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Review
Laser welding of dissimilar metal combinations

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The ability to manufacture a product using a number of different metals and alloys greatly increases flexibility in design and production. Properties such as heat, wear and corrosion resistance can be optimized, and benefits in terms of production economics are often gained. Joining of dissimilar metal combinations is, however, a challenging task owing to the large differences in physical and chemical properties which may be present. Laser welding, a high power density but low energy-input process, provides solutions to a number of problems commonly encountered with conventional joining techniques. Accurate positioning of the weld bead, rapid heating and cooling, low distortion, process flexibility, and opportunities for product redesign are its principal characteristics. The review describes the principles underlying laser welding of dissimilar metal combinations and highlights the above benefits in a number of practical applications. It is concluded that there is potential for its application in many industrial sectors.

1. Introduction
Industrial lasers are used for welding, cutting, drilling and surface treatment of a wide range of engineering materials. In the automotive industry, for example, the benefits of laser welding for joining sheet body panels, transmission components, and chassis members have been realized in production [1–5]. The high power density of a focused CO_2 laser beam provides many advantages over conventional joining techniques for rapid, repetitive, high-quality welding of long, straight seams, and axi-symmetric components. Multikilowatt neodymium yttrium aluminium garnet (Nd:YAG) lasers are also available, with the flexibility of fibre optic beam delivery, and their use in the field of complex three-dimensional processing is increasing. Around 30 000 industrial laser systems are currently in use, most having been installed in the last decade, of which about 20% are dedicated to welding [6].

Joints between dissimilar metals are particularly common in components used in the power generation, chemical, petrochemical, nuclear and electronics industries. The ability to use different metals and alloys in a product provides the designer and production engineer with greater flexibility, and often results in technical and economic advantages over components manufactured from a single material. Expensive materials with specific properties can be used in critical locations, with less expensive alloys being used in supporting or connecting roles.

Laser welding provides advantages over conventional fusion joining methods in specific applications in terms of productivity, weld quality, production flexibility, and manufacturing opportunity. Its process characteristics (high power density and low energy input) are particularly beneficial for a range of dissimilar metal combinations, but require special consideration for successful application. This review describes the underlying principles of laser welding of dissimilar metals, reviews recent research and applications work in the field, and compares the potential and limitations of the process with conventional joining techniques.

2. Principles of laser welding
2.1. Process characteristics
Laser welding uses the heating effect of a concentrated beam of coherent, monochromatic laser light to produce a fused weld bead. For a given joint and material combination, the principal processing variables are beam power, focused spot size and welding speed. An inert gas, such as helium or argon, is used to protect the weld bead from contamination, and to reduce the formation of absorbing plasma.

The power density available from an industrial laser beam spans many orders of magnitude, and can attain approximately 10^8 W cm^{-2}. A power density below approximately 10^6 W cm^{-2} allows welding to be performed in the *conduction-limited* mode. The beam energy is deposited on the material surface, transferred into the material by conduction, and a hemispherical weld bead is formed in a similar manner to conventional fusion welding processes. In contrast, a power

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density in the range 10^6–5×10^7 W cm^{-2} is sufficient to initiate local vaporization, and a narrow, deeply penetrating vapour cavity, or *keyhole*, is formed by multiple internal reflection of the beam. The keyhole is surrounded by a thin layer of molten material, and is maintained by an equilibrium between vapour pressure, surface tension and hydrostatic pressure. When the workpiece is moved relative to the beam, material at the leading edge is melted and flows around the keyhole, solidifying to form a deep, narrow weld bead, with a characteristic chevron pattern on the surface. Heat conducted into the surrounding material produces a narrow heat-affected zone (HAZ).

Many of the advantages and limitations of laser welding, in comparison with conventional fusion welding processes, originate from the properties of the focused beam and the keyhole. The high energy density maintains a deeply penetrating weld pool, enabling through-thickness welds to be made rapidly in a single pass. The resulting low energy input produces a small heat-affected zone with limited residual stresses and distortion, minimizing the need for reworking. Rapid cooling rates result in the formation not only of beneficial fine solidification microstructures, and limited HAZ grain growth, but also non-equilibrium phases, some of which may be detrimental to mechanical properties. Because the beam can be focused to a small spot, and is positioned numerically, precise control over the weld-bead location and chemistry are possible, although narrow fit-up tolerances are demanded. Welds can be produced at atmospheric pressure, in contrast to deep-penetration electron-beam welding, and the beam switched rapidly between applications. Capital costs are considerably higher than conventional arc processes, but can be offset by increased productivity, product quality and production flexibility.

An important feature of laser welding is the ability to use filler material, which may be introduced prior to or during processing, in the form of a powder, a preplaced profile or by continuous wire feeding [7–10]. Tolerances on the quality of abutting edges can thus be widened, and the chemistry of the weld metal controlled, the aim being to minimize physical and chemical mismatches between the parent materials. Fig. 1 shows a typical arrangement of shielding gas, plasma-suppression gas, and filler wire. The use of filler wire in laser welding is not currently widespread, principally because of the high degree of control required over the process variables, and the lack of knowledge concerning the properties of the weld produced. However, its use provides solutions in a number of applications, some of which are described later.

