Influence of process parameters on joining strength in microplasma arc welding

Kueng-Hueng Tseng

Welding Technology Section,
Department of Metal Processing R&D,
Metal Industries Research and Development Centre,
1001 Kaonan Highway,
Kaohsuing, Taiwan, ROC
E-mail: khtseng@mail.aritex.com.tw

Min Jou*

Department of Industrial Education and
Department of Mechatronic Technology,
National Taiwan Normal University,
Taiwan, ROC
E-mail: joum@ntnu.edu.tw
*Corresponding author

Yun Chang

Department of Mechanical Engineering,
National United University,
1, Lienda, Kungching Li, Miaoli,
Taiwan 36033, ROC
E-mail: yun@nuu.edu.tw

Her-Yueh Huang

Department of Research and Development,
Aritex Products Co., Ltd.,
No. 22 Huashi Road., Ta-Fa Industrial District,
Daliau Hsiang, Kaohsiung County,
Taiwan 831, ROC
E-mail: weldman.huang@msa.hinet.net

Abstract: The objectives of this research are to investigate the effect of welding parameters on the weld quality and to develop guidelines for a selection of suitable parameter ranges for microplasma welding. A series of experiments was conducted to explore how changes of welding parameters affect the strength of the weld for the thin stainless steel most often used in the industry. The experiment results show that workpiece exposure height must be above a minimum limit in order to prevent undesired joining. The strength increases as the current increases, with fluctuations, but still in the sufficient range. The minimum sufficient current for quality welds increases, while the minimum sufficient heat input decreases, as the travel speed increases.

Biographical notes: Kueng-Hueng Tseng is a Project Manager in the Metal Industries Research and Development Centre and the Chief Editor of the *Journal of Welding and Cutting*. He received a PhD from National Chiao Tung University. His research interests include microwelding, automation of welding processes and design and manufacture of arc welding equipment.

Min Jou is a Professor in the Department of Industrial Education and Department of Mechatronic Technology at National Taiwan Normal University. He received an MS from the University of Missouri-Rolla and a PhD from Rensselaer Polytechnic Institute. His research interests include automation of industrial processes, numerical modelling of manufacturing processes, mechatronics and e-learning technology.

Yun Chang is an Associate Professor in the Department of Mechanical Engineering at National United University. His research interests include fluid mechanics, modelling of manufacturing processes.

Her-Yueh Huang is a R&D welding engineer in the Aritex Products Co., Ltd. He received a PhD from National Chiao Tung University. His research interests include arc welding, foundry technology and materials science and engineering.

1   Introduction

Plasma Arc Welding (PAW) is one of the primary arc welding processes for precision joining of critical metal components (Martikaimen and Moiso, 1993; Nunes and Bayless, 1984). It is an attractive joining process because of, minimal surface preparation requirements, enhanced weld penetration potential and higher welding speed. In addition, PAW offers distinct advantages over laser beam and electron beam welding, due to its lower cost and its less-exacting process control requirements. Most studies of PAW, in industrial applications, are concentrated with joining thick metals using a current range of 25–400 A (Bashenko and Sosnin, 1988; Evans et al., 1998; Fuerschbach and Knorovsky, 1991; Halmoy et al., 1994; Martikainen, 1995; Metcalfe and Quigley, 1975a,b; Tomsic and Barhorst, 1984).

Microcomponents and systems play irreplaceable roles in many areas. For example, Micro Electro-Mechanical Systems (MEMS) provide effective solutions of automotive control, information technology, biomedical and environmental applications. Miniaturisation of components is critical and the joining and assembly of miniaturised components is also crucial. In recent years, manufacturers have faced the greatest challenges in the areas of microassembly (where small parts have to be placed very precisely relative to each other) and in packaging (where connections between the microparts and the environment are established). In many instances, the lack of suitable packaging solutions and microassembly techniques hinder the commercialisation of new products.

To mount different materials, like ceramics, plastics or metals to hybrid MEMS or other microsystems, sophisticated joining technologies are typically needed. Lugscheider, Bobzin and Lake used a low temperature joining process and Transient Liquid Phase (TLP) bonding (Lugscheider et al., 2000), to assemble microcomponents. The TLP is similar to technologies used to assemble electronic devices onto conductor paths (surface mount devices) or attach heat sinks on silicon power devices (Viswanath et al., 2000). The latter technologies require depositing a low temperature solder system locally onto the parts to be joined. In the work by Lugscheider, Bobzin and Lake, the TLP solder systems, Cu-Sn and Cu-In, were deposited on silicon and glass, by means of magnetron sputtering onto the parts to be joined. Because the characteristics of the film, including the microstructure, morphology, surface roughness and bond strength, depend on the deposition parameters, the deposition processes were carried out by adapting the parameters of discharge power and substrate heating, to obtain a defined film constitution.

