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Resistance and Laser Welding for Medical Devices

Medical devices use a variety of metal components that are often welded to form a secure and permanent bond. Options available for welding processes are limited due to constraints including part geometry, metallurgy, autogenous welds (i.e., without adding a solder or braze during joining), and the ability to make a single spot weld in a particular location. The restrictions quickly whittle down available choices to two processes, namely resistance welding and laser welding. These two processes are similar in that they are quite well suited to weld most medical alloys and yet are quite different in part design, process control, and bond formation. Anyone selecting between the two is faced with a difficult task and needs good understanding of their capabilities and limitations before making an informed decision. Understanding of these processes is critical when welding is to be outsourced and providing a robust design for the application becomes even more important. This article presents fundamentals, weld configurations, bond formation, process control, monitoring, and weld analysis for resistance and laser welding; information which will help the engineer make an informed decision.

Resistance Welding

As the name implies, resistance welding uses the resistance to current flowing through the parts to generate welding heat [1]. Current is provided through two welding electrodes which are connected to the secondary of the welding power supply and complete the circuit. The two electrodes also provide the welding force, applied with the help of a weld head, to ensure proper contact between the electrodes and the parts being welded. A power supply converts incoming high voltage and low current signal to a more usable low voltage and high current energy. Current values in range of 50 to 2000 amps are typical for medical device applications.

Heat generated at the weld has multiple functions. Initial portion of the welding heat is used to burn away any organic contaminants at the weld interface; a puff of smoke created during a weld pulse is evidence of such activity. Contamination from finger oils and dirt in the atmosphere is miniscule and typically does not affect the weld. However, if experimental results indicate otherwise, proper precautions must be taken and include washing parts with acetone and handling with finger cots. The weld surfaces must be free of contaminants such as mold release agents, stamping lubricants, and adhesives/polymers that creep into the weld zone. Naturally occurring surface oxides on most metals/alloys including stainless steels and titanium are not thick enough to impede welding.

A typical welding sequence, shown as a time diagram in Figure 1, starts with the moving electrode(s) coming down and applying the required welding force on the parts to be welded. After waiting for the mechanical systems to stabilize (squeeze time), the weld pulse is fired by the power supply. Following the weld pulse, parts are maintained under welding force and allowed to cool (hold time); it is during this cooling process that the weld develops strength. After the hold time, the electrodes are retracted and parts removed. The weld pulse can include an upslope, weld time, and a downslope. Use of squeeze time and upslope prevent electrode sticking and arcing where as the downslope allows flexibility in controlling weld temperature. More than one pulse can be used to condition the parts and in some cases multiple pulses can be used [2] to provide better heat balance.

<u>Weld Configurations</u>

Resistance welding offers many choices for weld configurations; schematics are shown in Figure 2. In opposed electrode welding the two electrodes apply force to pinch the parts between the electrode tips. Opposed electrode configuration is the most robust since the welding current has a unique path to flow through. Figure 3(a) is a photograph of a cross-wire weld between a Ni wire and an alloy post. In situations where access is limited to one side, as with welding tabs to a battery can, a parallel gap or a step weld can be an option. Parallel gap welds can be difficult to control since the welding current has the option to flow through either one or both layers. In situations where the top layer is more conductive than the base, a step weld can be used to force the current to flow through the weld interface. In configurations where the parts to be welded are significantly different in size or electrical conductivity or both, it becomes difficult to

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produce the required welding temperature in both components at the weld interface. An alternative is to use a projection weld on the bigger or more conductive component so as to provide better heat balance. A projection can be stamped, coined, or machined. Size of the projection has to match the size of the other part. For very thin Al foils welded to Tungsten rod, the rod surface roughened by machining marks or by abrading with sandpaper can act as microscopic projections for welding. Welding of thin foils and fine wires down to under a thousandth is possible with resistance welding since majority of the heat is generated at the weld interface and allows the foil/wire to partly retain its structural integrity.

A unique aspect of the resistance welding process is that the weld location is shielded by the parts themselves, thus producing internal welds. A benefit of forming internal welds is that the weld zone is not exposed to air and hence does not require shielding gas to prevent weld contamination. An inert shielding gas, such as Argon, can be used to avoid surface oxidation to produce cosmetically appealing welds.

