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FUNDAMENTALS OF METALS JOINING WITH LASERS

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Background

The intrinsic characteristic of a laser as a metals joining heat source is high intensity (high irradiance). Other advantages stem from the ability to optically manipulate the beam and the inertness of light. Optimal application of laser technology to metals joining is supported by a fundamental understanding of the physics of the process. The interaction of the laser beam with metals is highly materials and process dependent. Metals joining with lasers in an absence of an understanding of beam-materials interactions would appear to be a highly unpredictable process. This is because of the complexity of beam-material interactions. For example, absorptivity varies by more than an order of magnitude as a function of alloy, temperature, oxide thickness, and laser wavelength. Also, in most laser welding and brazing processing, evaporation of metal creates a significant plume, and beam-plume interactions can markedly alter the spatial distribution of energy at the plume-metal interface. The probability of the beam being absorbed by the plume increases with the square of the wavelength, whereas the propensity for scattering of the beam by particles in the beam is inversely proportional to wavelength. Also, the beam can be refracted due to thermal and compositional gradients in the plume. In selecting a laser process for a given application, understanding each of these physical effects and others is helpful. In many ways, the physics of metals joining with lasers is only qualitatively understood at the present time. This paper overviews the present understanding of the process and identifies areas where research is required to clarify our process understanding.

The Applied Lasers Processes

Lasers have been applied to the joining of metals. Specifically, lasers have been used in soldering, brazing, solid-state welding, and fusion welding. This papers only deals with the currently more important of these processes, soldering and fusion welding.

Fusion Welding

Fusion welding is easily the most mature of the the laser metals joining processes. Most fusion welding has been done with CW CO_2 or pulsed Nd:YAG lasers, although both pulsed CW CO_2 or CW Nd:YAG lasers are not new processes. Recent improvements in Nd:YAG laser technology that provide high quality beams in excess of 1500 watts average power will increase the importance of CW Nd:YAG lasers in fusion welding.

Many applications of laser welding stem from the advantages afforded by the ability to precisely, optically manipulate a small diameter heat source and the inertness of light. They involve what welding engineers term conduction mode welding, where laser energy is deposited at the upper surface of the weldment and energy is transferred with the weld either by conduction or convection. Fuerschbach has shown that the potential advantage of the high irradiance of lasers does not come into play during conduction mode welding[1]. Lasers can be used to produce weld geometries of higher aspect ratios (Depth/Width), and in these situations the high intensity of laser beams becomes important. This is especially true of welds made with high power (multi-Kwatt) CO_2 lasers and pulsed Nd:YAG lasers (typically observed at greater than $5x10^3$ watts/mm^2). The new high-powered CW Nd:YAG lasers also can produce welds with higher aspect ratio welds than can be achieved by pure conduction mode welding[2].

Laser Soldering

As electronic devices become increasingly smaller and packaging densities become increasingly higher, there is a growing realization that hand soldering and mass soldering techniques place geometrical limits on electronic assemblies. Laser soldering has been investigated as a possible alternative to conventional soldering techniques and some of the advantages of laser soldering have begun to become recognized.

As with laser welding, the ability to precisely, optically manipulate a small diameter, chemically inert heat source has been the principal motivator in the investigation of laser soldering. The intrinsic high irradiance of lasers generally has not been utilized in laser soldering, since power densities used seldom are in excess of 10^3-watts/mm^2. Rather the reasons for selecting laser soldering over conventional soldering processes relate to the fact that lasers can accurately deliver small quantities of energy to the precise locations to be soldered and within dimensions required of microminiature devices. A number of potential advantages stem from this capability. The most obvious is the ability to solder heat sensitive devices since little heat is delivered to the devices themselves. Metallurgical advantages also accrue from the low heat input. More rapid solidification results in finer grain structure[3,4]. Short solder times result in significantly less intermetallic compound formation between the solder and the metallization/substrate[4-6]. Localization of heat also affords some assembly advantages. Bridging can be minimized, and the need for solder masks is eliminated because areas between conductors are not heated and, when desired, adjacent conductors are not heated simultaneously. Also, when desired, standoff distances for surface mounted devices can be maintained by melting only a portion of the solder associated with a device at a time, thus avoiding floating the device on molten solder. A potential disadvantage of laser soldering regarding the tendency to produce the so-called "tombstone" or tipped device can be turned into an advantage by simultaneously delivering the required amount of energy to more than one location of the device by means of multiple beams. Localization of heat also supports populating both sides of a board, soldering of devices already attached to heat sinks, rework operations, and

