UNITEK MIYACHI CORPORATION

Nd:YAG Laser Welding Guide

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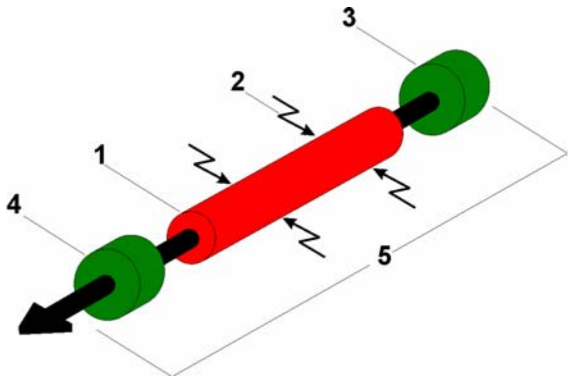
1. Laser basics

1.1 Introduction

The word “LASER” is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. The elements of a laser are –

1. Laser medium
2. Input “pump” energy
3. Rear total reflecting mirror
4. Front partial reflecting mirror
5. Resonator



There are two of types of Nd:YAG laser welders; continuous wave and pulsed. As the name suggests continuous wave or CW is either on or off, whereas pulsed lasers create welds by individual pulses. The pulsed laser utilizes high peak power to create the weld, whereas the CW laser uses average power. This allows the pulsed laser to use less energy to create the weld, with a smaller heat affected zone. This provides the pulsed laser with unrivalled spot welding performance and minimal heat input seam welding. Unitek Miyachi lasers are pulsed welders.

1.2 Principle of Laser Generation

The generation of a laser beam is essentially a three step process that occurs almost instantaneously.

1) The pump source provides energy to the medium, exciting the laser medium atoms such that electrons held with in the atoms are elevated temporarily 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 looses the excess energy gained from the pump energy by emitting a photon. This is called spontaneous emission and the photons produced by this method are the seed for laser generation.

2) The photons emitted by spontaneous emission eventually strike other electrons in the higher energy states. "Eventually" is 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 meaning they are in phase, of the same wavelength, and traveling in the same direction. This is called stimulated emission.

3) 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 mirrors define the preferential amplification direction for stimulated emission. In order for the amplification to occur there must be a greater percentage of atoms in the excited state than the lower energy levels. This "population inversion" of more atoms in the excited state leads to the conditions required for laser generation.

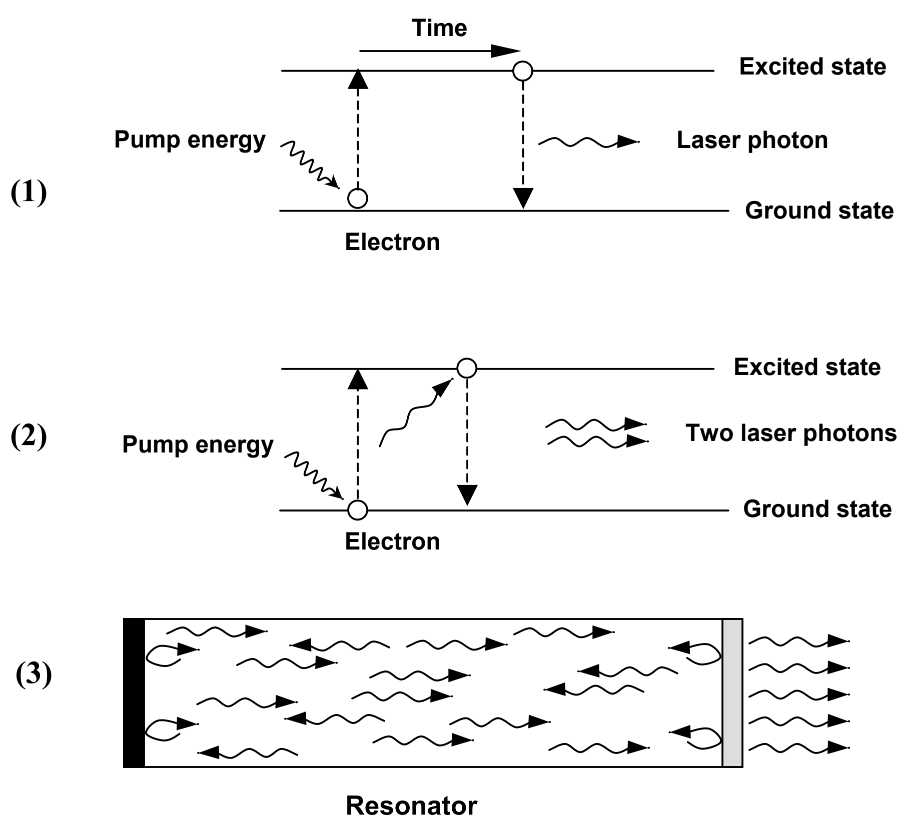


Figure B. Simplified schematic representation of the three stages to laser generation, including (1) Spontaneous emission (2) Stimulated emission (3) Amplification.