Selection of suitable welding electrode is also important since resistance welding is a contact process. Conductive Class II copper [1] electrodes are used for welding resistive materials such as stainless steels and titanium. For welding conductive materials such as gold, copper, or platinum, resistive electrodes made of molybdenum or tungsten are used. Improper selection of electrode material can lead to insufficient heating of the weld, electrode sticking, or surface contamination. If a configuration is such that no particular electrode is suitable, there may be an opportunity to introduce a third material to improve heat balance and take the focus away from the electrode material interface. An example is welding of nickel tab to titanium can which can be challenging. An option is to introduce a thin foil of stainless steel in between. The resistive stainless can help focus heat at the weld interface.

Type of Bond

A unique aspect of resistance welding is that the parts do not have to melt to form a bond; they only have to soften and be forced together. Metal atoms on either side of the weld interface will form a bond as long as there are no contaminants on the surface and the atoms are brought in close proximity. A bond formed without melting of the constituents is called a solid-state bond. A bond line is visible at the interface, as is seen in Figure 3 (b) in most cases except when welding similar materials where grain growth can occur across the interface. A solid-state bond is common when welding conductive alloys and refractory metals.

In addition to a solid-state bond, resistance welding can form a fusion bond where material on either side of the interface melts, mixes, and solidifies to form a weld. Fusion bond is quite common during welding of resistive alloys (Figure 3c) such as stainless steels. Even though presence of fusion might be thought of as preferred bond type, it is not often the case for medical devices where welding of dissimilar metals/alloys is common. A fusion bond between dissimilar metals can result in formation of intermetallic compounds which can produce a brittle weld. It is in welding of dissimilar alloys with a solid-state bond is where resistance welding finds its niche. When welding dissimilar metals that are very different in melting points, the lower melting alloy can melt and form a braze on the higher melting metal, as is seen in welding of stainless steel foils to a refractory pin (Figure 3d).

Resistance welding is frequently used where either one or both components have plating on the surface. The plating can be for improved corrosion resistance or to provide a good soldering surface. The plating alloy can act as solder/braze layer at the interface or just provide a good bonding agent to form a solid-state bond. A gold flash, with a Ni barrier layer underneath, is the most common variant. The gold layer can be easily welded to similar metals including Cu, Ni, Pt, and Pd. Resistance welding is also used where one or both components are tin (or solder) plated. The heat generated by current flow melts the plating and forms a solder fillet which on cooling produces a solder joint. Resistance welding is the only welding process that can produce all three types of bonds namely solder/braze, solid-state, and fusion.

Process Control and Monitoring

In resistance welding, the electrical energy in the form of welding current flows from the power supply (or transformer) to the weld head where it makes its way through the electrodes, the parts being welded and back to the power supply to complete the circuit. The energy consumed by the weld can be quantified by measuring voltage drop across the weld and current flowing through the weld. Statistical analysis of the data can be used to setup control limits. In addition to measuring the weld energy parameters, advanced power supplies have the ability to get feedback from the weld and control the energy delivered during the weld. Such closed-loop feedback can be setup to operate in current, voltage, or power mode. For example, in current control mode the power supply will provide a programmed amount of current and allow the voltage to change as required; voltage can then be used as a monitoring parameter. Each of these modes allows compensation for expected variation in weld resistance due to changes in surface roughness and part positioning. For example, current control mode has the ability to compensate for minor changes in oxidation levels. Voltage mode can be used to compensate for changes in electrode temperatures or prevent blowout of fine wires. Power mode can be effectively used to compensate for part positioning variations. In a weld configurations where either one or both component is a wire or one of them has a projection, weld displacement can be effectively used to monitor the weld. Measurement of weld displacement along with measurement of one electrical parameter has the potential to provide practically complete information about weld quality.

Laser Welding

Laser welding uses a focused beam of laser light to melt and weld the two parts [3]. It is a non-contact process and does not require any electrical connection to the part. A laser light source is used since it is monochromatic (single wavelength) and coherent (all rays are parallel) and hence can be focused down to a very small spot with sufficiently high energy density to melt metals. Laser energy is delivered in either pulsed or continuous mode. In pulsed welding, the laser energy is delivered in short burst of high energy pulses. Time scales are in few milliseconds and peak power is typically of the order or 3-

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5 kW. Pulses can be overlapped 80-95% to form a hermetic seal and is commonly used to seal Ti cans for implantable devices. Continuous mode welding is not common for medical devices and hence will not be discussed in this article.

