The Application of Laser Welding to Overcome Joint Asymmetry

High power density processes offer potential for tube-to-tube plate welding, and may become especially useful for thin-tube titanium vessels

BY E. J. MORGAN-WARREN

ABSTRACT. The work described aims to further the development of welding techniques for thermally asymmetric joints. A typical example is to be found in the construction of modern titanium heat exchangers where thin-walled tubes are welded to relatively massive tube plates.

A simple model was set up to compare the heat input requirements for the thick and thin components of an asymmetric joint, and to describe the effects of component dimensions, material thermal properties and welding parameters on the discrepancy between these requirements. The model shows that the effects of thermal asymmetry may be reduced by the use of a fast-moving high density heat source. The approach to symmetry improves as the welding speed is increased, and, for a given speed, is a function of the thermal diffusivity of the material and the component dimensions. Metals of low thermal diffusivity, such as titanium and steels, are favored, and for these materials a good approach to symmetry is predicted with speeds above 20 mm/s (47 ipm) and a tube thickness of 0.5 to 1 mm (0.02 to 0.04 in.).

Experimental laser welds were made between titanium sheets, 1 mm (0.04 in.) and 12 mm (½ in.) thick, to simulate the tube-to-tube plate joint configuration. The penetration characteristics were shown to be greatly superior to those obtainable with conventional GTA welding.

Laser welding is thus effective in overcoming the heat sink problems associated with joint asymmetry. Its advantages include a narrow weld bead and heat affected zone, reduced HAZ grain growth, reduced danger of atmospheric contamination and a high tolerance to variations in welding parameters and joint fit-up. The main problems to be overcome include weld bead root porosity and, for large structures, laser beam manipulation.

Introduction

The welding of two components with largely differing heat sink properties has long been an area of difficulty. A common case of the "thick to thin" weld is the tube-to-tube plate joint, where a thin tube is welded into a massive tube plate. The problem becomes increasingly severe as the tube thickness is reduced, and titanium heat exchangers using tubes of about 1 mm (0.04 in.) wall thickness are typical of the situation.

The difficulty lies in applying enough heat to cause melting of the massive component without excessive fusion of the thin part. (Most welding processes are limited in this respect by their inability to supply the high and finely focused power which is required to cause rapid and localized melting.) Techniques which have been devised to enable satisfactory joints to be made by arc welding usually require special joint preparations. Usually these either reduce the effective mass of the tube plate (e.g., the castellated preparation and internal bore welding) or they separate the tube and plate (e.g., the Revere method).

High density power sources, such as the electron beam and the laser, can provide the finely focused heat input necessary to produce localized melting. Electron beam welding is now a well-established technique and is used to make deep penetration welds with a minimum energy input and distortion. Normally this process requires a vacuum; thus, the workpiece must be contained in a vacuum chamber or the joint area evacuated locally.

The laser is less well-established as a welding tool but has some similar characteristics as a heat source. A vacuum is not required, however, and welding may be carried out in a protective atmosphere in a similar way to GTA welding. Thus, with heat sources available which approach the idealized "point source," it is possible to confine fusion to a very small area around the joint line. This, in itself, does not overcome the fundamental effect of joint asymmetry where each component requires a different heat input.

The problem of asymmetry is analyzed in the present paper, which shows that asymmetry can be reduced by welding at high speed. The speed necessary to effect a given improvement depends on the material and geometry of the joint. Titanium is shown to be particularly amenable to improvement. Thus, in view of the interest in tube-to-tube plate welds in titanium, the practical exploration of the laser welding of "thick to thin" joints is based upon this example.

Theory

Let us consider a seal weld between a thin tube and a massive tube plate (Fig. 1) in which a penetration equal to the tube wall thickness is required—Fig. 2. To a first approximation,

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E. J. MORGAN-WARREN is Research Officer, Marchwood Engineering Laboratories, Central Electricity Generating Board, Southampton, England.

