Developments in laser welding of metallic materials and characterization of the joints

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DEVELOPMENTS IN LASER WELDING OF METALLIC MATERIALS AND CHARACTERIZATION OF THE JOINTS

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Despite significant improvements in laser beam welding technology over recent years, there are still some complications in welding of metallic materials by laser beam welding to be overcome. As regards titanium alloys, the formation of undesirable martensite is the main concern except for titanium alloys which are lean in beta stabilizer additions. Intermetallic TiAl alloys are very susceptible to solidification cracking. Aluminium alloys are prone to cracking (liquation and solidification cracking) especially the heat treatable grades; alloys with a high Cu + Mg content exhibit a higher crack sensitivity. Another problem encountered in LB welding of aluminium alloys is the base metal degradation which is reflected by recrystallization and grain growth in non-heat treatable alloys and by dissolution or coarsening of the strengthening phase in heat treatable alloys. As regards, nickel alloys the main problems are related with strain ageing and liquation cracking in the HAZ. Nickel alloys strengthened by the gamma prime phase are particularly prone to strain age cracking (compared to gamma second type Inconel 718 alloys) and this is mainly due to a higher Al + Ti content. It is then recommended to use an overaged material before welding and also a local heat treatment. In C-Mn steels problems such as porosity, solidification cracking in the HAZ and fusion zone as for the other materials may occur. Strength mismatch aspects and related tensile and toughness properties of the joint are also addressed.

Key words: Laser welding; Nickel Alloys; Aluminium alloys; Carbon manganese steels; Titanium aluminides

Malgré des améliorations importantes apportées à la technologie du soudage par faisceau laser au cours des récentes années, il reste encore un certain nombre de problèmes à surmonter dans le cadre du soudage de matériaux métalliques. En ce qui concerne les alliages de titane, la formation de martensite indésirable est la principale préoccupation à l'exception du cas des alliages de titane pauvres en éléments stabilisant la phase bêta. Les alliages intermétalliques TiAl sont très sensibles à la fissuration à chaud. Les alliages d'aluminium sont sensibles à la fissuration (fissuration par liquation et à chaud), en particulier les nuances aptes au traitement thermique; les alliages à haute teneur en Cu + Mg présentent une plus grande sensibilité à la fissuration. Un autre problème rencontré en soudage au laser des alliages d'aluminium est la dégradation du métal de base due aux phénomènes de recristallisation et de grossissement de grain dans le cas des alliages non aptes au traitement thermique. En ce qui concerne les alliages de nickel, le principal problème est associé au vieillissement par déformation et à la fissuration par liquation dans la ZTA. Les alliages de nickel durcis par la phase γ' sont particulièrement sensibles à la fissuration due au vieillissement par déformation (par comparaison à l'Inconel 718) et ceci est dû à la plus forte proportion de Al + Ti. Il est dans ce cas recommandé d'utiliser un matériau survieilli et d'appliquer un chauffage localisé. Dans les aciers au C-Mn, les problèmes tels que la porosité et la fissuration à chaud dans la ZTA et la zone fondue peuvent se produire comme pour les autres matériaux. Les aspects relatifs à la différence de résistance entre le métal de base et le métal fondu (mismatch) ainsi que les propriétés de traction et de ténacité du joint sont également abordés.

Mots clés : Soudage laser ; Alliages de nickel ; Alliages d'aluminium ; Aciers au carbone manganèse ; Aluminures de titane

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1. LASER BEAM WELDING PROCESS

The joining of any material with another one has always been a necessity in engineering applications. Welding of two materials always caused changes or deterioration of the microstructural and mechanical properties of the original materials in the joint region. Joining of two different materials (dissimilar joints) leads to a much more complicated situation where each material's own micro – and macrostructural properties should be taken into account during the joining process on its joint quality determination and also later on its joint performance in service.

Advanced materials generally require noble joining techniques. Developments in new materials research should be conducted in a hand-to-hand fashion with an investigation on their weldability/joining capacity aspects. A sound joint quality of any new material has always been considered a "milestone" to its research & development scheme and more to its wide-spread applications.

The laser beam welding process is capable of delivering an energy density of greater than ≈ 10 kW/mm² to the workpiece, and thereby capable of deep 'keyhole' penetration. It is known that the laser beam welding process possesses a dual handicap of high investment and low thermal efficiency. However, it has a great advantage of optical manipulation of heat source (i.e. ease of working), low distortion of workpiece, higher accuracy and automization, and absence of vacuum working chamber in most cases, which justifies the shortcomings. The laser beam processes are therefore attracting a great deal of interest as a well-controlled heat source as a result of its potential capability for extremely high density in energy [1]. Lasers may be classified according to their mode of operation as continuous wave (CW) or pulsed wave (PW) lasers. Early lasers capable of melting and cutting materials were of the solid-state type with a pulsed output whereas the continuous lasers did not have sufficient power output for processing the materials. However, the development of the high power continuous wave (CW) CO_2 gas lasers (wave length of 10.6 μm) and the solid state Nd:YAG (Neodynium-Yttrium Aluminium Garnet) lasers (wave length of 1.06 μm) in the last two decades led to the application of the laser beam as the more general heat source in areas, such as cutting, welding, heat treating, soldering, brazing, cladding and hardfacing. Currently, almost all solid-state Nd:YAG lasers supplied for welding or heat treatment processes are integrated with the optical fibre system. An integration of revolutionary fibre-delivery system with Nd:YAG lasers significantly increased the flexibility and versatility of the laser system which is ideal for industrial robotic manipulation at multiple workstations for simultaneous outputs [2]. Furthermore, the Nd:YAG laser is better suited for laser welding of highly reflective materials, such as Al-alloys, than the CO_2-laser because of its higher power density due to its appreciably shorter wavelength (1.06 μm) [3, 4]. It should also be noted that for the same average power, PW Nd:YAG lasers provide much higher penetration levels than CW Nd:YAG lasers [5].

The laser beam welding is capable of joining a wide range of materials of interest in the aerospace industry as well as in many other industrial applications and often offers remarkable advantages over conventional fusion welding processes. Of particular interest is the ability to join the more difficult thin sheet alloys for aerospace and automotive applications [6] with minimal component distortion and high reproducibility of joint quality. The laser welded tailored blank manufacturing route appears to be well established in automotive industry. Furthermore, the use of "laser beam welded Al-alloy stringer-skin" fabrication route is currently investigated to reduce the weight of structures in aerospace applications. Another interesting aspect of the laser is the localized heating which makes it ideal for welding electronic components such as printed circuit boards, where high average temperatures even in small volumes surrounding the weld region is intolerable [3, 5, 7].

When the laser beam impinges upon the metal during the laser beam welding process (Fig. 1) it delivers its heat to the surface and further penetration beneath the surface relies upon the thermal conduction. The metal under the laser beam evaporates and a cavity or keyhole is formed through the thickness of the workpiece. By moving this keyhole along the joint between two pieces of metal, a weld is made. A recognized characteristic of laser beam welding (LBW) is deep penetration, narrow bead width and narrow heat affected zone typical of high power density welding. Fig. 2 illustrates the narrow weld zones in similar austenitic and dissimilar austenitic/ferritic steel laser welds. This configuration is achieved in a keyhole mode of welding in which the beam passes entirely through the joint to produce a full penetration weld. Applications have generally utilized the downhand welding position. However, it is also possible to do all position welding for complex shaped components. Further details of the laser beam welding process can be found in references 1-14.

2. WELDABILITY OF METALLIC MATERIALS

Despite significant improvements in laser beam welding technology over recent years, there are still some complications in welding of metallic materials by the laser beam welding process to be overcome. Laser beam weldability aspects of some advanced materials listed below will be considered in this manuscript.

- Titanium Alloys (incl. TiAl)
- Nickel-Based Superalloys
- Al Alloys
- Steels

Although the use of welding in the aerospace industry is rather limited compared to other major industries, it is gradually increasing as a result of cost effective fabrication considerations as well as the development of materials and advanced welding methods which provides minimum degradation of the material properties of the joint by producing optimum joint shape (minimum weld size and distortion). At present, the gas tungsten arc welding (GTAW) process is widely used to weld superalloys, such as Inconel 625, in aerospace industry. The laser beam welding process will make a great impact on welding of these materials provided that the metallurgical difficulties, such as solidification cracking, microfissuring, and base metal degradation in the HAZ region, are overcome. Furthermore, minimum distortion (for ease of final assembly and post weld operation/machining) and lower level of residual stresses (which avoids the degradation of fatigue and stress corrosion properties) are desirable features of the LB welds.