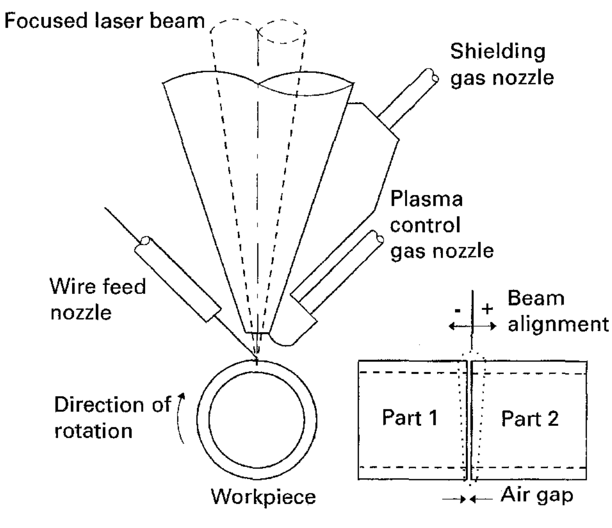

Figure 1 Typical processing geometry for dissimilar metal laser welding of a pipe using filler wire.

2.2. Application of laser welding

The majority of industrial applications of laser welding involve structural and stainless steels. However, as the understanding of the effects of process variables on weld quality improves, its application with non-ferrous alloys will become more common.

2.2.1. Materials and potential defects

Low-carbon and high-strength low-alloy steels are readily laser-weldable, provided that the composition is kept within the following approximate limits (wt %): $C < 0.12$, $Mn < 1.6$, $S < 0.01$, $P < 0.01$. High levels of sulphur and phosphorus, in combination with a coarse solidification microstructure and restraint, can lead to solidification cracking. The high cooling rate of laser welds normally results in a fully martensitic HAZ in medium- and high-carbon steels, as well as alloy steels, and so precautions such as preheating are required in order to avoid excessive hardness.

Porosity is a common problem in laser welds, particularly those of partial penetration. The high solidification rate of the weld bead, and the complex nature of the keyhole, are the principal characteristics which exacerbate the problem in comparison with conventional fusion welding techniques. In structural steels, fine-scale porosity (pores with a diameter less than 0.5 mm) normally originate from outgassing in steels with an oxygen content above 100 ppm. Large-scale porosity can be caused by instabilities in the keyhole, resulting in the formation of voids which become trapped in the weld bead.

Austenitic stainless steels can be laser welded, with the exception of free machining grades with a high sulphur content which are susceptible to solidification cracking. Ferritic stainless steels with relatively low carbon and chromium contents are also readily laser-weldable. The rapid thermal cycle induced during laser welding limits grain growth and loss of toughness. Martensitic stainless steel grades require the same precautions as medium- and high-carbon steels in order to avoid excessive hardness. Austenitic filler wires may be used to control weld-bead chemistry.

The high reflectivity of aluminium alloys to CO_2 laser light presents problems with regard to the initiation of a keyhole, which in combination with high thermal conductivity hinders its maintenance during welding. Porosity, originating from volatile alloy additions such as magnesium and zinc, as well as hydrogen which is highly soluble in liquid aluminium, is a common defect, as is solidification cracking in certain alloys. The low viscosity of molten aluminium results in weld-bead sagging – a backing plate may be required. Careful selection and control of process parameters, together with the use of an appropriate filler wire with crack-sensitive alloys, is required for successful welding. Multikilowatt Nd:YAG lasers, which give light of a shorter, more easily absorbed, wavelength, provide solutions to a number of process-related problems.

The principal obstacle to the use of laser welding for copper alloys is its high reflectivity. Electron-beam welding has become a well-established process for this material. Nickel-based alloys can be laser welded, providing conditions which may lead to solidification cracking are avoided. The main concern when welding titanium alloys is contamination of the weld pool with oxygen and nitrogen, which decreases toughness. The material must therefore be cleaned thoroughly prior to welding, and inert-gas shielding above and below the weld pool used to prevent atmospheric contamination and oxidation of solidified material. The rapid thermal cycles induced during laser welding reduce the extent of detrimental grain growth in comparison with conventional fusion joining processes.

2.2.2. Plate thickness and joint types

Single-pass full-penetration welds can be made in a 25 mm structural steel I-joint with a speed of $1\ m\ min^{-1}$ using a very high-power CO_2 laser (~ 30 kW); $1\ m\ min^{-1}$ is often regarded as a minimum value for economic application of laser welding in comparison with conventional fusion processes. Greater penetration can be obtained using electron-beam welding, although flexibility and productivity are reduced due to the need for a vacuum. At the other end of the application spectrum, an industrially common 6 kW CO_2 laser is capable of joining 0.3 mm steel sheet for cans, at rates up to $50\ m\ min^{-1}$. Welding performance with stainless steels is normally slightly higher than carbon–manganese grades owing to their lower thermal conductivity. The process itself imposes no lower limits to material thickness; these are generally set by fixturing and production considerations. Published data for the maximum thickness investigated in single-pass full-penetration laser welds in non-ferrous alloys are typically around half those of steels.