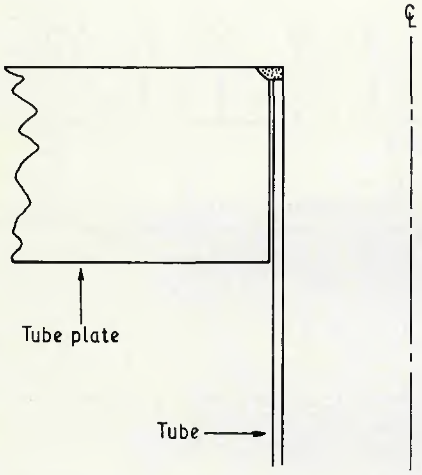

Fig. 1—Tube-to-tube plate weld configuration

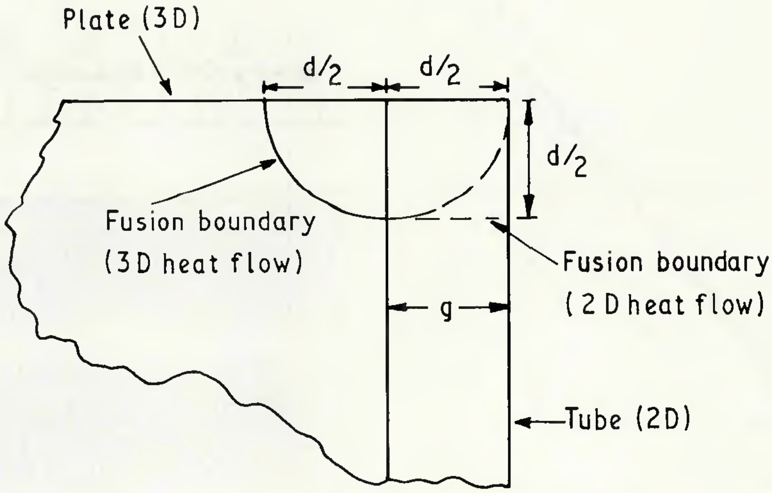

Fig. 2—Schematic of fusion boundary in tube (2D) and plate (3D)

this demands a fused zone equally distributed between the components and with a half width equal to the tube wall thickness. The difference in the heat sink capacities of the tube and plate, however, results in a different heat input requirement for each component.

The thick and thin components may be approximated to semi-infinite three-dimensional and two-dimensional plates respectively. Roberts and Wells[1] have used Rosenthal's heat flow equation[2] to obtain simple expressions for the fused width in terms of the welding parameters.

For the two-dimensional (thin) case, the expression for power input is:

$$q_1 = kTg\left(1.6 + 2\,\frac{vd}{\alpha}\right) \tag{1}$$

For the three-dimensional (thick) case;