1.3 Nd:YAG laser medium

The laser rod used in Nd:YAG laser welders and markers is a synthetic crystal of **Y**ttrium **A**luminum **G**arnet. The YAG material is the "host" material that contains a small fraction of neodymium, the active element. The substitution of the yttrium ions with neodymium ions is called doping, and typically the doping percentage is around 1 – 1.5%. The doping level is selected to optimize the lasing effect and prevent excessive strain on the crystal, as the Nd^{3+} ion is physically larger than the Y^{3+} ion. The YAG crystal is an ideal host for the lasing material Nd^{3+}, being physically hard, stable, optically isotropic, and has good thermal conductivity that permit laser operation at high average power levels. Neodymium is an excellent lasing material as it produces the highest level of powers than any other doping element. The dimensions of the laser rods are selected for power and optical quality, with the maximum rod size limited to around 15mm diameter and 200mm in length for reasons of crystal quality and thermal management.

1.5 The Pump Source

The active medium requires external energy input or "pump source" in order for lasing to occur. The choice of pumping sources depends upon the type of laser medium and type of laser. The Nd:YAG is a solid state laser, meaning that the medium is a solid crystal, and it uses light energy as the pump source. The light energy is provided by flash lamps for pulsed laser welders.

1.6 Resonator

The design of the resonator has a significant impact on the quality and the spatial power distribution of the emitted laser beam. The most commonly used resonator design is composed of two spherical or flat mirrors facing each other. The beam propagation properties are determined by the curvature of the reflective mirrors, and the distance these mirrors are apart. Optimization of the mirror curvature and spacing requires complex analysis, which is further complicated by thermal effects occurring in the laser rod crystal during laser generation. As the laser absorbs the pump energy, the laser rod heats up. If the frequency of the pump energy exceeds the thermal relaxation time of the crystal, the temperature of the crystal increases. This induces temperature gradients in the laser rod crystal that give rise to thermal lensing, whereby the crystal acts as a lens to diffract the laser-which reduces power.

For a pulsed welding laser the pump cavity houses the flash lamp and laser rod. It 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.

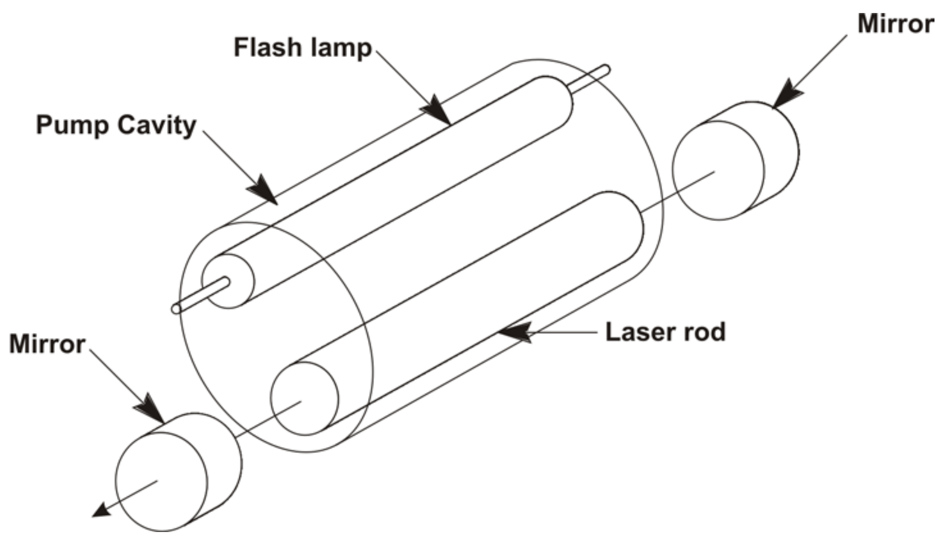


Figure C. Major components of a pulsed Nd:YAG welding laser optically pumped with a flash lamp.