Laser welding can be applied to many types of joint used in conventional welding processes. A summary of commonly used joints is shown in Fig. 2. The high penetration possible in a single pass eliminates the need for preparation of a V-groove, although a high standard of machining is required to ensure that the mating surfaces are in close abutment. Air gaps in the joint, as well as misalignment of the plates, are a major source of weld defects associated with incomplete groove filling, such as undercut and bead concavity. Accurate fixturing, which can be an expensive, time-consuming production phase, is therefore required with autogenous welding. The ability to use joints such as stake, edge fillet and flare, increases the opportunities for redesign of products. Very thick sections may be welded using multipass techniques and appropriate joint preparation.

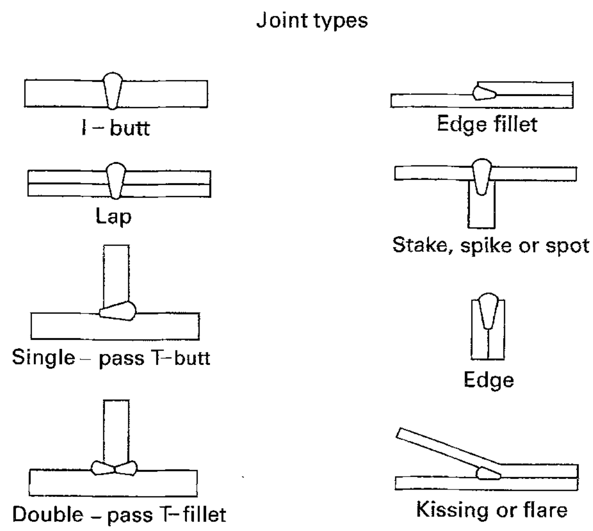

Figure 2 Joints commonly used in laser welding.

3. Fundamentals of laser welding of dissimilar metals

Dissimilar metal joints are characterized by compositional gradients and microstructural changes which produce large variations in physical and chemical properties across the joint. Potential problems include those associated with joining the component materials individually, and those specific to the different compositions and properties of the base materials in various proportions. Weld quality is dependent on the process variables, which comprise the characteristics of the laser beam, the particular processing parameters, and the physical and chemical properties of the base metals. The situation is complicated by the addition of filler material, which introduces additional variables such as feed parameters, and which widens the range of potential weld-metal composition.

3.1. Physical properties of the base materials

The principal physical properties of the base materials which influence laser welding are thermal conductivity, absorptivity, density, specific heat capacity, thermal expansion coefficient, and melting temperature. Data for some common engineering metals are given in Table I. Although values refer to pure metals, and some properties are temperature dependent, they can be used as a first approximation for assessing the weldability of dissimilar alloy combinations.

Metals of high thermal conductivity, such as aluminium and copper, dissipate energy rapidly, making it difficult to maintain a molten weld bead. Uneven heat dissipation in a joint comprising two metals with widely differing thermal conductivity may lead to the formation of an asymmetric weld bead, with the possibility of the joint line at the root being missed. Laser welding provides a higher energy density and more accurate control of energy input than conventional fusion welding methods, providing potential solutions to both the above problems. However, metals of high thermal conductivity generally possess low absorptivity, particularly for 10.6 μm wavelength CO_2 laser radiation, and additional factors such as preheating

TABLE I Room temperature properties of common engineering metals [11]

Metal	Melting temperature (K)	Boiling temperature (K)	Density ($kg\,m^{-3}$)	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	Specific heat capacity ($J\,kg^{-1}\,K^{-1}$)	Thermal expansion coefficient ($10^{6}\,K^{-1}$)
Fe	1809	3133	7870	78	456	12.1
Al	933	2793	2700	238	917	23.5
Cu	1356	2833	8930	397	386	17.0
Ni	1728	3188	8900	89	452	13.3
Ti	1940	3558	4500	22	528	8.9
Zn	693	1184	7140	120	394	31.0
Mo	2888	4883	10220	137	251	5.1
W	3673	5828	19300	174	138	4.5
Zr	2125	4673	6490	23	289	5.9
Nb	2740	5013	8600	54	268	7.2

TABLE II Laser weldability of binary metal combinations [13]. (E = excellent, G = good, F = fair, P = poor, * = no data available)