$$q_2 = \pi kTd\left(0.5 + \frac{0.3125\,vd}{\alpha}\right) \tag{2}$$

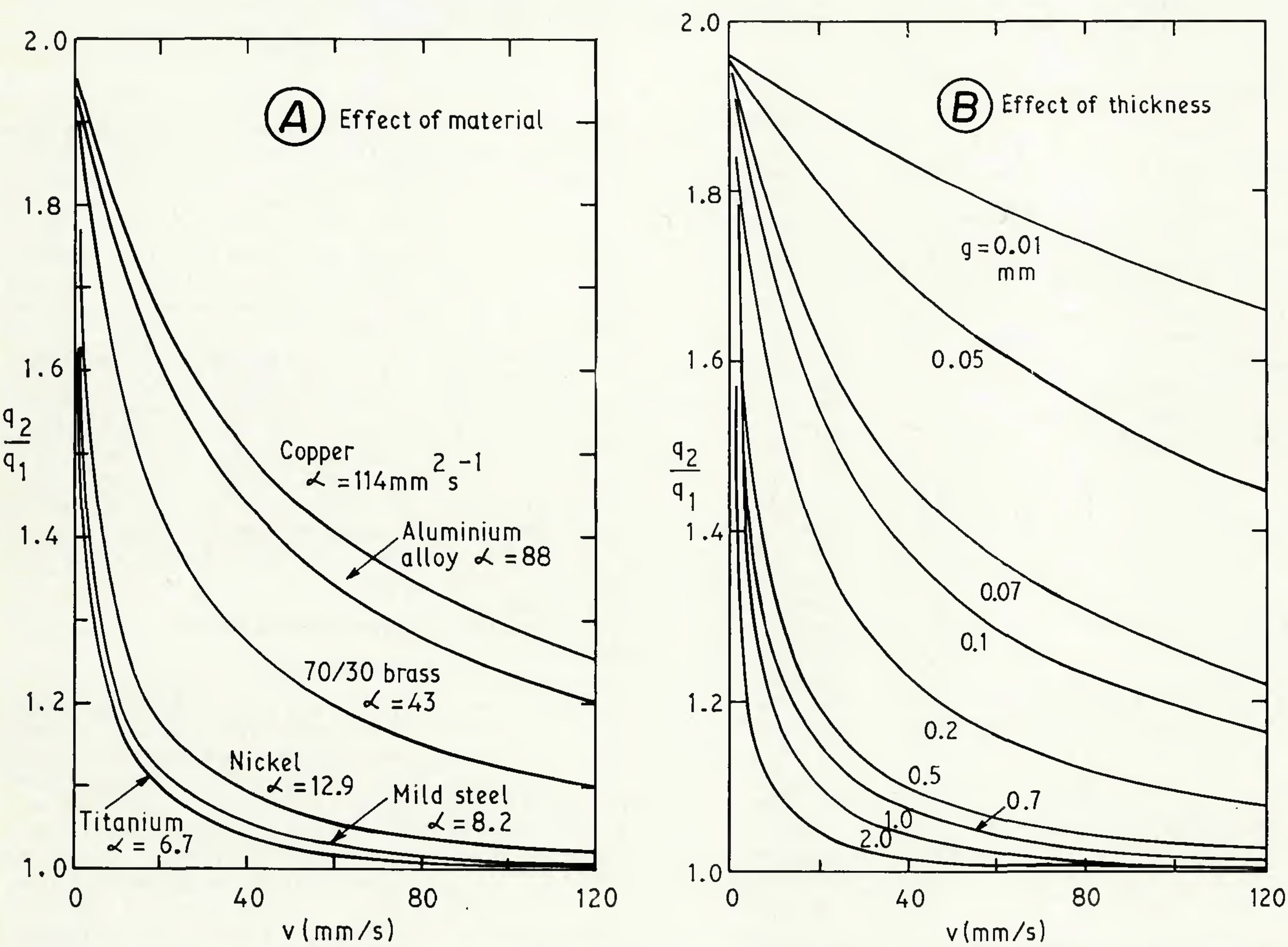

Fig. 3—Plots of power ratio q_2/q_1 against welding speed v for: A—materials of different thermal diffusivity; B—titanium of different sheet thicknesses

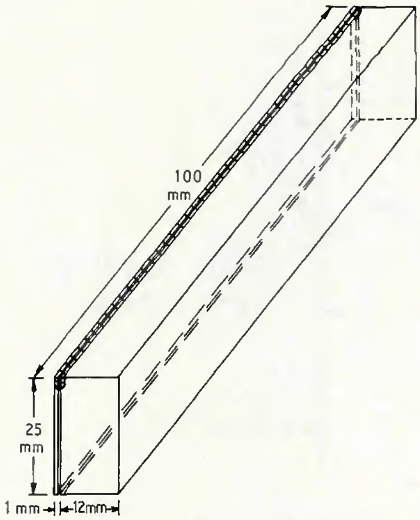

Fig. 4—Laser weld test specimen

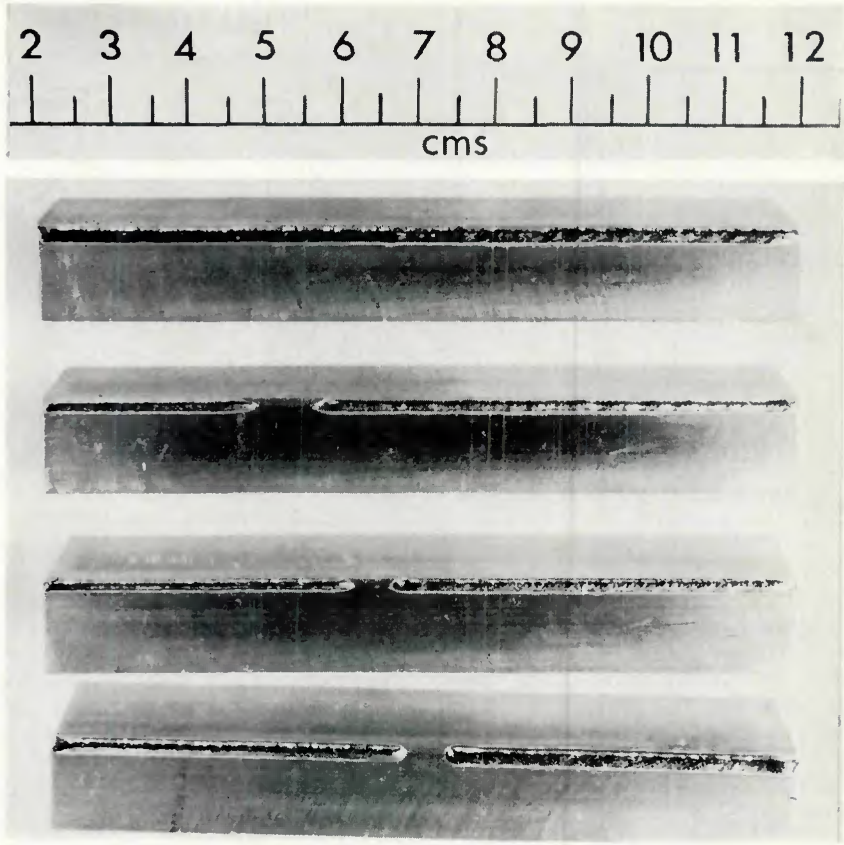

Fig. 5—General appearance of laser welds

where q is the power input (in watts, W), k is the thermal conductivity (W mm^{-1} deg C^{-1}), T is the temperature of melting less the ambient temperature (deg C), g is the sheet thickness (mm), v is the welding speed (mm s^{-1}), d is the fused width (mm), and α is the thermal diffusivity (mm^2 s^{-1}).