1.7 Laser safety

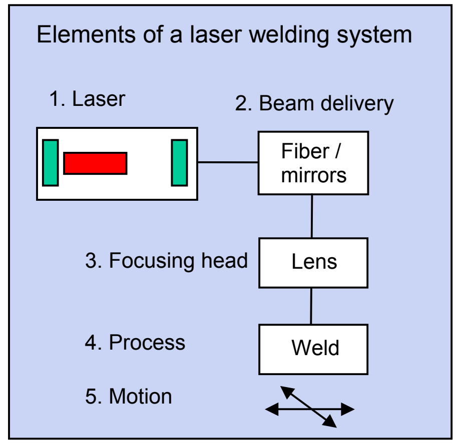
In the United States, the FDA Center for Device Radiation Hazards (CDRH) has jurisdiction over laser safety issues. In addition the Laser Institute of America offers guidelines and practices for laser safety. Aside from the nominal hazards associated with operating any piece of equipment, the main hazard associated with using Nd:YAG laser relates to direct or indirect exposure of the eyes to the laser radiation.

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 I eye safe environment. There are four levels of laser classes, Class IV to Class I, with the I being safest. A Class I eye safety is achieved by either wearing the appropriate safety goggles or containing all the laser radiation in a light sealed Class I enclosure/workstation. CDRH provides laser manufacturers and users with specific rules, standards and exposure limits for each type of laser and power level.

2. Fundamentals of Laser Welding

The pulsed Nd:YAG laser welding system comprises a number of elements –

Laser
Beam delivery
Focusing head
How a laser welds
Key welding parameters



2.1 Pulsed Welding Lasers

The laser used for welding is a flash lamp pumped Nd:YAG laser which produces a pulsed laser output. The Nd:YAG crystal is the most efficient and robust material that is available to handle the high power and heat generated within the crystal rod. In contrast to a laser marker that uses diode pumping and Q- switching, the pulsed laser welder requires a flash lamp. Diode's are unsuited for pulsing and Q-switching does not provide sufficient energy for welding.

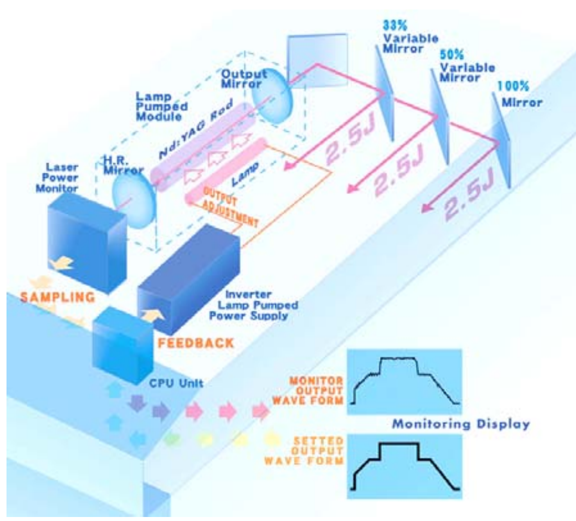


Figure D. Layout of a pulsed Nd:YAG welding laser showing the resonator and optical beam delivery components. Note the real time power feedback and the capability of energy or time sharing.

2.1.1 Real Time Power Feedback

Pulsed Nd:YAG lasers may be designed to provide a number of special features to optimize the weld process and increase reliability and repeatability for more demanding applications. Real time power feedback, through pulse width modulation of the source current, ensures excellent pulse to pulse stability and automatically delivers the same pre-set weld over the full life of the flash lamp.

2.1.2 Power Ramping

Power ramping features eliminate last pulse cracking in seam welding applications that may otherwise occur when using older laser designs. Power ramping allows the weld program to gradually increase the laser power at the beginning and end of the weld. It also provides a more cosmetically appealing weld.

