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PULSED LASER WELDING

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Laser welding is finding growing acceptance in field of manufacturing as price of lasers have decreased and capabilities have increased. Laser welding is unique since it offers non-contact autogenous welding process that is not affected by the electrical conductivity or magnetic properties of the materials being welded. Lasers can be used in pulsed or CW (Continuous Wave) mode. In pulsed mode, laser welds are similar to resistance spot welding and in CW mode they are similar to arc welding processes. While CW mode is common for larger structural welds and competes with arc welding processes, pulsed welding is common for welds in smaller components such as pacemakers, microwave enclosures, batteries, and sensors. Lasers can be used in pulsed mode to make seam welds where overlapping pulses are able to produce a hermetic seal.

The laser pulse has many features that need to be understood to fully appreciate and capitalize on the benefits of laser welding. This paper will discuss all aspects of the laser pulse including initial coupling, weld fusion, and cooling. Combination of these features can be effectively used to control weld penetration, weld size, welding mode (conduction vs. keyhole), residual stress, and related defects such as porosity and cracks.

KEYWORDS: Pulsed Laser Welding, coupling, fusion, cooling rate, residual stress, cracks, porosity.

INTRODUCTION

There are many attributes of laser light that are uniquely suited for laser welding. A beam of laser light is monochromatic (single wavelength) and collimated (parallel) and hence can be focused down to a very small spot where the photon density is high enough to melt metals and alloys in a matter of milli-seconds. Laser wavelengths are typically identified by the laser source used to produce laser light. The most commonly used for pulsed welding is 1.064 micron Nd:YAG wavelength that has the option of being transmitted through an optical fiber. A new generation of lasers called fiber lasers also have similar wavelength where the laser light is produced in the fiber itself. Fiber lasers have the benefit of producing good beam quality and hence can have much longer working distance (distance between lens and work piece), of the order of ten inches as compared to about two inches for conventional YAG lasers. Another source commercially available is the 10.64 micron CO_2 laser, thought that is more often used for continuous wave welding rather than for pulsed welding.

The laser beam can travel through air or vacuum with minimal loss of energy. In some applications, the entire laser delivery hardware including focus head and fiber can be mounted inside a glove box where the environment is controlled for oxygen and water vapor contamination as is necessary for welding of Titanium. If required, the controlled environment can be produced in a more confined space with the laser energy being delivered through a quartz window.

Laser welding does not require that the part being welded be electrically conductive as is required for competing technologies including resistance welding, arc welding, and electron beam welding. Consequently, lasers have been used to weld all types of materials including metals, ceramics/glasses, and plastics. In welding of metals, all the laser energy is absorbed on the surface of the metal where as in glasses, part of the energy is absorbed on the surface while the remaining portion is absorbed in the bulk. Welding of plastics is performed by facilitating absorption of laser energy at the weld interface either by using an absorptive layer or having one of the plastic be colored for preferential absorption.

Perhaps the most important aspect that has led to the growing use of lasers for welding is the ability to make spot welds. A laser beam focused down to a spot can heat, melt, and solidify metals in a matter of milli-seconds with minimal disturbance to adjoining volume of material and components. Consequently, laser spot welding is finding ever increasing applications in all segments of manufacturing including medical devices, sensors, batteries, and microwave enclosures. Along with growth in applications, there has been substantial improvement in laser power supply capabilities including closed-loop feedback and pulse shaping. As laser pulse welding is pushed to its limits in new and unique applications, it will be increasingly important to have good understating of the laser pulse and its effect on the parts being welded. This paper presents insights into the anatomy of a laser pulse and its effect on weld size, shape, residual stress, and defects.

ANATOMY OF A LASER PULSE

A laser pulse can be divided into three different segments: coupling, melting, and cooling. Even though the time frame for each segment is of the order of milli-seconds, and functions of each segment blend into the other, understanding the functionality of the three segments allows the user to carefully tailor the welding pulse to produce a desired result. Typical shapes of coupling pulses are shown schematically in Figure 1.

COUPLING

Metals and alloys are not transparent to laser light. Photons in the laser beam that hit a metal surface are either absorbed or reflected. Most metals/alloys are good reflectors of laser light at room temperature. Figure 2 shows a chart of room temperature absorptivity of typical metals as a function of laser frequency [1]. Consequently, majority the initial photons that hit the weld area are reflected from the surface. Energy from the select few photons that do get absorbed is converted to heat and raises the local temperature of the metal surface. As temperature increases, so does the absorptivity at the weld surface, and more of the photons that follow are absorbed. Increase in absorptivity with temperature leads to a chain reaction and in a very short time practically all the photons impinging on the weld are absorbed and the weld zone reaches melting point (Figure 3). This process of transitioning from initial photon reflection at room temperature to majority photon absorption in molten state is defined as coupling.