Simplification of (1) and (2) gives:

$$q_1 = A_1 + B_1 v \quad (3)$$

and:

$$q_2 = A_2 + B_2 v \quad (4)$$

where $A_1 = 1.6kTg$ and $B_1 = \dfrac{2kTgd}{\alpha}$

Similarly:

$A_2 = 0.5\pi dkT$ and $B_2 = \dfrac{0.3125\pi Td^2k}{\alpha}$

Inspection of equations (3) and (4) shows that the power requirement increases as the welding speed is raised. For "thick to thin" welding the requirement is for a symmetrical weld in an asymmetric heat sink. Hence the power input ratio, q_2/q_1, becomes an important parameter. Since for the weld bead geometry specified, $d = 2g$ (see Fig. 2), we find:

$$\frac{q_2}{q_1} = \frac{A_2 + B_2v}{A_1 + B_1v} = \frac{\pi\left[0.5 + \dfrac{0.625\ gv}{\alpha}\right]}{0.8 + \dfrac{2gv}{\alpha}} \quad (5)$$

and for a symmetrical weld, q_2/q_1 should be as near as possible to unity.

In the limit of high welding speed, $B_2v >> A_2$ and $B_1v >> A_1$, we find:

$$\frac{q_2}{q_1} \simeq \frac{B_2}{B_1} \simeq 1$$

In the limit of low welding speed, $B_2v << A_2$ and $B_1v << A_1$, we find:

$$\frac{q_2}{q_1} \simeq \frac{A_2}{A_1} \simeq 2$$

Several features emerge from this analysis. Referring to Fig. 3, they may be summarized as follows:

1. The ratio of the heat inputs required by the thick and thin components respectively is a function of the thermal diffusivity of the material, the thickness of the thin component and the welding speed, combined in the single parameter gv/α.
2. For a given material and joint geometry, the ratio of the power requirements falls from 2 to unity as the welding speed is increased. In other words, with higher welding speeds the heat sink becomes effectively more symmetrical.
3. The higher the thermal diffusivity of the material, the higher is the welding speed necessary to achieve a certain tolerance to asymmetry. Thus higher welding speeds would be required to overcome joint asymmetry in materials of high thermal diffusivity such as copper and aluminum, than in metals of low diffusivity, such as steel and titanium. To take an example from Fig. 3A, a welding speed of approximately 20 mm/s (47 ipm) is sufficient to reduce the heat input ratio to 1.1 for titanium. To achieve a similar effect in copper, speeds in excess of 140 mm/s (331 ipm) would be necessary.
4. A given reduction in the value of q_2/q_1 requires a greater increase in welding speed as the tube thickness is reduced. It can be seen from Fig. 3B that with titanium tubes 1 mm (0.04 in.) thick, the power input ratio is reduced to 1.1 at a welding speed of 20 mm/s (47 ipm). If, on the other hand, a thin foil (say, 0.1 mm or 0.04 in. thick) is to be welded to a thick block, a speed in excess of 100 mm/s (236 ipm) would be required to achieve a similar effect.

In order to realize the advantage offered by high speed welding, it is essential that the heat source be finely focused. The need for fine focusing follows from the requirement of a bead width equal to double the tube thickness. High power GTA welding cannot meet this requirement, but a laser can be focused to a fine spot size.

Experimental Work

Welding Trials

The foregoing simple analysis shows how a high power density welding process can be used in a high power, high speed regime to minimize the effects of asymmetry associated with the joining of thick and thin components. To investigate the use of the laser to implement these conditions, titanium sheets 1 and 12 mm thick (0.04 and ½ in.) were welded together face-to-face as shown in Fig. 4. This arrangement was chosen to simulate