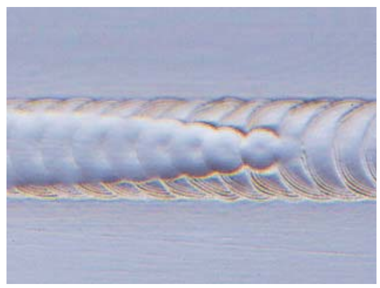
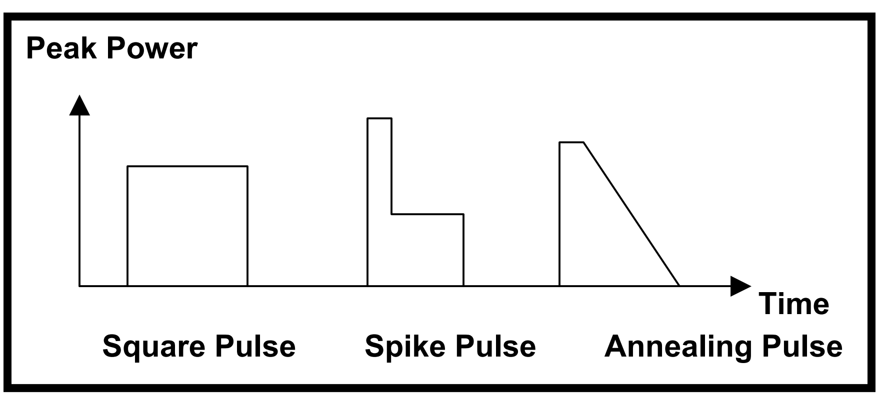


Figure E Fadeout capability on seam welds, to prevent last pulse cracking and ensure completion of smooth seam.

2.1.3 Pulse Shaping

Most welding cases use a square welding pulse as shown below. However there are a few applications where the use of pulse shaping can enhance welding. There are numerous pulse shapes, however, two basic pulse shapes are most commonly used. The first is for overcoming highly reflective material such as copper and aluminum, and the other is to minimize the thermal cycling experienced by the part during welding for materials susceptible to cracking.



Pulse Shaping Options

2.1.4 Time Share

Time share features permit one laser to be configured to deliver two or more welds to separate work pieces or separate workstations "sequentially". With time sharing, one laser can support multiple workstations using different weld schedules at each workstation. This greatly reduces laser costs.

2.1.5 Energy Share

Energy share features permit one laser to be configured to deliver two or more welds to the work piece "simultaneously", thus greatly increasing the number of welds per laser pulse. Each of the beams is properly balanced such that each weld nugget is identical in shape, area and depth.

2.1.6 Beam Delivery

The beam is delivered to the welding area using a flexible fiber optic cable, usually around five (5) meters long. Use of a flexible fiber optic cable greatly facilitates the integration of the laser into turnkey laser welding systems, factory automation equipment and robots. The laser beam is launched into the fiber using optics located with in the laser cavity. Fibers are available in two (2) types, Stepped Index or Graded Index. Fibers are also available in different core diameters, from 100 to 1000 microns. See section 3.4.2 for further details.

2.1.7 Focus Head

The fiber optic cable delivers the laser energy to the focus head. The focus head consists of optics which focuses the laser light emitted by the fiber on to the material being welded. Longer focal length lenses produce larger spot diameters while shorter focal length lenses produce smaller weld spots. (see 3.4.3 Focusing Optics for additional details)

2.2 How a laser welds

Laser welding is a non-contact process that requires access to the weld zone from one side of the parts being welded. The weld is formed as the intense laser light rapidly heats the material-typically calculated in milli-seconds. The flexibility of the laser offers three types of welds; conduction mode, conduction/penetration mode and penetration or keyhole mode.

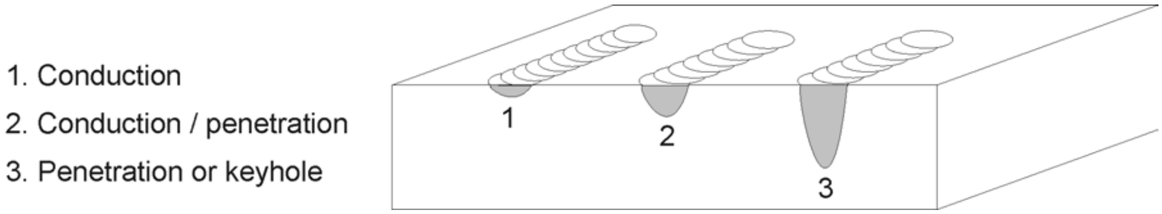


Figure F. Three types of welds created according to the power density and pulse duration of the laser pulse.

- Conduction mode welding is performed at low energy density forming a weld nugget that is shallow and wide.

- Conduction/penetration mode occurs at medium energy density, and shows more penetration than conduction mode.

