Marcin Alexy, Jörg Kundrat, Geoff Shannon

Resistance Welding and Laser Welding for Electrical Contacting and Micro Joining Solutions

Abstract: The connection of conductive parts for the purpose of electrical contact is one of the oldest, most common joining applications and is required in almost every industry. The electrical contacts realized by welding have to fulfil a wide range of requirements, which have to stay stable within narrow tolerance window over the entire life cycle of a product. These requirements are very good met by both resistance welding and laser welding and these are the two most common joining techniques used in electrical contacting and micro joining today. To successfully apply the resistance welding process suitable materials for contacts must be used. In majority of the cases the cooper alloys are agood compromise between high electrical conductivity and sufficient mechanical strength. Within the cooper alloys CuSn 0,15 is the best compromise for a number of typical applications. While there are a number of choices for laser for micro welding, the CW fiber and nanosecond fiber have distinctive application specialties; Nd:YAG is the established source, with great all around micro welding capability; CW fiber lasers provide excellent speed/penetration characteristics and the ability to weld conductive and dissimilar materials; QCW fiber offers similar capability to the Nd:YAG laser, with additional small spot and penetration features; and finally, the nanosecond laser provides great control using sub 400 nanosecond pulses for thin materials and fine spot applications, as well as some dissimilar materials bonding.

Keywords: resistance welding, laser welding, electrical contacts

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Introduction

The connection of conductive parts for the purpose of electrical contact is one of the oldest, most common joining applications and is required in almost every industry including automotive, electrical and electronic devices and medical devices. The materials of choice are in many cases cooper and cooper alloys due to the ability to efficiently conduct energy and transmit signals[1]. The technologies used to make these connections are driven by cost, joint performance, and volume requirements. As part sizes decrease and performance requirements increase, crimping, soldering and brazing techniques are becoming obsolete. In contrast, welding, which provides excellent joint integrity, longevity, and conduction performance, is quickly becoming the required standard.

Marcin Alexy, PhD, Jörg Kundrat – Amada Miyachi Europe; Geoff Shannon, PhD – Amada Miyachi America

The electrical contacts realized by welding have to fulfil at least following requirements:
- Low electrical resistance
- High thermal endurance
- High mechanical strength
- Good corrosion resistance

These properties have to stay stable within narrow tolerance window over the entire life cycle of a product. These requirements are very good met by both resistance welding and laser welding and these are the two most common joining techniques used in electrical contacting today.

Basics of Resistance Welding and Laser Welding

Resistance welding

Resistance welding is a thermo-electric process in which heat is generated at the interface of the parts to be joined by passing an electrical current through the parts for a precisely controlled time and under a controlled pressure (also called force). The name "resistance" welding derives from the fact that the resistance of the work pieces and electrodes are used in combination or contrast to generate the heat at their interface. Key advantages of the resistance welding process include:
- very short process time,
- no consumables, such as brazing materials, solder, or welding rods,
- operator safety because of low voltage,
- clean and environmentally friendly,
- a reliable electro-mechanical joint is formed.

Resistance welding is a fairly simple heat generation process: the passage of current through a resistance generates heat. This is the same principle used in the operation of heating coils. In addition to the bulk resistances, the contact resistances also play a major role. The contact resistances are influenced by the surface condition (surface roughness, cleanliness, oxidation, and plating).

Four parameters influence the quality of resistance welding primarily and need to be monitored closely to achieve best in class results: Materials, Energy, Weld Force and Time. Resistance welding has been an established joining technology for more than 50 years. Since then, a steady stream of advances in resistance welding systems has given users significantly improved capabilities to control various aspects of the process. For example, the introduction of DC inverter power supplies with basic closed-loop electrical modes provided the ability to accommodate changes in the secondary to specifically address part resistance. Also, polarity switching for capacitance discharge supplies to enable balancing of the weld nuggets, and more recently, the addition of displacement and electrode force measurement, provide manufacturers with more tools to ensure weld quality.