	W	Ta	Mo	Cr	Co	Ti	Be	Fe	Pt	Ni	Pd	Cu	Au	Ag	Mg	Al	Zn	Cd	Pb
Ta	E																		
Mo	E	E																	
Cr	E	P	E																
Co	F	P	F	G															
Ti	F	E	E	G	F														
Be	P	P	P	P	F	P													
Fe	F	F	G	E	E	F	F												
Pt	G	F	G	G	E	F	P	G											
Ni	F	G	F	G	E	F	F	G	E										
Pd	F	G	G	G	E	F	F	G	E	E									
Cu	P	P	P	P	F	F	F	F	E	E	E								
Au	*	*	P	F	P	F	F	F	E	E	E	E							
Ag	P	P	P	P	P	F	P	P	F	P	E	F	E						
Mg	P	*	P	P	P	P	P	P	P	P	P	F	F	F					
Al	P	P	P	P	F	F	P	F	P	F	P	F	F	F	F				
Zn	P	*	P	P	F	P	P	F	P	F	F	G	F	G	P	F			
Cd	*	*	*	P	P	P	*	P	F	F	F	P	F	G	E	P	P		
Pb	P	*	P	P	P	P	*	P	P	P	P	P	P	P	P	P	P	P	
Sn	P	P	P	P	P	P	P	P	F	P	F	P	F	F	P	P	P	P	F

may need to be considered. In this respect, an electron beam is absorbed more readily, although it is affected by differences in magnetic properties of the joint components [12].

Large differences in thermal expansion between joint components lead to the formation of large residual stresses, with implications for joint strength and fatigue properties. The low energy input of laser welding reduces the size of the HAZ, in comparison with conventional fusion welding methods, which can lead to a reduction in residual stresses. A filler material with an intermediate thermal expansion coefficient accommodates a limited amount of thermal mismatch, and is often a practical solution for laser welding.

The high energy density of a focused laser beam is sufficient to melt all engineering metals. However, large differences in melting temperature, and the proximity of the boiling temperature of one component to the melting temperature of the other, can lead to problems. Precise control over the location and magnitude of the energy input of laser welding can be used to limit melting of the low melting temperature component, allowing a brazed joint to be produced, thus reducing harmful effects.

3.2. Chemical properties of the base materials

Chemical mismatches between joint components can enhance diffusion of elements, and result in the formation of undesirable phases, deteriorating the mechanical properties of the joint. Phase transformations are determined by miscibility in the liquid and solid states, which depend on relative atomic size, crystal structure, chemical affinity and relative valency. Table II shows the relative weldability of various combinations of metals, based principally on their binary phase diagrams, but also taking into account practical experience.

Copper and nickel, for example, which have similar atomic diameters, the same f c c crystal structure, are both electropositive, and have one valency electron each, form a substitutional solid solution over the complete composition range. A tough solid solution can thus be produced, with good metallurgical and mechanical properties. If practical welding conditions are favoured, excellent weldability should result. Such combinations are denoted in Table II by class E.

Combinations of metals which are soluble in the liquid state, but completely insoluble in the solid state form a eutectic system. Silver–copper, lead–tin and aluminium–silicon combinations are typical of this type of system, denoted in Table II by class F. Eutectics are normally harder and more brittle than the primary phases, and their formation often leads to a reduction in ductility. Low melting point eutectics are particularly problematic, because they contribute to the mechanism of solidification cracking. The high heating rate of laser welding limits the time available for segregation, and the high cooling rate leads to the formation of fine solidification microstructures, both of which reduce the possibility of solidification cracking.

In a system of partial solid solubility, the two elements are completely miscible in the liquid state, but miscibility in the solid state is limited. These combinations are denoted in Table II by classes G and F. An acceptable weld may normally be produced, provided that certain measures are taken, such as the use of appropriate filler material, preheating, or suitable beam alignment.

Intermediate phases may also exist in the form of an intermetallic compound. The crystal structures of the majority of such compounds are complex, and are often hard and brittle. Fusion welds in which these phases form normally exhibit low ductility and high crack sensitivity. Lead–magnesium combinations are typical of this type of system, which is denoted in Table II by class P.

3.3. Processing parameters

The laser-beam parameters which are normally varied in practice are power, q (W), traverse rate, v (m s^{-1}), and focused beam radius, r_B (m). Power density, q/r_B^2 (W m^{-2}), energy per unit weld length, q/v (J m^{-1}), and energy per unit weld volume, $q/(vd)$ (J m^{-2}), where d is plate thickness, are variable groups which govern the temperature field in the weld, and consequently play a major role in determining the weld properties.

An analytical model of deep penetration welding [14] shows that the energy absorbed per unit volume of weld, $Aq/(vd)$, where A is the fraction of incident energy absorbed by the workpiece, governs both the cooling time of the weld in the temperature interval $T_2 - T_1$, Δt (s), and the width of the HAZ, w(m), bounded by the peak temperature isotherms T_3 and T_4

$$\Delta t = [Aq/(vd)]^2 (4\pi\lambda\rho c)^{-1} \times [1/(T_1 - T_0)^2 - 1(T_2 - T_0)^2] \quad (1)$$

$$w = Aq/(vd) [2/(\pi e)]^{1/2} (2\rho c)^{-1} \times [1/(T_3 - T_0) - 1/(T_4 - T_0)] \quad (2)$$

T_0 is the initial (or preheat) temperature (K), λ is thermal conductivity (W m^{-1} K^{-1}), ρ is density (kg m^{-3}), c is heat capacity (J kg^{-1} K^{-1}), and e is the base of natural logarithms (2.718). Under optimum welding conditions, substitution of a value of 0.7 for absorptivity [15], and average material properties corresponding to a temperature of approximately 60% of the melting temperature [16], allow Equations 1 and 2 to be used to characterize the effects of variations in process variables on weld properties. HAZ widths and cooling times of laser welds are thus predicted to be approximately an order of magnitude lower than arc fusion processes, which have implications for microstructural development and the residual stress state, described in the next section.