For instance, the problem of the porosity formation in laser welding of aluminium alloys is still needed to be solved. A certain amount of porosity can perhaps be allo-

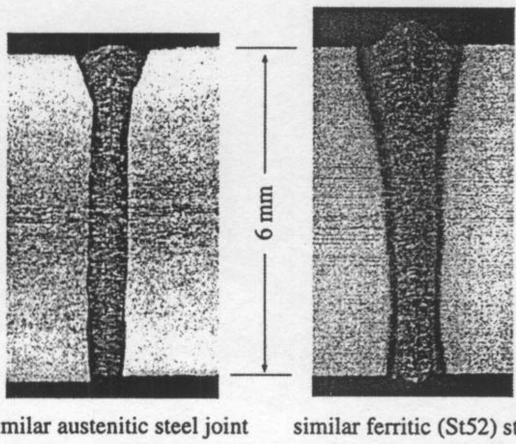


Fig. 2. Narrow weld zones in steel laser welds (note lack of HAZ in similar austenitic steel joint) [71].

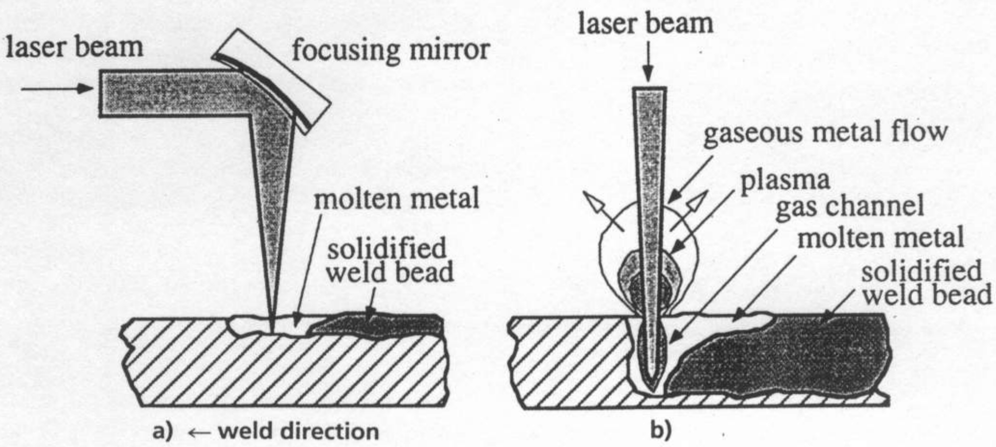


Fig. 1. Principles of laser beam welding [8].

wed in aluminium alloy weldments without the deterioration of joint performance, provided that they are small in size and uniformly distributed. However, a significant reduction in porosity level should be achieved and the significance of the presence of pores on the performance of laser joints should be fully understood to apply this fabrication process successfully for industrial applications. Another example is the high hardness and solidification cracking in laser welding of C-Mn steels. Laser welding of C-Mn steels in medium-to-heavy sections in ship-building and pipeline manufacturing industries displays a great potential provided that these problems are overcome.

2.1. Weldability of Ti-Alloys

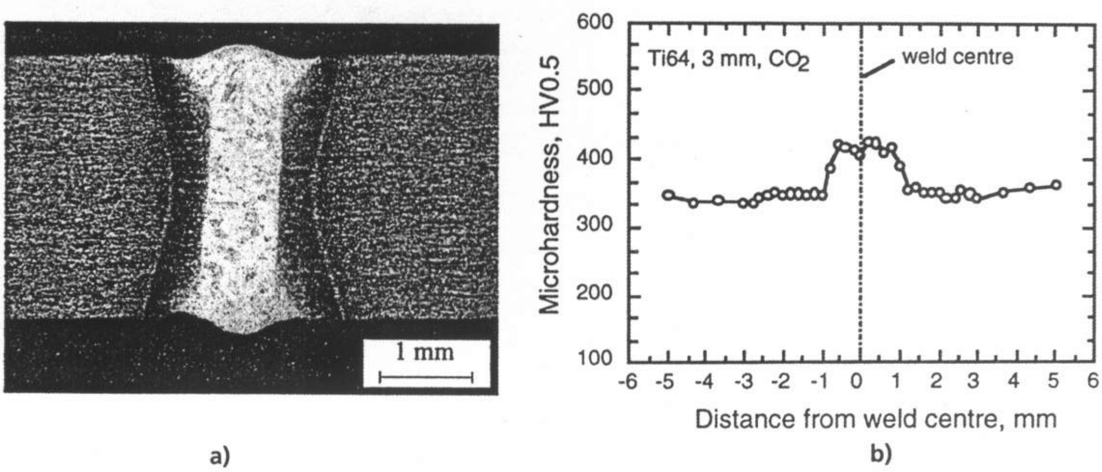
Titanium has a strong chemical affinity for oxygen, especially at elevated temperatures. Therefore, the melting, solidification, and solid-state cooling associated with fusion welding or post-weld heat treatment, if required, must be conducted in completely inert or vacuum environments. Titanium and titanium alloys can be readily welded by the LB welding process. The low thermal conductivity of the metal and high absorption of infrared light ensure good coupling and better weld penetration than for most other materials. With laser welding processes, protection of the immediate weld zone can be achieved by inert-gas shielding (during laser welding the top and bottom of the joint must be shielded with helium or argon of high purity). Power beam processes can be successfully utilized to obtain full penetration titanium alloy joints in thick sections with high depth to width ratios and little distortion without filler wire. The development of high power lasers makes the welding of thicker sections of these alloys also possible. Moreover, the LBW process does not require a vacuum chamber, which is an advantage over electron beam welding for some applications. Therefore, LB welding is also quite promising for welding of titanium alloys in heavy sections.

Residual stresses in titanium welds can greatly influence the performance of a fabricated aerospace component by degrading fatigue and stress corrosion cracking (SCC) properties. Moreover, distortion can cause difficulties in the final assembly and operation of high-tolerance aerospace systems. Therefore, LBW process, which produce full-penetration, single-pass autogenous welds are preferable to minimize these difficulties.

The formation of undesirable *martensite* in the weld zone is the only concern in welding of titanium alloys. However, this is not expected to be a problem in LB welding of titanium alloys, which are lean in beta stabilizer additions, eliminating the possibility of the martensite formation in the weld zone and subsequent hardness increase. Furthermore, the alpha-prime martensite, which forms in alloys lean in beta stabilizers, is not as hard and brittle as that exhibited by more heavily beta-stabilized alloys. The hardness profile of Ti64 CO_2 LB joint made using 3 mm thick plate shows that the hardness increase in fusion zone is not significant owing to low amounts of beta stabilizer elements in this alloy, Fig. 3 [72]. Moreover, solid-state cracking and porosity can be encountered in LB welding. However, these defects can be readily avoided by preweld cleaning of the workpieces and shielding of the weld zone from atmospheric contamination in the case of laser beam welding.

In the high cooling rate LB welding process, the predominantly martensitic or acicular structures produced in the weld fusion zone (no significant HAZ development) exhibit hardness and strength levels higher than those of the original base metal. Consequently, failures of the flat tensile specimens (loading transverse to weld) occur almost always in the base metal (strength overmatching). According to this kind of test results, these welds exhibit 100% joint efficiency. However, the ductility of the weld zone as measured by the longitudinal-weld-oriented bend or all-weld-metal tensile tests may be low. This is not a major concern in laser beam welding of titanium alloys which are lean in alloying additions, because the hardness increase in the weld zone due to the formation of an acicular structure is not significant. A satisfactory level of fracture toughness of these weldments is expected due to their microstructure which consists of either acicular alpha (transformed beta) or Widmanstätten alpha. It is also worth noting that *"the all weld metal tensile properties"* should be determined with proper testing procedures.