Coupling is affected by many factors. Coupling can be accelerated by photon density; higher the peak power at the beginning of the pulse, faster the rate of coupling and hence shorter the time it takes to couple. Coupling is also affected by surface conditions that can affect absorptivity. Oxides are better absorbers of laser energy and hence a thin layer of oxide can help. Coupling is also enhanced at a rough surface as compared to a smooth one; such a rough surface can be produced intentionally at the weld location by etching, machining, or stamping. Laser light is better absorbed by darker colors and hence a layer of graphite on the surface, in the form a pencil line drawn on the surface has been shown to increase coupling on materials that are highly reflective at room

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temperature. Coupling can also be affected by weld geometry; a butt weld configuration with a slight gap can provide an excellent improvement in coupling since the laser light is forced to go down the gap and provide multiple opportunities for absorption.

FUSION ZONE

Once coupling has been established, the next phase of pulse begins in establishing the weld fusion zone. At low power densities, the photons are absorbed only on the surface and heat generated is then dissipated into the interior of the metal via conduction; this type of welding is called conduction mode welding [2] and is shown schematically in Figure 4. Once the metal in the fusion zone is molten, some of the heat is also transferred to the interior by convection currents. Weld fusion zone produced by such a mode tends to be shallow and bowl-shaped. Figure 5 shows sections of typical laser welds.

At higher power densities, the weld molten metal opens up due to high pressure plasma and forms a keyhole (Figure 4). Formation of a keyhole allows the laser beam to go deeper into the metal. The photons now are absorbed below the surface and have the opportunity for multiple reflections thus further increasing effective absorptivity. Weld penetration in keyhole mode is conical in shape with higher aspect ratio. In pulsed mode, the keyhole that opens up during each weld pulse is closed at the end of the pulse. Freezing of the molten metal at the end of the weld can lead to entrapment of the high pressure plasma at the bottom of the keyhole leading to formation of a pore, as seen in Figure 5B.

During the second phase of the pulse, it is important to control weld temperature to ensure that the weld is well supplied with energy at the same time ensuring that the weld is not getting overheated. Excessive heating rate can cause weld metal being thrown out of the fusion zone in form of weld spatter. Control of weld temperature is easiest for high melting alloys such as stainless steels that are reasonably good absorbers of YAG laser photons. Controlling weld temperature without overheating is difficult for alloys of Aluminum which are good reflectors, have low melting point, and melt in a narrow temperature range. Since typical pulsed laser welds are of very short duration in the range of 1-10 milli-seconds, direct measurement of weld temperature is difficult and has to estimated based on weld results.

COOLING

The molten metal volume created during the second phase of the pulse is surrounded by a large mass of solid metal. If the laser pulse is terminated abruptly after establishing fusion, the weld will cool very rapidly. In fact, the pulsed laser spot weld has one of the fastest cooling rates, perhaps second only to resistance spot weld. Such fast cooling rates can cause many issues including trapped porosity, high residual stress, cracks, and excessive weld metal hardness. Some of these issues can be alleviated by controlling the cooling rate.

WELD SIZE AND SHAPE

Size and shape of the weld fusion zone developed during the pulse depends on input power density (combination of peak power and spot size), thermal diffusivity, and weld duration. Short duration pulses of high peak power produce a deeper weld but can also lead to excessive spatter. Pulses of lower peak power and longer duration produce a shallower weld with less spatter. Weld size, as measured by diameter on the surface, grows till it reaches a steady state once balance between heat absorbed and heat dissipation is established [3], as shown schematically in Figure 6. Weld penetration, as

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measured by the weld depth, is related to peak power and rapidly establishes steady state (Figure 6). When welding dissimilar materials, the weld nugget shape may appear non-symmetrical and is due to differences in thermal diffusivities and/or absorptivities, as shown in Figure 5C and 5D.