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control of thermally induced stresses. The localized nature of the heat source minimize the possibility of melting solder in adjacent locations or on the other side of the board. The localization of heat by lasers has frequently been cited as a hindrance to high production rate soldering. There are approaches for overcoming this potential disadvantage, such as multiple optical fiber delivery and incorporation of fiber optic delivery with pick-and-place mechanisms. The latter could eliminate a separate soldering assembly step.

Fundamentals of Fusion Welding with Lasers

Laser welding shares fundamentals with other fusion welding processes. Both the experimental and theoretical studies that have advanced the understanding of fusion welding processes revolve around delineating the roles of mass, momentum, and energy transfer. The foundation was in early conduction heat transfer models that assumed point heat sources and excluded much of the physics of the processes. The development of numerical models, using both finite element and finite difference methods, has been the key to developing a base of understanding heat and mass transfer in fusion welding processes, in general, and laser welding, in specific. Conduction and convection within the weld pool during laser welding has much in common with other fusion welding processes. The uniqueness of the process is related to how energy is transferred from the laser beam to the weld pool and the potentially high intensity of laser beams. Not surprisingly, the understanding of laser welding is best in those areas that overlap with other fusion welding processes. Research in other aspects of the process is still creating as many new questions as it is answering.

Modeling of Weld Pool Geometry

Development of numerical laser welding models has often started with a conduction heat transfer solution[7-10]. That is, although radiative and convective heat losses to the surroundings may be included in the solution, heat transfer within the metal is considered to occur by conduction only. Comparison of experimental results with conduction models can be very useful in determining the factor space where convection heat transfer dominates and in identifying missing physics. For example, application of Russo et al. two-dimensional conduction model[9,10] determined that vaporization is an important phenomenon during laser welding and that the fraction of the incident laser beam that is absorbed is a parameter that must be included in the determination of the temperature field. The energy available for fusion is dependent on the energy lost to evaporation. Measured values for mass losses and plume velocities were an order of magnitude lower than predicted by Russo et al. indicating, not only that evaporation was important, but that some of the important physics of plume formation was unknown.

<u>Conduction-Mode Welding.</u> Weld pool convection has become recognized as one of the most important fundamentals of fusion welding and experimental studies have confirmed that this is no less true for laser welding. Weld pool geometry (especially at the intermediate generally used in production laser welding) is generally influenced by convective heat transfer[11,12] and surface ripples result from convection[13,14] as does also compositional mixing[15]. Convection in a weld pool is illustrated in Fig. 1, which is a metallographic section of a single-pulse Nd:YAG laser weld of aluminum alloy 5456. Frozen convection patterns are clearly seen near the edge of the weld pool, including a weak convection cell nearer the center on the right side. The convective flow patterns are revealed by etching because evaporation of magnesium and manganese during welding resulted in compositional inhomogeneity. Similar experimental evidence of convection during laser welding has been observed for austenitic stainless steel[16].

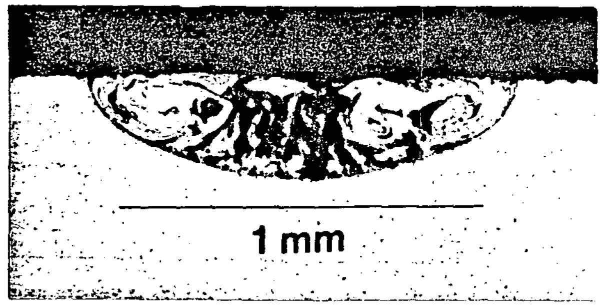

Figure 1. Photomicrograph exhibiting convection cells in pulsed Nd:YAG laser weld of aluminum alloy 5456 (5 ms 14 J/pulse).