4. Applications of dissimilar metal laser welds

Literature reports concerning laser welding of dissimilar metal combinations before 1970 concentrated on thin plates or wires selected for a specific engineering need. Very little data concerning the relationship between the welding variables, weld microstructure and the properties of the weldment were reported in early trials [17]. As available laser power has increased, and advances made in experimental procedure, industrial application of CO_2 and Nd:YAG lasers in welding of dissimilar metal combinations has increased. Examples are given below which illustrate practical laser welding procedures, weld microstructures and properties, some of the most common problems encountered, and the solutions developed. In addition to joining dissimilar metals, laser welding can also be used for joining different grades and thicknesses of a particular class of material.

4.1. Dissimilar grades

Tailored blanks, used in the automotive industry, are composite steel sheets which are constructed by joining pre-cut shapes of differing grade, thickness or surface treatment. They are used in car doors, for example, where a galvanised section for the base of the door is joined to thicker sections required for hinge supports, and ungalvanised material at the top of the door. Laser welding is particularly suitable for this type of application, because of its accuracy, speed, flexibility and the high quality of the weld bead produced. By pressing such a composite sheet in one operation, material savings of approximately 45% can be achieved, and the need for resistance spot welding and the construction of an inner frame can be avoided.

A joint between spheroidal graphite cast iron and steel allows the good castability of cast iron and the toughness of steel to be exploited in a single product. In laser welding practice [18], a nickel filler wire is used in order to obtain ductile austenitic weld metal, without the need for preheating. A sharp fusion zone is produced on the steel side, with a dilution zone of spheroidal graphite, and martensite and ledeburite on the cast iron side.

Different grades of aluminium alloys are often required in components, e.g. 6000 series extrusions and 5000 series plates. A major problem associated with aluminium alloy welding is susceptibility to solidification cracking, which is a function of weld-metal composition and the solidification temperature interval. 6000 series alloys may be welded using high-silicon 4000 series filler material, which increases the content of Mg_2Si above 1%, thus reducing crack susceptibility.

4.2. Stainless steel and carbon or low-alloy steel

Joints between austenitic stainless steel and carbon or low-alloy ferritic steel are required in many sectors of industry, to satisfy performance and economic criteria. There are two major concerns in these types of joints: martensite formation in the weld bead or low-alloy HAZ which may promote cold cracking; and hot cracking in fully austenitic weld metal. In the former case, normal precautions, such as composition control and preheating can be employed. In the latter, the aim is to produce an austenitic weld with a small amount of ferrite, which hinders crack formation, through weld-metal composition control by careful regulation of base metal dilution and/or the addition of filler material. Microstructure prediction diagrams are useful tools in this respect.

Continuous cooling transformation (CCT) diagrams, when used in conjunction with formulae, such as Equation 1, to estimate cooling rate, provide a means of predicting HAZ microstructure for C–Mn steels. Empirical formulae involving carbon equivalents are available for predicting maximum HAZ hardness, mechanical properties, preheat temperature and the likelihood of cold cracking, in terms of process variables [19]. For stainless steels, the Schaeffler diagram [20] uses axes of chromium and nickel equivalents to display compositional regions in which particular weld-bead solidification microstructures can be expected. The original diagram has since been developed to include the effects of nitrogen [21] and copper [22] on microstructure. However, such diagrams should be used with care with laser welding, because recent work [23, 24] has demonstrated a significant narrowing of the duplex ferrite–austenite region with cooling rates typical of laser welding, illustrated schematically in Fig. 3. In addition, rapid solidification may inhibit uniform mixing, resulting in inhomogeneous regions in the weld metal [8, 10]. The effect of variations in dilution of the weld metal by the base metals, and the addition of filler material, on weld microstructure can be estimated by constructing lines on the diagram between the composition coordinates of the constituent alloys.

In the power generation industry, the use of low-alloy ferritic steels for high-pressure piping becomes impractical in locations where the temperature exceeds 600 °C, due to insufficient strength and oxidation resistance. The use of austenitic stainless steels in the entire construction is often uneconomical. The most satisfactory design frequently relies on the use of both types of steels. The joints required can be welded using the diagram-based approach described above, in order to obtain a weld metal containing a small amount of ferrite. Martensite formation can be reduced by accurate location of the focused laser beam towards the austenitic steel side, thus reducing dilution from the ferritic steel [8, 10]. Satisfactory microstructure and hardness in autogenous laser welds has been reported for a range of structural and austenitic/ferritic stainless steel combinations [25]. Fig. 4 shows a laser weld between a structural steel stiffener to the outside of an AISI 316 stainless steel drum. A significant reduction in both welding time and the use of stainless steel resulted from the use of laser welding in preference to the conventional arc fusion process.