The laser source most commonly used for pulsed welding is referred to as a YAG laser which emits a near-infrared wavelength of 1.064 micron. Most metals that are not relatively conductive or reflective, such as Ti and stainless steels, absorb laser light reasonably well and welding is not a problem. Welding can be difficult for alloys of Cu, Au, Ag and Pt; the laser pulse has to be carefully programmed to produce coupling yet not produce excessive melting.

The typical welding sequence for laser spot welding is very similar to resistance welding sequence shown in Figure 1. The parts have to be brought and held in place to ensure proper presentation to the laser energy similar to combination of force and squeeze time for resistance welding. The weld pulse can have an upslope, weld time, and a downslope for reasons similar to those for resistance welding. An upslope prevents excessive heating and expulsion; downslope can be used to control cooling rate of the weld metal. Finally, the parts have to be held together during a hold time to avoid disturbing the weld as the fused metal cools and solidifies.

Weld Configurations

Laser welding also offers many choices for weld configurations; schematics are shown in Figure 4. Configurations include lap weld, butt weld, edge weld, and fillet welds. Also included is a schematic of seam weld which is essentially a series of overlapping spot welds; any of the laser configurations can be used in spot or seam weld configuration. Photograph of a lap seam weld is shown in Figure 5a. As is evident from the schematics, all metal laser welds are external welds since the laser energy is deposited at the weld from the laser energy impinging on it from the outside. Since the welds are external, only a small portion of the part to be welded has to be exposed to the laser.

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One of the main challenges to laser welding is to bring the two parts to be welded into intimate contact. Laser welding is not tolerant of any air gaps, especially between small parts. As a rule of thumb, the maximum air gap should be less than ten percent of the thinnest component. Use of fixtures is essential to ensure proper positioning and contact between parts. If holding the parts with fixtures proves difficult, the parts can be held together with tack welds prior to actual welding. Since the laser welding is non-contact process, it allows the designer to select weld locations that are not easily accessible for resistance welding electrodes and require a fusion weld as in welding of feed-throughs. Laser energy can also be transmitted through a quartz window for welding inside an Ar filled chamber.

Type of Bond

In laser welding, the absorbed weld energy is used to melt material across the weld interface. The molten material melts, mixes, and solidifies to form a bond. All laser welds in metals are fusion welds, as shown in Figure 5b and 5c; solid-state welds are not an option. Presence of a fusion weld zone that is exposed to the environment presents a different set of challenges. The exposed melt pool has the potential to exchange atoms with the environment. For alloys containing volatile elements, there is the possibility that some fraction of the volatile component can evaporate during welding. Of greater concern is the loss of material from the surface due to violent nature of the welding process that can throw off small globs of molten metal known as weld spatter. Usually, the volume lost is small but the spatter can get attached to other portions of the medical device and cause electrical short or mechanical malfunction. Control of the weld pulse profile is critical to avoid weld spatter.

Laser spot welds are formed in conduction mode or keyhole mode. In conduction mode, the laser energy interacts only with the surface of the metal or the weld pool. Heat generated by the absorption of the laser energy is transferred to the interior by conduction only and hence the name. The weld bead profile in section is shallow bowl shaped, as seen in Figure 5b. As power density of a pulse is increased, the weld can transition to the keyhole mode where the molten metal is pushed aside by the weld plasma and the laser

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light reaches down into the weld; Figure 5c shows a lap weld that appears to have transitioned to a keyhole mode and exhibits an inverted cone shaped profile with a higher aspect ratio.

Welding of dissimilar metals is more challenging since there is the potential to form brittle intermetallics in the weld pool. The metal combinations chosen should preferably form complete solid-solutions; an evaluation of the relevant binary phase diagram will provide that information. If intermetallics are present their detrimental effect can be reduced by offsetting the laser spot such that one of the metals will be a greater volume of the fusion zone, as seen in Figure 5b. If the melting points are dramatically different, one of the metals can be made to melt and braze over the other as shown in Figure 5d; very similar to resistance welding. Even though the weld in Figure 5d can be thought of as a braze, it should technically be considered a fusion bond since there is no added braze alloy and one of the components melts. Another option is to introduce a third metal at weld interface which is compatible with both components. A recent development in welding Nitinol to stainless steel with a patented weld alloy [4] is an example.