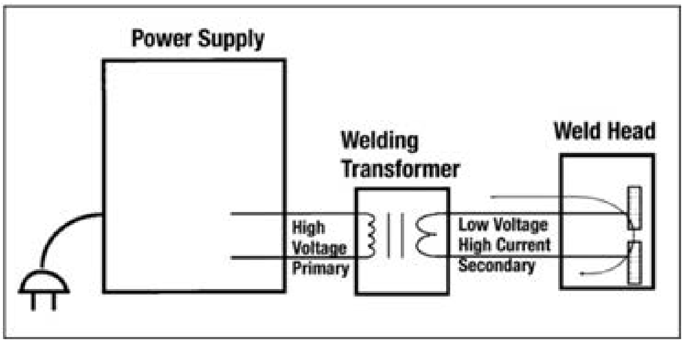

Fig. 1. The generic schematic of resistance welding machine

Fig. 2. Example of state of the art resistance welding machine: Advanced Active Welding System AWS3 with a motorized weld head MFP60 from Amada Miyachi.

Laser welding

Laser Welding is a welding technique used to join multiple pieces of metal through the use of a laser. A laser produces a beam of high-intensity light which is focused into a single spot to provide a concentrated heat source, allowing narrow, deep welds and high welding speeds. The process is frequently used in high volume applications, such as in the automotive and medical industry. The key Laser Welding Benefits are:

– contactless and low heat input,
– minimum part deformation,
– no tool ware,
– minimum metallurgical damage,
– very stable processes,
– very fast,
– easy integration in production equipment,
– low cost per weld for high volume applications.

Laser welding is quite new technology, introduced in the manufacturing marketplace in the mid-1980s. As laser technology has matured, and the awareness thereof spread, it has become an established process so that today, it is simply another tool in the manufacturing engineer's toolbox to be used and implemented as needed. The laser provides a high intensity light source that can be focused down to very small diameters (<100 micrometres). The concentration of light energy is sufficient to melt metals rapidly, forming an instantaneous weld nugget. The process is non-contact, has no consumables, offers instantaneous welding once positioned at the weld point location, provides sufficient control over the process to size the weld nugget according to requirements, and provides a number of implementation methods that can be geared toward individual manufacturing requirements. Laser welding enables joining of many materials and material combinations, can weld thick parts, and has no limitation on proximity of weld spots. There are two types of laser that provide solutions for the majority of electrical contact and micro joining applications: pulsed Nd:YAG and fiber. Both of these lasers offer different joining characteristics that can be selected as appropriate.

Resistance Welding Applications in Electrical Contacting and for Micro Joining Solutions

Resistance Welding in Automotive Applications

The product life cycle depends on the vehicle type and corresponds to a driven distance of

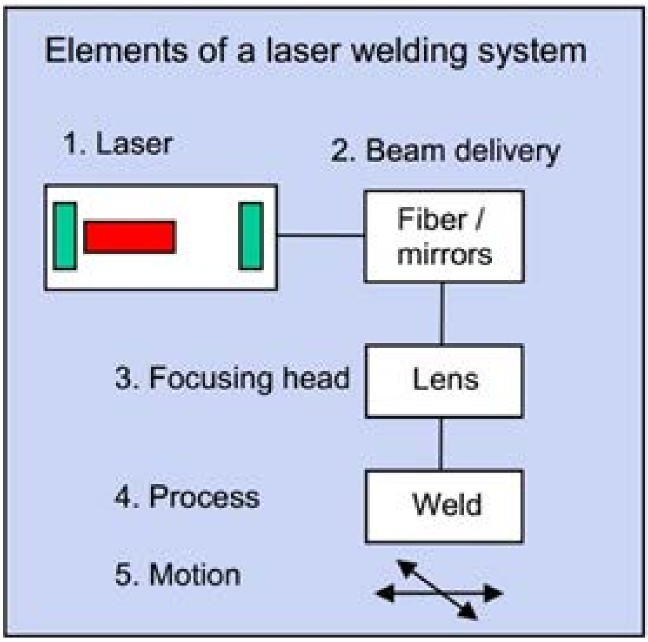

Fig. 3. Generic elements of a laser welding machine.

Fig. 4. Example of state of the art laser welding machine. NOVA6 Laser Welding System from Amada Miyachi

300.000 to 500.000 km, respectively to a period of operation from 10 to 15 years. Small installation space of the components with high level of integration is required and these two lead to temperature increase of the products due to high power density. Depending on the desired function of the device, there is a wide range of boundary conditions for the proper design of the electrical resp. signal contact points. For instance sensors deliver relatively small signal currents and because of that require small wire cross sections. At the same time the electrical motors of the servo steering require in the peak areas current ratings of some 100 A (Fig. 5.) and the starters have to be supplied even with a few kiloamperes for a short period of time. The thermal losses should be as small as possible and the requirement for reliability of the joint is mandatory. That leads to big cross sections of the contacting wires.