In the case of laser welding, buoyancy forces and surface tension drive weld pool convection. Since the early eighties, much of both the experimental and theoretical process research on laser welding has concerned the role of surface-tension-driven fluid flow, termed Marangoni convection[17-28]. For most pure metals, Marangoni convection is radially outward at the weld pool surface, which results in convection of heat to the edges of the weld. There are exceptions, notably austenitic stainless steel with small amounts of surface active elements such a S, O, and Se, where Marangoni convection is markedly altered and becomes radially inward at the surface, which tends to convect heat to the bottom of the weld pool[16-18]. The effect of Marangnoni convection on weld aspect (depth/width ratio) has been shown to be very important by both theoretical and experimental studies[16,20,21]. As compared with the pure conduction mode case, deviations of up to 150 percent have been predicted and observed.

<u>Penetration-Mode Welding.</u> Laser beams are also capable of producing penetration-mode welds similar to those often achieved by electron beam welding. In penetration-mode welding, the laser beam is focused onto or below the surface of the workpiece at sufficient irradiance to produce a metal-vapor-filled cavity, or "keyhole", (see Fig. 2). Dynamic equilibrium is

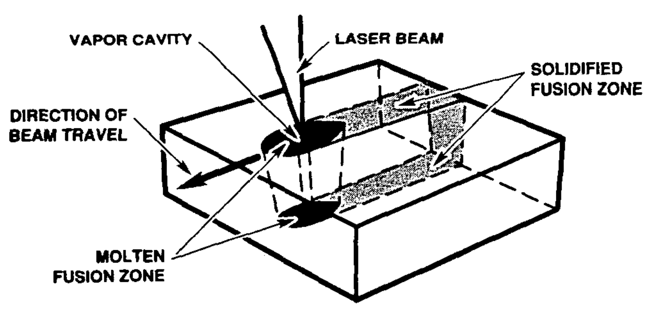

Figure 2. Deep-penetration laser welding. (After American Society for Metals, Metals Handbook, 9th ed., vol. 6, 1983)

established between a molten metal layer and the "keyhole" and this high aspect weld pool is translated through the metal being welded. Modeling of penetration-mode laser welding has demonstrated that the general geometry of these welds is predictable[29,30], although details regarding the geometry near the surface and generation of porosity near the root of the weld remain to be understood. Also, both modeling and experimental measurement of the surface temperatures within the "keyhole" have shown important temperature variations from top to bottom that influence not only fluid flows, but solidification times and, consequently, solidification structure[30,31]. Heiple et al. found that surface active elements have much less effect on weld geometry for penetration-mode welds than for conduction-mode welds[17], since the geometry of the former is mostly related to the geometry of the vaporized "keyhole," whereas the geometry of the latter is determined by convection.

Many laser welds produced in production at intermediate irradiances are believed to represent a condition accurately described by neither conduction-mode welding nor penetration-mode. Rather, the surface of the weld pool is depressed through a synergistic phenomenon resulting from reaction forces to evaporative and convective flows, rather than primarily by evaporative losses. These welds represent a conditon leading to penetration-mode welding but where a fully developed "key-mode" does not exist.

Coupling of Laser Energy into the Weld Pool

The ability of the numerical models of the weld pool to predict geometry, convective vectors, heating, and cooling rates, and local solidification times is dependent on the accuracy of the knowledge of the spatial and temporal distribution of energy incident on the weldment surface. In addition, the composition and structure (type and distribution of solid phase particles) of the surface influence absorptivity and convection. In view of these factors, a fundamental understanding of how energy is coupled into the weld pool or, stated in another way, the ability to predict the free surface boundary conditions of a laser weld is highly important to the overall understanding of laser welding.

In most practical applications of laser welding, a plume of evaporated metal forms over the weld pool. Both experimental and theoretical studies have been directed at characterizing the role laser of plumes in order to predict the spatial and temporal distribution of heat flux at the weld pool surface[18,33-48]. These studies underscore that the physical process observed for one set of conditions cannot be assumed to apply to others. The relevant physical processes can be expected to depend on materials, welding mode, pulse durations, surrounding atmospheres, and laser wavelength. Beam-plume mechanisms that have been considered include absorption[33-35,37,40,41,43,44,47], Mie scattering[33,39,42], and refraction[18]. The probability of the laser beam being absorbed (inverse) by the plume increases with the square of wavelength, whereas the photon scattering by particles in the beam decreases with increasing wavelength (inversely proportional to the 4th power of wavelength). Thus, plasma absorption is apt to be more important for CO_2 laser welding and photon scattering by particles in the plume is likely to be more important for Nd:YAG laser welding.