When high strengths are needed, a fusion welding process will typically be required. To this end, the parts to be joined must be locally melted using a certain heat source. Because of its high energy density and its accurate control of energy, laser has been used as a heat source to join microcomponents. For example, laser has been used in dental metal prosthesis (Bertrand et al., 2001; Santos et al., 2003). In a recent publication, a pulsed Nd: YAG laser of 400 W maximum output power, was used to join an optic-electronic coupler. A 0.3 mm thick stainless steel 304 sheets was spot welded onto a 0.33 mm thick stainless steel 304 sheet (Bertrand et al., 2000; Hand et al., 2000). It was revealed that both the focal point and the pulse duration, determine the depth of penetration and the shape of the weld. When the energy input is 2.5 J and the duration is 4 ms, a focus point 1.0 mm above the plate results in an incomplete penetration, less than 50%, on the second sheet. When the focal point is 0.5 mm above the plate, a complete penetration is formed. This indicates that the penetration is sensitive, not only to the input energy, but also to the focal point or the distribution of the input energy.

It can be seen that, although laser has advantages in terms of its high accuracy of energy control, it requires accurate control of the focal point in relation to the parts to be joined. It is also known the absorption of the laser energy is greatly affected by the surface condition of the workpiece (Tzeng, 2000a,b). Hence, in addition to the needs of the high cost of operation and initial capital investment, the application of laser requires highly qualified personnel, highly accurate preparation and control of welding conditions. To explore an alternative fusion welding technology for microjoining, this study explored the possibility and suitability of the microplasma arc welding to use in microfusion welding. The extensive use of microplasma welding in industrial applications is handicapped by the difficulty of choosing the proper process parameters. Limited study on microplasma welding conditions was available in the literature (Efimov and Zuev, 1977; Ilin and Mironov, 1974; Ivanov et al., 1985; Lu et al., 2004; Zhang and Liu, 2003; Zhang and Ma, 2001; Zhang et al., 2001). A typical application of microplasma welding is to join microswitch consist of a cold-rolled or stainless-steel thin-wall tube (Woodard, 1989). Some other possible applications, which require to keep heat input low to produce sound edge-joint, including stainless steel expandable bellows, aspiration needles, battery seals, catheter guide wires, diaphragm bellows, enclosure filters, microrelay cases, etc.

The motivation of this study is apparent because of the benefits of microplasma arc in microwelding. Firstly, the microplasma arc beam can be accurately controlled by its

orifice diameter. The diameter of microplasma arc beam can be as fine as hundred microns. Secondly, the energy distribution of microplasma arc beam is relatively insensitive to the position of the heat source above the parts, in comparison to laser welding. In fact, the energy density of the microplasma arc beam is nearly independent of the arc length and the arc length can be accurately controlled through the arc voltage. Thirdly, the microplasma arc system can be operated by welding operators and the operating cost in comparison with the laser system is negligible.

Despite possible suitability of microplasma arc in microwelding, there is a lack of systematical studies establishing basic knowledge and understanding of microplasma arc based microwelding. To address this need, this research studies the effect of different parameters on the weld quality, towards establishing the range of the parameters suitable for microplasma seam welding of 0.2 mm thick stainless steel sheets.

2   Experimentation and tests

The power supply used is a pulsed constant-current with a range from 1 to 15 A and a 75 V open-circuit voltage. The pulse frequency can be adjusted from 1 to 300 Hz. The torch is fixed to a one-dimensional motion system whose speed is adjustable. The experimental system is shown in Figure 1. The two sheets to be edge-joined are tightly sandwiched and held by the fixture. The up-end of their interface, which forms a weld seam and is supposed to be joined by the microplasma arc, is not sandwiched and the height of the unsandwiched part is defined as the workpiece exposure height 'D' (Figure 2). The dimensions of the sheets are 200 mm long, 100 mm width and 0.2 mm thick. The material is stainless steel SUS304. The length of each weld is 200 mm. Both the orifice gas and the shield gas are pure argon. Their rates, as determined by experiments, are 0.4 and 6 L/min, respectively. Because of the small amperage, the erosion of the electrode is insignificant and the tungsten is remachined after each 30 of 100 mm long welds. Experiments revealed that the arc length from 0.5 to 1.5 mm is acceptable and is fixed at 1.0 mm.

