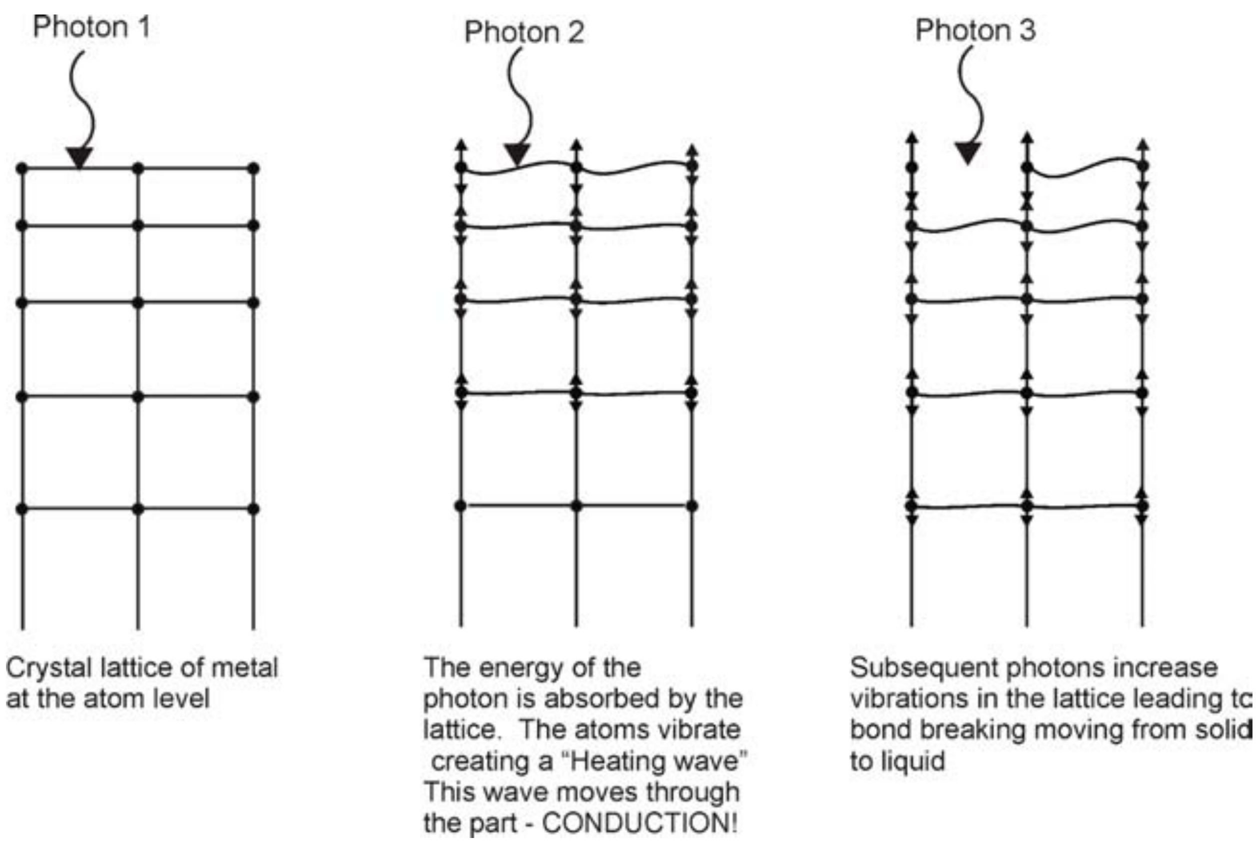


Figure 9 – Laser absorption and heating

Figure 10 shows a time-based schematic of laser absorption for welding. Even for metals that absorb well, such as steel, the laser is initially reflected. A small percentage of the laser is absorbed, heating the metal surface. The increased surface temperature increases the absorption of the laser power. This creates a snowball effect, in which the material is rapidly heated by the laser, leading to melting and formation of the weld.

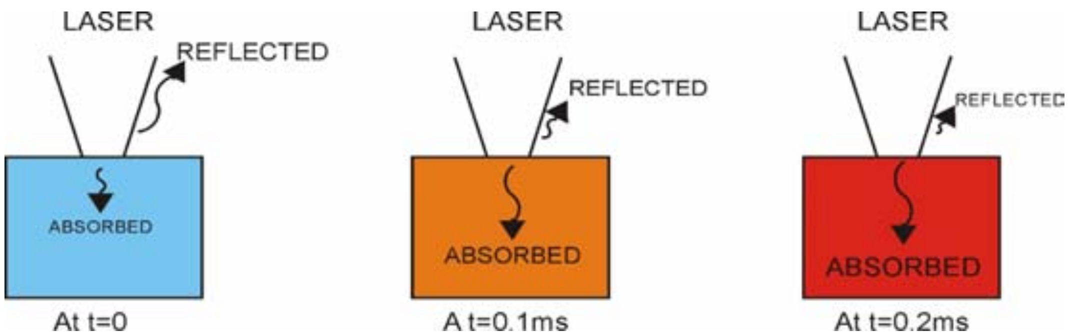


Figure 10 – Time-based schematic of laser absorption for welding

2.2 Laser welding modes

The laser is a high power density process that provides a unique welding capability to maximize penetration with minimal heat input. The weld is formed as the intense laser light rapidly heats the material – typically in fractions of milliseconds. There are three types of welds, based on the power density contained within the focus spot size: conduction mode, transition keyhole mode, and penetration/keyhole mode. See **Figure 11**.

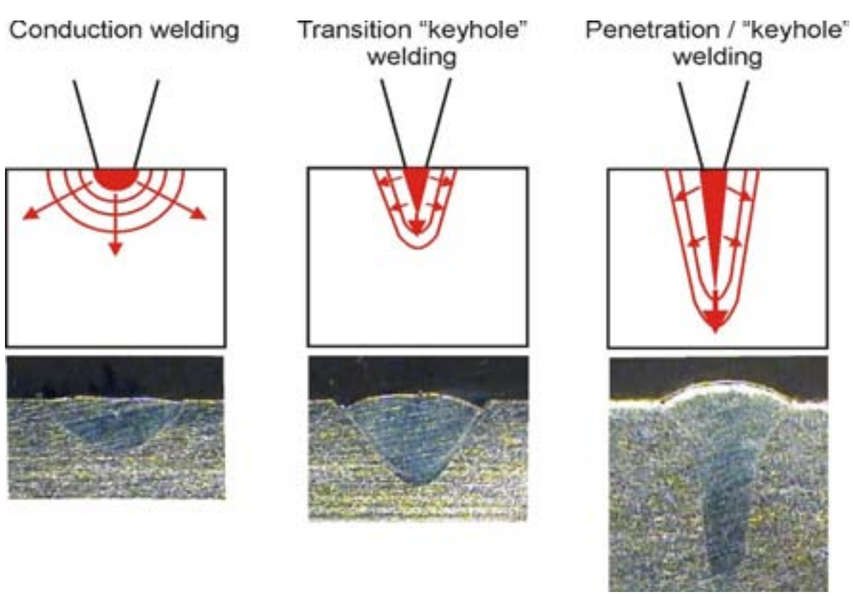


Figure 11 – Laser mode types

Conduction mode – Conduction mode welding is performed at low energy density, typically around 0.5 MW/cm², forming a weld nugget that is shallow and wide. The heat to create the weld into the material occurs by conduction from the surface. Typically this can be used for applications that require an aesthetic weld or when particulates are a concern, such as certain battery sealing applications.

Transition mode – Transition mode occurs at medium power density, around 1 MW/cm², and results in more penetration than conduction mode due to the creation of what is known as the "keyhole." The keyhole is a column of vaporized metal that extends into the material; its diameter is much smaller than the weld width and is sustained against the forces of the surrounding molten material by vapor pressure. The depth of the keyhole into the material is controlled by power density and time. Because the optical density of the keyhole is low it acts as a conduit to deliver the laser power into the material.

As shown above in **Figure 11**, if conduction welding can be thought of as a point source heating from the surface, then the keyhole can be thought of as a line source heating from within the metal providing a more efficient welding source. In transition mode the time or power density is just sufficient to create but not extend the keyhole deep into the part. Therefore, the welds exhibit shallow penetration with a typical weld aspect ratio (depth/width) of around 1. This mode of welding is used almost exclusively by pulsed Nd:YAG and fiber lasers for many spot and low heat input seam welding applications.

Keyhole or penetration mode – Increasing the peak power density beyond 1.5MW/cm² shifts the weld to keyhole mode, which is characterized by deep narrow welds with an aspect ratio greater than 1.5. **Figure 12** shows how the penetration depth rapidly increases when the peak power density is beyond 1 MW/cm², transitioning the weld mode from conduction to keyhole/penetration welding.

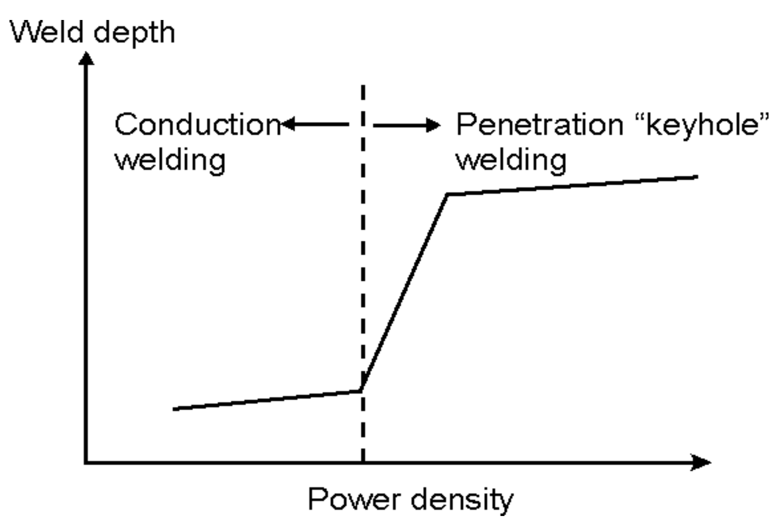


Figure 12 – Relationship between power density and weld mode

Penetration or keyhole mode welding is characterized by narrow welds. This direct delivery of laser power into the material maximizes weld depth and minimizes the heat into the material, reducing the heat affected zone and part distortion.

In this keyhole mode, the weld can be either completed at very high speeds – in excess of 20 inches per second with small penetration typically under 0.02-inch (0.5 mm) – or at lower speed, with deep penetration up to 0.5-inches (12 mm).

3.1 Pulsed and continuous wave operation

A weld can be created either as an individual spot or a seam weld. The laser output that creates these welds can be achieved in one of two ways:

A pulsed laser produces a series of pulses, discrete packets of energy, at a certain pulse width and frequency until stopped. The “pulsed” descriptor refers to a laser that can produce a peak power that is greater than its average power. A continuous wave (CW) laser produces extended output – the laser remains on continuously until stopped. For example, a 25 W pulsed Nd:YAG laser can produce peak powers of up to 5 kW for a few milliseconds. This means it can produce a spot weld that would require a CW laser sized at 5 kW! With pulsed lasers a seam weld is created by a series of overlapping spot welds. For a continuous weld the laser remains on for the duration of the seam.

A CW laser can also produce discrete pulses of laser light – known as gated or modulated output. In this case the CW laser peak power does not exceed the laser’s rated average power. An Nd:YAG laser operates only in pulsed mode; diode lasers operate in continuous wave; and fiber lasers can operate in both modes. This is highlighted in **Figure 13.**

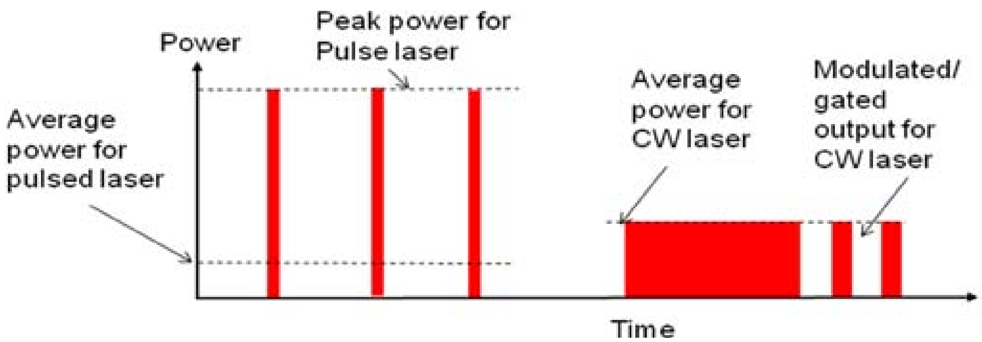


Figure 13 – Comparison of laser outputs: pulsed, CW and modulated

Choosing when to use pulsed, continuous wave, or modulated output is determined by the specific application. Spot welding typically uses pulsed operation. For seam welding, the selection is made based on heat input and cycle time. For instance, when seam welding an implantable device, a pulsed laser is used to minimize heat input and maintain a uniform weld around a complex geometry with varying welding speeds. In contrast, for airbag initiators, welding at high speed using CW operation is favored.