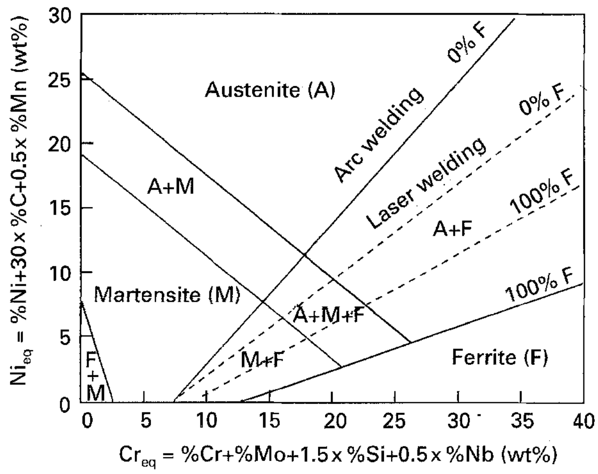

Figure 3 Schaeffler diagram [20] showing schematically the reduction in the extent of the ferrite/austenite region for high cooling rate processes (- - -) [23, 24].

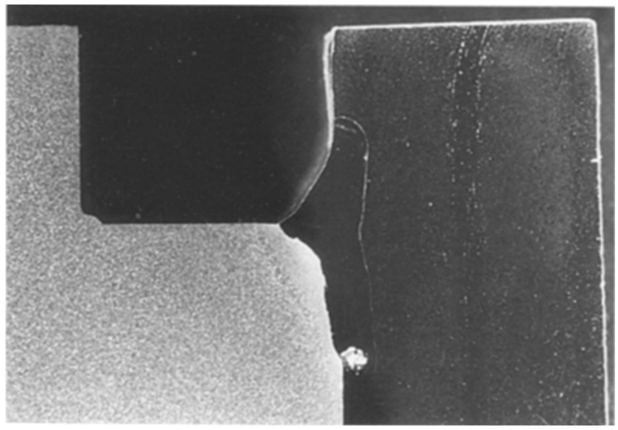

Figure 4 Laser weld between a structural steel stiffener (left) and an AISI 316 stainless steel drum. 3% nital etchant, mag × 6.25.

The energy input of gas and arc processes such as tungsten inert gas (TIG), metal inert gas (MIG), manual metal arc (MMA), plasma arc (PA) and submerged arc (SA), can be an order of magnitude greater than that of laser welding. The cooling and solidification rates are, therefore, lower, increasing the risk of segregation and the formation of brittle intergranular phases. The fusion and heat-affected zones are larger, producing more distortion and larger residual stresses. Alignment of the heat source relative to the joint line, and the subsequent control of dilution is more difficult. A study of the properties of laser, PA and TIG welds in austenitic/ferritic joints indicated that HAZ widths in laser welds were around one-quarter and one-sixth of those in plasma and TIG welds, respectively [26]. Axial shrinkage in tube/tube joints was about one-half and one-quarter of that in plasma- and TIG-welded joints, respectively [26]. Furthermore, the residual stress state in laser welds was superior to that of plasma and TIG welds; lower in magnitude with a more restricted zone of tensile stress.

In some applications failure may occur due to cyclic thermal stresses, carbon migration, low oxidation resistance of the ferritic steel, and metallurgical deterioration in the form of coarse carbides and sigma-phase formation at elevated temperatures. The use of a nickel-based filler material minimizes the physical and chemical mismatches of the base materials, and improves the high-temperature service properties of the joints. Tolerances on the alignment of the beam can be widened, whilst avoiding martensite formation in the weld bead [10]. Diffusion of carbon across the ferritic steel/weld metal interface, which causes a soft decarburized zone in the ferritic steel is reduced. In addition, the width of the interfacial hardened zone [27] and the magnitude of residual stresses at the interface can also be reduced.

Solidification cracking, or hot cracking, may occur in the weld metal during cooling, predominantly at the weld centre line or between columnar grains, at temperatures typically 200–300°C below the melting temperature. The susceptibility of weld metal to this type of cracking is increased by a coarse solidification microstructure, a high concentration of elements such as sulphur and phosphorus, and the presence of tensile stresses. Techniques such as variestraint and trans-variestraint testing assess solidification cracking susceptibility. The Suutala diagram [28] uses axes of composition equivalents in order to demarcate regions in which solidification cracking is likely, for arc welding of stainless steels. However, solidification mechanisms in laser weld metal are not well understood, and little experimental data are currently available. Recent work [29] has indicated that compositions predicted to be crack-free with conventional welding may exhibit cracking with pulsed laser welding. This finding corresponds with the observation of an increase in the extent of the crack-sensitive, fully austenitic phase region of the Schaeffler diagram under conditions of rapid solidification, Fig. 3. Universal cracking tests for laser welding are not yet available, although a weldability test for pulsed-laser welding has been developed [30].