Intermetallic Ti-alloys: Intermetallic gamma (TiAl) alloys for high temperature applications are very susceptible to solidification cracking, resulting in the requirement for a preheat or controlled cooling, as a result of their low ductility and high modulus [15, 16]. The major challenge for successful welding of these alloys is to cope with their low ambient temperature ductility. The joinability of Ti-Al



a) b)

Fig. 3. CO_2 LB weld of Ti64 produced using 3 mm thick plate: a) optical micrograph showing the joint and b) hardness profile [72].

based intermetallic alloys is an important factor in determining their wider utilization since their fabrication is limited which is a direct result of their low room temperature ductility. There is, therefore, an increasing interest in the fabrication of these alloys by LB welding with preheating (about 700°C) and solid-state bonding techniques. Some success has already been reported in joining of these alloys by laser beam welding process and diffusion bonding. However, there is still need for further research on the crack-free LB welding of these alloys and more data on mechanical properties of welded joints.

2.2. Weldability of Al-Alloys

Although some problems may be encountered in LB welding of some of these alloys, sound joints can be produced with proper precautions (i.e. surface cleaning etc.). However, there are some inherent difficulties in LB welding of aluminum alloys. These alloys are prone to cracking, base metal degradation in the HAZ regions (HAZ softening) may occur and a high level of porosity may form. Moreover, the high laser reflectivity of aluminum alloys should also be considered in LB welding of these alloys.

Non heat treatable aluminium alloys can only be strengthened by solid-solution and/or strain hardening in contrast to heat-treatable alloys which are strengthened by second-phase particles. The absence of precipitate-forming elements in these low-to moderate-strength aluminum alloys becomes a positive attribute when considering weldability, because many of the alloy additions needed for precipitation strengthening (for instance, Cu + Mg, or Mg + Si) can lead to liquation or hot cracking during LB welding. Furthermore, joint efficiencies are higher in non-heat-treatable alloys since the base metal/HAZ degradation due to the weld thermal cycle in these alloys does not involve the coarsening or dissolution of precipitates as it is the case in heat-treatable alloys. However, all aluminium alloys possess certain inherent characteristics, such as tenacious oxide layer, high thermal conductivity, high coefficient of thermal expansion, high reflectivity, solidification shrinkage almost twice that of ferrous alloys, relatively wide solidification-temperature ranges, and high solubility of hydrogen when in molten state. Therefore, some difficulties, which are namely crack sensitivity, propensity for porosity, and strength loss in the weld metal, can be encountered in laser beam welding of these alloys. These aspects must be considered before successful LB welding can be employed [17, 18].

Crack sensitivity: All aluminium alloys exhibit a propensity for weld metal cracking due to their large solidification temperature range, high coefficient of thermal expansion, large solidification shrinkage due to large change in their volume upon solidification. The weld crack sensitivity of heat-treatable aluminum alloys is particularly of prime concern due to the greater amounts of alloying additions present in these alloys, which also exhibit a tendency to form low melting constituents. Weld cracking in aluminum alloys may be classified into two main groups based on the mechanism responsible for cracking and crack location, namely *liquation cracks* and *solidification cracks* [17].

Liquation cracking takes place in precipitation-hardenable alloys as a result of the relatively large amount of alloying additions available to form eutectic phases. These constituents have low melting points, thus liquate (melt) during welding, and accompanied by tears provided that sufficient stress is present [17, 19, 20]. Higher heat input widens the partially melted region and makes it more prone to tearing. Thus, it is not expected to be of a prime concern in laser beam welding of aluminum alloys which is a low heat input process.

Solidification cracking or hot tearing is cracking in the weld zone caused by the inability of the liquid to support the strain imposed by solidification shrinkage and thermal stresses [17, 21-23]. The degree of restraint of welded assemblies plays an important role in crack sensitivity by increasing the external stress on the solidifying weld. Hot tearing takes place within the weld fusion zone and is influenced by weld-metal composition and welding parameters. Fig. 4 shows solidification cracking in a dissimilar austenitic/ferritic steel laser beam weld.

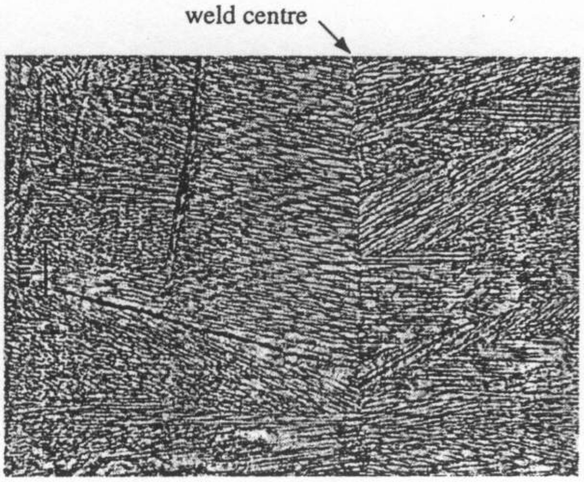


Fig. 4. Soldification cracking in a dissimilar austenitic/ferritic steel LB joint [71].

The crack susceptibility (castability) index for Al-Cu-Mg ternary alloys generated by Pumphrey and Moore in 1948 [24] is normally used to predict the weldability of aluminum alloys. Crack sensitivity curves of various binary Al-systems have also been experimentally determined [25-30] and can be used to predict the relative crack sensitivity behaviour of complex alloy systems. Alloys with high Cu + Mg exhibit a higher crack sensitivity. The most notable examples are alloys 2024 (Al-4.4 Cu-1.5 Mg) and 7075 (Al-5.6 Zn-2.5 Mg-1.6 Cu).

High heat inputs, such as high currents and slow welding speeds, are believed to contribute to weld solidification cracking [31]. Another factor contributing to the hot tearing is the weld metal grain size. The weldability of aluminum alloys can be improved through the refinement of the weld metal grain size [32]. The weld metal grain sizes produced by LB welding are usually fine due to rapid cooling involved in this process. Low heat input LBW process may thus reduce weld crack sensitivity. High constraint conditions, which also contribute to cracking, can be avoided by proper joint design. However, LBW process can result in cracking when magnesium, a high-vapor-pressure alloying element, is boiled off. Furthermore, it is known that the loss of magnesium causes a loss of strength at the melted weld zone (weld strength undermatching). This can be prevented by use of adequate filler wire.

Porosity: Porosity in aluminum weldments is caused when hydrogen gas is entrapped during solidification, which has an appreciable solubility in molten aluminum and a limited solubility in the solid. Both non-heat-treatable and heat treatable aluminum alloys are susceptible to hydrogen-induced weld metal porosity. Fig. 5 shows the formation of pores in the fusion zone of a CO_2 LB welded alloy 6061. Porosity can best be avoided by minimizing hydrogen pick-up during welding and by removing the oxide layer prior to welding. This can be accomplished by proper removal of hydrocarbons, use of high-grade (low-dew-point) shielding gas, and careful storage of filler wire (i.e. protection from exposure to moisture and oil) [17]. It has been experienced that filler wire is often the primary source of hydrogen contamination in arc welding.

If wire feeding is used in LB welding, care should be exercised to minimize hydrogen contamination. Care should also be taken with the use of shielding gas in LB welding in order to minimize hydrogen pick-up. Moreover, surface hydrocarbons of the parts to be welded must adequately be removed just before welding to minimize porosity.

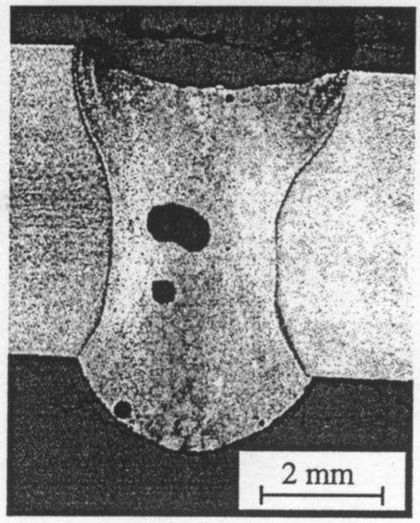


Fig. 5. Optical micrograph of alloy 6061 CO_2 LB weld joint showing porosity formation in the weld metal and weld pool collapse (plate thickness is 5 mm) [72].