3.2 Laser power stability

Particularly in micro welding, the small weld volume means that small changes in input power will result in large changes to the weld. The consistency of laser power to the workpiece for each weld is important. Typically, lasers are specified for ± 3 percent power stability over the laser’s operating temperature range. If the environmental temperature around the laser can be controlled to within ± 1-2°C, the power stability can be further optimized, to a range of ±1 percent.

It is worth noting that the measurement devices used to measure laser power are specified to ± 3 percent accuracy, so care needs to be taken if lower stability is needed and must be measured.

For pulsed Nd:YAG lasers, consistent power output is achieved using real time power feedback that occurs during the weld pulse to ensure that the delivered pulse precisely matches the demanded pulse.

Figure 14 shows how closed loop power feedback for Nd:YAG laser enables the supplied pulse to exactly match the demanded pulse, irrespective of lamp or diode lifetime. In addition, at the start of a pulse train the non-feedback pulsed laser can sometimes show inconsistency.

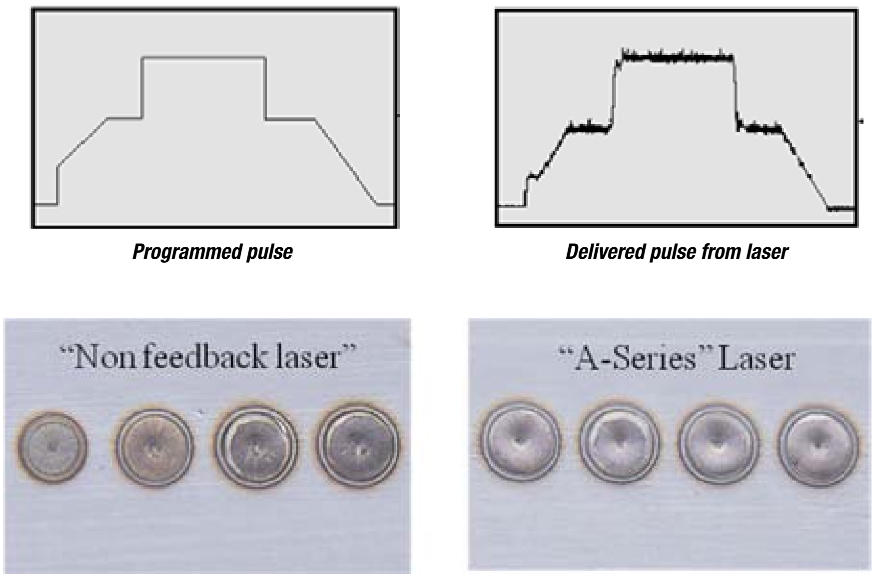


Figure 14 – Closed loop feedback enables delivered pulse to match programmed pulse

The architecture of the fiber laser provides good inherent stability with no cold start instability, so there is no need for power feedback to maintain weld consistency.

3.3 Wavelength

For the majority of metal welding applications, wavelength is not a significant factor. Many welds can be made on a variety of materials using a wavelength around 1 micron. The exception to this is copper. Copper and certain copper alloys are so reflective to the 1 micron wavelength that welding is very difficult. Extremely high power density is required to overcome the reflectivity; however, once absorption occurs, there may be too much power, which can lead to weld blow outs. Inconsistent reflection of copper is also an issue. The same part can react differently to successive pulses that may weld, not weld, or drill the part. For seam welding applications, a single mode fiber laser may be able to overcome copper reflectivity. However, this laser source would not be suitable for fine micro welding applications because it could grossly overheat the part.

To successfully micro weld copper, a good choice is a 532 nm or green wavelength, which can overcome material reflectivity. The 532 nm wavelength can be used in two different ways. Use the 532 nm to initiate absorption, and then create the weld using 1 micron wavelength, or use only 532 nm wavelength to make the weld. The former method works best for high speed seam welding and the latter is best for spot or short seam welds. **Figure 15** shows a weld in copper using a 1 micron wavelength laser (left) and a 532 nm green wavelength laser (right).

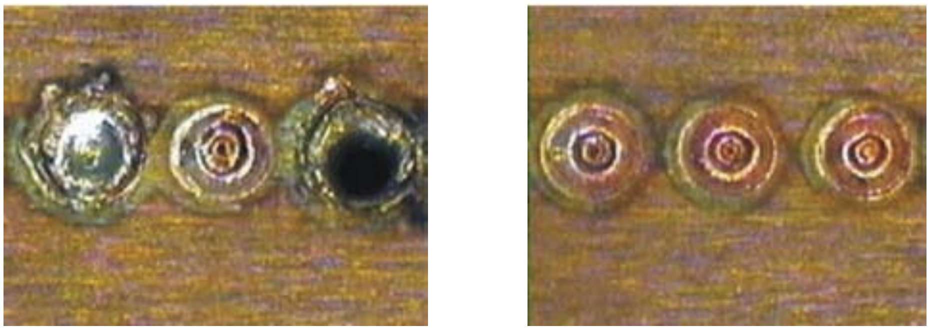


Figure 15 – Welding copper with 1064 nm and 532 nm wavelengths

Aluminum is another material that is reflective to 1 micron wavelength. It can be welded with 1 micron wavelength lasers but has a reflectivity dip at 808 nm. Diode lasers operating at 9xx nm wavelengths, although not quite at 808 nm, may offer process advantages in terms of weld stability and penetration performance for seam welding applications.

3.4 Power ramping

Power ramping refers to using a ramp up of laser power at the start of the weld or ramp down of laser power at the end of the weld. Ramp down is most commonly used; for hermetic laser sealing and seam welding as it creates a smooth reduction of the weld penetration or transition from keyhole to conduction weld, or to avoid last pulse or end of seam cracking due to high solidification rates.

Figure 16 shows how a power ramp down at the end of a seam weld can be used to prevent cracking and ensure a defect-free completion of a seam.

Figure 16 – Power ramping

This concept can also be extended when seam welding small parts, particularly circumferential welds, which heat up the part during the welding process. Maintaining the same power for the entire duration of the seam results in increasing penetration along the seam as the laser pre-heats the part. Power ramping can be used to offset this effect, by tuning the power ramp down to match the part thermal build up such that the part is not overheated and penetration is consistent along the seam.

4.1 Laser beam delivery

All lasers between 532 nm and 1070 nm deliver the laser to the welding area using a flexible fiber optic cable. The convenience of fiber delivery greatly facilitates the integration of the laser into turnkey laser welding systems. Typically the length of the delivery fiber is between 5-10 meters (m), though it can be up to 50 m, depending upon the type of laser being used. This enables flexible positioning of the laser, which can be particularly useful for certain production lines.

Pulsed Nd:YAG lasers and diode lasers use delivery fibers that can be directly disconnected and replaced at the laser in the event of damage. For some fiber lasers, the delivery cable is spliced directly to the lasing fiber – in this case if the delivery fiber is damaged, the entire fiber laser must be returned for repair. Alternatively, an external fiber coupler can be used (as shown in **Figure 18**), as well as other modular fiber laser architectures that avoid this issue by design. If an optical coupler or modular fiber laser is used, only the process/delivery fiber must be replaced, which can be completed on site. Note that a single mode laser can only be used with the delivery fiber spliced directly onto the lasing fiber.

All solid state lasers can be delivered to the workstation using flexible fiber optic cables. **Figure 17** shows a pulsed Nd:YAG with a coiled fiber and focus head. The tip of the fiber optic delivery cable is shown on the right photo. The illuminated part is the core, whose diameter determines the focus spot size, along with optics in the focus head.

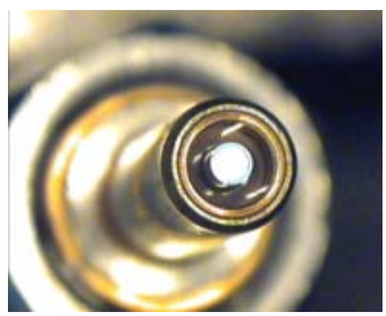


Figure 17 – Pulsed Nd:YAG laser with a coiled fiber and focus head

Figure 18 shows an external coupler for a fiber laser, which allows the process fiber to be replaced in the field. The external coupler also contains a shutter, to comply with CDRH regulations.

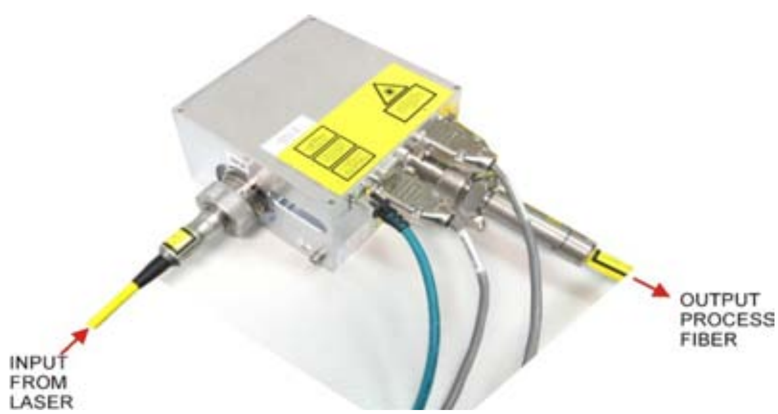
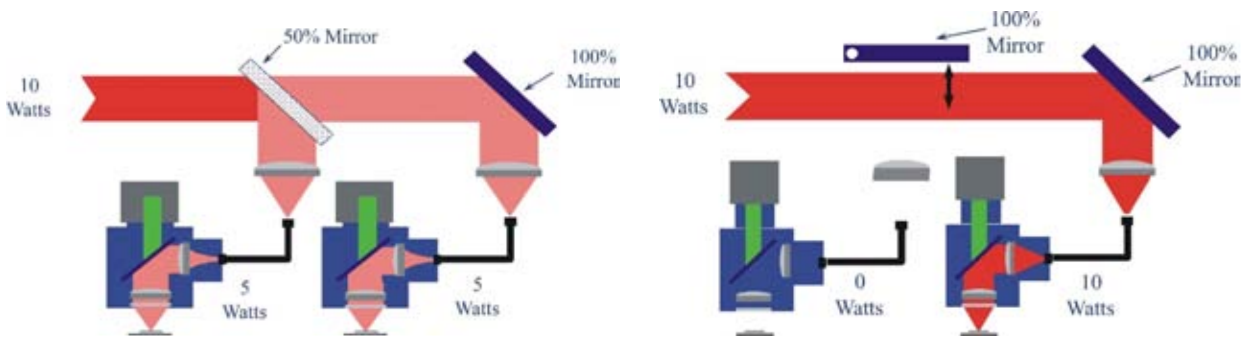


Figure 18 – External coupler for a fiber laser

4.2 Time share and energy share

A single laser can have multiple outputs, which can support single weld heads in multiple workstations or multiple weld heads in a single workstation. These multiple outputs from the laser can be fired sequentially or simultaneously. Sequential firing is known as time share and simultaneous firing is known as energy share. Sharing multiple beams from a single laser can offer productivity and cost benefits. Use of time or energy share can be financially quite attractive because laser costs can be offset by increased utilization efficiency. Energy sharing (**Figure 19**, left diagram) offers simultaneous processing, while time sharing (right diagram) offers serial processing.



Energy share outputs ***Time share outputs***

Figure 19 – Energy share vs time share outputs

4.3 Focus head

The focus heads directs and focuses the output from the laser delivery fiber onto the work piece. **Figure 20** shows a schematic of a 90 degree focus head, where the fiber connection is horizontal and the focus direction is vertical. There are two configurations of this head: diverging beam or collimated beam.

The diverging beam results from a connectorized fiber, either QBH, LLK-Q, or another type. In this case the first optic in the focus head is the collimating lens, which transforms the diverging laser into near parallel/collimated light. A 90 degree reflector, known as a dichroic, directs the laser downwards through the focusing lens.

The left diagram shows a right angle or 90 degree focus head with a diverging fiber. The right diagram shows a right angle or 90 degree focus head with a collimated fiber.