The hot-cracking mechanism in CO_2 laser welds of dissimilar metals involving martensitic stainless steels has been investigated [31]. Extensive hot cracking in welds between 15-5PH and HP 9-4-20 steels was observed, whilst welds between PH 13-8 Mo and HP 9-4-20 were crack-free. Hot-cracking was attributed to the formation of a niobium carbide–austenite eutectic constituent, which was absent in the niobium-free PH 13-8 Mo alloy.

4.3. Steel and copper

Joints between steel and copper alloys are often required in marine environments, and are also required in the metals extraction industry. Differences in their melting temperatures and thermal conductivities, as well as compositional effects, are the main sources of difficulties in joining. Weld cracking is a particular problem, resulting from the combined effects of migration of copper to grain boundaries in the steel and the presence of tensile stresses.

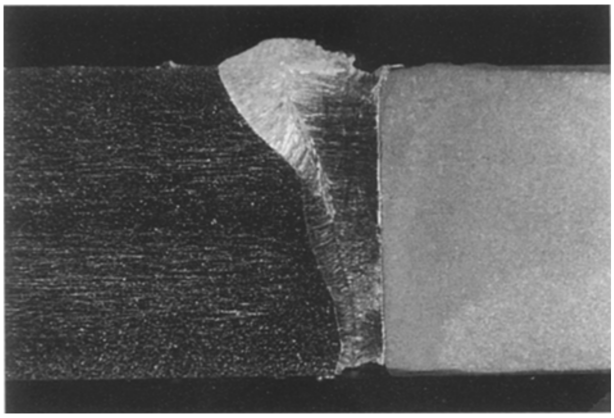

Figure 5 Laser weld between copper (right) and AISI 304 stainless steel. 10% oxalic acid etchant, mag × 10.

Fig. 5 shows an autogenous laser weld between copper and AISI 304 stainless steel. In the application, copper is required for electrical conductivity, and stainless steel for corrosion resistance and stiffness. The weld is produced by forming the bead in the stainless steel, and allowing heat transfer to fuse a limited amount of copper. Thus the formation of intermetallic compounds is minimized. The joint was formerly made by MIG welding which required the copper to be preheated to 600 °C. The high power density of laser welding allowed this requirement to be lifted, whilst welding time was reduced. In other similar studies, promising mechanical properties (tensile failure in the parent material, good peel strength, and a lack of metallurgical problems), have been attributed to the high energy of the laser beam and the accuracy with which it can be located [32]. Vacuum-tight joints have been produced by laser welding between the copper face and steel substrate of mirrors used for the transmission of laser beams [33].

Nickel shims [34] and a BAu-4 powder braze alloy [35] have been used as filler materials in difficult steel–copper alloy combinations. Because nickel and copper are mutually soluble in both the liquid and solid states, the potentially harmful effects of pure copper are reduced.

4.4. Steel and aluminium

Joints between aluminium and various types of steel are of particular importance in cryogenic applications. Storage tanks are made from aluminium alloys, but the transfer lines to the tanks are typically made from stainless steel for reasons of strength, control of heat flow, and to enable the attachment of valves and bellows. The proximity of the vaporization temperature of aluminium and the melting temperature of steel, the formation of brittle intermetallic compounds at the interface, and the large difference in thermal conductivity, create problems when attempting to produce such joints by fusion processes.

Solid-state processes are normally used in such applications. Little has been reported with regard to the use of laser welding; however, the process offers a number of potential solutions to problems. Careful alignment of the laser beam in order to melt the aluminium and produce a brazed joint would limit intermetallic formation. Alternatively, the insertion of a spacer made from silver, nickel, copper or an aluminium alloy, as used in fusion arc welding [36] has been shown to have the same effect. In such applications, mechanical fastening is often used, although leak-tight joints are difficult to achieve, and the technique may result in an increase in overall weight, which may be undesirable in some applications.

4.5. Steel and nickel

Joints between steel and nickel alloys are required in power plant and electrical applications. The heat resistance of the nickel component is often the determining factor in its selection. Laser welds between AISI 403 martensitic stainless steel and Inconel 600 have been made succesfully using EN 82 nickel-based filler wire [37]. Potential problems when welding these materials include cold cracking and reduced toughness in the martensitic HAZ and partially melted or unmixed stainless steel zones, and hot cracking of the austenitic or semi-austenitic weld metal and partially melted or unmixed nickel-base zones. The high manganese content of the nickel-base filler was found to be effective in minimizing the formation of liquid grain-boundary films and preventing hot cracking. Dilution of the weld bead by less than 22% with the stainless steel was recommended. The high accuracy with which the beam may be aligned allowed this tolerance to be met.

Satisfactory joints between AISI 316 stainless steel and Monel have been produced by using Inconel 82 filler metal, because it tolerates dilution from both base materials [35]. Successful autogenous laser welding of AISI 304 stainless steel to Invar, in a trimetallic strip used in an electronics application, has also been reported [38].

An extensive study of Nd:YAG laser welding of various stainless steels and nickel-base alloys [39] revealed the presence of a larger number of cracks in the dissimilar joints than in welds of either component material alone. Dissimilar welds involving Inconel 82 exhibited more cracks than those with Inconel 600, which was attributed to the higher sulphur content in the latter (0.003 and 0.01 wt %, respectively). Analysis of fracture surfaces indicated sulphur segregation to the crack faces. Dissimilar stainless–nickel alloy welds with less than 0.003 wt % S were reported to be crack-free.