WELD POROSITY AND SPATTER

Some of the common weld defects that can be controlled with changing the pulse shape are weld spatter, porosity, and cracks. Weld spatter is defined as the molten metal droplets that are thrown out from the fusion zone. Spatter can be controlled by reducing the peak power and reducing the weld temperature. However, changing those settings can also lead to a reduction in weld penetration. Porosity can form in a laser weld for multiple reasons. One reason is the rapid closing of the keyhole at the end of the weld pulse. A longer cooling segment can be utilized and encourages the porosity to rise to the top; depending on the depth of the weld, the porosity may not be completely expelled from the weld. Porosity can also form due to gases released when contaminants are vaporized. To avoid such porosity, a longer upslope should be utilized to assist in burning away the contaminants before fusion is established. A low energy pre-pulse can also be used, if required. Another reason for porosity is vaporization of low vapor pressure materials such as zinc in galvanized and galvannealed steel. It is difficult to control such porosity by pulse shaping alone and it is recommended that the zinc plating be removed prior to welding. Pores can form in presence of gases that have high solubility in molten metal but poor solubility in solid metal. An example is pore formation due to release of hydrogen as molten Aluminum solidifies. Hydrogen is often accidentally introduced in the form of moisture absorbed in the surface oxide layer or water vapor present in the shielding gas.

WELD CRACKING

There are three main criteria for cracks to form in welds including presence of a defect, high stress state, and brittle material. Microscopic defects are present in practically all welds and are difficult to avoid. Additionally, the weld configuration often introduces geometry defects that provide locations of high stress concentration that can start a crack. A high state of stress is often present in all welds and especially spot laser welds that have one of the highest cooling rates of all welding processes. Such stress, especially in brittle materials such as high-carbon steels, can often lead to cracking. Rapid multi-axial cooling in a three dimensional molten metal can often lead to very high stresses and cause cooling cracks even in apparently ductile metals such as Aluminum. Cooling stresses can be effectively reduced by introducing a relatively long cooling segment after the fusion pulse. Slow cooling can reduce martensite fraction in hardendable steels. Cracks that are typically related to cooling stresses are shown schematically in Figure 7 and will appear transgranular in weld sections. Stresses induced due to welding are not the only reason for crack formation; cracks can also form due to metallurgical issues and due to excessive constraints on the weld due to part design and fixturing.

SUMMARY

Laser welding is a non-contact autogenous welding process that is an excellent choice for making spot welds. A laser pulse that produces a spot weld has multiple components including coupling, fusion, and cooling segments. Understanding contributions from each is critical to developing a robust welding process that produces a desired weld without any associated weld defects.

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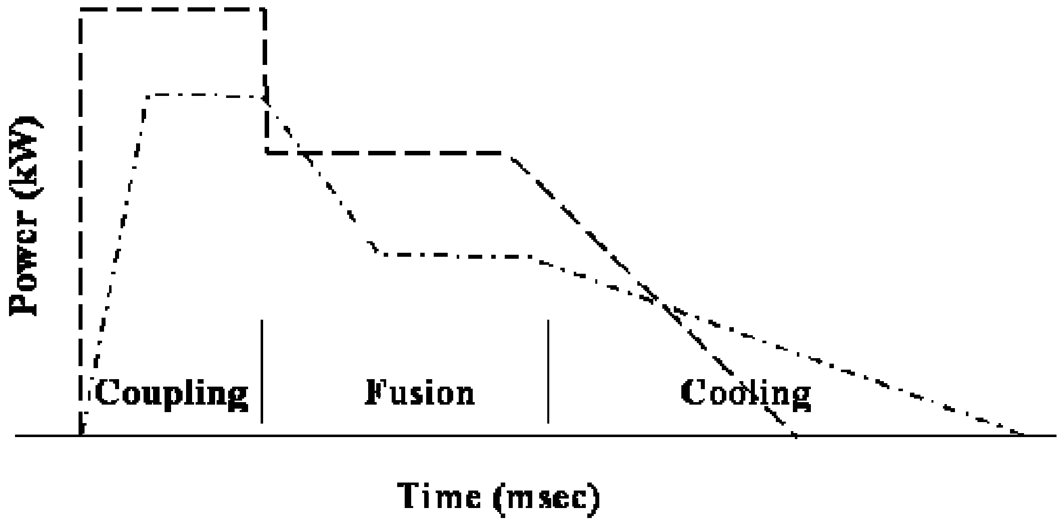

Figure 1. Anatomy of a laser pulse showing coupling, fusion, and cooling segments for two typical pulse shapes. Pulse times, shapes, and energy/power per segment, can vary based on application.