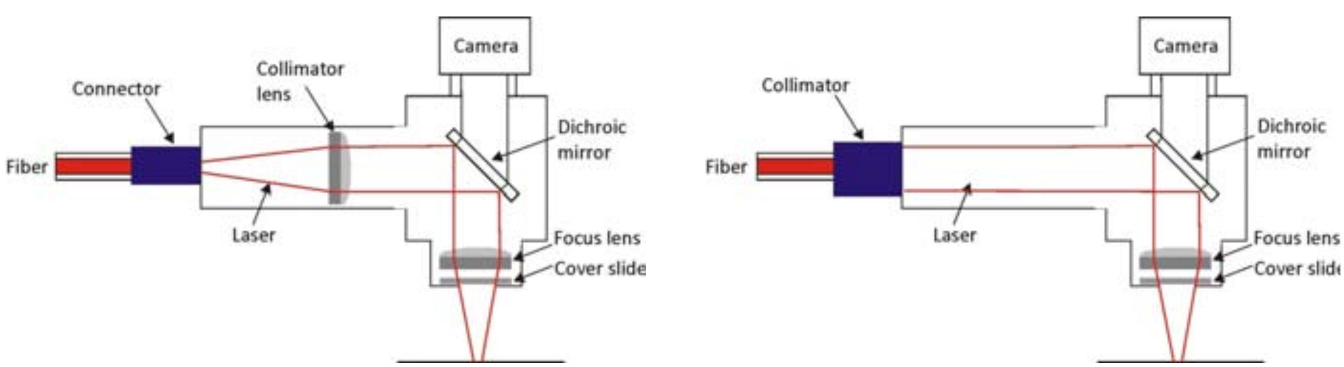


Figure 20 – Schematic of a 90 degree focus head for diverging and collimated fiber output

If the laser is terminated with a fixed collimator, the collimator lens in the focus head is not required. If the beam diameter from the fixed collimation can be used as is, no further optics are required. However, if the fixed collimation beam diameter requires modification, a beam expander can be added.

Figure 21 shows a QBH connector providing a diverging beam output (top) and a QCS connector providing a collimated output (bottom).

Figure 21 – QBH style diverging beam output vs a QCS style collimated output

The final optic in the focus head is the cover slide, which protects the focus lens from dust and spatter. The cover slide is a consumable that must be checked frequently and replaced as needed. Buildup of excessive dust and debris on the cover slide will eventually lead to power absorption and a reduction in the power that reaches the part, and will ultimately affect the weld.

The dichroic mirror used in the focus head has a coating that reflects the laser but allows visible light to pass through. This enables the use of an in-line camera mounted to the focus head that provides a direct view of the weld area. This is useful as it can be used for focus verification, manual alignment of parts, vision alignment of parts, and as a tool for weld inspection.

The use of an in line camera is shown in **Figure 22**. The dark spots are the weld, and the crosshairs indicate where the laser is targeted.

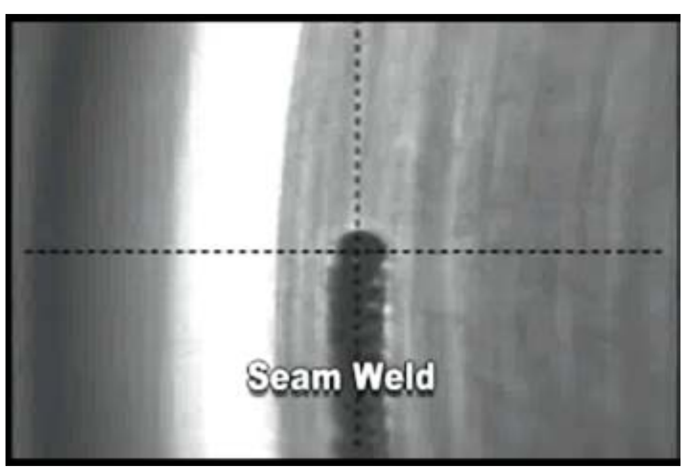


Figure 22 – In-line camera shows top down view of weld area

4.3.1 Optical focused spot size

4.3.1.1 Diverging connector

For fiber-delivered lasers with diverging beams from the delivery fiber, the size of the focused laser is determined by three factors: the delivered fiber's core diameter, the collimation lens focal length, and the focal length of the focus lens in the focus head.

Essentially, the fiber core diameter is imaged by the focus head, so the ratio of the focus focal length to the collimation focal length determines the magnification ratio of the core and the subsequent focused spot size.

Figure 23 shows the relationship of optical spot size to the fiber core diameter and the optics in the focus head.

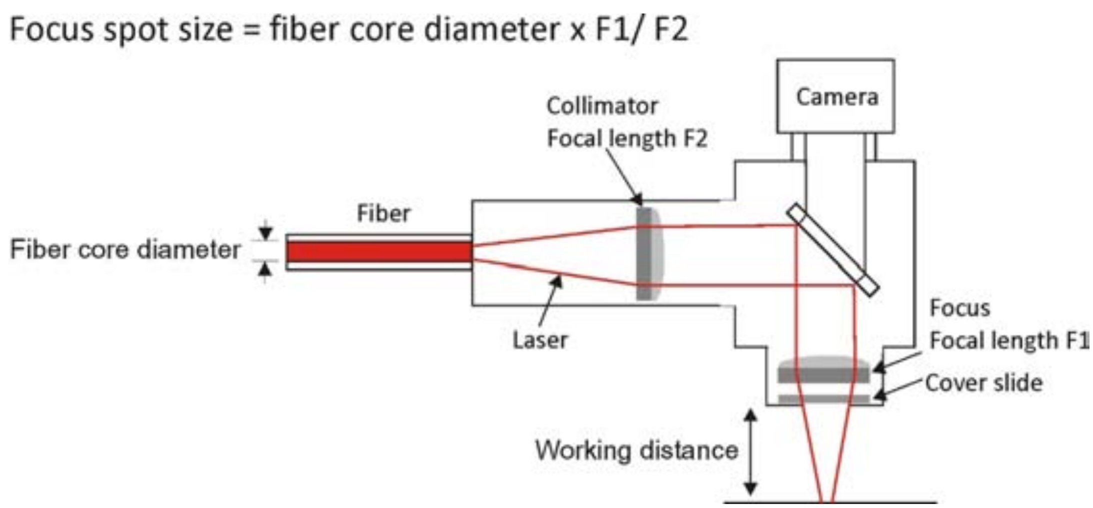


Figure 23 – Diverging connector focal size

4.3.1.2 Collimator connector

For the collimation case, the optical spot size is determined using the free space equation:

Focused spot size = $1.22\ \lambda M^2 F/D$

Where λ = wavelength (m)

M^2 = laser beam quality factor

F = focal length of focusing optic (m)

D = Laser beam diameter at focus optic (m)

4.3.2 Selecting the optical spot size

At first glance, selecting the optical spot size seems difficult because there are an almost infinite number of possible optical spot sizes when one considers the possible combinations of core fiber diameter and focus head optics. In reality, the choice is usually straightforward. Many pulsed micro welding applications use optical spot sizes from 0.008-0.02 inches (0.2-0.5 millimeters). Very fine welding application usually use spot sizes around 0.004 inches (0.1 mm).

Figure 24 illustrates the proper selection of spot size. For penetration welding the typical spot size is around 0.015-0.03 inch (0.25-0.75 mm). Longer focal lengths – around 8-10 inch (250-300 mm) – should be used to avoid excessive spatter issues on the cover slide.

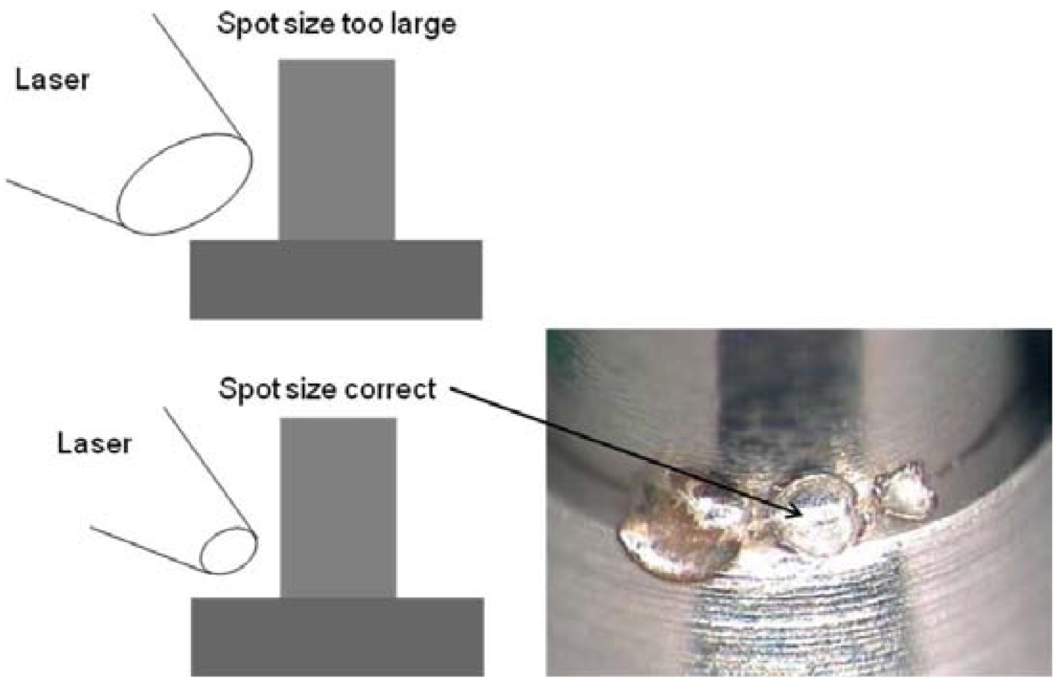


Figure 24 – Selecting proper spot size

Before welding any parts, one must complete a weldability analysis. This analysis should begin with a consideration of material selection, joint design , fit-up tolerances, and required weld functionality, for example strength, electrical contact, or sealing.

5.1 Material selection

Selecting a material that satisfies both part functionality and manufacturability is fundamental to a successful laser welding process. The most common material used for micro welding is 300 series stainless steel, along with aluminum alloys and titanium. This contrasts with penetration welding, where many forms of carbon steel are welded. **Table 1** summarizes the weldability of the most common materials used.

Material	**Comments**
Aluminum	1050, 3003 and 6061 to 4047 are OK. Continuous wave welding increases weldability of alloys such as 5052 and 5082. Aluminum alloys should be tested thoroughly for crack sensitivity
Beryllium copper	Good welds. Potential safety hazard exists from the beryllium oxide fumes
Carbon steel	Good welds. Carbon content should be less than 0.12% for pulsed welding, up to 0.2% for continuous wave welding
Copper	Good welds. High energy levels required to overcome surface reflectivity unless 532 nm wavelength welding laser used.
Nickel alloys	Good welds, especially with alloys such as Hastelloy-X, Inconel 600 and 718
Nitinol	Good welds. Care needed to avoid brittleness
Phosphor bronze	Good welds
Stainless steel	304 and 304L produce excellent welds 316 and 316L are OK provided Cr/Ni ratio is greater than 1.7 303 is not recommended due to cracking tendencies. Can be matched with friendlier materials such as 304. A CW laser can be used to increase weldability. 400 series require testing for crack sensitivity.
Titanium	Good welds
Tungsten	Brittle welds

Table 1 – General material selection guidelines

5.1.1 Welding dissimilar metals

In some specific markets, for example battery and medical device manufacturing, there is an increasing need to weld dissimilar materials. The trend is also found across general manufacturing, as a way to maximize part performance as individual component material can be selected for optimized operational properties rather than compromising functional properties of a lesser material to ensure weldability.