A greater concern for medical devices is the ingestion of gaseous elements into the molten metal. The usual culprits are nitrogen, oxygen and hydrogen. Of the medical alloys, Ti based alloys are the most susceptible. Most Ti welding is performed in an Ar-filled glove box where the oxygen level is maintained at below 10 ppm and hydrogen (present as moisture) has to be controlled to a dew point of -60ºC. There is the possibility of release of oxygen and/or moisture that has been absorbed on the surface of the components introduced into the glove box; baking of the parts prior to introduction into the glove box is an option. Oxygen contamination can be visually identified by discoloration of the Ti weld as the color changes from dull grey to shades of tan. A dark tan or blue discoloration indicates significant contamination. Oxygen contamination will also be evident in the metallurgical evaluation of the weld sections. It is the hydrogen contamination that is challenging since it cannot be identified even with optical and SEM microscopes. Furthermore, hydrogen contamination has the potential to cause delayed cracking that is difficult to predict.

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Some Ti welds and majority of laser welds on steels, Pt, and other medical alloys are made in enclosures (for laser safety) but not necessarily in a glove box. For such applications, the fusion metal is shielded from air by a shielding gas. Again, the most common shielding gas is dry Argon which essentially flushes oxygen and nitrogen away from the weld zone. Shielding gas can be provided coaxially with the laser beam or as cross-flow. In either event, the goal is to flood the area around the weld with the shielding gas. Shielding gas should not be introduced as a sharp jet since the jet has the potential to actually drag adjacent air into the weld.

Process Control and Monitoring

Most modern spot welding lasers offer feedback control to ensure that a programmed amount of energy is delivered to the weld. The feedback loop operates by leaking a small fraction of laser energy out of the rear reflector mirror and compared to programmed levels. The feedback is still within the laser cavity and does not reflect any changes to the actual delivered energy due to changes in the delivery system such as broken fibres, misaligned lenses, or dirty cover glass. Hence in addition to internal feedback, laser energy is periodically monitored with a laser thermopile to confirm laser stability. A thermopile looks like a small hockey-puck and measures the laser energy by converting it into heat and measuring the change in temperature. Additional issues that could affect the weld include focus height and spot positioning, neither of which are diagnosed by the thermopile. Unfortunately, direct feedback from the laser weld itself is not yet available in pulsed laser welding.

Weld Testing and Analysis

Medical device welds are tested for strength; common configurations are pull, peel, and shear test. Most engineers are familiar with the issues related to mechanical testing but that is only half of the story. The other half, often ignored, is the metallographic analysis of weld cross-sections. Metallographic evaluation includes observation of weld micrographs with optical microscope and scanning electron microscopes. Optical micrographs will reveal presence of cracks, porosity, heat imbalance (uneven weld

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nugget), and bond type (fusion/solid-state/solder-braze). A strong bond formed with resistance welding is often incorrectly presumed to have a good fusion nugget even though no such correlation exists. Only way to find out the bond type is to observe the weld sections. Cracks in the weld nugget or in the vicinity are not acceptable under any circumstances while porosity can be tolerated as long as they are well trapped in the fusion (Figure 5c) zone and not anywhere near the edge of the weld. If segregation of elements or contamination is suspected, then elemental analysis with an SEM can reveal additional details. Presence of cracks, porosity, and elemental segregation will provide added clues to weld performance over the longer term under operating conditions. Metallographic analysis is essential to gather this information which may not be completely reflected in the results from mechanical testing.

Summary

Laser welding and resistance welding processes are commonly used welding processes for medical devices. The two processes are in many ways similar yet different. Both processes are able to make a small single spot welds and are able to weld all of the commonly used medical device metals and alloys. They can be used in a typical lab environment and can be easily placed in clean rooms. Both have the ability to produce autogenous welds, i.e., weld the two parts directly without having the need to add additional material as in brazing or soldering. However, there are many differences that were discussed in the earlier sections and are listed in Table I. One of the main differences is the type of bond formed by the process. Resistance welding offers three choices including solid-state, fusion, and reflow solder/braze whereas laser welding produces a fusion weld only. The second major difference is that resistance welding produces an internal weld which typically does not require shielding gas but requires greater real estate on the part. On the other hand laser welding produces external welds where only a small volume of material needs to be exposed but often requires shielding gas. Resistance welding is better suited to weld fine foils and wires while laser welding is robust for producing hermetic seam welds. Selection between the two processes

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should be done carefully and in keeping the capabilities and limitations in mind so that the manufacturing process is robust.