Figure 1   Microplasma welding system

Three parameters are chosen to adjust the welding process variables and welding conditions: the average current '*I*', the travel speed '*V*' and the workpiece exposure height *D*. Because a low exposure height requires substantial cooling for the fixture and the ultra-thin sheets will deform if the exposure height is large, the exposure height should be in a certain range. It is found that acceptable welds can be made if the exposure height is between 0.2 and 0.6 mm. The five different levels of the exposure height, 0.2, 0.3, 0.4, 0.5 and 0.6 mm, will be used. For each level of the exposure height, four levels of travel speed, that is, 700, 850, 1050 mm/s and 1350 mm/s, will be used. To change the heat input, the current may vary from 4 to 9 A. However, to produce appropriate heat input, the actual range of current for each travel speed may vary.

Figure 2 Workpiece exposure height
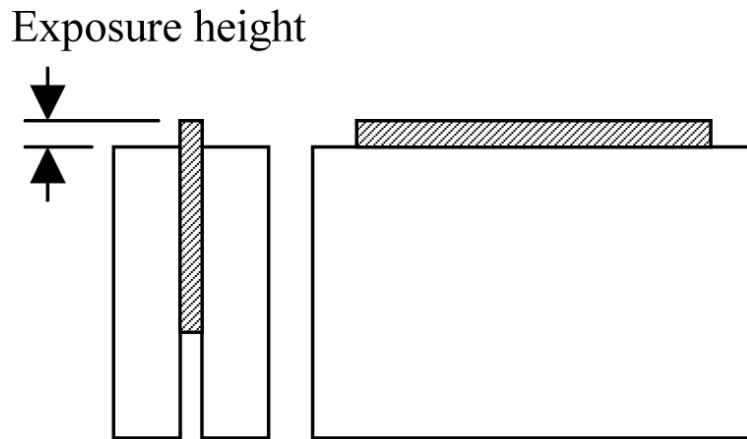
3 Results and discussion

In order to investigate the effect of welding parameters (i.e. exposure height, travel speed, current) on the weld quality and to develop guidelines for a selection of suitable parameter ranges for microplasma welding. A series of experiments was conducted to explore how changes of welding parameters affect the strength of the weld for the thin stainless steel most often used in the industry. The weld strength was evaluated by conducting peel tests. A standard testing procedure is applied to evaluate the weld quality (Auto/Steel Partnership, 1997). The repeatability of the experimental system was first evaluated by making five welds on separate test specimens under exactly the same welding conditions. The variation of the strength is within 5%. The mean value and the standard deviation of the strength for these five welds indicate reasonably good repeatability for the experimental system. In this study, each test was conducted three times to improve statistical reliability. The experimental results are shown in Figure 3 (0.2 mm exposure eight), Figure 4 (0.3 mm exposure eight), Figure 5 (0.4 mm exposure eight), Figure 6 (0.5 mm exposure eight) and Figure 7 (0.6 mm exposure eight).