It is important to assess the metallurgy of the weld when considering two materials to weld, as many desirable dissimilar material combinations create intermetallic regions that can cause brittleness. Brittle welds are weaker than either of the two materials in the weld. Therefore, it is critical to conduct fitness for purpose testing. When assessing if a material combination is viable for a specific application, it is important to minimize heat input and laser time on the part. **Table 2** provides general guidelines on dissimilar material selection

Material 1	Material 2	Comments
Aluminum	Cold rolled steel	Can be bonded; brittle intermetallics are created at the interface. Fitness for purpose testing essential.
Aluminum	Copper	
Stainless steel	Nitinol	
Stainless steel	Titanium	
Stainless steel	Inconel	OK with certain alloys (304 with 600/700), need to watch for cracking. When welding, offset into the steel to promote high Cr/Ni ratio in weld metal
Stainless steel	Copper	OK
Copper	Phosphor bronze	OK
Titanium	Aluminum	OK with certain aluminum alloys (1xxx & Ti-6Al-4V)

Table 2 – Dissimilar material selection guidelines

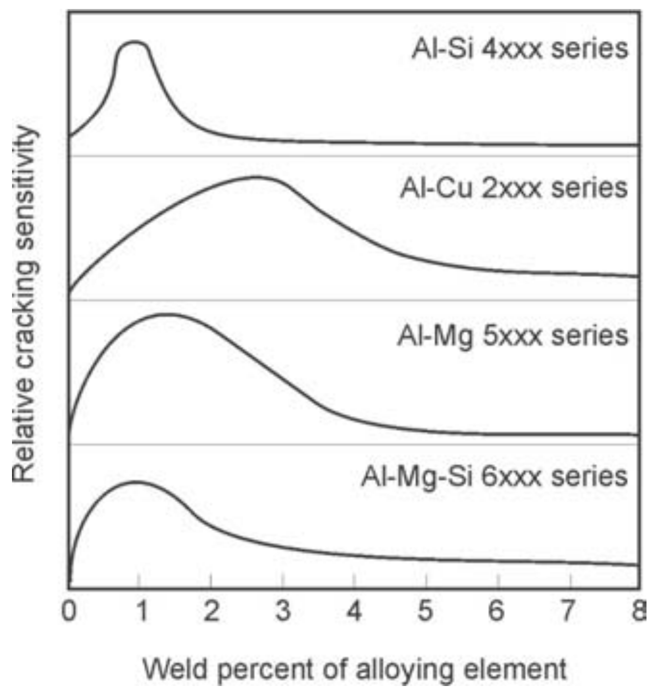
Welding different alloys within the same family of metal should also be considered as dissimilar welding – and approached with the same caution. The common families are stainless steel and aluminum.

Welding stainless steels within the 3XX series is generally successful, but it is worth noting that 303 and 316 are problematic materials. Because 303 is a free-machining steel containing sulfur, it is poor for welding, causing cracking and porosity. However, pairing it with 304L can produce a weldable combination – providing the mixing ratio favors the 304L. This can be further mitigated by using a CW rather than pulsed laser, as the CW laser reduces the thermal cycling of the parts.

For the 316, the final chromium/nickel ratio of the weld material must be greater than 1.7 to ensure reliable welds devoid of cracking. Again, the use of a CW laser helps in welding of 316.

Welding the 4XX series can be problematic, due to its carbon content and the other alloying elements for ferrite stabilization. However, welding is generally helped by welding to 3XX steels.

Welding different aluminum alloys can be considered dissimilar material welding, due to the large differences among these alloys. The important factor is ensuring that the percentage of the alloy elements in the weld does not promote cracking. With electronic packages, seam welding is routinely completed between 6061 and 4047 aluminum alloys, because the level of Silicon (Si) in the 4047 moves the overall alloy percentage into the safe 7-8 percent range. **Figure 25** shows how the percentage of the alloy element relates to cracking sensitivity.



Alloy	3003 (Al-Mn)	5052 (Al-Mg)
Key alloying element	Mn 1-1.5%	Mg 2.2-2.8%
Weld % of key element	1.1 – 1.4% Mg	

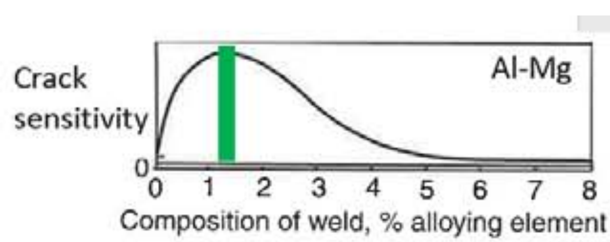


Figure 25 – Alloy elements and cracking sensitivity

Joining two different aluminum alloys that are each weldable must be undertaken with an understanding of the final alloy composition. For example, when two weldable alloys such as 3003 and 5052 are welded together, they are prone to cracking.

5.1.2 Plating

Plating material, thickness, and method of plating can each have a significant effect on the welding process, particularly micro welding.

For example, tin and nickel are the materials most commonly used for plating. Nickel is generally preferable to tin because tin's low boiling point creates significant weld spatter. Note when welding

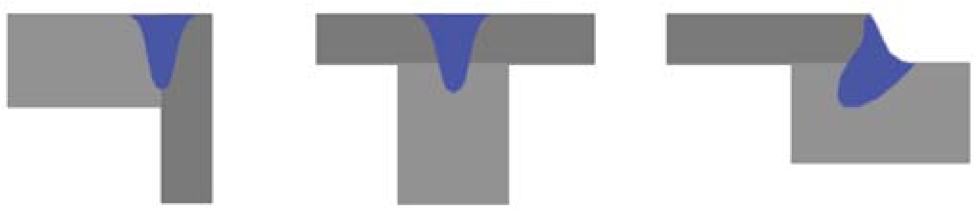
300 stainless steel with a nickel coating, there must be sufficient weld volume to dilute the effects of the nickel on the chromium to nickel ratio, which must be maintained above 1.7 for reliable crack free welding. In certain applications gold is plated on top of the nickel. In this case, a gold coating thickness above 50 micro-inches may induce weld cracking.

The plating method also has an effect. Electro-less plating creates welding problems, due to the inclusion of phosphor and other contaminants during the plating process. An electrolytic plating method is recommended.

The effect of the plating on the weld also depends upon the application. For example, there can be no plating in the weld area when hermetic welding aluminum packages. However, kovar and stainless steel can be sealed with an electrolytic nickel plating.

5.2 Joint design and fit-up

Laser welding is a non-contact process that requires only single-sided access, so a wide range of joints geometries can be welded. The most common weld joint designs are shown in **Figure 26**. Most other types used are a variation of these.



Butt *Lap / Tee/ Stake* *Fillet*

Figure 26 – Common weld joint designs

The most significant requirement for reliable laser welding is a close fit-up at the joint interfaces. Laser spot or seam welding is usually an autogeneous process, which means that no filler material is added during the welding process. Therefore, if the welding interfaces are too far apart, there is insufficient weld material to bridge the gap – or the weld will be undercut or under-filled. This is especially important to consider when migrating from other welding processes that use filler materials for bridging gaps between parts.

As a rule of thumb, the gap should never be more than 10 percent of the thinnest material or of the weld penetration, whichever is less. It must be stressed that gap tolerance is case-specific, and should always be fully examined and quantified by actually welding production parts. **Figure 27** shows the recommended maximum gap for different weld joint designs.

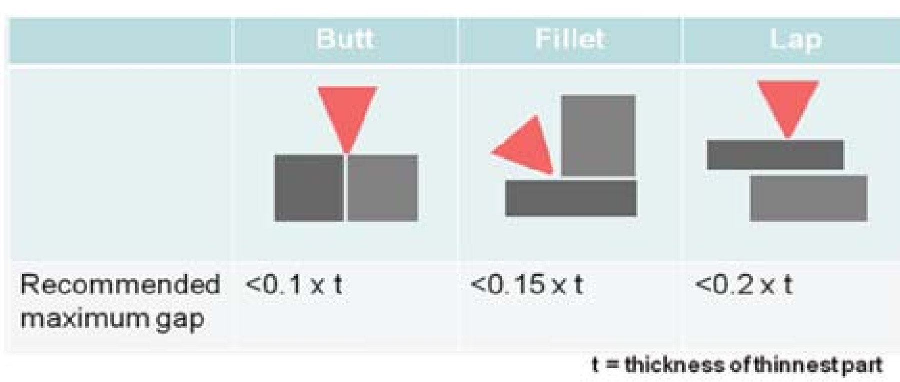


Figure 27 – Recommended maximum gap for weld joint designs

5.3 Tooling and position tolerances

The focused spot diameter for laser welding applications is typically 0.004 to 0.03 inches (100 to 600 microns). Smaller spot diameters, less than 0.004 inches (100 microns), may be required for very fine welding applications, but in this instance a lap weld should be used because alignment to a joint line is not practical. For butt and fillet joints, the position of the joint under the laser must be precise enough such that the focused spot does not miss the joint. The tolerance of this misalignment is a function of the focused beam diameter. **Figure 28** shows the relationship between fit up and spot size. As laser-joint alignment decreases, the focus spot size must be increased – in this case to maintain the same welding speed the laser power would need to be increased to maintain the same power density.

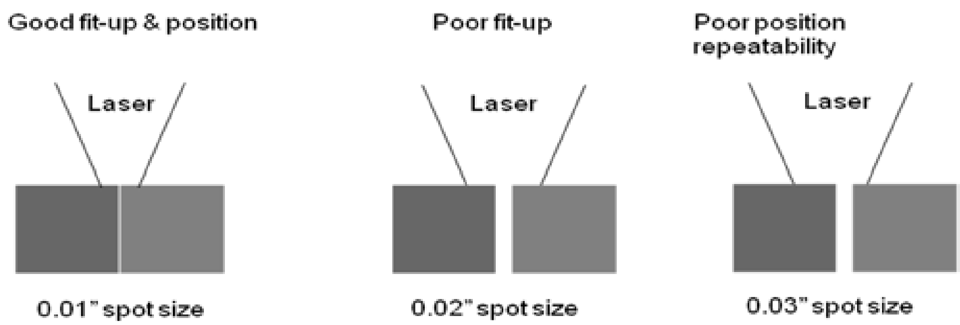


Figure 28 – Relationship between fit up and spot size

In certain cases the fit-up variance may be accommodated by superimposing motion of the beam laterally to the welding direction. This is achieved using a scan head implementing the "wobble" function. The spot size remains constant and the amplitude of the lateral motion is adjusted according to fit-up. **Figure 29** shows a schematic of a single mode fiber laser and scan head that would enable the tailored weld profiles shown in the photos below the diagram.

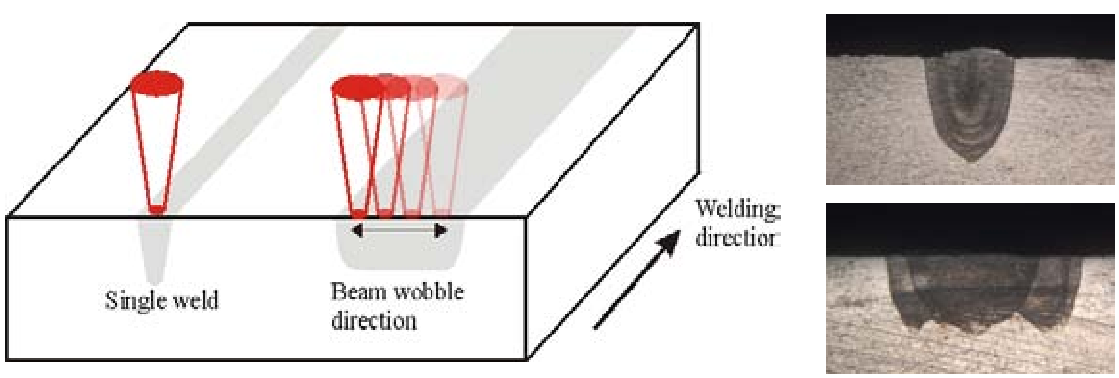


Figure 29 – Schematic of single mode fiber laser with and without wobble
Note that linear weld speed was the same for both

In addition to accommodating part fit-up, the wobble technique can be used with single mode lasers to maximize penetration with optimized weld width using a much lower power laser than would normally be required.

Not only is the distance between the interfaces important, so too is the geometry of the interfaces themselves. For example, particularly in micro welding, the tolerance is maximized if the interface edges have no radius or chamfer at the edges.

In addition to part fit-up and tracking of the weld seam, maintaining the distance from the focusing optics to the workpiece (known as the working distance), is also important. When troubleshooting production systems, it is common that the root cause of an issue is not knowing where the position of focus is, and not having a means to verify this position. The process depth of focus that defines the working distance tolerance is determined by the optics and laser used. Using longer focal length focusing optics increases the depth of focus, and at the same time increases the focus spot size. Therefore, there is a balance between maximizing the depth of focus and enlarging the spot size too much. For micro welding the depth of focus can be as little as ± 0.008 inch (0.2 mm) whereas for penetration welds ± 0.03 inch (0.75 mm) is typical.

The processing depth of focus should be established by experimentation. As a rule of thumb, this tolerance is nominally about 0.5 percent of the lens focal length. Therefore, when a 4 inch (100 mm) focal length lens is used, the depth of focus is around 0.02 inch (0.5 mm).

Figure 30 shows how the working distance tolerance relates to the processing depth of focus with different focusing lenses. To accommodate a larger tolerance, a longer focal length is needed. This leads to an increase in focus spot size and slower welding speeds.