Similarly high requirements are valid for actuators for example for fusible cut-out or for airbag detonators (Fig. 6). At these applications it is very important, that der electrical resistance between the both welding points fits to a very tight tolerance window. High reliability demands are also valid for solenoid coils, these coils are based of enamelled cooper wire with diameters starting with 0,025 mm (Fig. 7.).

The above mentioned requirements necessarily limit the possibilities of application of suitable materials. Because of that mostly cooper and cooper alloys are used. In majority of the cases the cooper alloys are a good compromise between high electrical conductivity and sufficient mechanical strength. The electrical conductivity ($\lambda_{el.}$) of technically pure cooper (e.g. E-Cu58) is approx. 58 MS/m. That means E-Cu58 is the second best electrical conductor, the best is silver with 62 MS/m. In comparison to e.g. steel the tensile strength is relatively poor (300 N/mm²) but it can be increased by a number of different alloying components.

With the addition of 0,15% Sn an increase in strength to a level of approx. 490 N/mm² and with the addition of 6% Sn a strength of even approx. 720 N/mm² could be achieved. However, that increase is followed by the decrease of electrical conductivity to a level of approx. 50 MS/m respectively 9 MS/m. Hence the electrical conductivity of CuSn6 is similarly to the level of steel S235 (old name St37) CuSn 0,15, with approx. 490 N/mm² and an electrical conductivity of approx. 50 MS/m, is the best compromise for a number of typical applications [2].

Resistance welding in precision, electrical engineering and electronics

The typical quality requirements of electrical contacts for security-relevant welds in the automotive engineering are e.g. reproducibility of the joining process, reliability of the joint and the possibility of full process monitoring. These requirements are perfectly met by resistance welding and create the basis for a number of further applications in a wide range of industrial sectors. In this way resistance welding is suitable for welding of hard metal tools

Fig. 5. Example of a high current application: choking coil wire, wire diameter 3 mm.

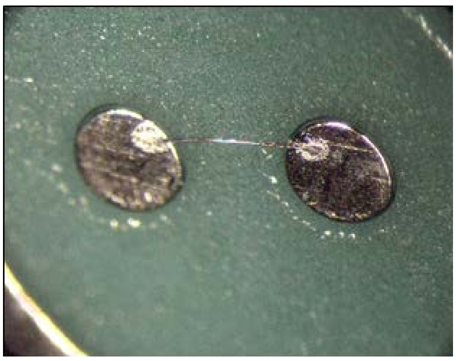

Fig. 6. Example of micro-application: airbag detonator, wire diameter 24µm.

Fig. 7. Example of a enamelled cooper wire application, cooper wire to a square terminal, wire diameter 70µm.

Fig. 8. Example of a precision engineering application: dental drill with hard metal tip.

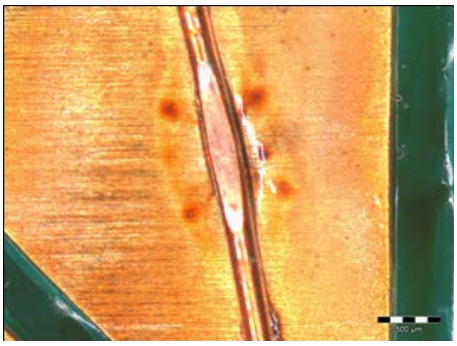

Fig. 9. Example of electronics application: welded cooper enamelled wire with a diameter of 50 μm.

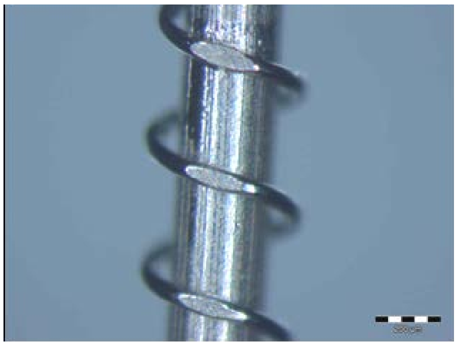

Fig. 10. Example of a lighting application: tungsten wire with a diameter of 60 μm, electrode of a discharge tube.