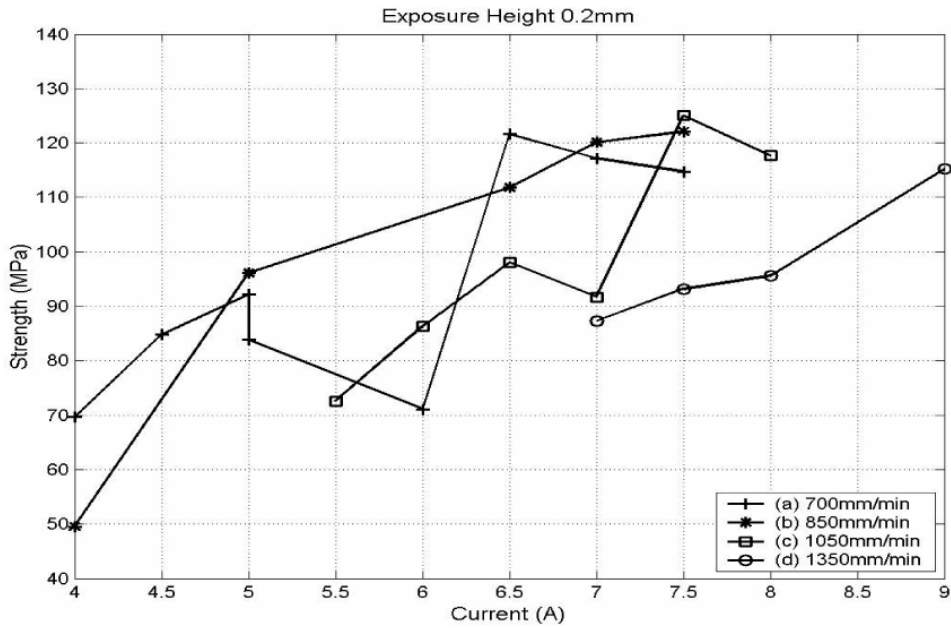**Figure 3**   Strength under 0.2 mm exposure height
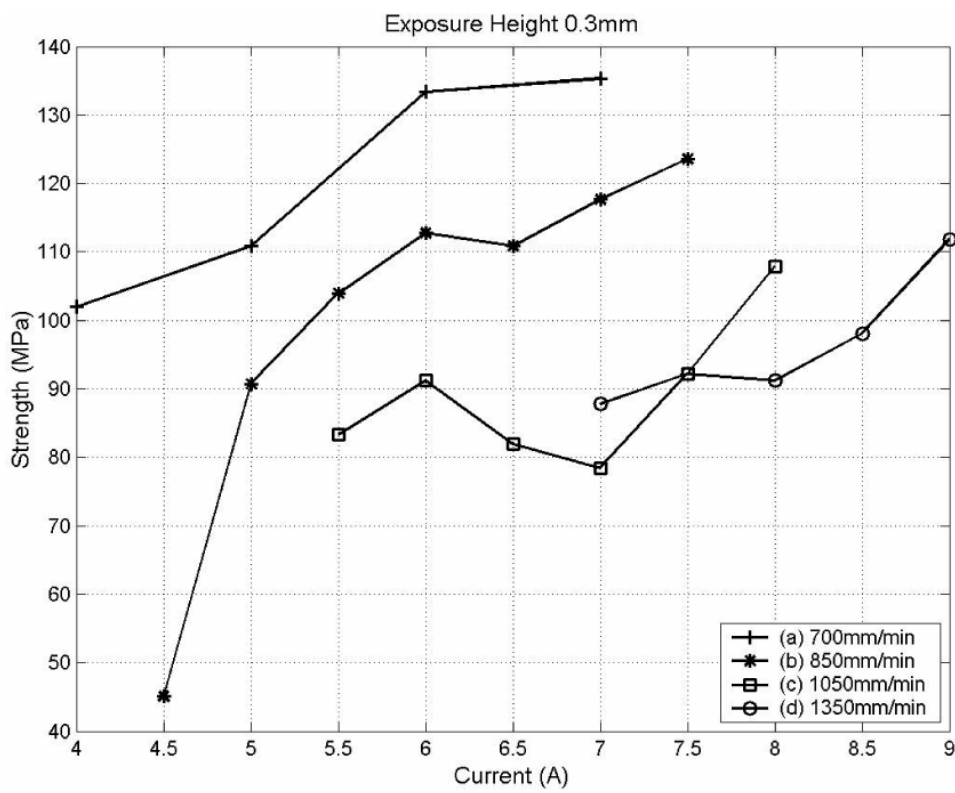

Figure 4   Strength under 0.3 mm exposure height

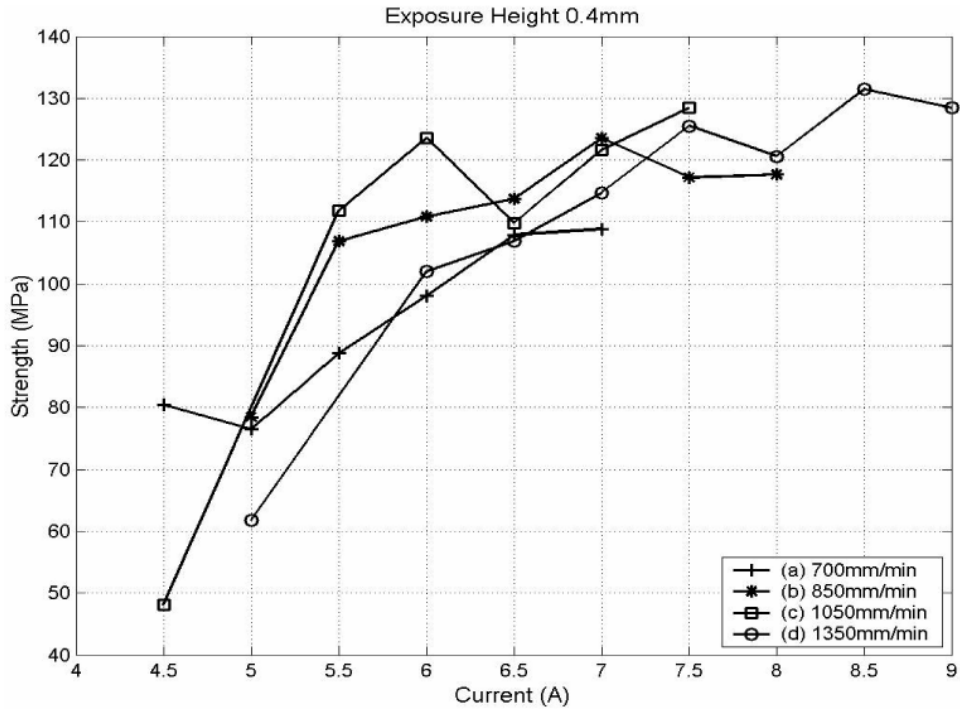**Figure 5** Strength under 0.4 mm exposure height