Base Metal Degradation: Another problem, which can be encountered in LB welding of aluminium alloys, is the loss of strengthening elements in the heat affected zone and/or fusion zone (strength undermatching). The extent of base-metal degradation is determined by the welding process and parameters [17, 33]. Conventional arc welding processes involve the application of 10^3-10^4 W/cm^2 arc intensity and slow weld speeds (< 15 mm/s), which leads to excessive heat input into the base metal, thus resulting in a coarse weld microstructure and a wide HAZ. Unlike the case of non-heat-treatable alloys, in which the base metal degradation is limited to recovery, recrystallization, and grain growth, HAZ damage in heat-treatable alloys involves the dissolution or coarsening of the strengthening phase present. Consequently, the HAZ degradation of heat-treatable alloys is much more severe than that experienced in non-heat treatable alloys [17]. Figs. 6 and 7 show electron beam weld joints of alloys 5005 (3 mm thick) and 6061 (5 mm thick) and their hardness profiles,

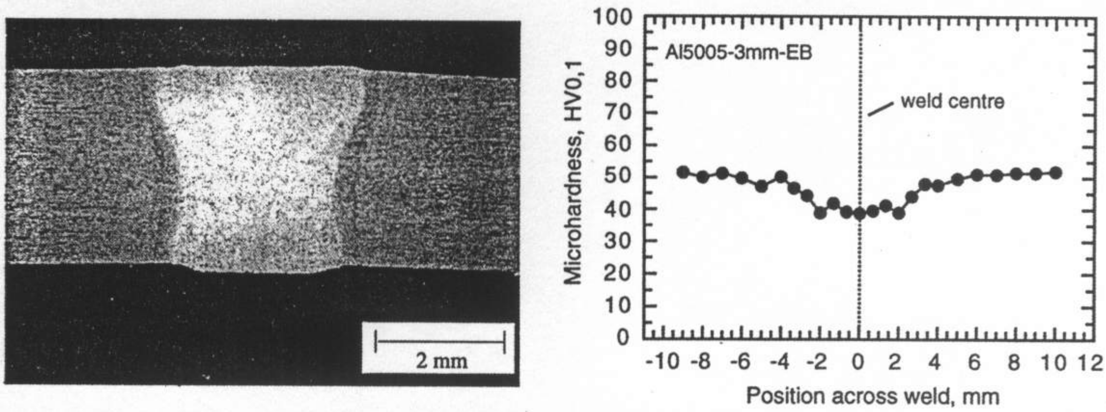


Fig. 6. EB weld joint of alloy 5005 produced using 3 mm thick plate: a) optical micrograph showing the joint and b) hardness profile [72].

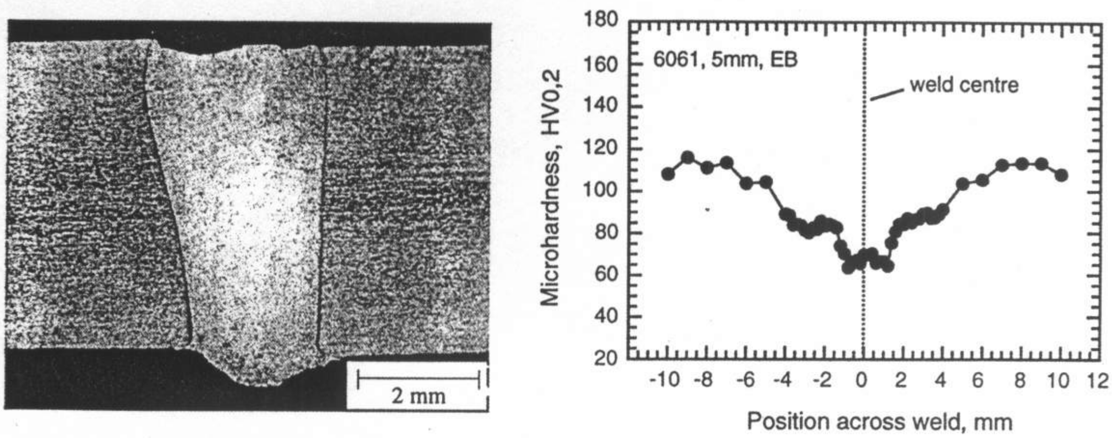


Fig. 7. Cross section and hardness profile of EB weld joint of alloy 6061 produced using 5 mm thick plate [72].

respectively, underlining more severe loss of strength (undermatching) in fusion zone in heat-treatable alloys [72]. However, in contrast to non-heat treatable alloys, heat-treatable alloys can fortunately be post-weld heat treated in order to recover the strength of the HAZ.

The width of the HAZ can be significantly reduced by LB welding due to the low heat input involved. Therefore, the HAZ softening can be considered as a limited problem in the LB welding process. However, the base metal degradation, which is loss of strengthening elements during welding, may occur in the fusion zone. Several researchers have reported alloying addition evaporation (e.g., Mg and Zn) during laser beam welding of aluminium alloys [34-37]. This problem is particularly pronounced in the highly alloyed aluminium alloys. In non-heat treatable alloys, the reduced strength due to the loss of alloying addition (reduced solid solution strengthening) cannot be recovered. In heat treatable alloys, the reduced strength as a result of the loss of the alloying elements can also be not recovered with subsequent heat treatments due to a reduced ability of the alloy to precipitation harden as a result of a lower alloying element concentration. This problem can, however, be overcome by utilizing proper welding parameters and/or suppression of the plasma with a properly designed shielded gas nozzle [35]. The other alternative is to use filler wire [38].

If the weld metal has significantly lower strength than the base metal (high undermatching), almost all of the applied strain will be concentrated in the weld metal in transverse tensile test. Thus, the weld metal will be the weakest part of the joint and thereby the location of failure when the joint is loaded transverse to the weld in tension. This is particularly the case for high-strength Al alloys. Typically, joint ductility measured over a 50 mm gauge length will be 2 to 4% even though the actual weld metal ductility approaches 10 to 12%. However, this does not mean that the weld metal is intolerably brittle. It is due to the very small size of the weld metal which undergoes constrained plastic deformation in the transverse tensile test resulting in very low ductility levels, Fig. 8 [72]. The level of ductility achieved in such tests is obviously dependent on the length of the "*gauge length*" used in the specimen.

2.3. Weldability of Superalloys

Solid solution hardened superalloys generally exhibit good weldability and are often used in the as-welded condition. However, adequate precautions must be taken in order to avoid liquation cracking. The fusion welding of precipitation-hardenable superalloys is much more complicated. The physical metallurgy of precipitation-hardenable superalloys that determine weldability is governed by the precipitates used for age hardening (γ' and γ'') and those associated with solidification and solidification segregation (primarily, Laves and carbides). There are two types of cracking encountered in welding of these alloys, namely *strain-age cracking* and *liquation cracking*.

Strain-age cracking was first investigated and understood for the wrought alloy Rene 41 by Hughes and Berry [39, 40]. They demonstrated that strain-age cracking was an aspect of the gamma prime aging reaction in the HAZ of weldments. This reaction might occur during welding or in subsequent heat treatment, but regardless of the timing. The γ' precipitation in the matrix results in strengthening of the matrix so that all the solidification strains of the weldment are transferred to the grain boundaries in the HAZ causing them to fail and form microcracks. The possibility of strain-age cracking is lower in LB welding process compared to conventional arc welding since LBW produces a very narrow HAZ, if any.

Ni-based superalloys that are strengthened by γ' precipitates are more prone to strain-age cracking than are those that are strengthened by γ'' precipitates (e.g. Inconel 718) due to the more sluggish reaction of the γ'' phase. Prager and Shira [41] proposed the plot in Fig. 9, which was modified by Kelly [42] to include alloys such as René 220C, IN939, IN909 and René 108, which demonstrates that the phenomenon of strain-age cracking is due to the total (Ti+Al) content. Both titanium and aluminum are γ' formers in many superalloys, the strengthening phase that

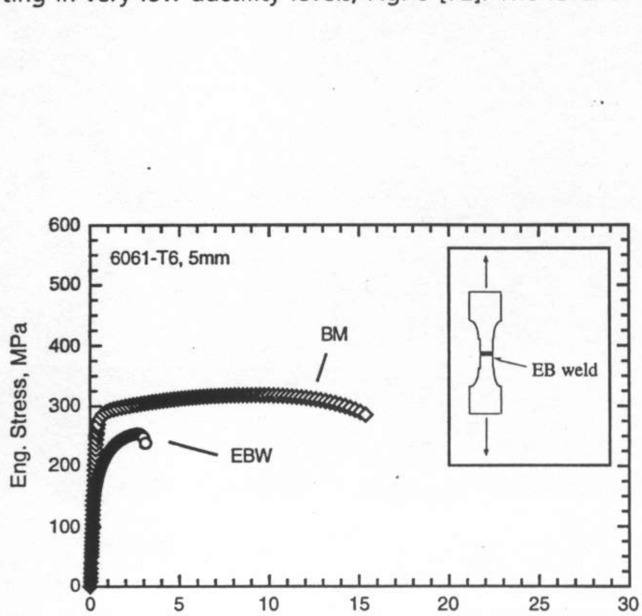


Fig. 8. Comparison of stress-strain curves of base material and EB weld joint for alloy 6061 (plate thickness is 5 mm) [72].