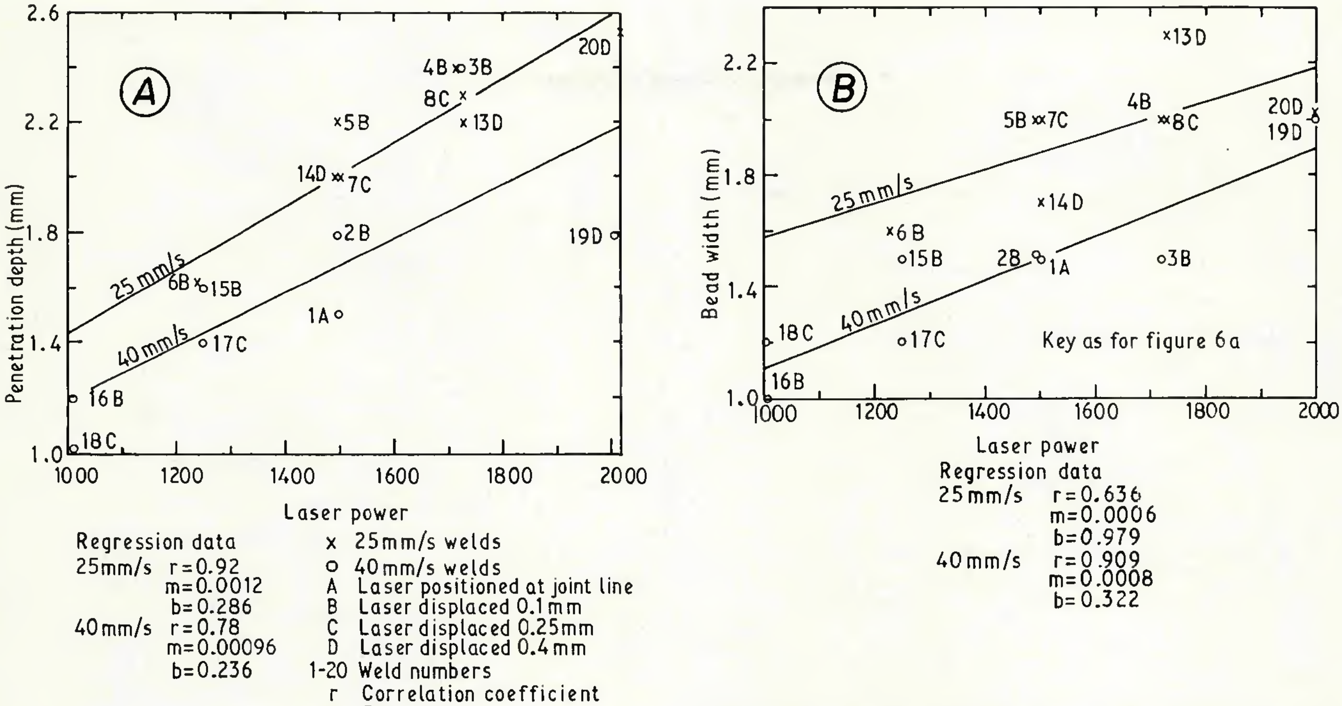

Fig. 6—Plots against laser power for welds made at 25 and 40 mm/s: A—penetration depth; B—weld bead width

the thermal conditions existing in a tube-to-tube plate face seal weld.

The work was carried out in collaboration with BOC Limited, using a 2 kW CO_2 laser machine. The laser beam was focused using a 75 mm (2.95 in.) focal length lens, giving a spot diameter at the focal point of 0.25 mm (0.0098 in.). The beam was focused at the workpiece surface, and was at normal incidence. The primary shielding gas was helium (flow rate = 10 litres per min, i.e., 21.2 cfh), but an outer ring and trailing shield of argon were also used.

The principal parameters to be varied were laser power and welding speed. However, the effects of joint fit-up and point of heat source application were also examined. Consistent with the speed effects described above and with prior laser welding experience, welding speeds of 25 and 40 mm/s (59 and 94 ipm) were used, and power was varied between 1 and 2 kW. The point of application was varied from the joint line to positions up to 0.4 mm (0.016 in.) towards the thick member, to enable edge effects to be assessed. In addition to the close butt welds, trials were made with tapered gaps between the plates (0–0.25 mm, 0–0.0098 in.) and with the thin plate both recessed and proud (0.4 mm, 0.016 in.) with respect to the thick.

Relationship between Process Parameters and Weld Characteristics

The general appearance of the weld beads is shown in Fig. 5. The welds as produced were covered with a black titanium sublimate (the result of evaporation and rapid cooling); this was easily wiped off to show a bright silver-colored weld bead.

Weld penetration depth and bead width varied between approximately 1.0 and 2.5 mm (0.04 and 0.098 in.). Figure 6 shows the variation as a function of laser power and welding speed. Separate straight line relationships were obtained for the two speed levels, with significant levels above 90%. The separate relationships for each speed are combined in Fig. 7 to give the width and depth as functions of the laser heat input (i.e., q/v). The high correlation coefficients obtained for these relationships demonstrate the significance of heat input as a single parameter which combines the separate effects of power and speed.

The experiments showed that, at high speeds and within experimental limits, the power required for a given bead size is directly proportional to the speed. This is in accord with equations (3) and (4) where the contributions of A_1 and A_2 become relatively small when the value of v becomes large. It is thus clear that at high speeds, q_1/v and q_2/v approach the constant values, B_1 and B_2 respectively for a constant bead size, a relationship that seldom applies in conventional autogenous welding processes.

It is interesting to compare the theoretical and actual heat input values which give rise to welds of the various dimensions obtained. However, since the laser produces deep penetration welds, the bead shape in this case is not directly amenable to comparison. To make the required comparison, an equivalent bead width was calculated for each weld. This is the width of a semicircular bead having the same cross-sectional area as the actual bead. Treating each bead for this purpose as a semi-ellipse of width x and depth y, the equivalent bead width, d*, is given by:

$$d^* = \sqrt{2xy}.$$

The theoretical power for each d* value was calculated using the three-dimensional relationship, equation (2). (Referring to Fig. 3, the reader will recall that at the relevant welding speeds the power levels for the two-dimensional and three-dimensional cases are within 10%.) Figure 8 shows the relationships between the theoretical and actual power requirements obtained on the above basis, both for the two speeds considered separately and for the whole batch taken together. The three straight line relationships obtained are very similar and significant at the 99% level.