Figure 6 Strength under 0.5 mm exposure height
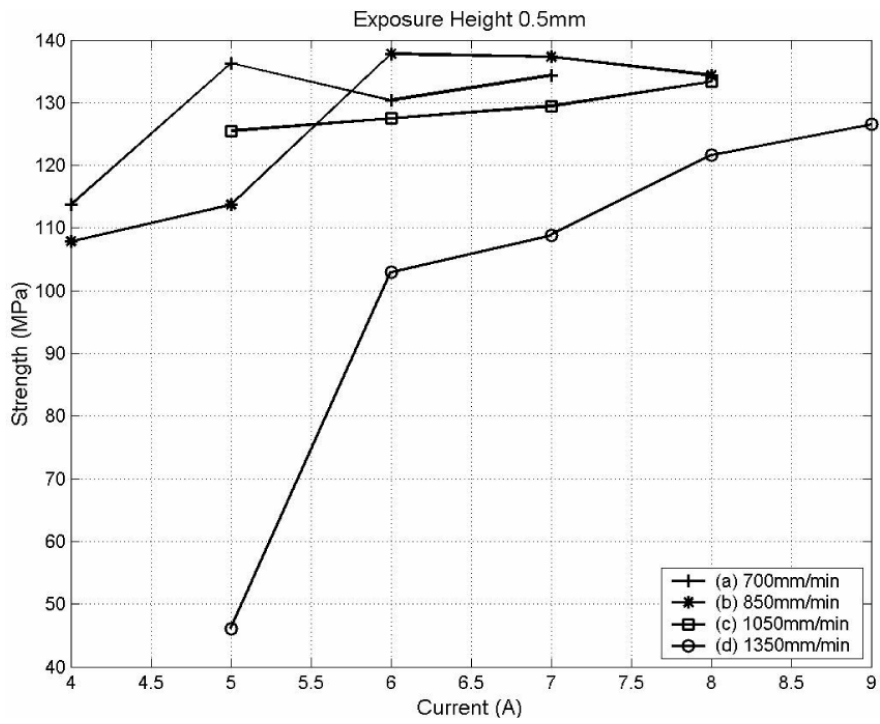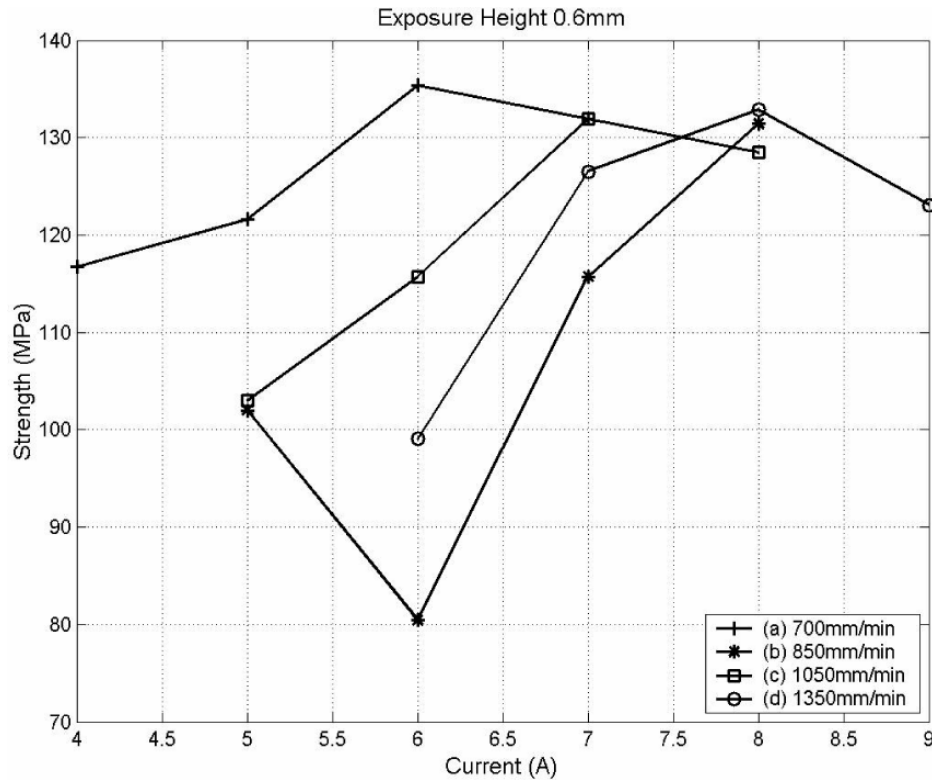
Figure 7   Strength under 0.6 mm exposure height