(Fig. 8.) and highly stressable tools and other products can be produced. In similar way antennas from thin enamelled copper wire can be welded to conductive contact pads on organic substrates and the welds enable the transfer of security-relevant information content in a wide temperature range (Fig. 9.).

Further example is the lighting industry, where high-melting metals can be welded without cracks to very sensitive sintered metal (Fig. 10.). Other welding techniques, where the material is melted during the welding process have strong disadvantage for such kind of application, because the setting process is quite problematic and leads to brittleness and cracks.

Nd:YAG or fiber laser: choosing the best option for electrical contacting and micro welding applications

Four lasers can be used for micro welding: pulsed neodymium-doped yttrium aluminum garnet (Nd:YAG), continuous wave (CW) fiber, quasi continuous wave (QCW) fiber, and nanosecond fiber. Each laser type offers unique features that work best for specific applications. In some cases, several laser types may work; in that case, cost of ownership and serviceability can tip the scales[3].

Nd:YAG – Peak powers and pulse widths perfect for electrical contacting and micro welding

With the Nd:YAG laser, the active gain medium is neodymium, which is doped into a host crystal of yttrium aluminium garnet. This solid rod of material is typically 2-5 mm in diameter and around 100 mm long. Micro welding Nd:YAG lasers are optically pumped using flash lamps and typically emit light with a wavelength of 1064 nm, but can be frequency doubled (532 nm, green). The laser's optical design is relatively simple; its heart is the power supply that drives and controls the flash lamp voltage and allows precise control of peak power and pulse width during the laser pulse using internal optical feedback.

With excellent pulse control, the Nd:YAG laser also offers high peak powers in small laser sizes, which enables welding with large optical spot size. This translates to maximized part fit-up and laser to joint alignment accommodation. An example is a 25 W laser that can provide 6 kW of peak power, sufficient to weld steel and aluminium with a 600 micron spot size. The pulsed Nd:YAG laser has been around for many decades and has by far the largest install base. In today's laser landscape, it is best suited to spot welding application under 0.02-inch penetration and seam welding heat-sensitive packages. Fig. 11. includes a few examples of Nd:YAG laser welding.

Fiber lasers – Great focusability with selectable beam quality

A fiber laser is generated within a flexible doped glass fiber that is typically 3 to 9 meters long and between 10 and 50 microns diameter. Ytterbium is used as the doping element because it

Fig. 11. Nd:YAG laser welding. Left: wire to ring spot weld, middle: electrical connections, right: medical tool weld.

provides good conversion efficiency and a near 1 micron output wavelength, which matches well with existing laser delivery components. The laser is generated wholly within a fiber, so there is no need to align the medium to cavity mirrors, nor is it necessary to maintain optics and alignment as with the pulsed Nd:YAG laser. The very efficient lasing process means the fiber laser can be small, air cooled, and provide high wall plug efficiencies.

The fiber laser's unique characteristics are its "focusability" and its range of range of beam qualities, which can be tuned for each welding application. The two ends of the beam quality spectrum are single mode and multi-mode – single mode is defined by a beam quality or M2 less than 1.2, while multi-mode is generally above M2 of 2. The mode defines how well the laser can be focused and the power density distribution across the laser. Fig. 12 is a schematic of single and multi-mode fiber lasers.

The differences between single mode and multi-mode lasers are shown in Figure 13. All welds are shown in 1,5 mm thick stainless steel – (a) represents a 500 W single mode fiber laser with an M2 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 M2 value of 15 at 100 IPM with a150 micron spot size; and (c) shows a 1kW multi-mode fiber laser with an M2 value of 15 at 80 IPM with a 250 micron spot size.