Nd:YAG welding of S 6-5-2 hardened tool steel and Fe40Ni soft iron–nickel alloy components used in a magnetic armature, indicated that the incidence of hot cracking could be minimized through the use of a small air gap ($< 40\ \mu m$), a joint geometry which minimized restraint, argon or nitrogen shielding gas, by positioning the beam at the joint line (± 0.05 mm), and the use of an applied energy between 70–100 $J\,cm^{-1}$ [40].

4.6. Aluminium and copper

Joints between aluminium and copper are often required in electrical components and radiators. Joining difficulties originate from the large difference in melting temperature and the possibility of formation of brittle intermetallic phases. Pulsed autgenous laser welding of electrical leads made from these materials has been demonstrated, and good electrical and mechanical properties of the joints reported [41].

The use of tin as a potential filler material originates from its use as a solder base for joints involving copper, and its ability to form a eutectic system with aluminium. Sound weld beads have been obtained using Nd:YAG laser welding [42]. The welds were characterized by solid-solution hardening, an absence of intermetallics, cracks and porosity, and satisfactory joint strength. Ductile fracture occurred during tensile testing at 150 MPa, which is around five times higher than the tensile strength of pure tin. The use of a high silicon 4043 aluminium filler material for laser welding of 6061 to both copper and beryllium–copper in an electrical component, has been shown to prevent solidification cracking often found in 6000 series welds [35]. Good mechanical properties and electrical conductivity were reported.

4.7. Aluminium and lead

The miscibility of aluminium and lead in the solid state is very limited, and autogenous laser welding would not normally be expected to produce joints with satisfactory mechanical properties. However, successful laser welding of aluminium alloys to lead, for use in instruments, through the use of a tin interlayer has been reported [43]. The interlayer allows quasi-eutectic weld metal compounds to be formed, avoiding the formation of intermetallic compounds, giving a hardness between those of the base materials. An additional factor is that the interlayer possesses thermophysical properties similar to the base metals.

4.8. Other applications

Electron-beam welding is used to join a tool steel strip of saw teeth to a carbon steel backing [44]. This has also been accomplished by laser welding followed by post-weld heat treatment [45, 46]. Laser welding has also been applied to join cobalt-based sintered diamond to steel to produce disc saws for stone cutting [47]. The disc requires the stiffness of the high-carbon steel, whilst the teeth require the hardness of the sintered diamond. The product is traditionally produced by brazing, but in this application the laser provides the following advantages: higher processing rate, lower distortion, increased strength, and the elimination of expensive filler material and a processing oven. However, laser welding also possesses a number of drawbacks: the stiffness of the disc may be reduced due to the need to use a lower carbon steel, difficulties in replacing lost teeth, and possible blowholes which influence the appearance of the products. Careful control of processing parameters is required.

Various applications of Nd:YAG laser welding of dissimilar material combinations have been reported [42]. Joining of cemented tungsten carbide to a tool steel substrate in the manufacture of a pressing tool is associated with the following problems: the high carbon content of the carbide makes surface wetting difficult; differences in thermal expansion coefficients generate large stresses; and intermetallic phases are likely to be formed. The use of cobalt filler foils, together with preheating to reduce martensite formtion, has been shown to give visually good welds, which resisted cracking in repeated compressive stress testing. Joints between stainless steel and a cobalt alloy for a gyro were obtained by locating the beam on the cobalt alloy side of the joint in order to reduce the amount of sulphur and phosphorus contributed to the weld bead from the stainless steel. An Fe–Co–Ni–V alloy was joined to a high melting temperature tungsten-based alloy by forming a brazed joint.

Laser welding of metal-matrix composites has also been demonstrated. A study of laser welding of Ti–6Al–4V alloy to SiC fibre-reinforced Ti–6Al–4V composite indicated that by locating the beam in the non-reinforced component, laser welding avoided serious fibre damage, enabling joints with a strength exceeding 800 MPa to be produced [48].

5. Conclusion

Laser welding possesses a number of features which provide advantages over conventional processes for joining dissimilar metal combinations. The high power density of the focused beam is sufficient to fuse the most important engineering metals and alloys, and overcomes many of the problems associated with large differences in thermal conductivity. The small size of the focused beam and the accuracy with which it can be positioned allow the fusion ratio of the base materials to be controlled, thus providing control over the formation of sensitive microstructures. The low energy input results in rapid solidification and high heating and cooling rates. Thus the extent of segregation may be reduced, finer and novel solidification microstructures produced, and the extent of grain growth minimized. However, precautions must be taken to avoid excessive hardness in hardenable alloys. Although capital laser equipment costs are currently considerably higher than for arc welding equipment, improvements in productivity, quality, design opportunities and production flexibility can be achieved. The process shows potential for solving a range of dissimilar metal joining problems in many industrial sectors.

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