3.1   Workpiece exposure

The major function of fixture is to minimise the distortion and thus prevent, the sheets to be joined, from being separated from each other and maintain the location of the weld seam. Figure 2 shows the relationship between the fixture and the exposure height. In this study, the torch travels along the nominal weld seam and no seam tracking system is used. Observation of experiments revealed that the plasma jet always aims at the weld seam with satisfactory accuracy. No significant gap was observed between two sheets. The weld geometry and heat-affected-zone are symmetric on the two sheets being joined in all experiments. The experimental data clearly indicates quality welds with strength 98 MPa or above, can be obtained for all exposure heights used; that is, from 0.2 to 0.6 mm. Hence, a 0.2 to 0.6 mm exposure height range can ensure the fixture will function appropriately during edge-joining of 0.2 mm stainless steel sheets.

Another function of the fixture is the absorption of the heat from the workpiece. Water-cooling is an effective way to maintain a constant temperature of the fixture, thus providing a constant heat transfer condition for the joining process and the workpiece. This constant heat transfer condition is critical for precision and microjoining, which require accurate control of both the heat input and welding conditions. In addition, by controlling the temperature of the fixture and the exposure height, the cooling rate can be controlled for material property. Because the heat input is relatively low in comparison with thermal capability of the fixture in this study, the fixture temperature is

approximately at the room temperature during each run of welding. This helps maintain the heat transfer condition to be constant. Of course, in order for the fixture to function appropriately as a heat absorber, the exposure height must not be excessive. Experiments revealed that the weld geometry and HAZ are constant along the weld seam. This implies 0.6 mm is an acceptable upper limit of the exposure height, from a heat transfer condition control point of view.

A small exposure height further improves the effectiveness of the fixture for controlling the weld seam location, the heat transfer condition and their consistency along the weld seam. However, to use a small exposure, the possible undesirable joining between the workpiece and the fixture must be prevented. One effective way is to water-cool the fixture. When the fixture is not water-cooled, the exposure height must be above a minimum limit in order to present the undesired joining between the fixture and the workpiece. In this study, the fixture is not water-cooled. Experimental results show that 0.2 mm is an acceptable minimum exposure height for edge joining of 0.2 mm stainless steel sheets.

3.2 Tendency of strength

Experiment results (Figures 3–7) show that for each exposure height, quality welds with acceptable strength 98 MPa or above are achievable. To achieve quality welds, the parameters, (i.e. the travel speed and current) must be appropriate. As shown in the Figure 3, if the parameter vector is defined as (V, I), experiment using (1350 mm/min, 9 A) achieves the quality weld, while a quality weld is obtained in experiment using (700 mm/min, 6.5 A). Experimental results provide data for analysing welding parameters. Take the experiments with 0.2 mm exposure height as an example. For experiments with 1350 mm/min travel speed, the average strength increases as the current increases from 7 to 9 A. It shows strength increases as the heat input increases in experiments with 1350 mm/min travel speed.

Would the strength keep increasing if the heat input continues to increase? To answer this question, one can examine experiments with 1050 mm/min travel speed. When the current is in the lower range, that is, from 5 to 6.5 A, the strength increases as the current increases. However, from 6.5 to 8 A, this tendency becomes unclear. Firstly, when the current increases from 6.5 to 7 A, the strength is reduced. Then, the current increases from 7 to 7.5 A, the strength jumps from 91.7 to 125 MPa. However, when the current increases again from 7.5 to 8 A, the strength decreases. This phenomenon indicates that the strength may not necessarily keep increasing as the heat input increases. Now the question is what disagreement is revealed of the strength versus current in experiments with 1350 mm/min travel speed. There are a few possibilities:

1   there are no relationships between the strength and the current
     (heat input) at all

2   the strength increases as the current (heat input) increases but
     with possible fluctuations

3   the strength increases to a peak and then decreases as the current
     (heat input) increases but with possible fluctuations.