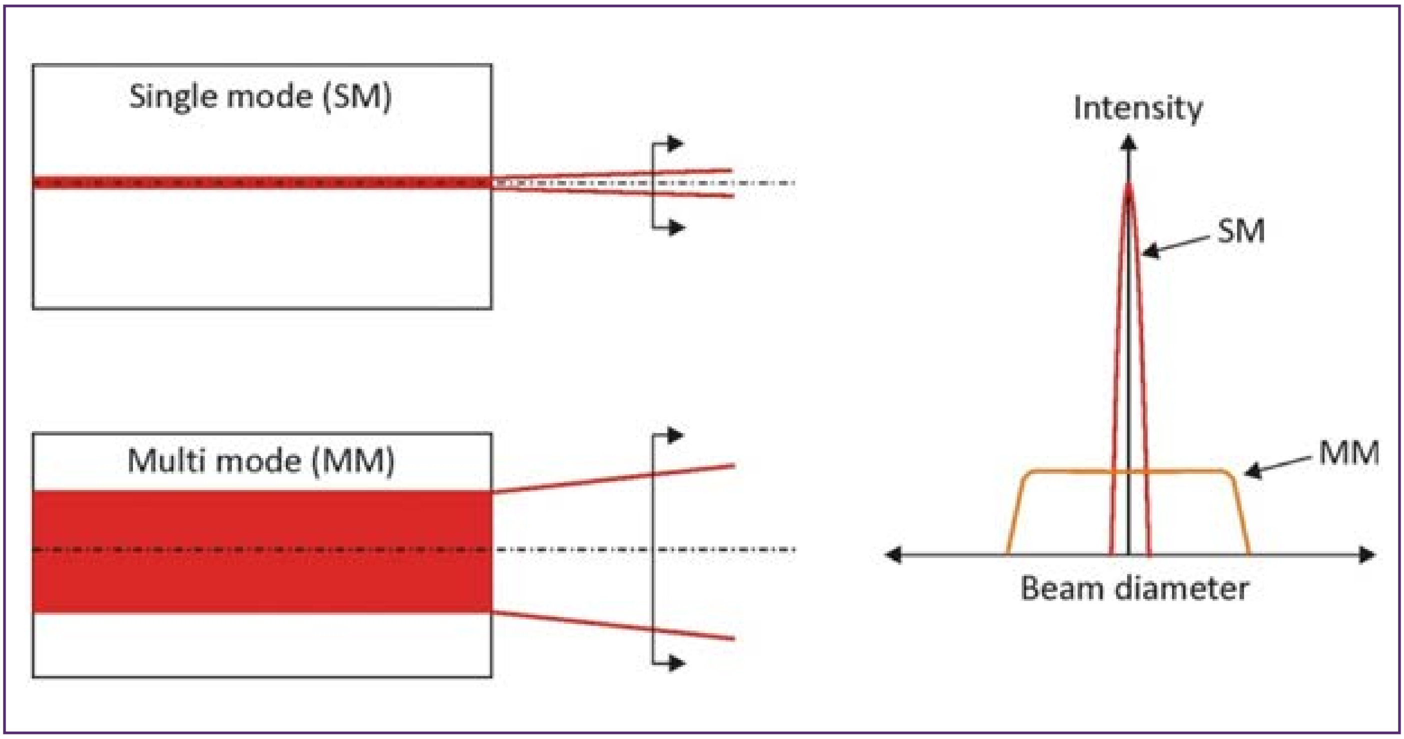

Fig. 12. Schematic of single and multi-mode fiber lasers.

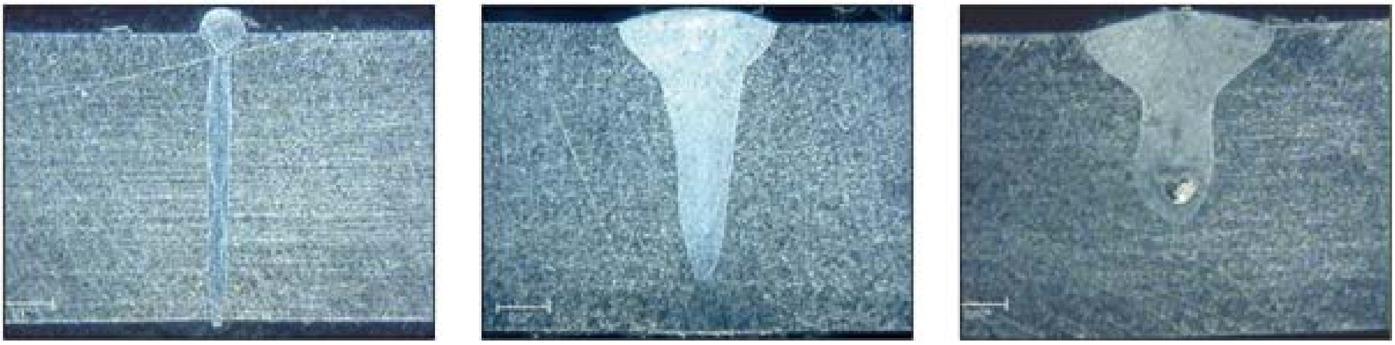

Fig. 13. Beam quality effect on weld for a single-mode and multi-mode laser.