<u>Absorption by Plasma.</u> Signification ionization or plasma formation is absent under some conditions[33,44] and present in others[41,43, 47]. Miyamoto et al.[47] observe that absorption of beam energy by an ionized plume during CO_2 laser welding is greater during penetration-mode welding than during conduction-mode welding, which they ascribe to both greater pathlength through the plasma and a higher degree of ionization as a result of the high irradiance required for penetration-mode welding.

<u>Scattering by Particles.</u> The role of particles in scattering the beam appears to be very dependent on both materials and processes. Matsunawa et al.[42] observed significant loss in incident beam irradiance due to scattering during the pulsed Nd:YAG laser welding of titanium[42], whereas Peebles and Williamson found that condensed vapor particles do not appear in the path of the beam during a laser pulse during the pulsed Nd:YAG laser welding of aluminum[33]. Figure 3 from previously unpublished work by Peebles and Williamson shows attenuation of a laser beam due to photon scattering by particles in the vapor plume produced during the pulsed Nd:YAG laser welding of austenitic stainless steel and commercially pure

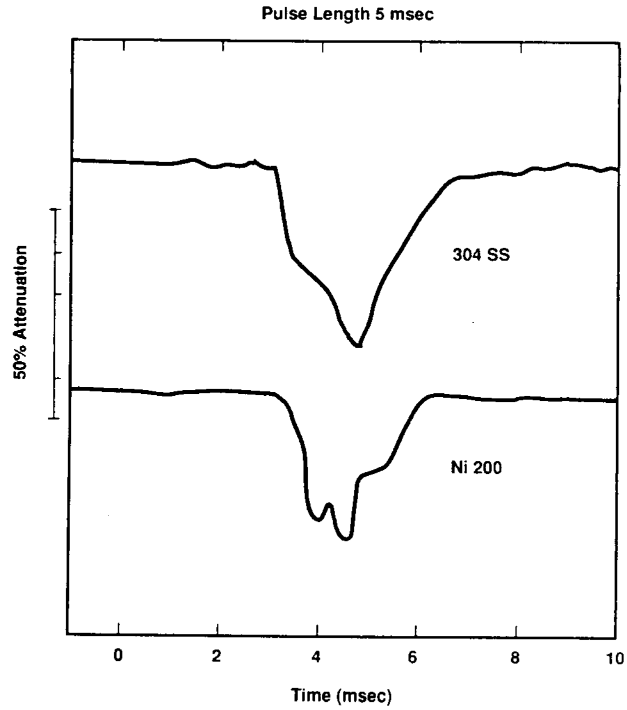

Figure 3. Plot showing attenuation of laser beam due to photon scattering during pulsed Nd:YAG laser welding of 304 austenitic stainless steel and commercially pure nickel.

nickel. It should be noted that these attenuation data were obtained with a He-Ne laser and, consequently, the observed attenuation is greater in magnitude than would be expected for a Nd laser. Matsunawa et al.[42] also found that beam attenuation due to photon scattering by condensed vapor particles is much less significant during welding at sub-atmospheric pressures.

<u>Refraction of Beam by Plume.</u> Results of experiments in ranking pulsed Nd:YAG laser welding of austenitic stainless steel strongly suggested an affect of the laser plume other than scattering or absorption[16,18]. These experiments were accomplished by producing some welds while a purge gas (argon) with a velocity of 30 m/s was directed parallel to the weldment surface to blow most of the plume away. These welds were compared with welds made under normal conditions where the laser plume was present, but under otherwise identical experimental conditions. The effect of the plume on the weld geometries suggested that the plume was altering the spatial distribution of energy at the weld pool surface. To support this interpretation, a Huygens-Kirchoff diffraction code was developed to determine the changes in the laser intensity distribution that could result from the presence of the plume[18]. Because the geometry of the plume varies as a function of time and the temperature distribution within the plume is not well defined, the results of this code are only qualitative. The code predictions, however, clearly indicate that refraction of the beam can both reduce the intensity at the center of the beam to low values at the weld pool surface and spread the energy over an area of significantly larger radius. This would reduce the temperature gradient near the center of the weld pool and, consequently, alter Marangoni convective flow. Figure 4 shows cross sections of two welds made in a low-sulfur (0.005 wt.%) 304 stainless steel. A Nd:YAG laser pulse with an energy of 9.8 J, and a duration of 5 ms, was used in each case. Welds 4a and 4b were made without and with the cross-flow purge gas, respectively. There is a large difference in the weld depth (0.33 mm for 4a and 0.14 mm for 4b) for these two welds. For low-