References:

1. Resistance Welding Manual, Fourth Edition, Resistance Welder Manufacturers' Association (RWMA), 1900 Arch Street, Philadelphia, PA 19103.
2. Kelkar, G.P., "Why use multiple-impulse resistance welding? : An explanation of the process, its heat balance mechanism," pp. Practical Welding Today, Nov/Dec 2004.
3. Duley, W.W, Laser Welding, New York, John Wiley & Sons, 1998.
4. "Method of Welding Titanium and Titanium Based Alloys to Ferrous Metals," Patent No. 6,875,949 B2, Edison Welding Institute, Columbus, OH.

Table I. Summary comparison of resistance and laser welding process attributes.

Feature	**Resistance Welding**	**Laser Welding**
Contact Process	Yes	No
Type of Bond	Fusion, Solid-state, Solder/Braze	Fusion
Weld Type	Internal	External
Direct Feedback	Yes	No
Shielding Gas	Not required	Required for some metals
Welding Thin foils and fine wires	Easier	Difficult

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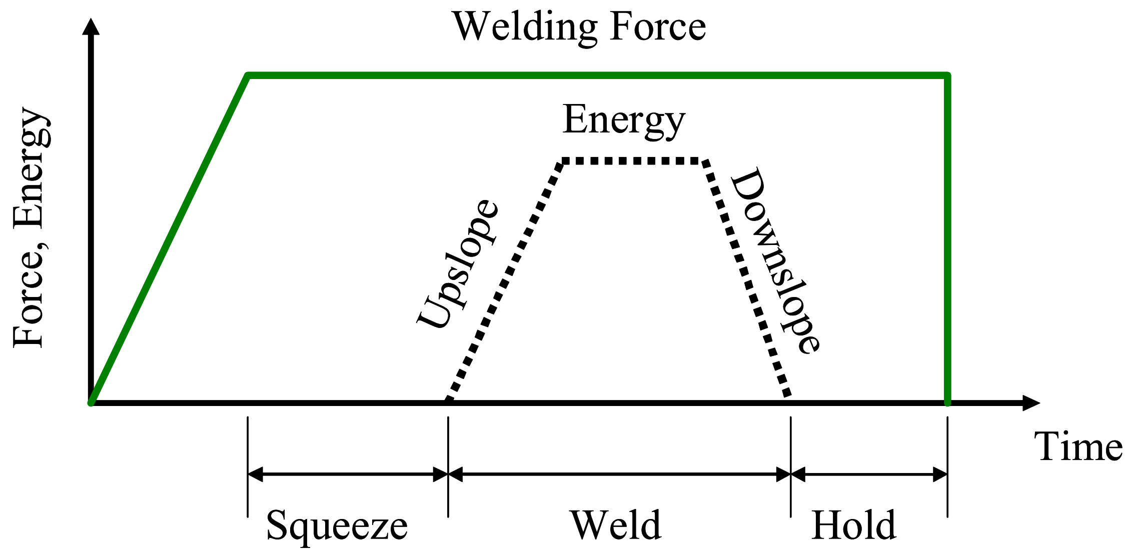

Figure 1. Schematic showing the time diagram for resistance spot welding.

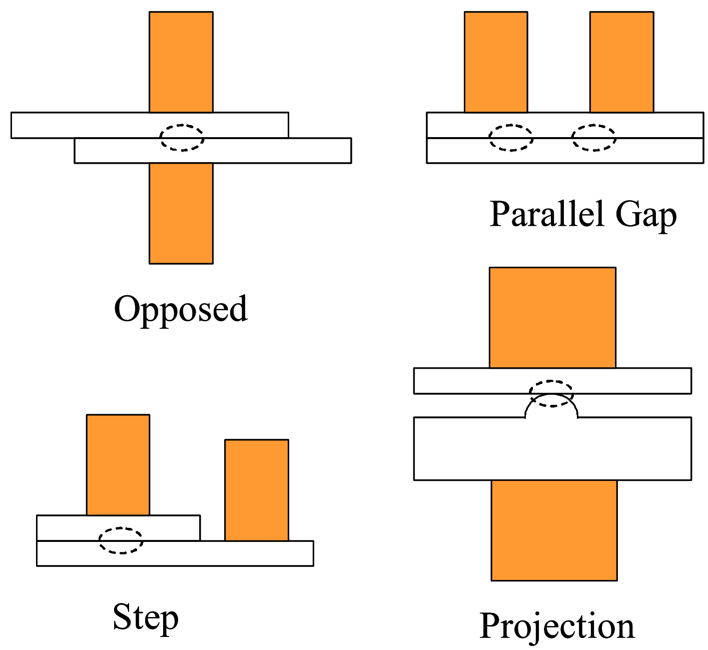

Figure 2. Weld configurations commonly used for resistance welding. Electrodes are shown red in color and the weld location is shown as an ellipse with a dashed line boundary.