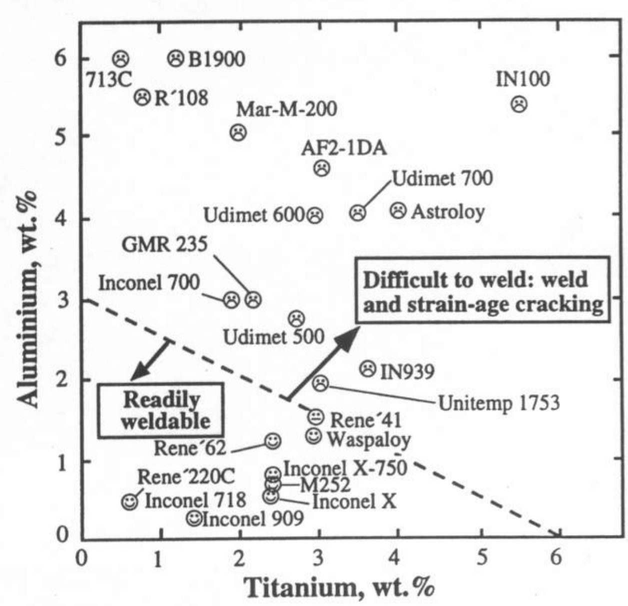


Fig. 9. Prager and Shira's plot of weldability versus Al and Ti content, with several Ni-based superalloys included by Kelly [42], based on strain-age cracking susceptibility [41].

forms rapidly at certain temperatures. When the (Ti+Al) content exceeds 4 wt%, strain-age cracking becomes a significant problem. The most effective means of preventing strain-age cracking is to overage the material prior to welding, which will not protect the HAZ, or to use controlled heating and cooling cycles for welding and subsequent heat treatment.

Liquation cracking in the HAZ of superalloy weldments is first observed by Pepe and Savage [43]. Phases that form during solidification, such as MC carbides and Laves phases, have the potential to initiate melting in the HAZ during welding and spread along the grain boundaries. The melting, often referred to as liquation, occurs as a result of a reaction between the dissolving precipitate and the matrix, resulting in liquid grain boundary films in the HAZ, well away from the fusion zone. Such a location prevents backfilling and promotes liquation cracking. The liquid film is incapable of absorbing the strain produced due to the contraction of the liquid metal in the fusion zone during solidification and therefore, causes the grain boundaries it occupies to separate and form HAZ microcracks. Such cracking may be termed liquation cracking, hot cracking, or microfissuring.

Other factors, such as large grain size [17, 44-48], heat treatment, and high impurity levels [17, 42, 46, 49-60], may also promote HAZ cracking in superalloys. It is also worth pointing out that HAZ microcracking is apparently a function of both the boron at the grain boundaries and the lowest liquating temperature phase reaction present in the system. Liquation cracking is expected to be a concern in LB welding of these alloys. Some success in obtaining crack-free welds has already been reported. However, there is a lack of mechanical data of the weldments reported.

The other problem which is encountered in LB welding of precipitation hardenable superalloys is the base metal degradation. The heating cycle involved in welding can result in the solutioning of age-hardening constituents which will reduce the strength of the weld zone (undermatching). Temperatures immediately adjacent to the fusion zone will reach and exceed the recrystallization temperature, resulting in grain growth and elimination of the retained strain energy from thermomechanical processing. These effects can significantly alter the properties of the weldment. The base metal degradation is expected to be the major concern in LB welding of precipitation-strengthened superalloys, such as Inconel 718 and A-286. However, this problem can also be overcome with proper welding parameters (achieved within Brite-Euram Project ASPOW) as demonstrated in Fig. 10, which illustrates a LB joint of Inconel 718 and its hardness profile with no indication of base metal degradation in weld region [72]. Fig. 10 also shows the formation of some Laves phase, $(Ni,Mo)_2(Nb,Cr)$, particles in the fusion zone which is expected to have a negative influence on the fracture toughness of fusion zone.

2.4. Weldability of C-Mn Steels

Steel is a good absorber of light wave lengths produced by CO_2 and Nd:YAG lasers and many steels are readily weldable by this process. A series of studies describing the successful use of LB welding to different steels in various industrial applications can be found in the literature. However, the chemical composition (particularly C, P, and S contents as well as carbon equivalent) of the structural steels significantly influences the laser weldability of these materials. In modern structural steels the carbon content is significantly reduced and the strength is attained by alloying elements and/or thermal processing during rolling. These fine grained steels are particularly suitable for low heat input laser welding process to avoid the development of a coarse grained microstructure in the HAZ region. However, low heat input and high cooling rate (high welding speed) typical of this process promote the formation of hard and brittle microstructures (i.e. martensite) within the narrow weld and HAZ regions of steels subjected to solid state phase transformations. Since the hardness values reached in these regions are usually well above those specified in standards and codes, expensive and time consuming qualification procedures are required for individual components [61]. Fig. 11 shows the hardness peak in the hardness profile of similar ferritic steel LB joint in contrast to the hardness profile of austenitic steel LB joint with no hardness increase in fusion zone [62]. It has been reported [63] that the use of IIW formula for carbon equivalent (Ceq) is not adequate to assess the hardening effect in the fusion zone of the laser welds of C-Mn steels.

The weld formation and quality of LB steel weldments are usually associated with three aspects: porosity, solidification cracking and high hardness in the HAZ and fusion zone. Pores are formed as a result of dissolved gases or gases arising from contaminated surfaces, trapped process gases or evaporation of alloying elements. In the case of steels, porosity has been in general associated with low grade rimmed steels with oxygen contents above 100 ppm especially as thin sheet material, although the literature also reports this type of defects on weldments produced in higher steel grades [64]. Because of the excessive weld cooling rates the rate of escape of bubbles eventually formed in the fusion zone is usually lower than the rate of solidification resulting in various degrees of porosity in the final weld. Recent studies on different steel grades, thickness and welding speeds have shown that generally the porosity level associated with slower welds is higher than those connected with faster welding speeds [64]. The evaluation of the weldment quality revealed that higher porosity levels, irrespective of parent plate type, do not have a particularly detrimental effect on weld joint properties due to strength overmatching shielding effect.

At high cooling rates of the LB welding, the effect of alloying elements on the resulting microstructure decreases as martensite becomes the dominating structure. The maximum hardness of the martensite formed is then determined by the amount of carbon in solution. Due to the transformation kinetics on heating the austenite formation temperature increases with increasing heating rates (i.e. at about 1000°C/s the formation of austenite starts at temperatures slightly above 900°C) [65]. Moreover, the austenite formed at this heating rate is usually not homogeneous, or in other words, the available carbon might not be completely dissolved. The maximum hardness of the martensite formed from this heterogeneous austenite will be a function of the dissolved carbon and not directly related to the total amount of alloying elements. Nevertheless, laser beam welds in steels presenting solid state phase transformations are generally characterized by the presence of hard and brittle structures in the fusion zone and HAZ which might have a negative effect on the deformability and toughness of the weldment. An obvious solution or attenuation of such problem is a tighter control of the