Continuous wave (CW) fber lasers

For high speed seam welding applications this laser is operated in continuous wave mode, which means that the laser output remains on until being turned off. For spot welding either a single weld or a seam, the laser output can be pulsed or, more correctly, modulated – turning the laser on and off rapidly. The CW laser's peak power is the same as its maximum average power, so focused spot sizes are generally under 100 microns to attain sufficient power density for welding with power levels under 1 kW. Due to the small optical spot size, lap and fillet weld geometries are preferred. Butt welding is possible if there is good part fit-up or if a seam location vision system is used. An alternate is using a scan head that can create motion lateral to the weld direction, known as wobble, which can effectively widen the weld to decrease joint alignment sensitivity. Cw fiber lasers are well suited to general seam welding up to 1,5 mm depth for a 500 W laser, high speed seam welding of same and dissimilar materials, and producing spot welds under 100 microns in diameter. Figure 14. includes examples of CW fiber laser applications.

Quasi-continuous wave (qcw) fiber lasers

The QCW fber laser's peak power and pulse width characteristics are similar to those of the Nd:YAG laser, though the parameter range is not quite as broad. Similar to CW fiber lasers, the QCW lasers offer single mode to multi-mode options with spot sizes from 25 micrometers to 1 mm as needed for the application. These lasers also shine in small spot size applications and penetration applications, although they do provide a fairly comprehensive coverage of many micro welding applications. Figure 15 shows QCW fiber laser application examples.

Nanosecond fiber

The nanosecond fiber laser is a more recent addition to the lasers offered for welding. It is the same laser used for laser marking applications, and is a very cost effective solution that can be repurposed very effectively for certain welding applications. The nanosecond laser provides

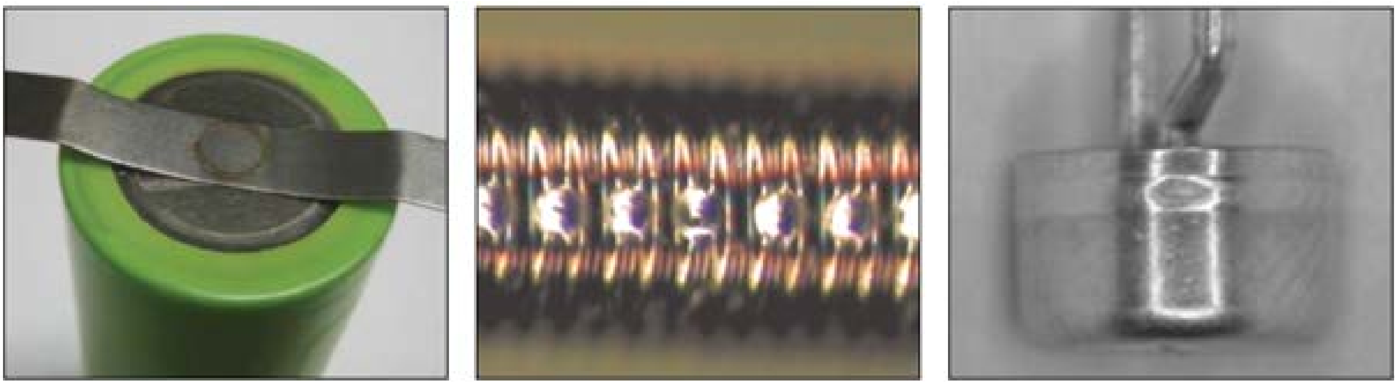

Fig. 14. CW fiber laser applications. Left: high speed welding of copper tabs to steel battery cans, middle: coil welding with sub 100 micro spot welds, right: welding airbag detonators.