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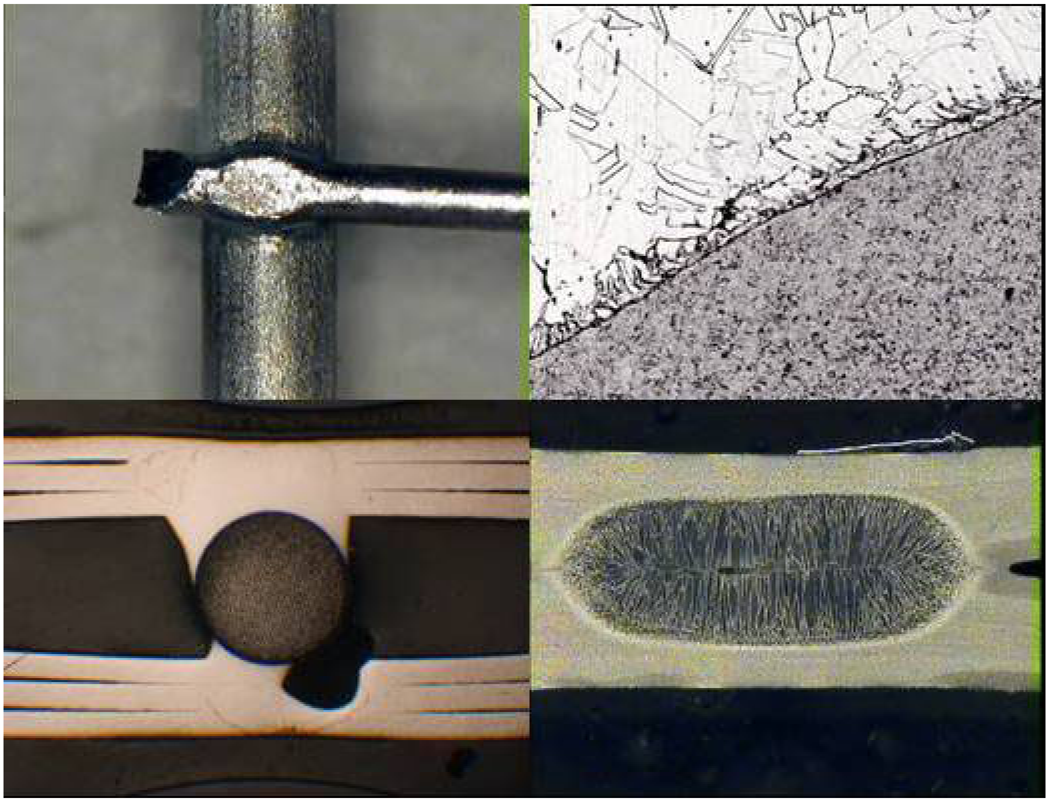

Figure 3. Photographs of resistance welds. Clockwise from top left (a) Nickel wire weld to an alloy post, (b) Solid-state bond interface showing distinct weld line, (c) weld nugget formed in a fusion bond, (d) braze formed by molten steel on refractory metal pin.