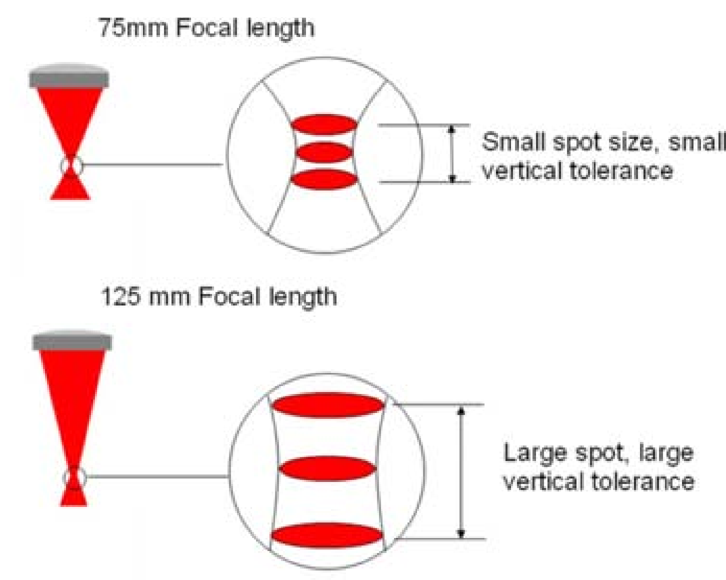


Figure 30 – How tolerance to working distance relates to processing depth of optics and focal length

Tooling is a key factor in laser welding, and access of the laser to the weld must be considered when designing tooling. The converging beam has a cone angle that can be used to model the laser access to avoid any possibility that the laser might clip the tooling. The cone angle is controlled by the focal length of the focus lens. Longer focal length provides smaller cone angle and more accessibility. Typical cone angles are 2-10 degrees. **Figure 31** is an example of the cone angle.

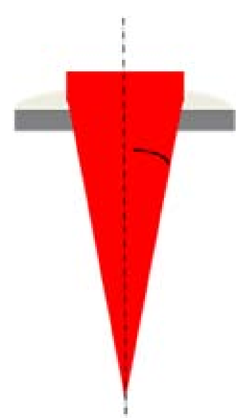


Figure 31 – Cone angle

The term pulsed parameters applies here to both pulsed and modulated/gated lasers, as described in Section 3.1. The weld created by each pulse is determined by the peak power density and duration of that pulse. Important laser parameters are defined as follows:

Peak power – This is a direct parameter that can be set on the laser, and defines the maximum power of each pulse. The units of peak power are watts (W).

Pulse width – The pulse width is the duration of the laser pulse. The units are milliseconds.

Pulse energy – The pulse energy is the energy contained within a pulse. It is the product of peak power (P_p) and pulse width as depicted in the equation $E = P_p \times t$. The units of pulse energy are joules (J).

Pulse repetition rate

The pulse repetition rate equates to the number of pulses per second, which can be expressed in units of Hz or pps.

Average power

This applies when more than one pulse is used, for example for seam welding. It represents the power averaged over the period of the pulse, and is the product of the pulse energy and the pulse repetition rate (frequency). $P_{ave} = E \times Hz$. The units used are watts (W).

Optical spot size

The optical spot size is the diameter of the focused laser spot on the work piece. Note that this is not the same as the weld width, which in the majority of cases is larger than the optical spot size. *See Section 4.3.1 for more details.*

Figure 32 illustrates these relationships, with a top surface view of a single spot weld.

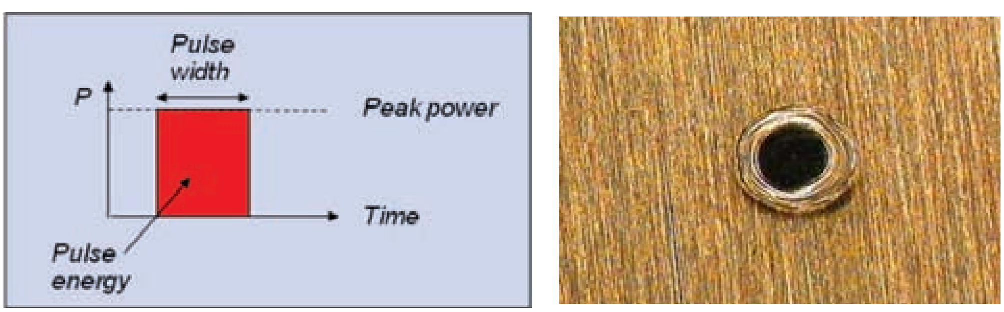


Figure 32 – Relationship between peak power, pulse energy, pulse width

Figure 33 shows the laser pulse's important parameters, which include peak power, average power, pulse width, pulse energy, and frequency or pulse repetition rate. The accompanying photo shows the surface of the weld and how the seam is comprised of individual overlapped spot welds.

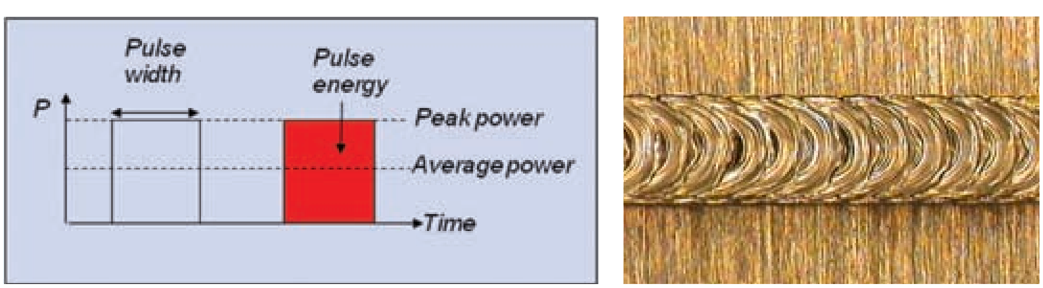


Figure 33 – Laser seam parameters

6.2 Optimizing peak power and pulse width

For both pulsed and modulated/gated welding the peak power and pulse width are the key parameters to optimize.

- The peak power is the main parameter for the weld, and is used to control penetration
- Pulse width is a fine tuning parameter that is used as a fine adjust to penetration and weld width, as well as stabilization of the weld if needed
- The pulse repetition rate or pulse frequency controls the heat into the part and thermal heat cycle for a seam weld.

Figure 34 shows the effects of increasing pulse width and peak power on weld dimensions.

Peak power	Pulse width		
	2 ms	4 ms	7 ms
0.25 kW			
0.5 kW			
0.75 kW			
1.0 kW			
1.25 kW			

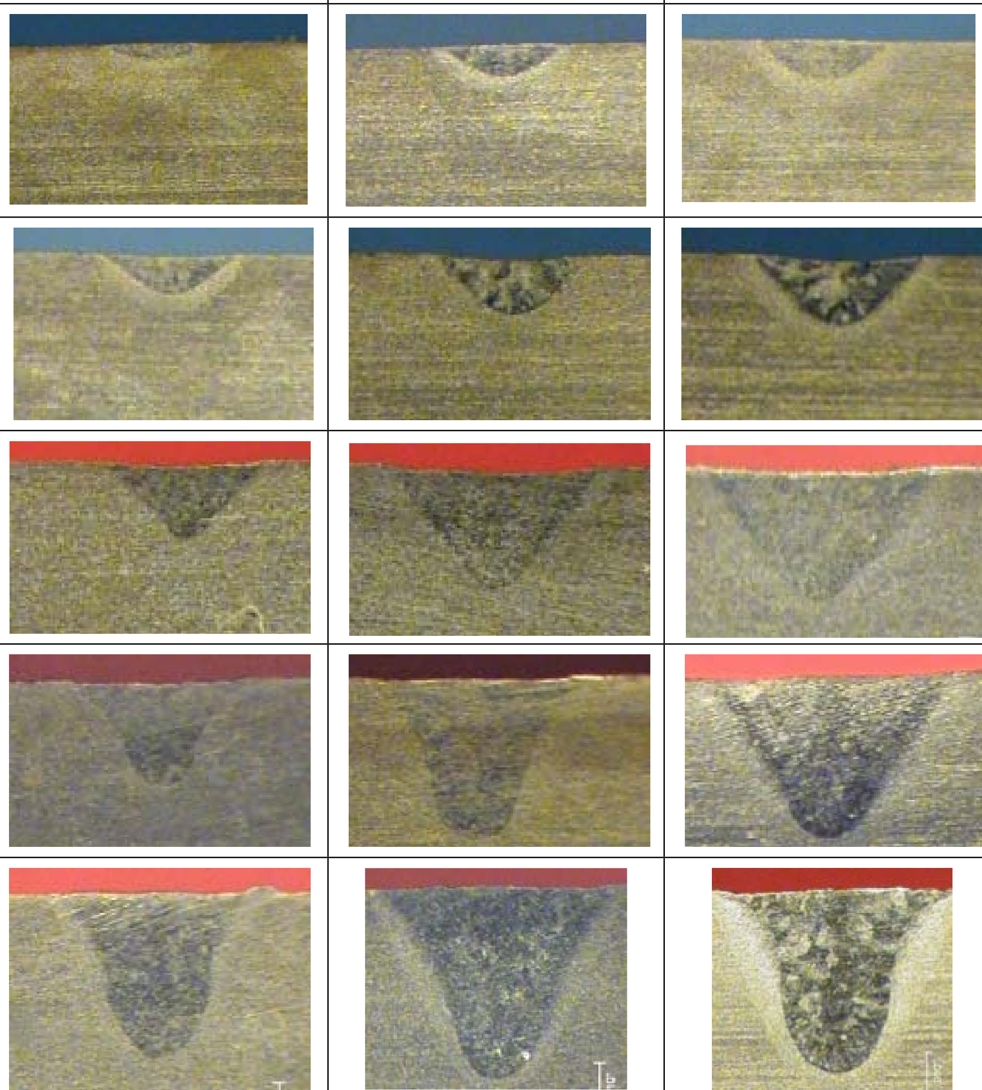
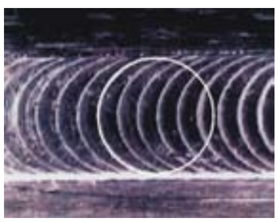


Figure 34 – Effect of pulse width and peak power on weld dimensions

Increasing the pulse width increases the weld dimensions and heat affected zone through increased heat conduction time. Optimum peak power is defined as the peak power that creates the deepest penetration at a given energy without material expulsion. Welds made with high peak powers exhibit narrow deep welds that exert a high thermal cycle on the weld material. To increase weld width, reduce the thermal cycling, and minimize depth variation, the pulse width can be increased to introduce a more conduction-based welding mechanism.

6.3 Seam welding

Seam welding involves placing a series of spot welds on a part with a specific physical separation. Seam welding parameters include the pulse repetition rate, measured in pulses per second (Hz) and the linear part travel rate or welding speed. The weld spot to spot overlap percentage is defined by the percentage of the previous spot that is covered by the subsequent one. For hermetic or seam seal welding, this is typically 80-90 percent. For strength-only welds, about 60-70 percent is more common. The spot overlap percentage is a function of speed, pulse repetition rate and focused spot diameter. **Figure 35** shows the relationship of spot diameter, welding speed and pulse repetition rate.



Spot overlap = welding speed/spot diameter x pulse rep rate

Figure 35 – Spot overlap example

The effective seam penetration is a function of the weld spot overlap. Increasing overlap percentage provides a penetration closer to the maximum penetration of the spot. **Figure 36** is a schematic representation of spot overlap versus effective penetration depth for various overlap percentages.

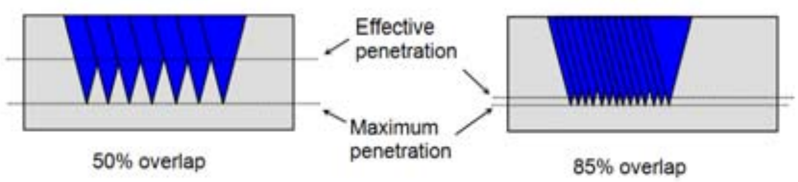


Figure 36 – Schematic of spot overlap vs effective penetration

For example, for a spot diameter of 0.005 inch, and an overlap of 50 percent, with a pulse repetition rate of 10 Hz, the welding speed is shown by the following formula:

Welding speed = 0.005 x (1 – 0.5) x 10 = 0.025-inch/second

6.4 Pulse shaping

In pulsed or modulated/gated welding, most welding applications use a simple square pulse shape, as shown on **Figure 37** (a). A square pulse is defined by the natural ramp up and down of the laser. This is a step function and so the natural pulse from the laser is called "square."