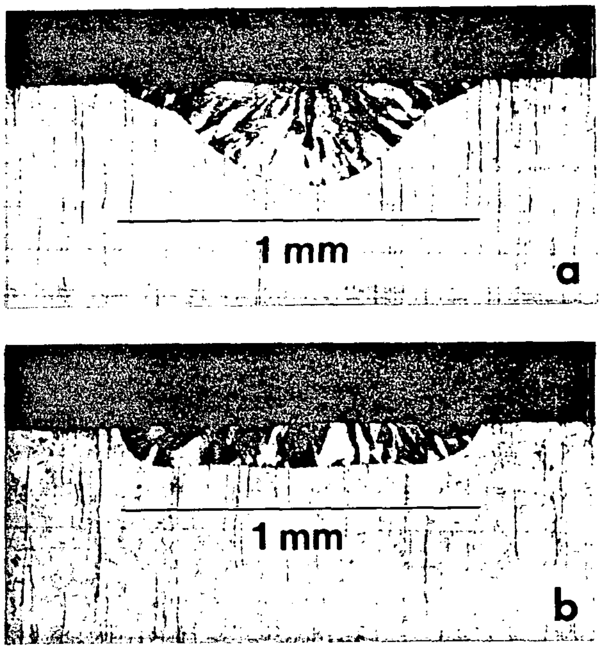

Figure 4. Photomicrographs showing effect of laser plume on weld geometry of low-sulfur 304 austenitic stainless steel: (a) without transverse Ar flow, (b) with transverse Ar flow. Both welds 5 ms, 9.8 J/pulse pulsed Nd:YAG laser weld; 0.005 wt. % S.

sulfur welds, surface tension is believed to be inversely proportional to temperature[11,17]. The argon cross-flow would be expected to reduce the effect of the plume refraction and result in normal or, by comparison, steeper surface temperature gradients. Consequently, the absence of the plume would be expected to increase the convection of heat towards the edges of the weld and result in the wide, shallow weld observed. The consistency of the above argument is supported by the fact that in similar weld geometry comparisons made for high-sulfur (0.05 wt.%) 304 stainless steel, greater weld penetration was observed for welds made with argon cross-flow (see Fig. 5). For high-sulfur welds, sulfur acts as a surface active element that reverses the normal dependence of surface tension on temperature. For high sulfur welds, a higher temperature gradient is promoted by the absence of the plume and results in more convective flow of heat to the center of the weld. This flow continues by coming together and moves towards the root of the weld, which tends to increase weld penetration as was observed.

Instability of Laser Plume. High speed photography of vapor plumes for pulsed laser welds have shown that laser plumes are quite often unstable[40]. They tend to grow with time, collapse, and regenerate multiple times during the period of a given laser pulse. Any of the beam-plume interactions cited above can be used to explain this behavior. Evaporation depends on depositing sufficient energy at the weld pool surface as the combination of flux and fluence reaches the threshold to support evaporation, a laser plume begins to form. At some point, one of the above mechanisms may become sufficiently important to attenuate, or redistribute the incident laser energy so that the flux (or irradiance) is no longer sufficient to sustain the same evaporation rate. Then the plume will begin to diminish in size or collapse. But as the plume decreases in size and density, the incident flux will increase at the weld pool surface and the rapid evaporation will again increase. Thus, if any one or a combination of the above mechanisms becomes significant to the process, the plume formation will be expected to become cyclic. This introduces a significant complication to the modeling of laser welding