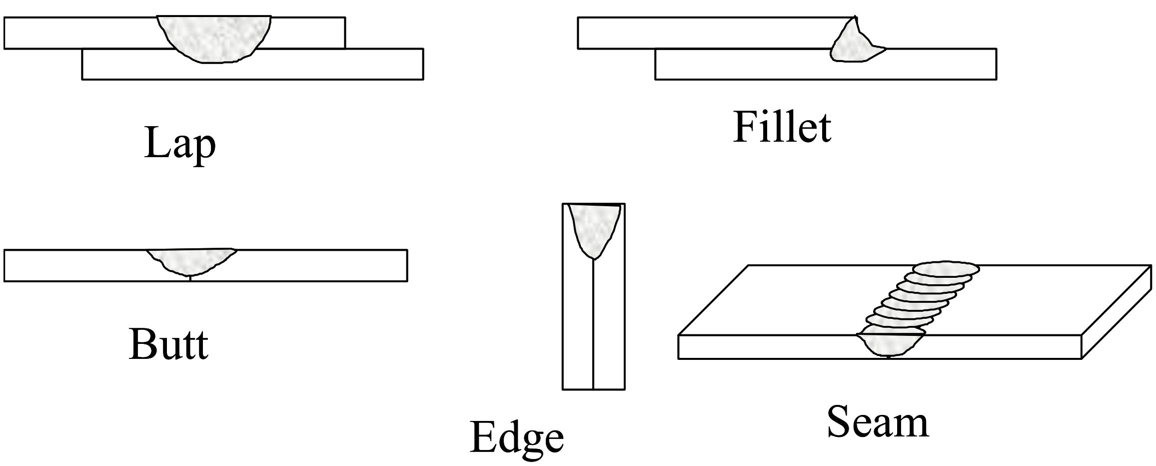

Figure 4. Schematics of weld configurations for laser welding. Fusion zones are shaded. Any of the configurations can be seam welded with overlapping spot welds.

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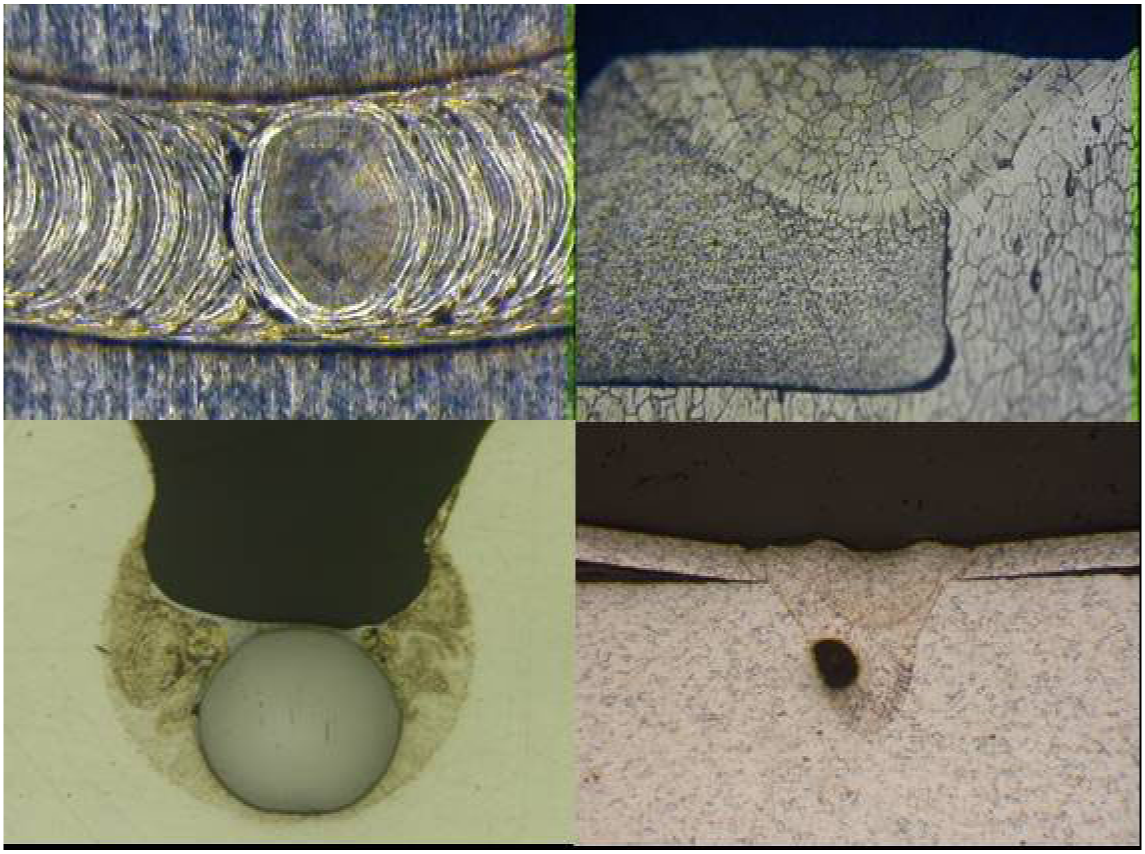

Figure 5. Photographs of laser welds. Clockwise from top left (a) lap seam weld showing overlapping pulses including the last pulse, (b) butt weld between two components showing offset pulse location, (c) cross-section of weld in (a); note formation of porosity in the weld, (d) braze formed by a lower melting alloy on a refractory metal wire.