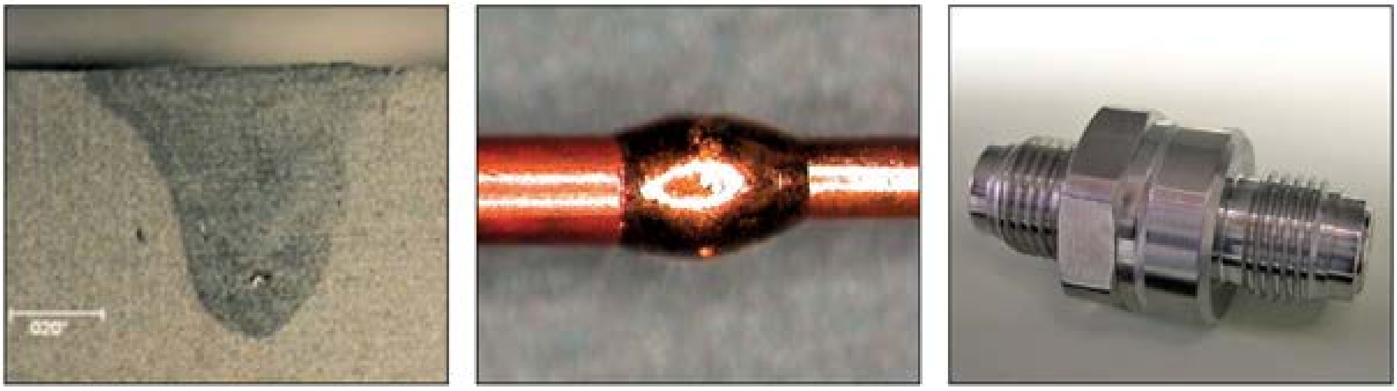

Fig. 15. QCW fiber laser examples. Left: Cross section of 1,5 mm deep weld for thick aluminum package seam sealing, middle: guide wire weld, right: sensor seam weld.

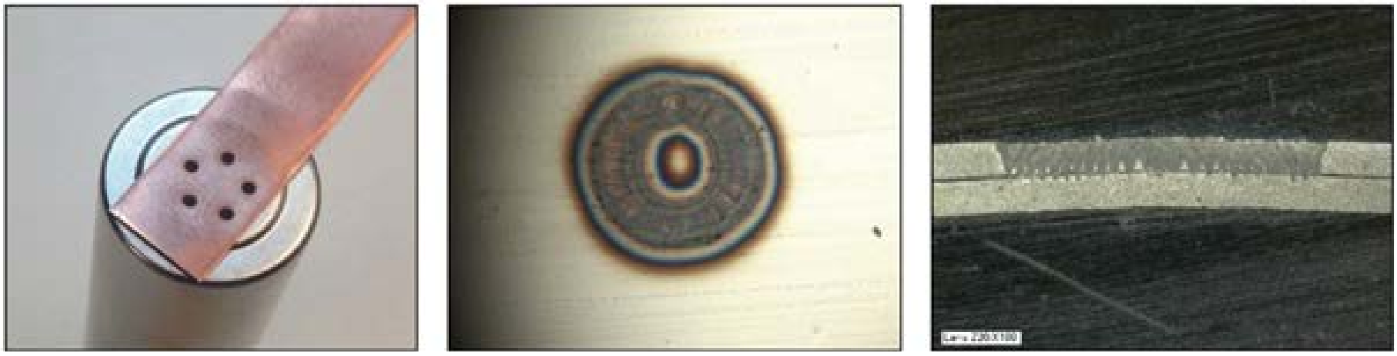

Fig. 16. Nanosecond fiber laser applications. Left: Low volume battery tab welding, middle: top view of weld 20 micrometer thick foil, right: cross section of seam weld using the "wobble" function in 250 micron thick titanium.

multikilowatt peak power, but with pulse widths around 60-250 nanoseconds that can be delivered between 20-500 kHz. This high peak power enables welding of almost any metal, including steels, copper, and aluminium. The very short pulse widths enables very fine control for welding small parts, as well as the ability to weld dissimilar materials. See Figure 16. for examples of nanosecond fiber laser applications.

Summing it all up

While there are a number of choices for laser for micro welding, the CW fiber and nanosecond fiber have distinctive application specialties [4-5]. Nd:YAG is the established source, with great all around micro welding capability; CW fiber lasers provide excellent speed/penetration characteristics and the ability to weld conductive and dissimilar materials; QCW fiber offers similar capability to the Nd:YAG laser, with additional small spot and penetration features; and finally, the nanosecond laser provides great control using sub 400 nanosecond pulses for thin materials and fine spot applications, as well as some dissimilar materials bonding. Cw lasers are simply turned off and on as needed, but can be modulated to provide a pulsed output. Nd:YAG and QCW fiber are typically 0.2-4 kW peak power and 0.1-10 ms pulse width. Ns fiber lasers operate at around 10 kW peak power and 60-200 ns pulse widths. Fig.17. shows each laser's peak power and pulse width regimen.