It is apparent the first possibility is unlikely. The relationship between the strength and the heat input can also be seen in experiments in Figure 3, where the travel speed is 850 and 700 mm/min, respectively. The strength increases as the current (heat input)

increases. However, in Figure 3 (line a), the strength exhibits a behaviour in relation to the current (heat input) similar to that in Figure 3 (line c). Overall, despite the fluctuations, the strength does increase with the current before the strength becomes sufficient or approximately 98 MPa. After the strength exceeds the sufficient level of 98 MPa, the strength may reduce or vary, but in the sufficient range when the current increases. A similar tendency of the strength in relation to the current (heat input), can also be observed for other exposure heights in Figures 4–7.

The above tendency of the strength in relation to the current (heat input) is understandable. When the penetration is insufficient, an increase in the penetration can significantly increase the strength; but the increase rate should reduce as the penetration increases. When the penetration reaches a certain level, the strength would saturate with the increasing penetration. On the other hand, the increasing heat input, in addition to increasing the penetration, also increases the heat-affected-zone and affects the microstructures and material properties. The strength thus may fluctuate, but due to the sufficient penetration, still stay within the sufficient range.

3.3   Effect of travel speed on heat input

Consider 98 MPa as the minimum requirement of sufficient strength. Data in Figure 8 clearly suggests minimum current needed to achieve the sufficient strength or the minimum sufficient current for short, increases with the travel speed. Of course, this tendency is reasonable because, in order to achieve the sufficient penetration, the current needed must increase as the travel speed increases.

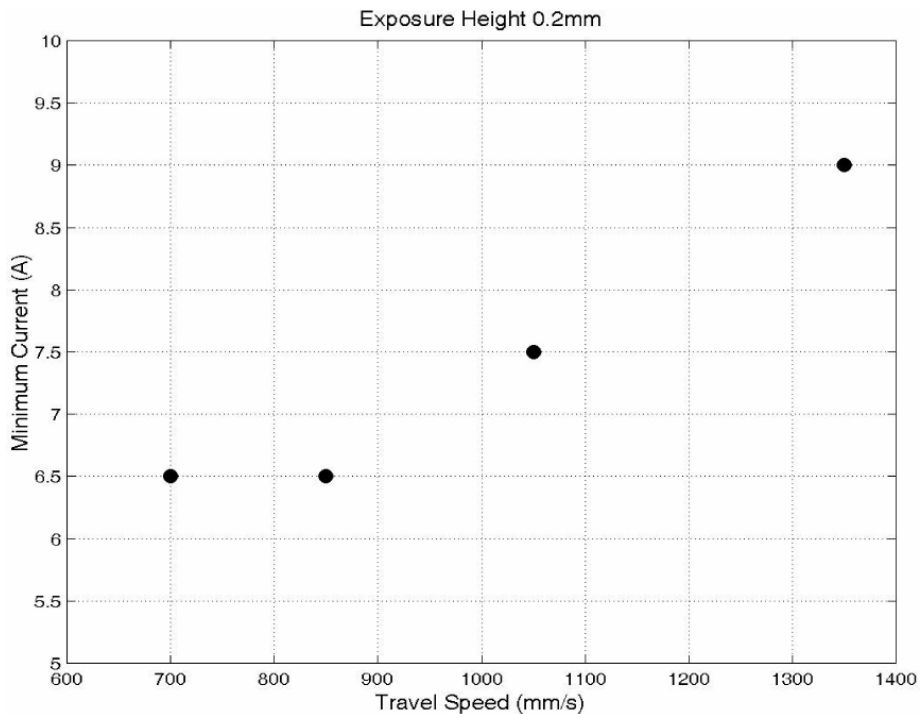**Figure 8**   Minimum current for sufficient strength

Figure 9 depicts the tendency of the minimum heat input per unit weld needed for producing the sufficient strength or the minimum sufficient heat input, in relation to the travel speed. In the calculation, the voltage is assumed to be 25 V. It can be seen, as the travel speed increases, the minimum heat input per unit weld needed to produce the sufficient strength decreases. It implies heat input efficiency increases as travel speed increases. This is also understandable because heat dissipated from the workpiece, primarily through the fixture, decreases when travel speed increases or weld time decreases.