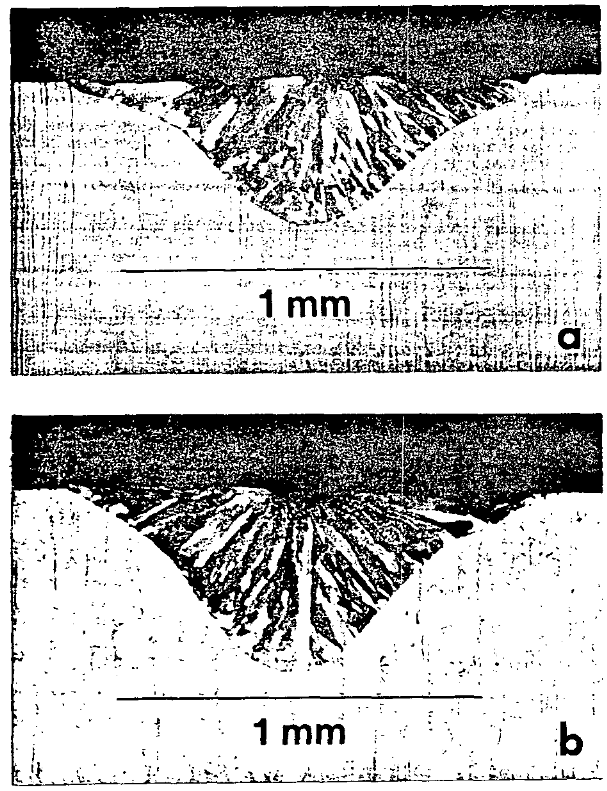

Figure 5. Photomicrographs showing effect of laser plume on weld geometry of high-sulfur 304 austenitic stainless steel: (a) without transverse Ar flow, (b) with transverse Ar flow. Both welds 5.7 ms, 17.3 J/pulse pulsed Nd:YAG laser weld; 0.05 wt. % S.

processes. Perhaps stochastic computational methods will be needed to treat this complex aspect of the process.

Absorption of Energy at Surface. The photonic energy that is not absorbed or scattered by the plume, must still be absorbed by the weldment surface to achieve melting. Russo et al. have applied the Drude "free electron" model to the prediction of laser energy absorption. Their model also includes correction for surface roughness[9,10]. The amount of reflected energy increases with characteristic wavelength. At 0.5 μm the majority of the energy is absorbed by most metals (Ag being a notable exception), whereas absorption is down in the 0-20% range for 10.6 μm light. In practice, absorption is a complex phenomenon that is dependent on material, temperature, surface conditions, including roughness and oxide layers, and angle of incidence. Because these factors change throughout the welding process, absorption is difficult to accurately model. Other mechanisms such as diffusion, evaporation, and even mechanical disruption of surface films are occurring simultaneously that influence absorption.

H. L. Tardy (Sandia National Laboratories) in unpublished work used an integrating sphere (see Fig. 6) to measure the laser energy that was not absorbed during pulsed Nd:YAG laser welding. An example of his data is presented in Fig. 7, which is for welds made on polished and unpolished commercially pure aluminum. This work was done in collaboration with the study of the role of the metal vapor plume by Peebles and Williamson[33]. Their data found no support for significant absorption or scattering of energy by the plume. Consequently, we assume that most of the energy reached the surface and Tardy's data primarily represents the energy reflected from the surface. Particularly interesting is the fact that absorptance for the polished aluminum remains

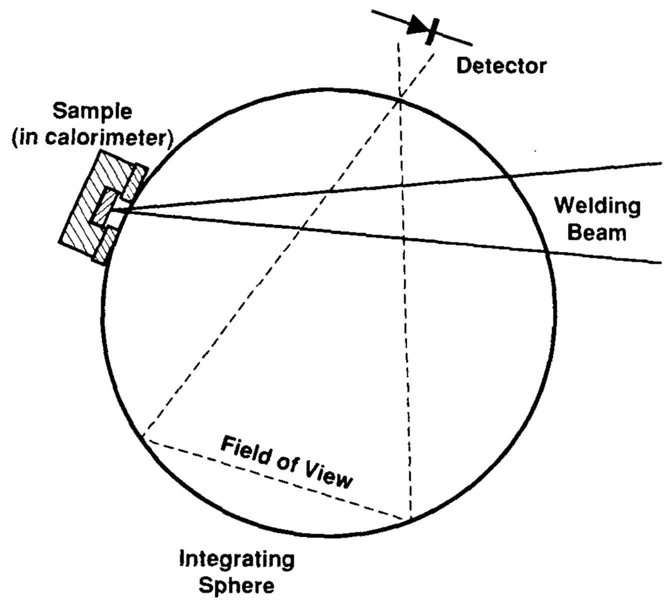

Figure 6. Schematic representation of integrating sphere apparatus used to measure laser energy not absorbed during pulse Nd:YAG laser welds.