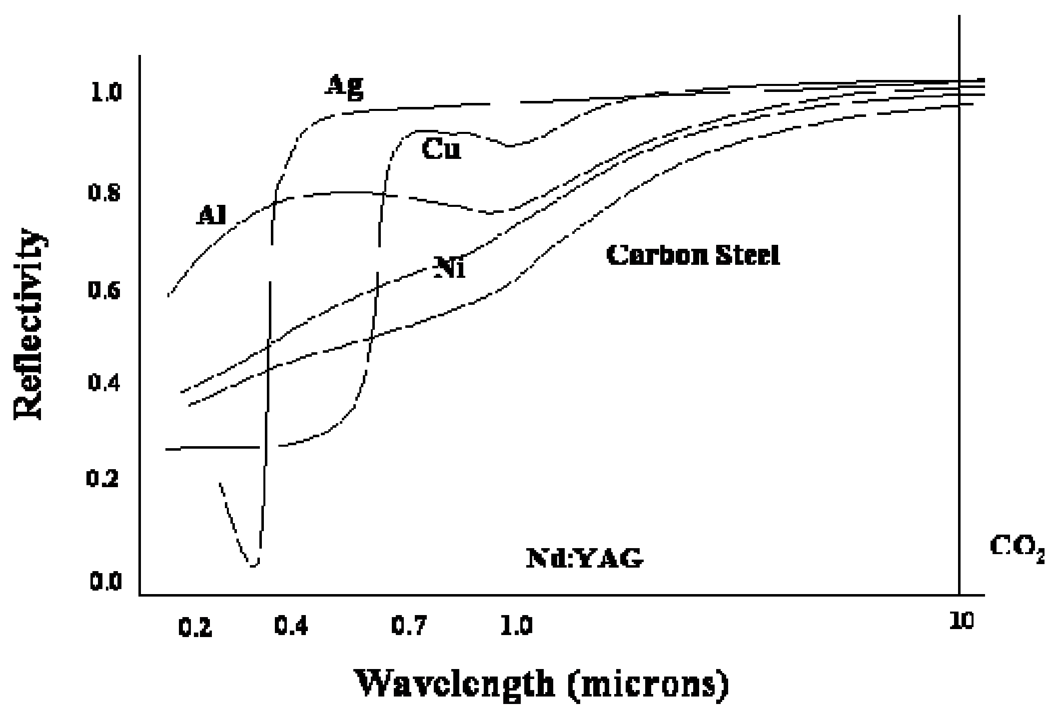

Figure 2. Absorption of laser energy by metals at room temperature. Note that metals that are white in color such as silver are good reflectors of YAG laser light. Metals that are grey in color such as steels are good absorbers of laser light at room temperature.

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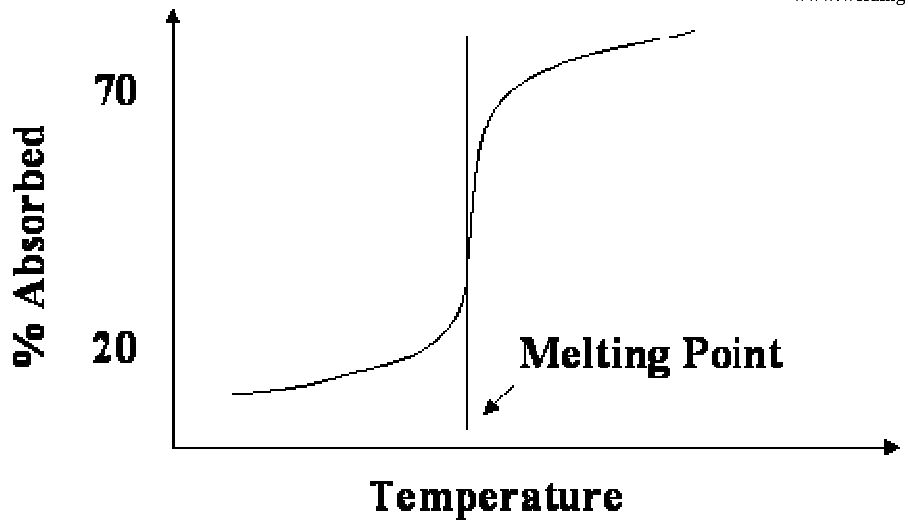

Figure 3. Schematic shows increase in laser absorption with temperature; absorption increases dramatically as the metal melts. The shape of the absorption curve varies for different metals but overall shape is similar.