It is noteworthy that the lines intercept the actual power axis at values around 500 watts and have a slope of less than unity. The reason for this is certainly complex; it does reflect the need for a threshold power level to achieve keyholing and a fusion zone.

The Effect of Fit-up and Laser Beam Position

Tolerance to joint fit-up is an impor-

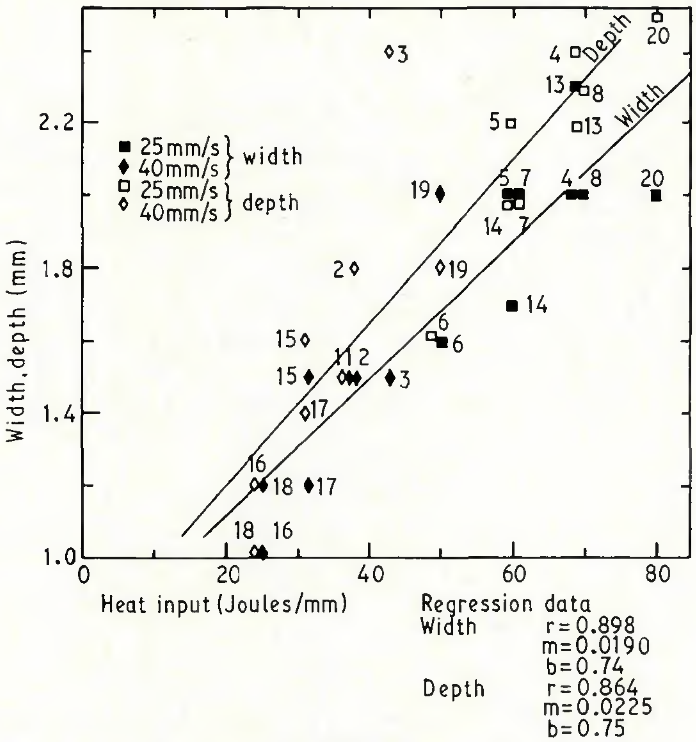

Fig. 7—Plot of weld depth and width against heat input

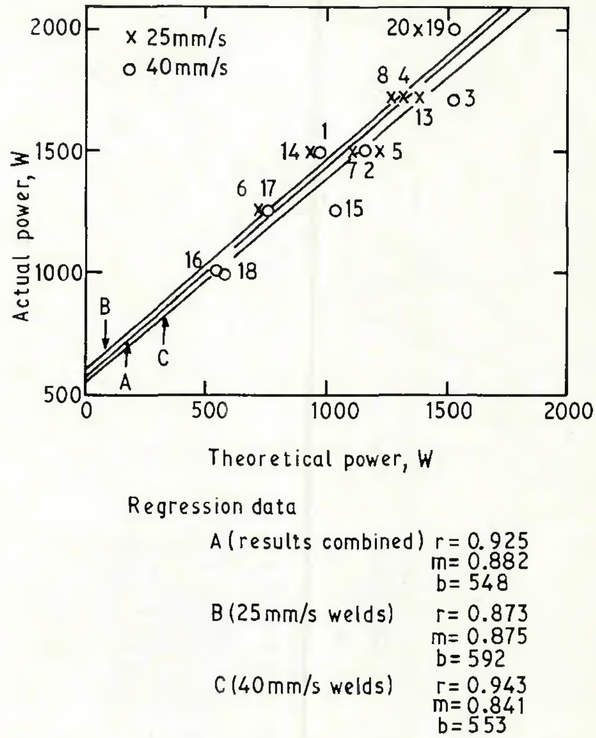

Fig. 8—Plot of actual power against theoretical power required, based on equivalent bead widths (see text)

tant factor in the viability of a welding process. The limited variations incorporated in this work did not give rise to any apparent deterioration in weld quality. Where the thin plate was proud (edge standing high) with respect to the thick, the weld bead was similarly proud, and there was some evidence of increased penetration associated with the gap of 0.25 mm (0.0098 in.) between the plates.

Where narrow weld beads are produced by a finely focused heat source, the position of the heat source in relation to the joint line can be critical. Thus in electron beam welding, for example, beam misplacement has been known to cause the fused bead to miss the joint line. In the present case, the effect of beam displacement on the position of peak penetration was discernible, particularly at the maximum of 0.4 mm (0.016 in.) from the joint line. However, the bead was sufficiently wide and flat-bottomed for the loss in joint line penetration to be less than 10%.