- The penetration or keyhole mode welding is characterized by deep narrow welds. In this mode the laser light forms a filament of vaporized material know as a “keyhole” that extends into the material and provides conduit for the laser light to be efficiently delivered into the material. This direct delivery of energy into the material does not rely on conduction to achieve penetration, and so minimizes the heat into the material and reduces the heat affected zone.

2.3 Key Welding Parameters

The key welding parameters can be divided into two parts, those that concern the parts themselves and the laser parameters.

2.3.1 Joint Design and Fit-up

As laser welding is a non-contact process there are a broad number of joint geometries that can be welded. In addition the laser is able to weld into areas with limited access. The main joint designs are show in Figure G. Ideally in any weld joint the thinner material is the top sheet.

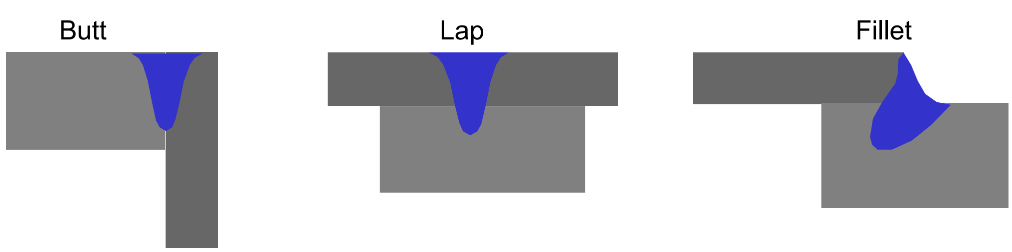


Figure G. Most common weld joints, most other types are variations on these.

The most significant requirement for reliable laser welding is close fit-up at the joint interfaces. Laser spot or seam welding is usually an autogeneous process, meaning 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. For best results the gap should be zero or an interference fit. However, since this is often not practical, some gap is allowed. As a rule of thumb this gap should never be more 10% of the thinnest material or of the weld penetration, whichever is less. It must be stressed that gap tolerance is case specific, and always should be fully examined and quantified by lab tests.

2.3.2 Part Alignment

The focused spot diameter for laser welding applications is typically 100 to 1000 microns. Smaller spot diameters (25-50 microns) may be required for very fine welding applications such as medical Guidewires or micro-electronic devices. 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 and to a lesser extent the joint design. Vertical tolerances, while less critical, also play a role to achieve the tightest possible focused beam.

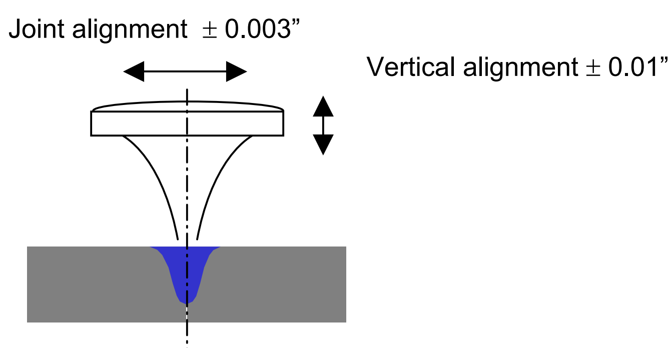


Figure H. Nominal part alignment tolerance to laser, the lateral tolerance is critical, vertical is large and more forgiving to the process.

Vertical tolerance relates to ensuring the focus spot at the joint has sufficient energy density to make the weld. This tolerance is called the depth of focus and is nominally about 0.5% of the lens focal /collimator length. Therefore, when a 100 mm collimator and 100 mm focal length lens combination is used, the depth of focus is around 0.5mm.

2.3.3 Material Selection and Plating

The laser can weld a wide range of steels, nickels alloys, titanium, some aluminum alloys and even copper, however there are materials that are better suited to laser welding and some that are difficult or impossible to laser weld. As with any other joining technology certain types of materials are difficult to weld unless they meet certain material characteristics. The material characteristics specific to laser welding are; a) the materials reflectivity, b) the effect of the high thermal cycling and c) the vaporization of volatile alloying elements.

The most commonly welded material is steel, and the general selection rule is to keep the carbon content under 0.12%. For stainless steels, ensure that the Cr/Ni ratio is greater than 1.7. Stainless steel alloy ANSI 303, many 400 series alloys and high carbon steels should be avoided due to a high carbon, phosphor and sulfur content. Generally, nickel alloys and titanium are highly weldable, with aluminum alloys and copper being case specific.