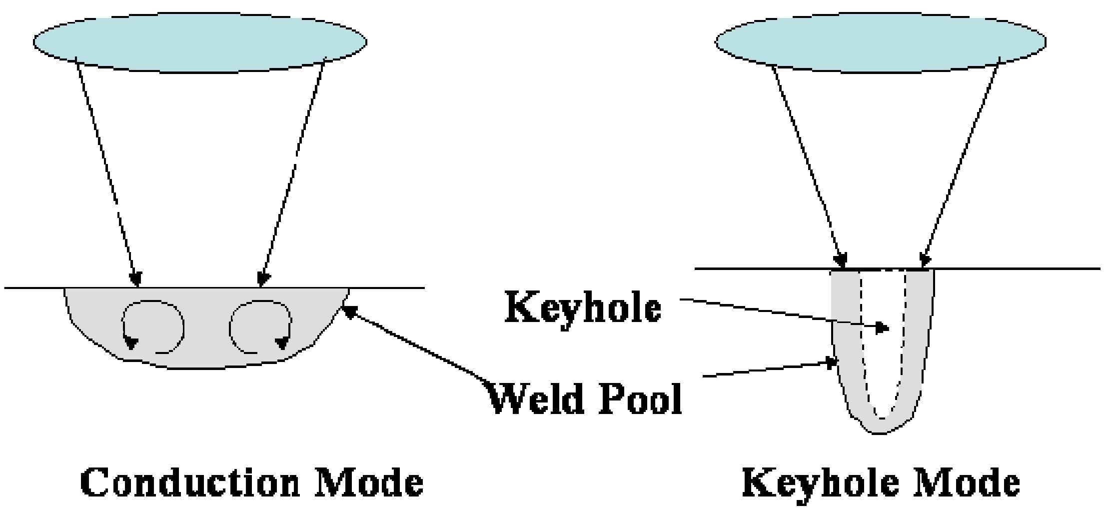

Figure 4. Schematic sections of welds in conduction and keyhole modes. Conduction mode welds are wide and shallow where as keyhole mode welds are narrow and deep.

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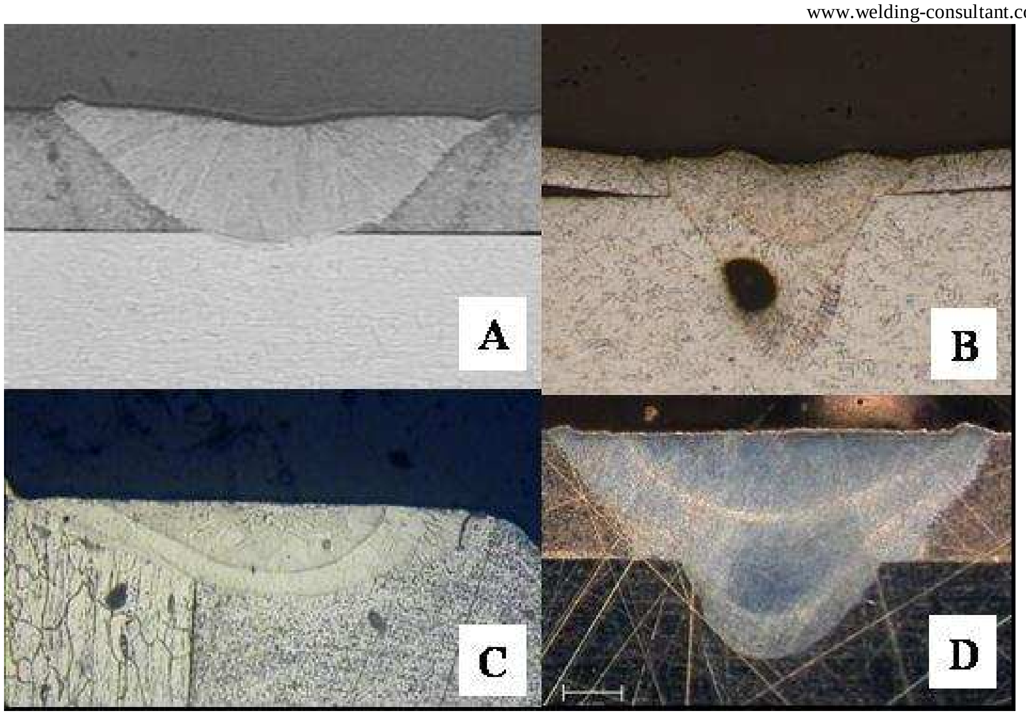

Figure 5. Laser weld cross-sections showing shallow conduction weld (A), pulsed keyhole weld (B), and weld sections affected by difference in thermal diffusivity (C) and reflectivity (D) of the two parts being welded.