Metallurgical Examination

A typical macrosection of a laser weld is shown in Fig. 9A; for comparison, a GTA weld in a similar configuration is shown in Fig. 9B. It can be seen that the penetration in the laser weld is between two and three times the thickness of the thin sheet whereas, in the GTA weld, a penetration of less than half the thickness has been achieved. Furthermore, in the laser weld the heat-affected zone (indicated by grain growth) extends little beyond the fused bead itself, compared with the extensive HAZ, extending to several times the penetration depth, in the GTA weld.

One undesirable feature of the laser welds was the presence of root porosity. This was found to consist of discrete bubbles of approximately 0.2 mm (0.0079 in.) diameter at intervals of 1 to 2 mm (0.039 to 0.079 in.) along the length of the weld—Fig. 10.

Detailed examination revealed little evidence of atmospheric contamination in the laser welds, although some blue-gray surface oxide was seen in the heat-affected zone. However, no hardening was detected in the bulk of the metal; thus, it is unlikely that interstitial solutes had penetrated to a significant extent.

Microhardness measurements showed weld metal and HAZ hardness levels in the range 180-190 HV compared with base metal levels of 190 and 165 HV in the thick and thin plates respectively. Grain diameters in the laser welds were typically in the range 0.2 to 0.5 mm (0.0079 to 0.0197 in.) compared with 0.3 to 0.8 mm (0.012 to 0.03 in.) for GTA welds.

Discussion

The Welding Process

The laser welding experiments have demonstrated the ability of the high power density and high welding speed to overcome the problem of joint asymmetry.

In addition to this important feature, the process appears to offer a number of potential advantages over low power density processes such as GTA welding. Thus, the laser provides a depth of weld penetration equal to or greater than the thickness of the thin component (the tube, in the case of tube-to-tube plate welding), without the need for complex weld preparation. The weld bead and heat-affected zone are narrow, and HAZ grain growth and weld bead grain size are lower than in the case of GTA welding. The metallurgical effect on the original components is thus reduced.

The rapid thermal cycle associated with laser welding has a further important advantage in the welding of reactive metals. The absorption of atmospheric gases by these metals at high temperatures is dependent on the time of exposure and the concentration of contaminant in the shielding atmosphere. Thus the short time at high temperature leads to a reduced level of weld contamination and a greater tolerance to impurities in the shielding gas.

The tolerance to variations in welding parameters and joint fit-up observed in this work is significant. Where joints of similar configuration are welded by conventional processes, particular care is needed to avoid either lack of fusion or over-melting of the tube. However the laser welding experiments have shown that a broad operating envelope exists for this process. This has not been fully explored, and is an aspect that would merit further investigation.

The Mechanism of Porosity

The welds produced were found to contain porosity, which is a common feature in electron beam and laser welding. Causes which have been suggested include outgassing of the metal, and the entrapment of shielding gas, air, or a void by the collapse of the keyhole wall during welding.[5] In the specific case of titanium, porosity in GTA welds has been attributed to argon[6] and to hydrogen,[7] entrapped by the roughness of the abutting faces of the material.

In the case of laser welding, the entrapment of either air or inert gas would appear to be the most likely causes. Since titanium readily absorbs atmospheric gases, bubbles resulting from entrapped air would not survive, provided that the metal were fused for sufficient time. The shrinkage of a bubble due to the absorption of nitrogen into the molten metal wall is analyzed in the Appendix. There, the calculations show that air bubbles would be absorbed in the laser weld pool during the molten stage.

Porosity would therefore appear to result from the entrapment of the primary shielding gas, helium, by the collapsing keyhole. This problem has been largely overcome in electron beam welding by beam manipulation. It is likely that a comparable solution will become available as the development of laser welding progresses.

Application to Tube-to-Tube Plate Welding

The investigation described in this paper has demonstrated the potential of the laser for tube-to-tube plate welding. The use of the laser for welding structures, however, is largely dependent on the beam handling capability. A high power laser is really a fixed installation, and beam movement is achieved by means of mirrors.

The most amenable applications are those where the workpiece can be moved and only small adjustments of the beam position are necessary. The beam could be moved in a circular path for tube-to-tube plate welding without difficulty; if the structure were small, the work could be moved to bring each joint into position. For large structures such as high capacity chemical heat exchangers or condenser tube bundles, which are not readily movable, the beam itself would have to be moved from joint to joint. This could be done by mirrors, but a better solution might be to transmit the laser light via flexible light guides.