The plating material and method of plating can also have a significant effect on the welding process. For example, electro-less nickel plating creates welding problems due to the inclusion of phosphor and other contaminants during the plating process. The recommended plating method is electrolytic. The thickness and type of plating is also a consideration, for example, a gold coating thickness above 50 micro-inches may induce weld cracking.

2.4 Laser Parameters

The weld created by each pulse is determined by the peak power density and duration of that pulse. The number of pulses per second, pulse overlap and the welding speed additionally defines a seam weld.

- The peak power density controls the weld penetration and is a function of the fiber type and core diameter, focus optics, and laser peak power output.
- The pulse width controls the heat into the part, weld width and thermal heat cycle.
- The pulse repetition rate or pulse frequency also controls the heat into the part and thermal heat cycle.

2.4.1 Glossary of Terminology

Peak power
This is a direct parameter that can be selected on the laser. It controls 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 milli-seconds.

Pulse energy

The pulse energy is the energy contained with in a pulse and is product of peak power and pulse width. $E = P_p \times t$, units are joules (J).

Pulse repetition rate

The pulse repetition rate equates to the number of flash lamp pulses per second and may be expressed in Hz or pps.

Average power

This applies when more than one pulse is used for 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). $P_{ave} = E \times Hz$,units are watts (W)

Peak Power density

The peak power density is the concentration of the power at the part, and is determined by dividing the peak power by the focus spot size area. Spot size is given by fiber core diameter x focus head magnification. Units are W/cm^2.

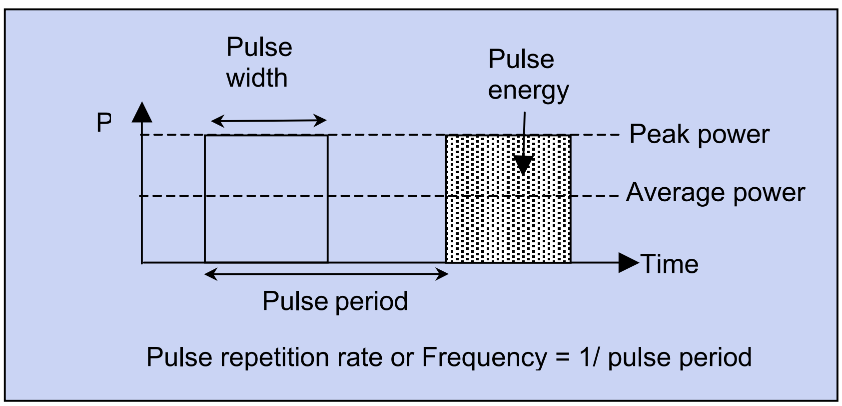
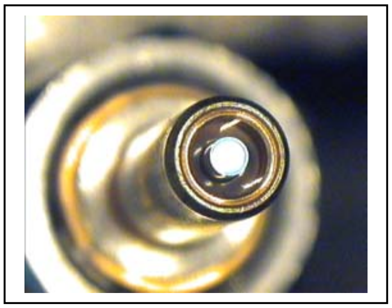


Figure I. Shows the important parameters of the laser pulse, including peak power, average power, pulse width, pulse energy and frequency or pulse repetition rate.

2.4.2 Fiber Optic Cable

The laser is delivered from the to the weld area via a fiber optic cable. This cable is constructed with a central core that carries the laser, a cladding region that acts as a mirror to the laser such that all the light remains in the core, and an outer metal jacket to protect from light leakage. The core diameter of the fiber can vary in diameter according to the required spot size needs and input laser power. In terms of focused spot size the core diameter directly affects the final focus spot size, and therefore the peak power density.



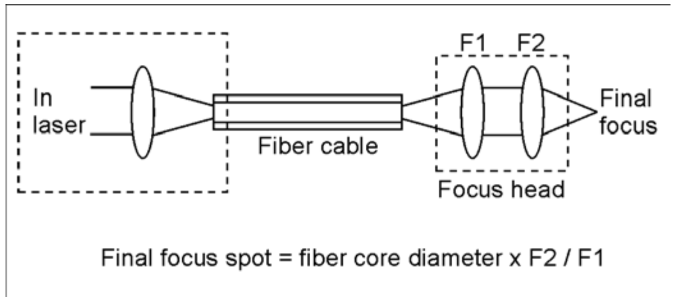


Figure J. The end of fiber shows the illuminated silicon core though which the beam is transmitted, the surrounding silicon cladding, and the steel jacketed connector. The light is confined with in the central core by differing refractive indices between the core and cladding material such that total internal reflection of the laser light occurs. The laser is launched into the fiber at the laser using focusing optics, and then is collimated and focused at the weld area by the focusing head.