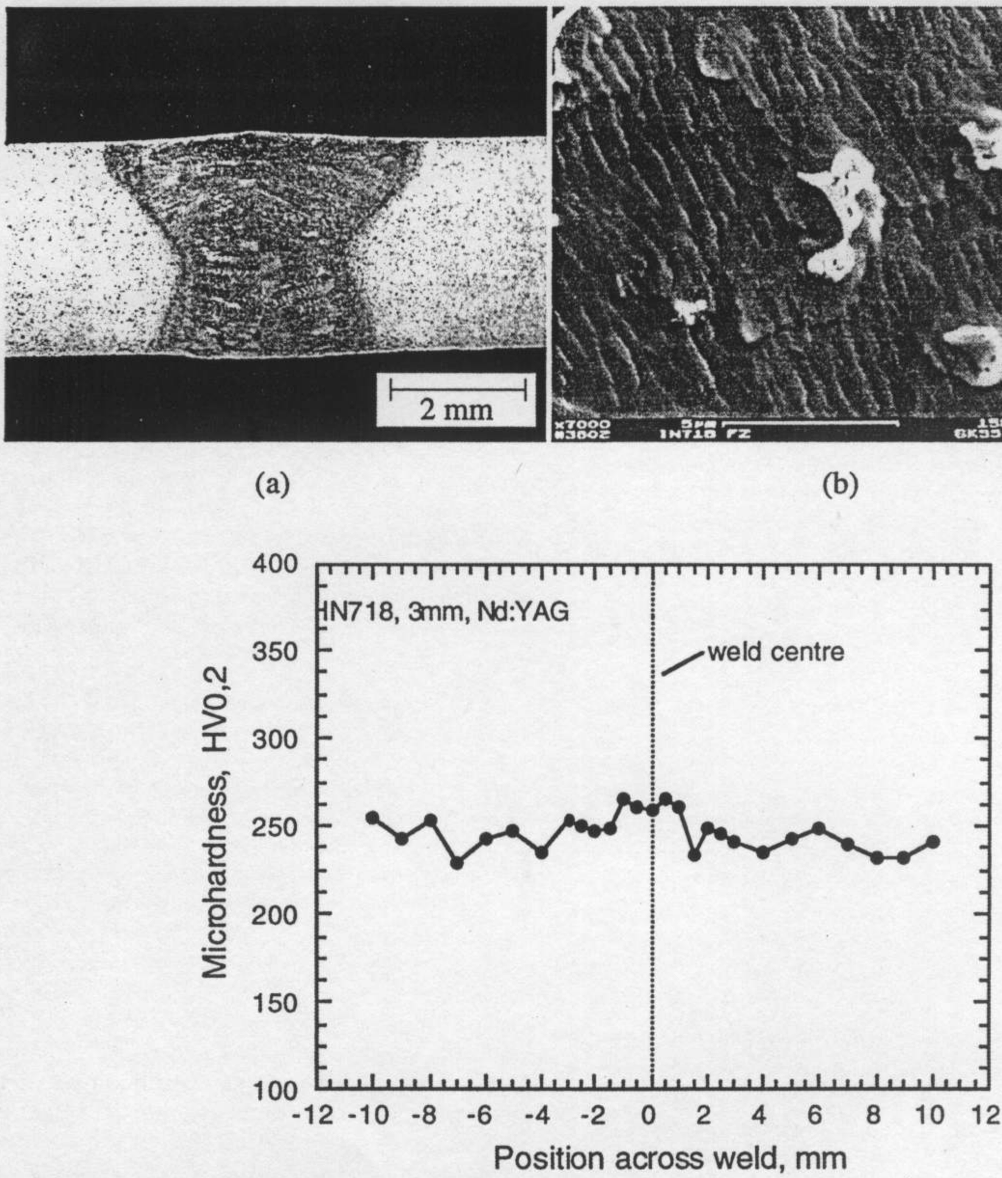


Fig. 10. Nd:YAG LB weld joint of Inconel 718 produced using 3 mm thick plate: a) overview of the joint, b) scanning electron micrograph of the fusion zone showing Laves phases, and c) hardness profile [72].

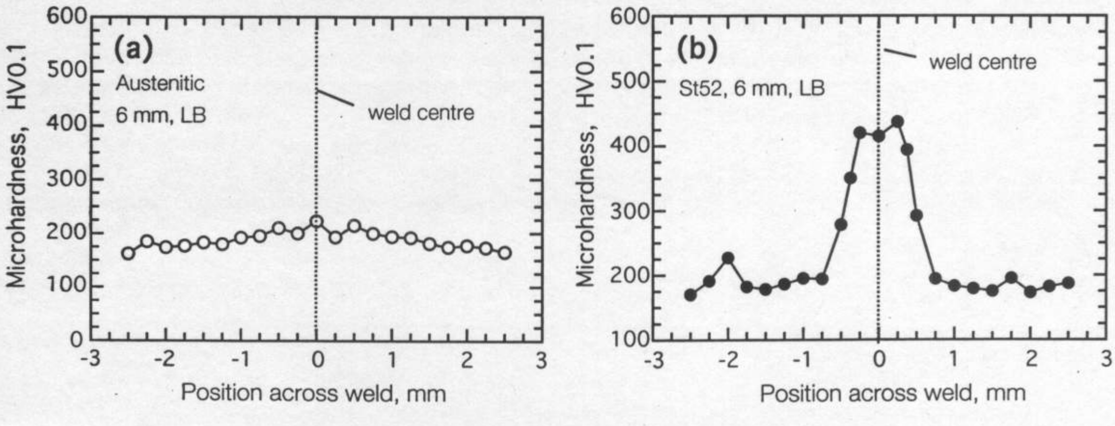


Fig. 11. Hardness profiles of steel LB joints shown in Fig. 2: a) similar austenitic (1.4404) and b) similar ferritic (St52) joint [62, 71].

base metal chemical composition particularly in the case of C, S and P contents [66].

Solidification cracking is caused by segregation surrounding solidifying grains or dendrites of restrained welds. In the case of steels elements such as sulphur, phosphorous and boron which form low-melting point constituents during the last stages of solidification reduce grain boundary surface tension. In the presence of a minimum level of tensile stress or restraint cracking occurs. In welding, the magnitude of these stresses is a function of joint geometry particularly depth of weld penetration.

In summary it could be said that the susceptibility to form solidification flaws depends on:

the geometry of the joint, the shrinkage involved in solidification, the coarseness of the solidifying structure and the amount and species of segregation. Fig. 5 shows solidification cracking in a dissimilar austenitic/ferritic steel laser beam weld as an example. The narrow and deep geometry characteristic of laser welds results in very low aspect ratios (bead width/bead height). It has been shown [67] that in the case of laser welds in Ni-Cr-Mo steels the total crack length increases as the bead shape becomes cylindrical. Hence, for a given chemical composition, parameters favouring a reduction of the aspect ratio such as increasing laser power and welding speed promote solidification cracking. The occurrence of solidification cracking has also been shown to be directly related to external restraint. Recent studies have, however, revealed that small amounts of solidification cracks are non-critical to structures. Furthermore, it is possible to control or avoid these flaws by a combination of steel composition and welding parameter selection. Nevertheless, this may reduce the productivity of the laser welding process [68].

Laser welding is also about to become a rapid manufacturing tool in the automotive industry for welding of thin steel sheets (blank or Zn-coated) by replacing the conventional spot welding process.

3. STRENGTH MISMATCH PROBLEM OF LASER BEAM WELDS

It is common practice to obtain weld metals which display higher strength (overmatching) than the steels used in various engineering structures. By doing this, a beneficial shielding effect of the higher yield strength weld metal (defective region in most cases) on a defect from imposed strains can be expected.

Despite significant improvements in LB welding technologies over recent years, it still remains difficult to characterize narrow LB welds in a unique fashion and to produce quantifiable mechanical properties. General guidance on design aspects of LB welded joints is currently lacking for potential users so that they are often reluctant to opt for such a welding process despite the available technology to fabricate the joint. Present standards do not take into account the characteristic features of LB welds stemming from high energy density, high welding speed, high solidification rate and the small volume of base material affected. Many LB weld joints, therefore, may fail according to the available standards, even though their mechanical performance is sufficient. Thus, additional non-standard tests, which consume time and money, are often requested by the industries.

Tensile Testing: Due to very small LB weld zone (approx. 2-3 mm), standard round tensile specimens cannot be extracted to determine the local *weld zone tensile properties*. Flat microtensile specimens can easily be produced and tested in order to determine the mechanical property variation across the weld joint. The extraction of these specimens is schematically illustrated in Fig. 12 [70, 71]. Fig. 13 shows full stress-strain curves of laser beam welded C-Mn steel joints determined by testing microtensile specimens.