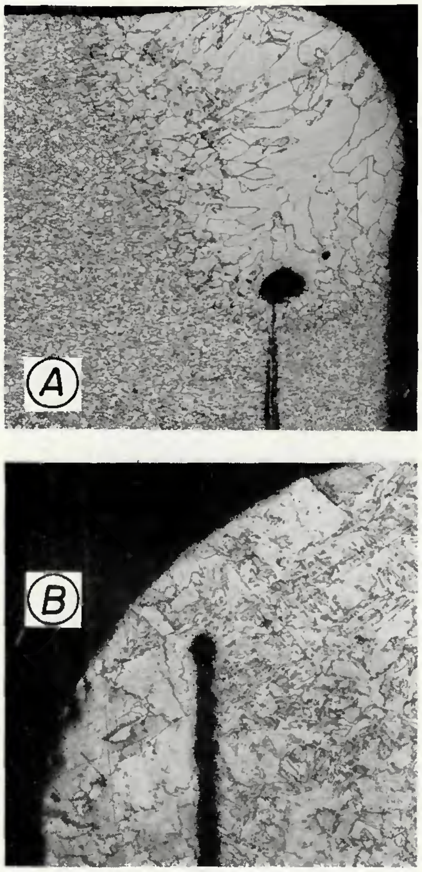

Fig. 9—Macrosections of welds in titanium: A—typical laser weld, ×25; B—GTA face seal weld, ×50 (reduced 36% on reproduction)

At present, light guide systems capable of carrying the high power required for welding are not available. However, the technology in this area is progressing rapidly, and a suitable system may become available in the future. Such a means of beam handling would enable the full potential of laser welding to be realized.

Fig. 10—Fracture face of laser weld showing root porosity. ×70 (reduced 50% on reproduction)

Conclusions

1. Consideration of the physical characteristics of welding thick components to thin has demonstrated the need for a focused high power, high speed heat source, e.g., an electron beam or laser.

2. The use of a high welding speed reduces the effects of joint asymmetry. The advantage to be gained depends on the joint geometry and the material. For titanium, the benefit is more readily achieved because of its low thermal diffusivity; for tube-to-tube plate welding with a tube wall thickness of 1 mm (0.04 in.), a realistic improvement is obtainable at practical welding speeds.

3. Using a laser, a range of welding conditions predicted by simple heat flow considerations was examined experimentally. Face-to-face butt welds were produced between titanium sheets 1 and 12 mm (0.04 and ½ in.) thick, with power levels from 1 to 2 kW and speeds of 25 and 40 mm/s (59 and 95 ipm).

4. Welds were found to contain root porosity, and this appears to be a process effect. It is likely that this will be reduced, as in electron beam welding, by beam manipulation with progress in the development of laser welding.

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Appendix: Absorption of Entrapped Air by Titanium Weld Metal

Let us assume that in close butt welding an average gap of 0.01 mm (0.0004 in.) is present and that the weld penetration depth is 2 mm (0.079 in.). This would provide 0.02 mm^3 of air per 1 mm (1.79 cu ft/in.) length of weld. At the temperature of the molten pool (2500–3000 K) this could give rise to approximately one bubble of radius 0.25 mm (0.0098 in.) per 1 mm (0.04 in.) length. We wish to assess whether such a bubble would be absorbed before the weld metal freezes.

If the bubble radius is r and the time t, the shrinkage rate for a spherical pore is $-dr/dt$. The bubble shrinks by molecular absorption into the solid, and for a constant molecular density n in a spherical bubble the number of molecules present, N, falls as:

$$\frac{-dN}{dt} = \frac{d}{dt}\frac{(4\pi r^3 n)}{3} = 4\pi r^2 n\,(dr/dt) \qquad (A1)$$

Molecular absorption is a function of F, the flux of molecules to the surface, times α, the probability of absorption. Thus:

$$\frac{-dN}{dt} = 4\pi r^2 \alpha F. \qquad (A2)$$

Equating (A1) and (A2) we find:

$$4\pi r^2 n \frac{dr}{dt} = 4\pi r^2 \alpha F$$

Hence:

$$\frac{dr}{dt} = \frac{F\alpha}{n}$$

Standard kinetic theory of gases gives:

$$F = \tfrac{1}{4} n \bar{v}$$

where $\bar{v} = \sqrt{\frac{3kT}{m}}$

$\bar{v}$ = mean molecular velocity, k = Boltzmann's Constant, T = temperature, and m = molecular mass.

$$\frac{dr}{dt} = \frac{\alpha\bar{v}}{4} = \frac{\alpha}{4}\sqrt{\frac{3kT}{m}}$$

Taking $k = 1.38 \times 10^{-23}$ J/°K, T = 2500°K, $m = 28 \times 1.66 \times 10^{-27}$ Kg for nitrogen, and $\alpha = 10^{-3}$ (extrapolating from data by Gulbransen and Andrew[8]), then:

$$\frac{dr}{dt} = 0.37 \text{ m/s}$$

At this rate of shrinkage, a bubble of 0.25 mm (0.098 in.) radius would be absorbed in less than 10^{-3} seconds. In the weld samples the pool was approximately 3 mm (⅛ in.) long, which, at speeds of 25 to 40 mm/s (59 to 94 ipm), indicated that the fused time is of the order of 0.1 s. The bubbles could not survive, therefore, if they consisted principally of atmospheric gases.