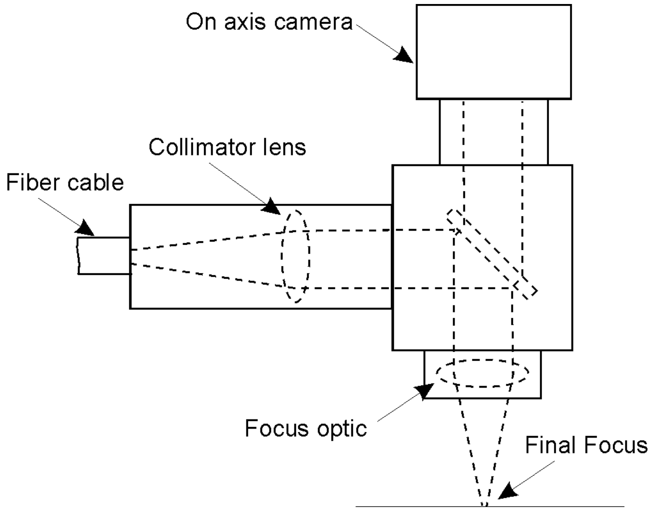
For example a 300 micron core fiber has half the focused spot size of a 600 micron core fiber, and so has four times the peak power density. However, the 600 micron fiber has no power limitations whereas the 300 micron fiber does. The selection of fiber is application related. Aside from the core diameters there are two types of fibers, a stepped index (SI) and graded index (GI) fibers.

The difference between the two is that the stepped index fiber tends to homogenize the beam structure while the graded index fiber tends to maintain the mode structure of the laser through the fiber length. This offers different welding characteristics in terms of weld penetration, weld width and weld stability. Determining which type of fiber to use is dependent on the application.

2.4.3 Focus Optics

The focus head effectively images the end of the fiber on to the part. The fiber optic delivers the beam to the focus head where the beam is firstly collimated, and then focus to a spot. The image is either enlarged or reduced according to the ratio of the collimating and focus lens.

The focus optics can be used to fine tune the spot size for an application or provide a reduced spot size when a large core diameter fiber must be used for handling higher power. The selection of final focus lens focal length also determines the standoff distance of the focus head from the part.



$$\text{Final spot size} = \text{core diameter of fiber} \times \frac{\text{focal length of collimator}}{\text{focal length of focusing optic}}$$

Figure K. The focus head usually has a camera mounted on axis to the laser beam path to directly view the weld area before, during and after the weld is completed. The camera greatly assists the operator in acquiring the weld joint and positioning the laser beam to the most optimum location. The relationship in terms of final spot size for the diameter of the fiber optic cable and focus head lenses is also given.

3.4.4 Peak Power and Pulse Width

The peak power, measured in watts, directly affects the peak power density, measured in watts/cm². Peak power density controls weld penetration. The pulse width, usually measured in milli-seconds, controls the heat into the part.

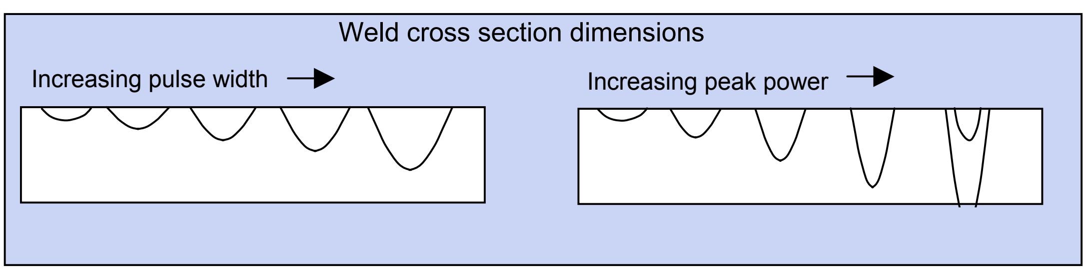
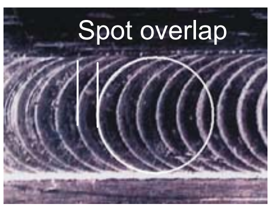


Figure L. The effect on weld dimensions of increasing pulse width and peak power on weld dimensions is shown.