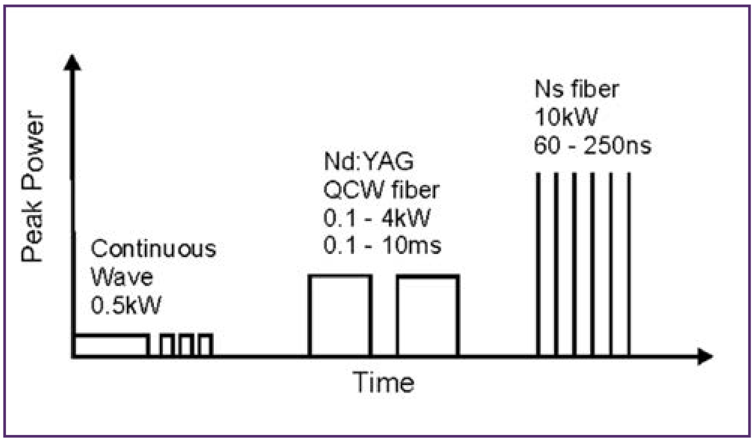

Fig. 17. Peak power and pulse width

The most interesting match-up is the Nd:YAG and the QCW fiber laser, which offer similar welding capabilities; both have high peak power and millisecond pulse widths for large diameter (>200 micron) spot and seam welding. The Nd:YAG laser has been around forever and has a massive install base and end user familiarity, while the QCW laser is the relative newcomer with some strong cost of ownership features. From a welding perspective they are quite close; points of consideration that tip the scale are the cost of ownership and serviceability. The QCW laser does not use flash lamps, which reduces maintenance costs. The Nd:YAG laser is fully serviceable in the field. The choice then can become somewhat of an equipment preference, driven by whether the user requires a laser that is cheaper to run or one that can be maintained 24/7. Table 1. provides a general summary of the characteristics of lasers for micro welding. The information can be used to help guide which laser would be the best option for a particular application.

Fig. 18. Examples of integrated systems for battery pack manufacturing. Left: Jupiter Resistance Welding system from Amada Miyachi, right: Jupiter Laser Welding system from Amada Miyachi.

Table 1. Summary of lasers for micro welding

Laser type	Typical power level	Penetration limit	Typical optical spot size	Core applications	Comments
Pulsed Nd:YAG	5 W – (2.5 kW peak) 25 W – (6 kW peak) 150 W – (7 kW peak)	1 mm	0.4 mm	Micro welder for all weld types.	Can be fully serviced in the field Flashlamp consumables
CW fiber	200 W – 1 kW	2.5 mm	0.08 mm	Penetration and high speed seam welding applications, small spot welds, conductive materials and dissimilar materials.	Cannot be serviced in the field No laser consumables
QCW fiber	150 W – (1.5 kW peak) 300 W – (3 kW peak) 600 W – (6 kW peak)	1.5 mm	0.4 mm	Micro welder for many weld types, capable of optical spot size < 0.002".	Cannot be serviced in the field No laser consumables
Ns fiber	50-100 W (10 kW peak)	0.4 mm	0.05 mm	Thin material < 200 microns thick, small spot welds, dissimilar materials.	Cost effective Cannot be serviced in the field No laser consumables

Examples of turnkey manufacturing systems

Today there is a wide range of manufacturers offering products in the area of resistance and laser welding. Among others Amada Miyachi designs and manufacture a complete range of resistance welding power supplies and lasers specifically designed for both low and high volume manufacturing processes. Technologies are matched to production needs as either standalone products or fully integrated system solutions. Solutions can be adapted to accommodate welding of dissimilar metals. An optimized software application, developed in Amada Miyachi laboratories, is typically delivered with each system. Figure 18 shows some examples of integrated systems for battery pack manufacturing, including a conveyor fed automation cell, a laser tab welding system with fire suppression deployment, and a resistance welding system.

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