However, there are applications in which the use of programmed pulse shaping can enhance welding. There are numerous pulse shapes available, though two basic pulse shapes are most commonly used. The first is used to increase stability when welding aluminum. The second is used to minimize the thermal cycling experienced by the part during welding, especially for materials susceptible to cracking; to reduce weld porosity; or to improve the weld's visual appearance.

In **Figure 37** (b), a high leading edge enables the laser to initiate the weld in aluminum; once molten, the pulse reduces the power so the weld is not overheated. In **Figure 37** (c), the first 30-50 percent of the pulse contains the energy for welding, the second part controls the cooling rate of the weld to prevent cracks, reduce porosity, or improve weld appearance.

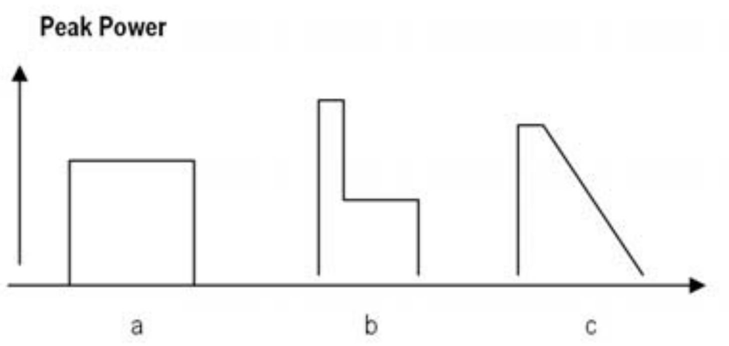


Figure 37 – Pulse shaping

6.5 Pulsed laser weld examples

Figure 38 shows examples of the many materials and parts that can be laser welded.

		
Seam sealing RF packages	***Medical tool assembly***	***Battery can seam seal and tab welding***
		
Electrical connections	***Seam sealing medical implantable devices***	***Implantable medical device seam sealing***

Figure 38 – Laser welding examples

7.1 Introduction

As noted in Section 3.1, continuous wave (CW) operation means the laser is turned on and remains on until turned off. The maximum output power from a CW laser is the same as its average power. Therefore, a 1 kW CW laser can only ever output 1kW maximum power. This contrasts with the pulsed laser, which can output a power many times its average.

A CW laser is used for speed and penetration, as opposed to the pulsed laser discussed in Section 6, which is primarily used for finesse applications. CW mode lasers can be either fiber or diode and can be used in either keyhole/penetration or conduction mode, as described in Section 2.

7.2 Keyhole/penetration welding

As discussed in Section 2, if the laser's power density is increased above 106 watts per cubic meter (W/cm^2), the laser heats the material beyond its vaporization point, leading to the creation of a vaporized element known as a "keyhole" that penetrates into the work piece. The keyhole provides two key processing conditions. The first is that it enables almost 100 percent absorption of the laser power (irrespective of absorption of the solid metal). The second is that the keyhole acts like a conduit, similar to a light pipe, delivering laser energy efficiently into the material.

The keyhole mode's high efficiency in creating depth can be used across the weld depth range. Examples include high speed welding of thin battery tabs, or much deeper welds for many automotive power train components, such as gearboxes and torque converters.

Figure 39 provides a closer look at the process, including the welding plume, fluid flow of the molten metal, and keyhole stability. It also indicates the elements of the keyhole/penetration welding process, including arrows in the melt pool depicting fluid flow and in the keyhole depicting vapor pressure.

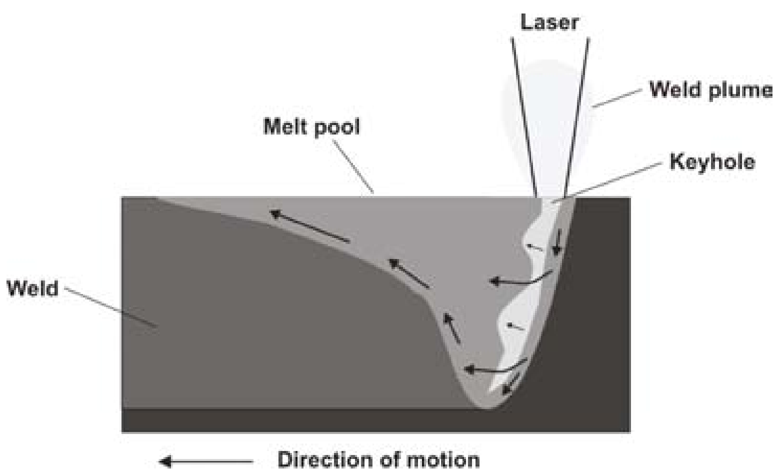


Figure 39 – Keyhole welding process and elements

Keyhole welding is a balance between fluid forces of the melt pool and the vapor pressure of the keyhole. It is worth noting that this is a highly dynamic situation, with the keyhole changing shape rapidly. Reliable welding is achieved when the balance is stable, albeit with local variances.

7.3 Continuous wave laser parameters

With CW lasers, the three laser parameters of concern are optical spot size, beam quality and power. The first and last of these are most familiar, but being able to select specific beam quality with resolution, rather than simply Gaussian or flat top, is a newer concept.

7.3.1 Optical spot size

CW lasers do not have the high peak powers of the pulsed laser, so the optical spot size is smaller to ensure sufficient power density for welding. In most welding applications an optical spot size of around 0.003-0.015 inch (0.05-0.3 mm) is used. When really small spot sizes are needed, a single mode laser may be used that can provide an optical spot size of around 0.001 inch (0.025 mm).

7.3.2 Selectable beam quality

Beam quality, also called the M^2 number, refers to how efficiently the laser can be focused and defines the power density cross section distribution through the beam. Simply put, the M^2 value is a comparison of the laser to that of a perfect laser with a pure Gaussian mode.

The single mode and multi-mode laser, defined in Section 1.4.2.3, are at the two ends of the M^2 spectrum. A "perfect" laser has an M^2 value of 1, the single mode laser has an M^2 of 1.1-1.3, and the multi-mode lasers have an M^2 value larger than 2.

One may ask the question, "Wouldn't a more perfect beam always be better?" The answer is "No!" In laser welding, increased penetration and speed are directly related to better beam quality. However, weld stability and part or position tolerance accommodation favor lesser beam quality. Therefore, for any given manufacturing process, users must find a balance between welding performance, the quality of the weld, and the size of the process window. It should be noted that there is always the option to reduce the quality of the beam to match the application, but it is impossible to increase the quality of the laser once it has exited the laser generator.

The two extremes of beam quality for a single and multi-mode laser can be seen in **Figure 40**. All welds are shown in 0.06-inch thick stainless steel – (a) represents a 500 W single mode fiber laser with an M^2 value of 1.2 at 300 inches per minute (IPM) with a 30 micron spot size; (b) shows a 700 W multi-mode laser with an M^2 value of 15 at 100 IPM with a150 micron spot size; and (c) shows a 1 kW multi-mode fiber laser with an M^2 value of 15 at 80 IPM with a 250 micron spot size. There is no doubt that the penetration and speed of the single mode laser is impressive. However, this would be restricted to lap welding geometries of parts that need connectivity over mechanical strength. From an economic viewpoint, using a lower powered laser is always the goal, because the lower capital expenditure provides a greater return on investment (ROI).

(a) *(b)* *(c)*

Figure 40 – Beam quality effect on weld for a single-mode and multi-mode laser

For small spot micro welding, the required weld diameters are typically under 100 microns (0.004 inch), and a high beam quality is essential. In many cases, these applications require a focused spot of around 30 microns (0.0012 inch), which precludes lower beam qualities.

7.3.3 Laser power

Power is one of the primary laser parameters for CW lasers. This section offers a general guide on the effect on weld dimensions of increasing power along with power versus speed. The data is provided for reference only, and has been selected using commonly used optical setup and beam quality values for these types of welds.

7.3.3.1 Single mode fiber laser welding

The single mode fiber laser enables extremely high power density, which can be used to weld highly reflective materials with relatively low average powers. For example, in **Figure 41**, the left graph shows penetration and speeds for aluminum and the lower graph shows the same relationship with copper, using a 500 W single mode laser.

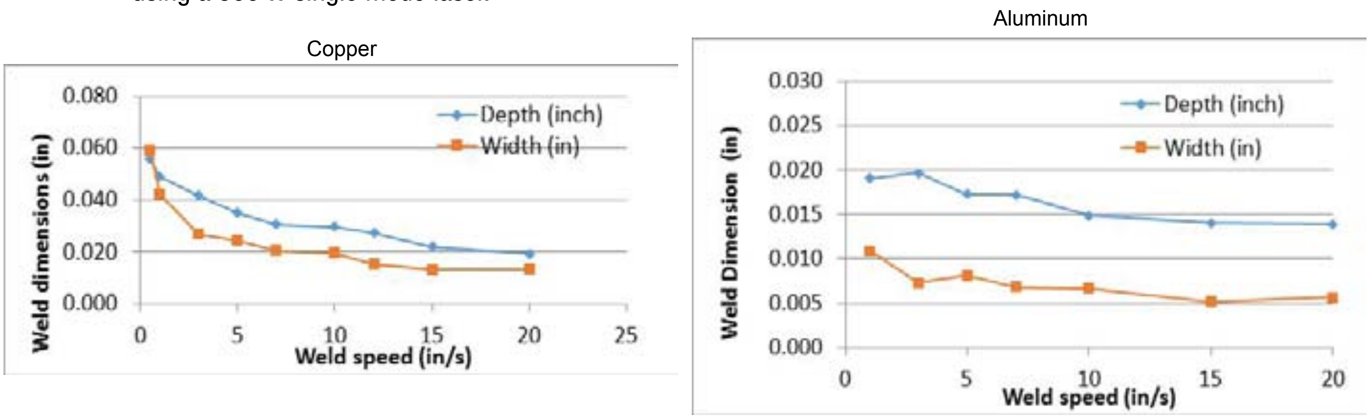


Figure 41 – Penetration/speed for aluminum and copper

Table 3 compares the power density of a multi-mode versus a single mode laser. Before single mode lasers, welding of aluminum or copper required high power multi-kilowatt laser powers. The single mode laser has made welding both aluminum and copper accessible using only a 500 W laser, while maintaining good welding speeds. The table shows the reason for this – the single mode laser provides extremely high power densities. The very high power density also appears to provide an interesting effect – with increasing speed, seen above in both aluminum and copper in **Figure 41,** there is a power density threshold value above which weld dimension are largely independent of welding speed. This provides exceptional processing capability when lap welding thin materials, such as battery tabs or fuel cell laminates.

Laser power	Mode	Focus spot size	Power density
500 W	Single mode	25 microns	102 MW/cm^2
10000 W	Multi-mode	150 microns	56 MW/cm^2

Table 3 – Comparison of multi-mode versus single mode laser

In **Figure 42**, we see a cross section of a 500 W single mode laser welding through 0.015 inch thick copper into steel at 600 IPM. Note the angled weld; the head is angled to prevent any issues with back reflection.

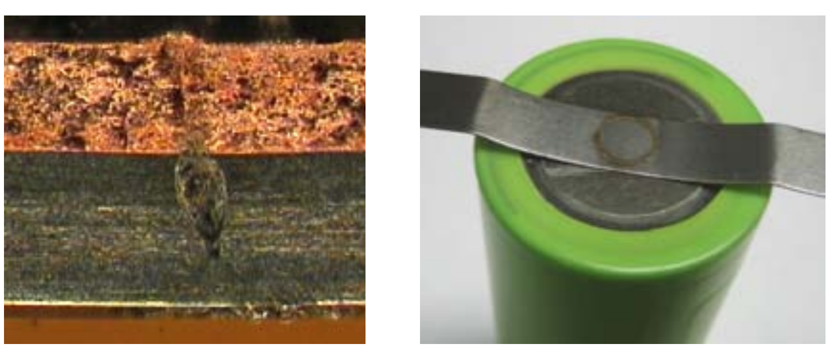


Figure 42 – Single mode laser welding through copper into steel

7.3.3.2 Multi-mode fiber laser welding

Many welding applications require weld dimensions and production fit-up tolerances that align with a multi-mode laser. Power levels for single mode fiber lasers are generally limited to around 1kW due to the maximum size of a single module. In contrast, multi-mode lasers can be made from combined modules and typically range from 500 W up to 8000 W. The multi-mode laser can provide single pass penetration to 0.5 inch. However, most weld depths are in the range of 0.04-0.25 inches.

Figure 43 shows the bead on plate welding data for a 5 kW fiber laser with 333 micron spot size.