Fracture Toughness: There are no fracture mechanics based testing procedures available for power beam weld

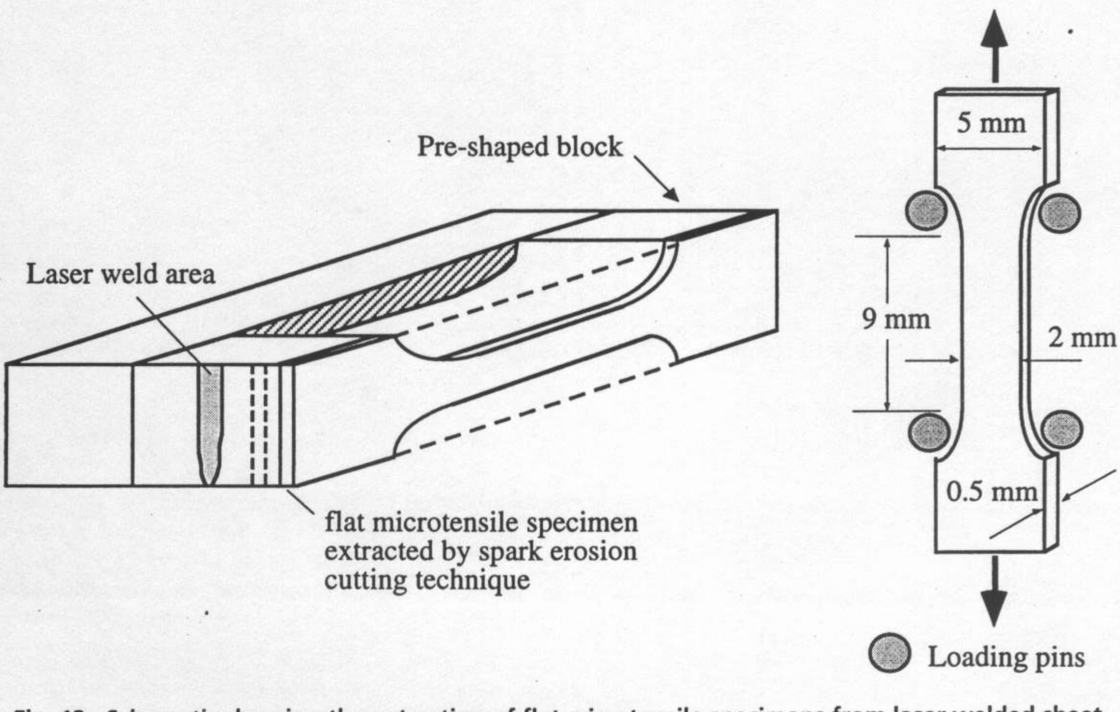


Fig. 12. Schematic showing the extraction of flat microtensile specimens from laser welded sheet by spark erosion cutting [71].

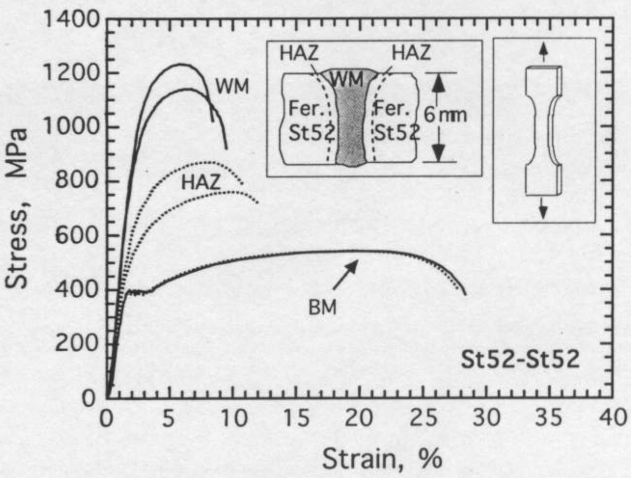


Fig. 13. Full stress-strain curves obatined by testing microtensile specimens extracted from the base metal (BM), weld metal (WM) and HAZ regions of CO_2 laser beam welded St52 steel joint [71].

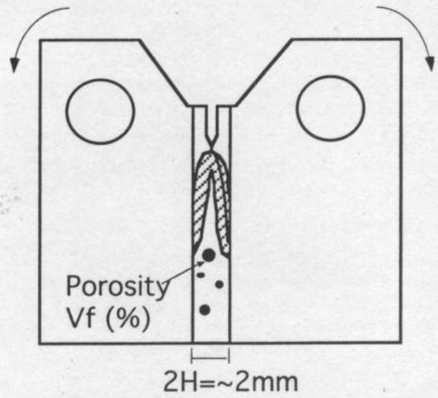


Fig. 15. Schematic showing confined plasticity development within the lower strength weld region of Al-alloy laser beam weld. An increase of constraint at the crack tip occurs due to the lack of participation of the parent plate in the deformation process.

joints despite the wide and inevitable use in modern engineering structures. This discrepancy is due mainly to the lack of information on the interaction between the base metal and fusion zone, which have different mechanical properties. Substantial differences in strength properties **(mismatching)** of the base metal and narrow fusion zone of the LB welds inevitably occur due to the rapid thermal cycle of the joining process.

Almost all LB welded structural C-Mn steels exhibit weld metal region of higher hardness and strength (possibly with lower toughness) compared to the base metal (overmatching) due to the rapid solidification and single pass natures of the welding process. Small laser weld region with its high hardness and strength makes it almost impossible to determine the fracture toughness properties (intrinsic) of the weld region using conventional Charpy-V impact [69] and Crack Tip Opening Displacement (CTOD) toughness [62] testing specimens due to the crack path deviation towards the softer base metal, as schematically illustrated in Fig. 14. The crack path deviation into the softer base material of a C-Mn steel (grade St52) LB weld joint is shown in Fig. 16.

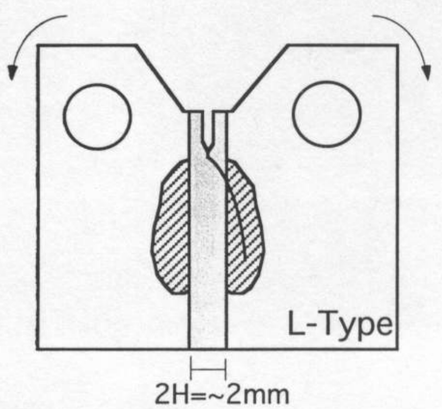


Fig. 14. Schematic showing extensive plastic zone development in the soft base metal of C-Mn steel laser beam weld. The crack path deviation inevitably occurs towards the lower strength base metal and the toughness result obtained represents the base metal.

An extensive development of plasticity at the lower strength base metal regions of C-Mn steel laser welds inevitably occurs due to the small size of the weld seam both in laboratory specimen and components in service if test/service temperature corresponds to the upper shelf regime. This remote deformation causes a stress relaxation (lower constraint) at the crack tip located at the possibly lower toughness (higher hardness and strength) weld region and hence prevents the occurrence of brittle fracture (by crack path deviation, see Fig. 16) since the critical cleavage fracture stress cannot be reached for the martensitic weld metal.

Therefore, it can be speculated that low level of fracture toughness of the LB weld region of the C-Mn steels does not matter if the base plate can deform plastically (i.e. the base plate should not be in the lower shelf of ductile-brittle transition regimes) and hence accommodates the applied strain significantly by relaxing the crack tip or defect at the lower toughness region.

The toughness result obtained from such a specimen will be higher due to tougher base metal, but the obtained toughness level should not necessarily be classified as "invalid" toughness result. An inevitable interaction between lower strength base metal (at a distance of about 1.5 mm to the weld zone) and the crack tip will occur and hence relaxes the stress-state at the crack tip.

Therefore, inevitable extensive plasticity development in the parent plate of the C-Mn steel laser welds may minimize the structural significance of the lower toughness small weld seam under some circumstances (i.e. depending on the temperature and defect size). If lower toughness weld or HAZ regions of the C-Mn steel welds cannot control the failure behaviour of the standard laboratory specimen, no extra effort (i.e. artificial LB weld configurations or specimen design to force the crack to remain within the weld seam) should be made for the determination of fracture toughness of LB welds. This may be achieved in laboratory scale specimens, but service behaviour of LBW joints will follow its own natural course.