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.

2.4.5 Seam Welding

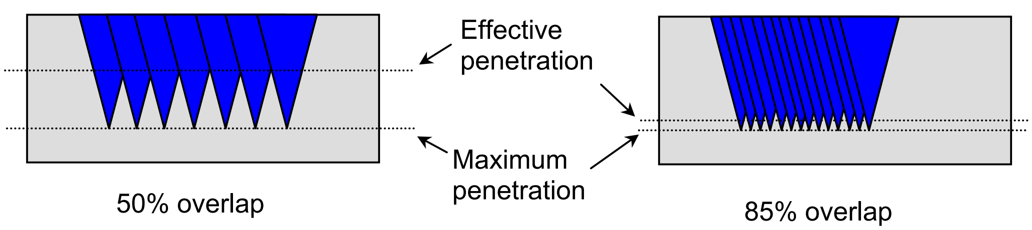
The additional parameters for seam welding are the pulse repetition rate, measured in pulses per second (Hz) and the linear part travel rate or welding speed. Spot overlap percentage, a function of speed, pulse repetition rate and focused spot diameter is also used in the equation for determining the best laser for the job and for determining the total weld cycle time.



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

Figure M. Shows the relationship of spot diameter, welding speed and pulse repetition rate.

When seam welding a balance is reached between the pulse penetration parameters, the welding speed and pulse repetition rate. In most cases this is worked from initially selecting the pulse penetration parameters, the effective penetration and therefore the spot overlap, and then determining the welding speed.



Welding speed = Spot diameter x (1-Spot Overlap/100) x Hz (units in/s)

Figure N. Shows a schematic representation of overlap versus effective penetration depth for various overlap percentage.

For example, for a spot diameter of 0.005", and an overlap of 50%, with a pulse repetition rate of 10Hz, the welding speed is given by –

Welding speed = 0.005 x (1 – 0.5) x 10 = 0.025"/second.

Weld penetration is determined by the spot overlap percentage, and welding speed.

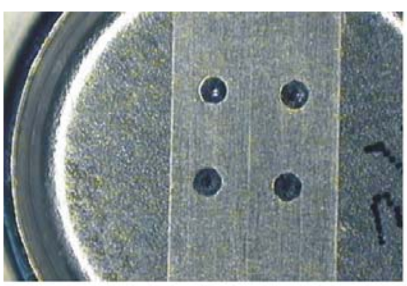
The level of overlap determines the effective penetration. Good mechanical strength may be achieved at 40-60% overlap. However, for hermetic welding applications, 70-85% overlap is typically required. As the overlap is increased the welding speed is reduced.

2.4.6 Cover Gas

Cover gas is used to prevent rapid oxidation of the weld zone due to atmospheric oxygen. Argon, helium or nitrogen inert gas is directed at low pressure and flow volume into the weld zone during the welding process to shield the weld zone from atmospheric oxygen. The mechanical properties and weld strength are usually unaffected by cover gas. Welds made in the presence of cover gas are shiny and more cosmetically appealing. The cover gas can also be used to cool the part minimizing the heat affected zone, and overall thermal loading.

2.5 Examples of Welds

Many materials and parts can be laser welded, below are a number of examples –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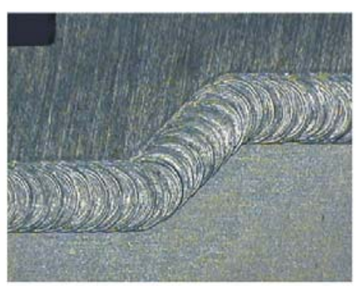
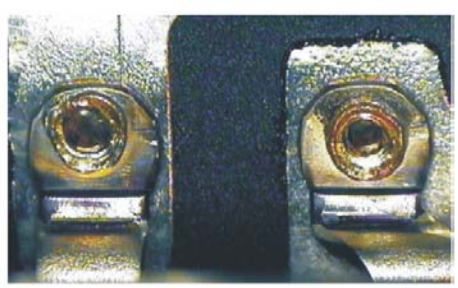

KOVAR PACKAGE SEAL


GUIDE WIRE


TUBE ATTACH


HERMETIC SEAL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