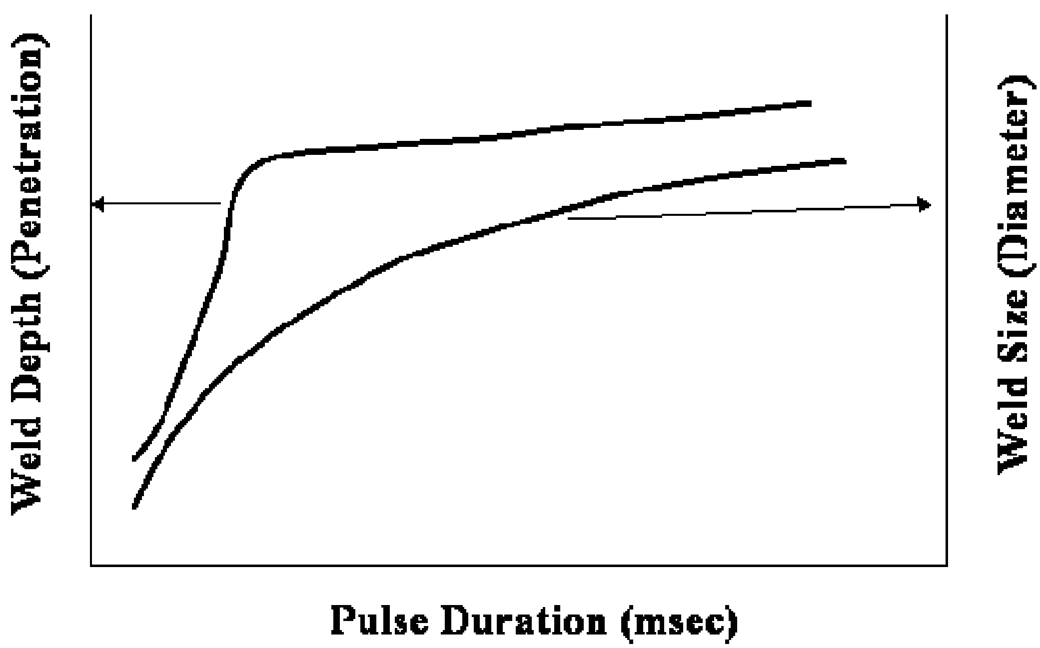

Figure 6. Graph showing effect of time on weld penetration and weld size at a given peak power.

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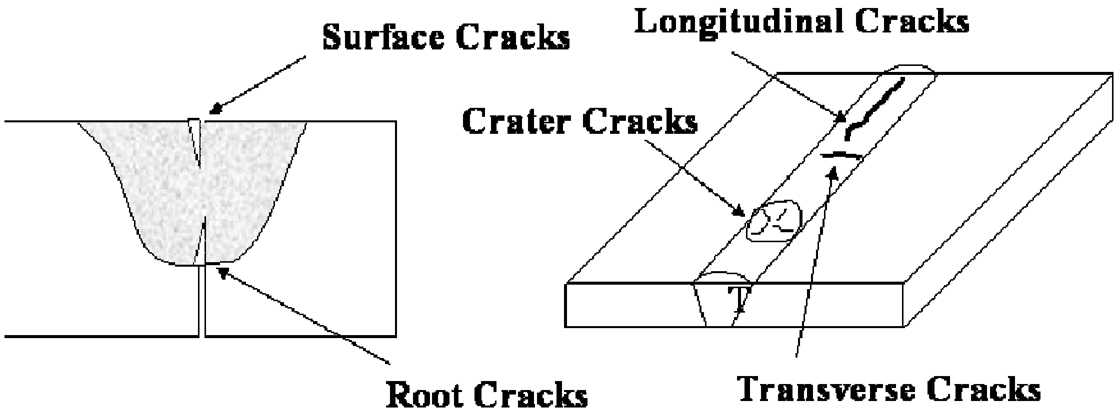

Figure 7. Schematic showing typical locations for crack formation during rapid cooling induced stresses. Other factors such as part restraint and materials could also affect residual stress and cracking.