As mentioned in section 2.2, laser weld regions of most Al-alloys exhibit lower hardness and strength compared to the parent plate. Contrary to the C-Mn steel specimen, Fig. 14, the confined plasticity development at the vici-

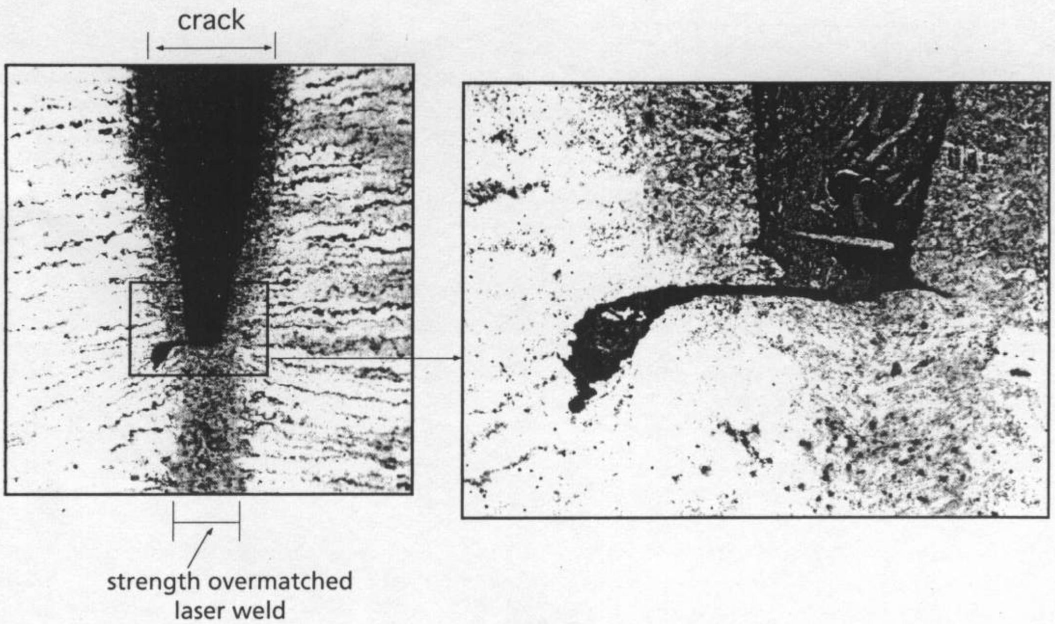


Fig. 16. Crack path deviation into the softer base metal in a similar ferritic steel (St52) joint.

nity of a crack tip of the LB welded Al-alloy is schematically shown in Fig. 15. This phenomenon has been experimentally demonstrated in weld joints with undermatching weld zone as illustrated in Fig. 17. According to the experimental observations and some numerical studies, the crack tènds to develop at the interface region (the border of plastic incompatibility) between the base metal and the softer weld region. It should further be noted that the very small size strength undermatched weld region (2H) would increase the load carrying capacity of the specimen or component at the cost of reduction in ductility or deformation capacity of the weld joint. The reduction in ductility of an alloy 6061 EB weld joint containing undermatching weld zone is shown in Fig 8. The overall strength of the joint is also lower than that of base material due to a relatively large weld zone produced in EB welding.

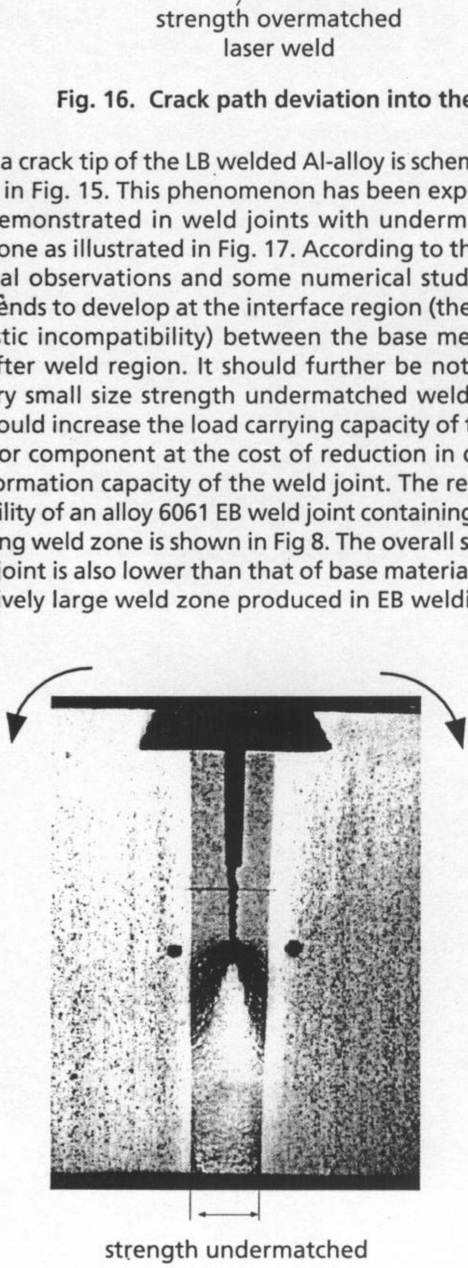


Fig. 17. Optical micrograph showing confined plasticity development due to the strength undermatching in the weld region in a bend specimen.

Defect Assessment: Considering the very narrow LB weld metal size, the "shielding effect" of the higher yield strength weld seam of C-Mn steels (from externally applied strain) on a defect present within the weld seam could be of a very different magnitude than the shielding effect observed on conventional larger sized weld joints. Global deformation and fracture behaviour of the LB weld joints which include inevitable participation of the neighbouring base plate in the deformation process, as mentioned earlier, should be respected and considered. Therefore, the defect assessment procedures or standards developed for conventional weldments need to be modified for laser beam weldments. The fracture assessment of such welds for structural integrity requires detailed information on the effects and/or interactions of each part on the overall fracture behaviour. As far as known, no systematic study concerning the effects of local strength mismatching on power beam weld joint performance has yet been conducted. Presently, the lack of any international standard for incorporating mechanical heterogeneity (mismatch) in laser beam structural weldments and related safety assessment procedures urgently requires the development of a technology applicable to civil, aerospace, oil and gas, power generation, chemical, process ànd ship building industries as well as being acceptable by designers and producers of structural materials.

For these very reasons, an European Brite-Euram project **ASPOW** (**As**sessment of Quality of **Po**wer Beam **W**eld Joints) has recently been established [72] predominantly by industrial companies to establish the European framework of the destructive and non-destructive testing and assessment issues of laser and electron beam welds of over 20 metallic materials.

4. FINAL REMARKS

Some success has already been reported on laser beam welding of aluminium alloys, titanium alloys, superalloys, and steels in the surveyed open literature. However, there is still a lack of comprehensive mechanical properties data on these joints and some weldability problems should also be overcome, such as *porosity*, particularly in aluminium alloys, and *cracking*, particularly in intermetallic materials. There is still a need for further research for a full understanding of the relationship between the welding parameters and the mechanical properties of the power beam joints.

Distinct information on the relationship between the type of porosity and weld process parameters is still lacking. Furthermore, no information is available on the structural significance of pores and HAZ degradation of Al-alloy weldments. Therefore, there is a need for an NDT defect catalogue particularly for the assessment of Al-alloy LB weldments. This has a particular importance to develop a new damage tolerance concept for laser or friction stir welded (FSW) aerospace structural components.

Moreover, the evaluation of the mechanical properties of the power beam welds, particularly for superalloys and intermetallic alloys, has not yet been fully made. Conventional testing procedures cannot be applied straightforward to the LB welded joints, particularly in the presence of strength over – (i.e. C-Mn steels) or undermatching (i.e. Al-alloys) between the weld metal and the base plate.

The laser beam weldability of these alloys is currently being investigated and the weldments are assessed in a Brite-Euram Project, ASPOW. The aim of this project is to correlate the microstructure and mechanical properties of the power beam weldments and provide reliable mechanical property data and information on the fracture behaviour of these joints. Another objective of this project is to develop an NDT defect catalogue for various power beam welded alloys for structural assessment of these joints. Finally, a european defect assessment procedure specifically tailored to laser and electron beam welds is in preparation.

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