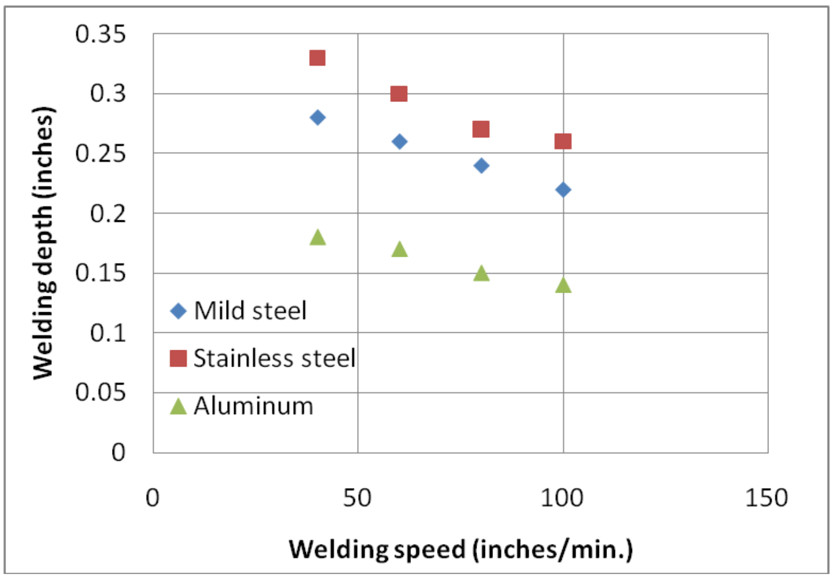


Figure 43 – Bead on plate welding data

Figure 44 shows the cross sections of penetration and speed data for 3 and 5 kW fiber lasers. The multi-mode laser shows a similar effect to that of single mode lasers; as speed increases, penetration is reduced only a small amount, while weld width reduces as conduction times are reduced with more speed.

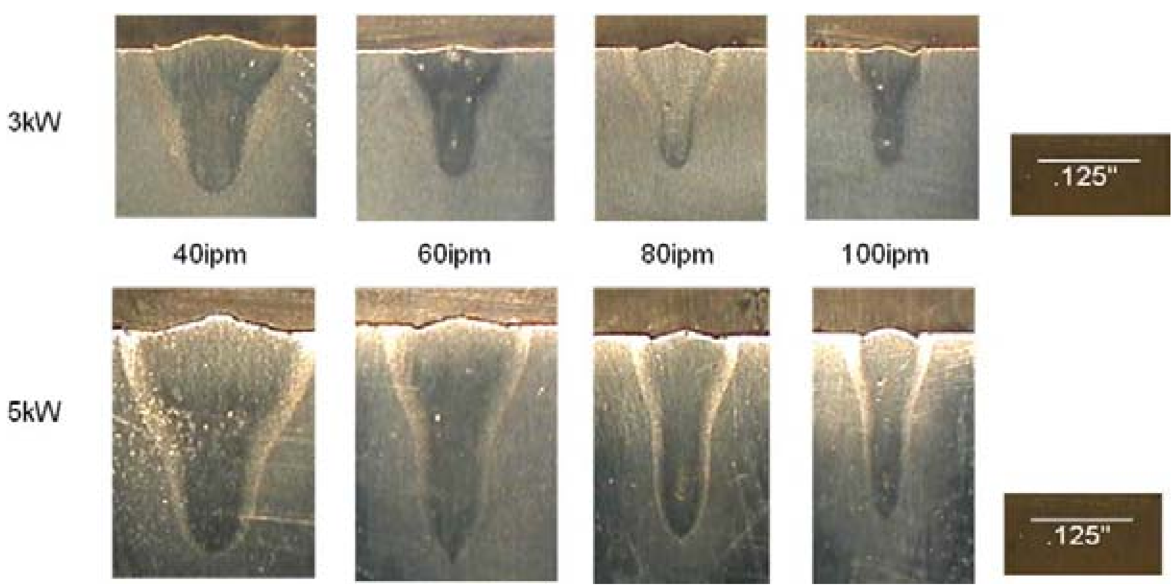


Figure 44 – Cross sections of penetration and speed for 3 and 5 kW fiber lasers

7.3.3.3 Direct diode laser welding

Direct diode laser welding is comparable to fiber multi mode welding in terms of welding performance. **Figures 45 and 46** show welding of stainless steel and aluminum. **Figure 45** shows penetration data on stainless steels at different power levels. Optical spot size is around 0.008 inch (200 microns).

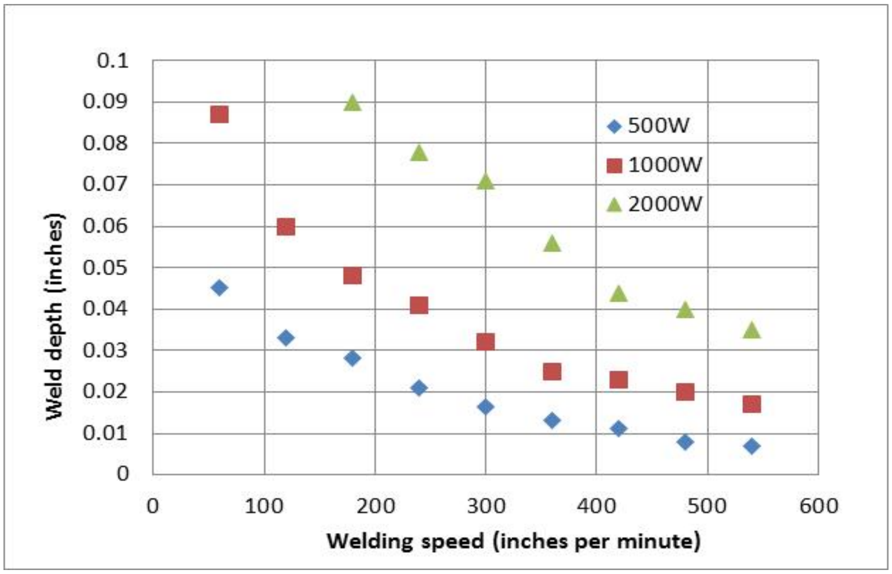


Figure 45 – Diode laser welding of steel

Figure 46 shows penetration data on 5xxx aluminum at different power levels. Optical spot size is around 0.008 inch (130 microns). It is worth noting that even at 500 W and a 130 micron spot size, the diode laser is still able to couple into aluminum.

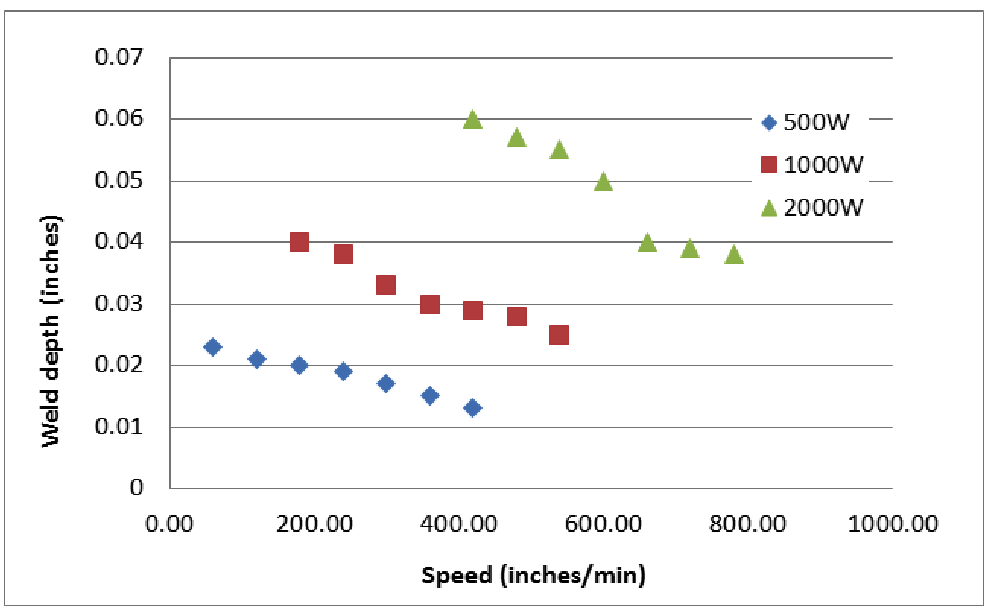


Figure 46 – High speed laser welding of aluminum with a 2kW diode laser

7.4 Examples of CW laser welding

Figure 47 shows a variety of examples of CW laser welding.

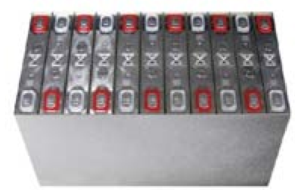
		
Part fabrication	***Automotive crank case***	***Large battery can seam seal and tab welding***
		
Automotive steering column	***High speed seam welding of air bag initiators***	***High speed battery tab to terminal***

Figure 47 – Examples of CW laser welding

7.5 Conduction welding

7.5.1 Introduction

Conduction welding, as described in Section 2, occurs at much lower power densities than that of keyhole welding. In contrast to the dynamic nature of keyhole welding, conduction welding offers an extremely stable welding option. Conduction welding is most often called for by the need for aesthetic qualities or to avoid the particulate that is generated by keyhole welding. When used on stainless steel, the resulting conduction weld has a very smooth and highly aesthetic appearance, which can be used on an external part surface. In battery welding seam sealing, some manufacturers use conduction welding to ensure that no particulate can enter the battery internal volume.

Figure 48 shows a conduction weld on a pressure sensor using 500 W at a speed of 4 IPS.

Figure 48 – Conduction welding

An assist gas may be used in laser welding for a number of reasons. The specific gas type and delivery method is determined by the application and power level.

8.1 Providing an inert environment

The need to prevent oxidation and maintain the liquid metal in an inert atmosphere may be required depending upon the material being welded – or simply to provide an aesthetic shiny weld. Certain materials, such as titanium and Inconel, require shielding for weld quality. However, other materials, such as stainless steel, typically do not benefit from an inert environment for weld strength. Particularly in micro welding the use of an assist gas is used primarily to create shiny aesthetic welds.

The gas used must be inert (either fully or partially), and must be heavier than air to be able to displace air efficiently. Argon and nitrogen are the most commonly used gases in welding processes. Helium is occasionally used for critical penetration welds. To simply provide an inert environment for the weld, the gas is directed at low pressure and low flow volume into the weld zone. A key requirement of the gas delivery mechanism is that it provides a laminar flow that does not create turbulence that may draw in surrounding air. **Figure 49** shows a long tube that promotes laminar flow delivering argon to the weld area for oxidation protection.

Figure 49 – Tube promoting laminar flow of argon

For welds under 0.04-inch weld depth, the gas type selected has little effect. However, increasing penetration favors nitrogen over argon to reduce weld porosity.

Figure 50 shows two welds completed at the same processing conditions: 500 W at 0.5 inches per second. Argon was used in the left hand picture and nitrogen was used on the right. Although a cross section captures a small part of the weld the lack of porosity when using nitrogen was seen consistently between the two assist gas types. Also a coaxial nozzle can be used to provide omni-directional coverage for penetration welds that require x and y motion.

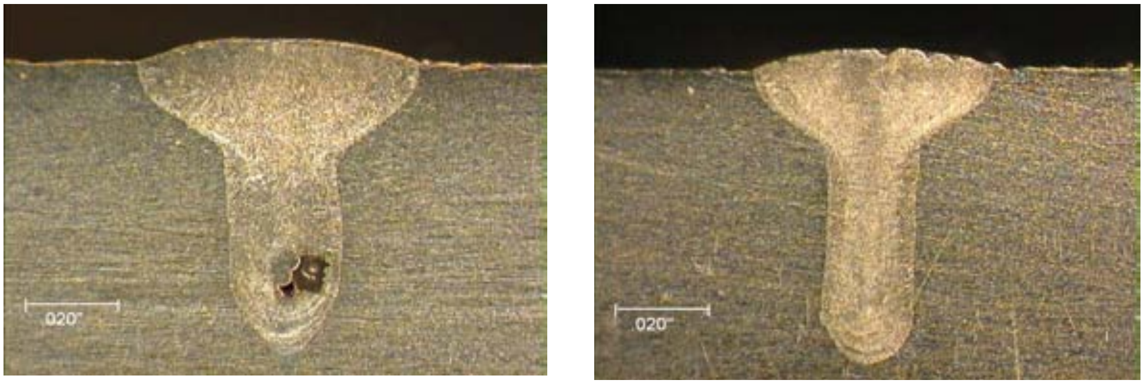


Figure 50 – Welds using argon (left) and nitrogen (right) on stainless steel

8.2 Reduce beam blocking

With increasing laser power beyond 1000 W, and particularly for multi-kilowatt welding, the laser tends to be blocked and/or de-focused by ultra fine particles generated from the creation of the keyhole. The use of a cross flow jet pushes the particles out of the direct beam path to the weld point and so minimizes the attentuation effect. In high power welding, the cross jet is typically clean dry air and is positioned above the weld so it does not interfere with the inert gas coverage around the weld. For shorter focal length optics this function may also be provided by the air knife described in Section 8.3. **Figure 51** shows use of a cross jet to reduce beam blocking.