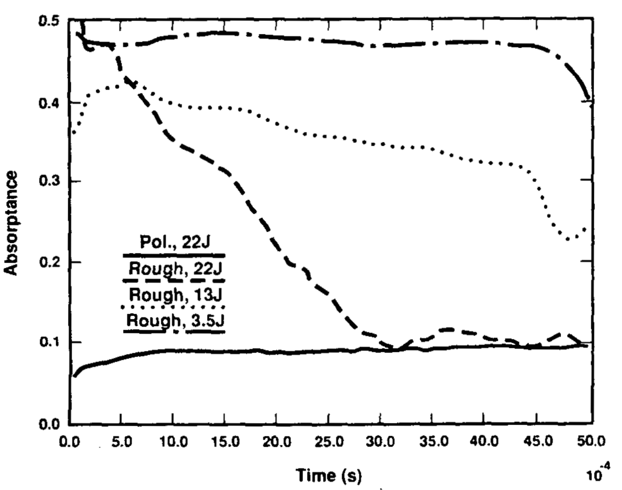

Figure 7. Plot showing absorptance of commercially pure aluminum during pulsed Nd:YAG laser welds for both polished and roughened surface conditions at various laser pulse energies.

relatively constant throughout the laser pulse. The Drude model would have predicted an increase in absorptance with temperature. Perhaps even more interesting is the fact that high rate cine photography revealed that the plume grows and collapses several times under these welding conditions. If this behavior corresponded to absorption of energy by the plume, the absorptance data should have shown a corresponding variation, because the integrating sphere measured all of the laser energy that was not absorbed by the metal. This observation tends to support the Russo et al. diffraction model[18)] because a redistribution of energy incident with the surface could markedly affect evaporation rate without affecting absorption. The decrease in absorption as a function of time for the surface-roughened samples corresponds to the onset of melting.

Fundamentals of Soldering with Lasers

Development of laser soldering has been mostly empirical. In principle, many of the approaches to understanding laser welding are also applicable to laser soldering. Certainly heat transfer models should prove useful in determining the required energy inputs in terms of both temporal and spatial distribution. Also, coupled thermal-stress codes have the potential of predicting thermally induced stresses in soldered assemblies. Analytical models of laser soldering are in fair to good agreement with experimental results with respect to required energy and soldering durations[4,49]. The actual process is complex because absorption of energy is dependent on material, temperature, surface conditions, including roughness and oxide layers, and angle of incidence. In the case of soldering, these factors can vary markedly during the time of soldering, especially surface conditions and angle of incidence. Cox has shown that the absorption of laser energy or fluxed soldered joints can vary significantly over the duration of a laser pulse[50]. Because of these changes in conditions, Whitehead et al. concluded that the spatial distribution of energy should be varied during the laser "on time."[51]. They demonstrated very significant improvements in the wetting of leadless chip carriers to metallization on a printed wiring board by varying the beam energy profile while laser soldering. Conceptually, computer control of both spatial and temporal distribution could be used to improve solder joint quality.

One intrinsic problem encountered in laser soldering is the wide variation in absorptance of the different materials used in soldered assemblies. Solders and most metal conductors are highly reflective, whereas fluxes and board materials may either readily absorb laser energy or transmit it, depending on laser wavelength. Jellison and Keicher found that laser process control can be improved by using a shorter wavelength[52]. They employed frequency doubling to obtain 0.5 μm light from a Nd:YAG laser. Energy absorption is not only much improved for the metals at this wavelength compared to that for 1.06 μm, but the difference in absorption among the various materials is reduced, which makes heating of the metallization without damaging substrates or charring flux easier to accomplish.

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