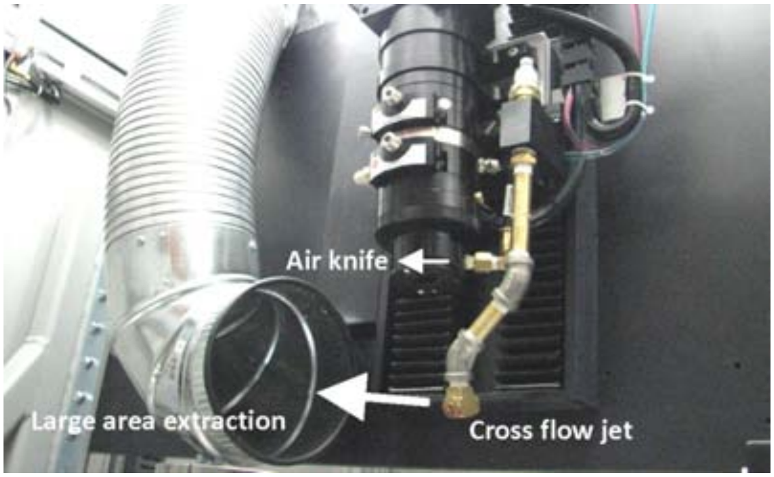


Figure 51 – Cross jet reduces particulate beam blocking for multi kilowatt welding

8.3 Protecting laser optics

Fumes are generated during the welding process. At low penetration levels – under 0.02 inch (0.5 mm) – these fumes are relatively light, and the use of assist gas helps redirect the fumes away from the focus head, extending the time between cover slide cleanings. When penetration increases and/or when keyhole welding aluminum, the use of a high pressure cross flow jet or air knife positioned immediately below the cover slide prevents any weld fumes attaching to the cover slide and helps deflect spatter away from the central part of the cover slide. It is worth noting that the best defense against weld spatter is to maximize focal working distance, rather than relying on an air knife.

The implementation of assist gas for welding can be critical, and when optimizing a weld this should be carefully selected.

Summary

This document should be used as a guide to provide the knowledge necessary to make informed decisions on laser welding. It can be used to help optimize current production processes and educate those new to the process. Users should always work with companies knowledgeable about the fine details of laser welding to provide a manufacturing solution optimized for specific production requirements.

Autogeneous process – No filler material is added during the welding process.

Beam quality – Also called the M^2 number, refers to how efficiently the laser can be focused and defines the power density cross section distribution through the beam. The M^2 value is a comparison of the laser to that of a perfect laser with a pure Gaussian mode.

Butt joint – a joint geometry in which two pieces of material are placed side by side and the weld is made at the interface between the two materials.

Collimating lens – An optic in the focus head, which transforms the diverging laser into near parallel/ collimated light.

Conduction mode – Welding performed at low energy density, typically around 0.5 MW/cm^2, forming a weld nugget that is shallow and wide. The heat to create the weld into the material occurs by conduction from the surface.

Continuous wave (CW) laser – A laser that produces extended output – the laser remains on continuously until stopped.

Diverging beam – Defined as a laser that is increasing in size with distance; occurs when using a connectorized fiber, either QBH, LLK-Q, or another type.

Fillet joint – A joint geometry in which the materials are placed one on top of another. The weld penetrates the top layer into the second layer, creating the weld.

Focus head – Directs and focuses the output from the laser delivery fiber onto the work piece.

Gallium arsenide (GaAs) – Medium most commonly selected for high power diode laser.

Gated or modulated output – A CW laser that produces pulses of light output. The peak power does not exceed the laser's rated average power.

Gaussian mode – Defines the power distribution in the laser cross section that has a maximum at the beam center which drops away similarly to a bell curve to the edges.

Keyhole or penetration mode – Occurs when peak power density is increased beyond 1.5MW/cm^2. Characterized by deep narrow welds with aspect ratio greater than 1.5.

Lap joint – A joint geometry in which the parts are placed one on top of the other and the beam is directed at an angle to produce a weld along the surface where the pieces meet.

Laser resonator – Controls how the laser is generated in the laser medium. Consists of a rear 100 percent reflector and a front partial reflector.

Multi-mode fiber lasers – Lasers that use core diameter fibers greater than 50 microns.

Optical coupler – Used to de-couple the lasing fiber from the process/delivery fiber.

Optical spot size – Diameter of the focused laser spot on the work piece. Note that this is not the same as the weld width, which in the majority of cases is larger than the optical spot size.

Optics – The general term that covers all the optical elements in the focus head, and includes the collimator lens, beam expander, dichroic mirror, focus lens and cover slide.

Optimum peak power – Peak power that creates the deepest penetration at a given energy without material expulsion.

Peak power – Parameter that directly controls weld penetration that can be controlled and programmed on the laser. The units of peak power are watts (W).

Photons (Laser light photons) – The laser is comprised of many small packets of light energy that are known as photons traveling in the same direction and in phase.

Plume – When a keyhole is formed, metal vapor is ejected above the melt pool. This acts to ionize the surrounding gas, which can be observed as a white plume above the weld.

Power ramping – Increasing or decreasing the laser power at the start of the weld and at the end of a seam weld.

Pulse energy – The energy contained within a pulse. Product of peak power (P_p) and pulse width.

Pulse width – Duration of the laser pulse, measured in milliseconds.

Pulsed laser – A laser that can provide a higher peak power than its average power.

Seam welding – The length of weld produced by keeping the laser turned on in CW mode or by placing a series of spot welds on a part.

Sequential firing – Also known as time share firing, refers to multiple laser outputs fired one at a time.

Simultaneous firing – Also known as energy share firing, refers to multiple outputs from a laser that all fire at the same time.

Single mode fiber laser – Refers to small core diameter fibers, between 10-20 microns, that restrict the laser to a single transverse mode that results in a power density cross section through the laser that has a high central maximum that falls off sharply.

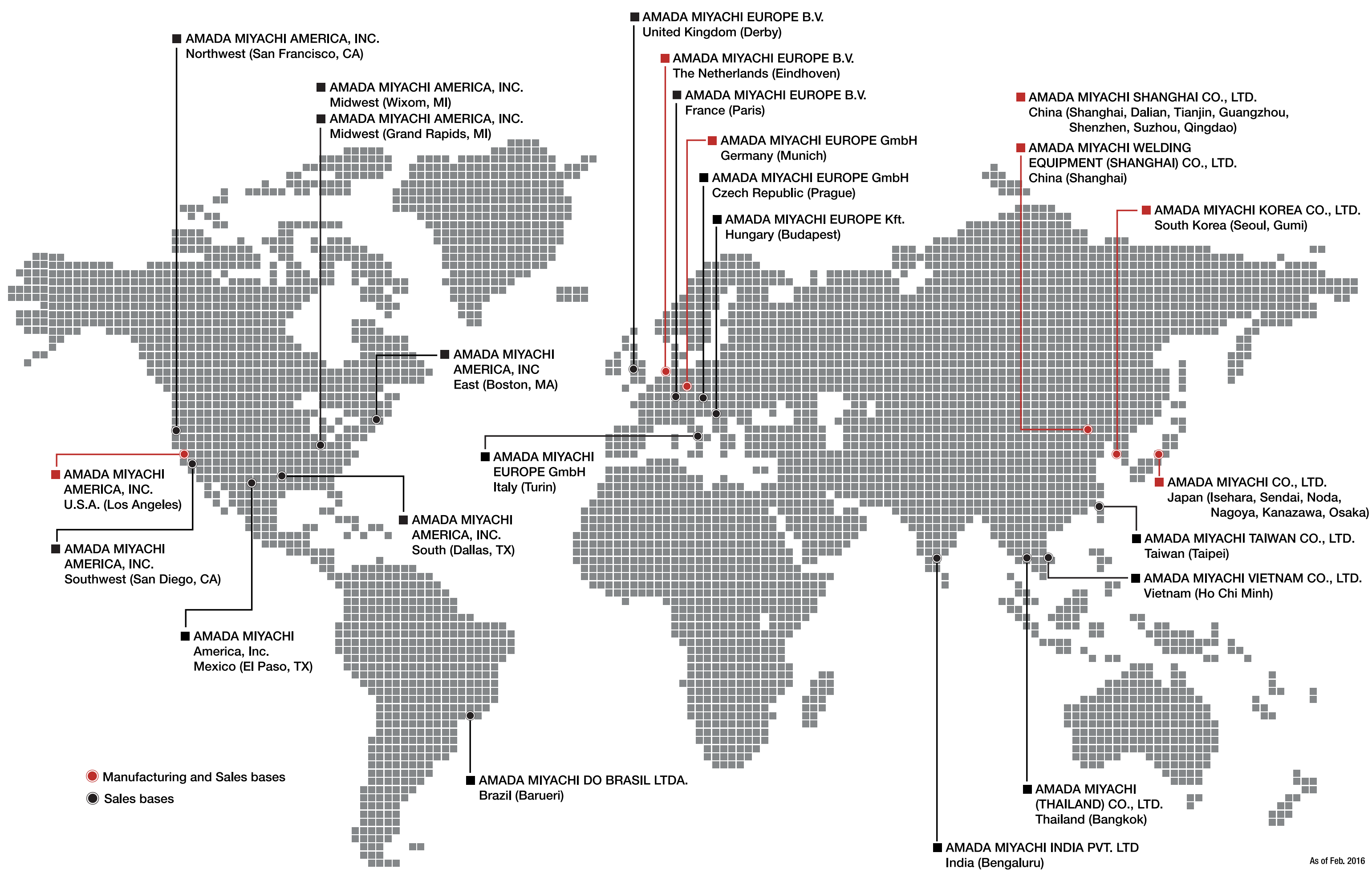
Spot to spot overlap percentage – In spot welding, percentage of the previous spot that is covered by the subsequent one.

Square pulse – Natural ramp up and down of the laser. Typically, this is a step input.

Transition keyhole mode – Occurs at medium power density, around 1 MW/cm^2, resulting in more penetration than conduction mode. This mode is used almost exclusively by the pulsed Nd:YAG laser, for many spot and seam welding applications.

AMADA

Your Global Partner



AMADA
AMADA MIYACHI AMERICA, INC.
1820 S. Myrtle Ave. • Monrovia, CA 91016 US
T: (626) 303-5676 • F: (626) 358-8048
info@amadamiyachi.com • www.amadamiyachi.com
ISO 9001 Certified Company • 24/7 Repair Service: 1-866-751-7378

MIYACHI UNITEK | MIYACHI PECO | MIYACHI EAPRO | BENCHMARK

AMERICAS

Amada Miyachi America Midwest
Wixom, MI 48393
T: (248) 313-3078
midwestsales@amadamiyachi.com

Amada Miyachi America Mexico
El Paso, TX 79925
T: (915) 881-8765
mxsales@amadamiyachi.com

Amada Miyachi do Brasil Ltda.
Sao Paulo, Brasil
T: +55-11-4193-3607
antonio.ruiz@amadamiyachi.com

EUROPE

Amada Miyachi Europe GmbH
Puchheim, Germany
T: +49 (0) 89 83 94 030
infode@amadamiyachi.eu

ASIA

Amada Miyachi Co., Ltd.
Noda, 278-0016 Japan
T: +81-4-7125-6177
sales@miyachi.com

Amada Miyachi Shanghai Co., Ltd.
Shanghai, China
T: +86-21-6448-6000
zqzhang@msc.miyachi.com

Amada Miyachi Korea Co., Ltd.
Gyeonggi-do, Korea
T: +82-31-8015-6810
dykim@mkc.miyachi.com

Amada Miyachi Taiwan Co., Ltd.
Taipei, Taiwan R.O.C.
T: 886-2-2397-4778
keigaku@miyachi.com

Amada Miyachi (Thailand) Co., Ltd.
Samutprakarn, Thailand
T: +66-2751-9337-8
info@mtl.miyachi.com

Amada Miyachi Vietnam Co., Ltd.
Ho Chi Minh City, Vietnam
T: +84-8-3771-7972

Amada Miyachi India Pvt., Ltd.
Bangalore, Karnataka
T: 080-4092-1749 & 3549
info@miyachiindia.com

follow us on:

05/16