Figure 9   Minimum heat input for sufficient strength
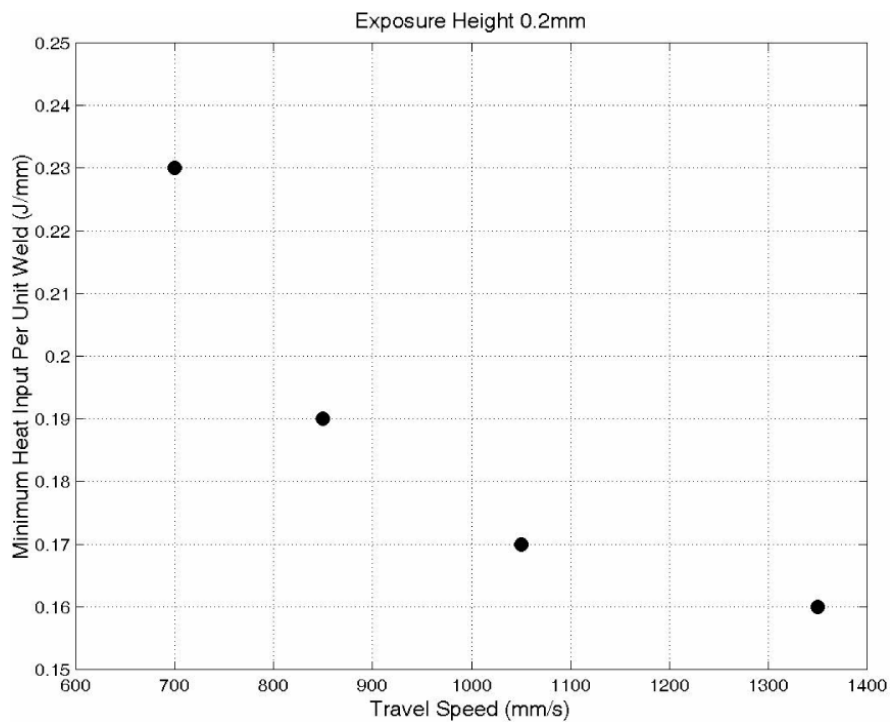
The tendencies of the minimum sufficient current and heat input, in relation to the travel speed, revealed in Figures 8 and 9, respectively, can also be observed in larger exposure heights. As shown in Figure 10, except for $D = 0.4$ mm, the minimum sufficient current does increase as the travel speed increases, like it does for $D = 0.2$ mm. Also, the data in Figure 11 shows that, except for $D = 0.3$ mm, the minimum sufficient heat input decreases as the travel speed increases. Hence, overall, the minimum sufficient current increases, while the minimum sufficient heat input decreases, as the travel speed increases.

3.4   *Effect of exposure on heat input*

In addition to the travel speed, the minimum heat input per unit weld length, for producing quality welds with sufficient strength, also depends on the exposure height. This dependence is apparent because the heat dissipated from the workpiece through the

fixture decreases as the exposure height (the distance of the weld seam to the fixture) increases. As can be seen in Figure 12, despite some exceptions, the minimum heat input needed to produce a sufficient penetration of weld assuring sufficient strength, is smaller when the exposure height is larger.

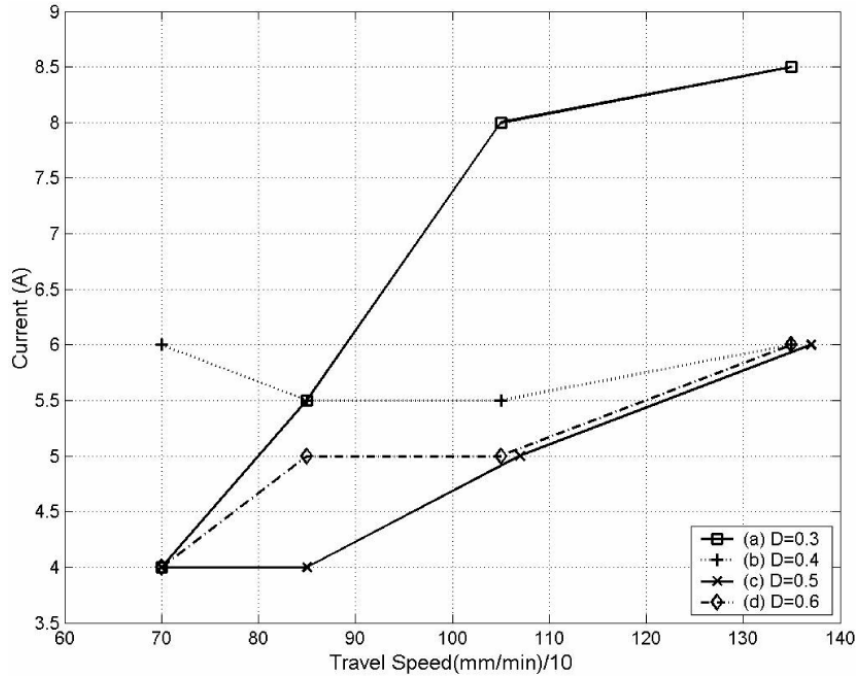**Figure 10**   Minimum current for sufficient strength

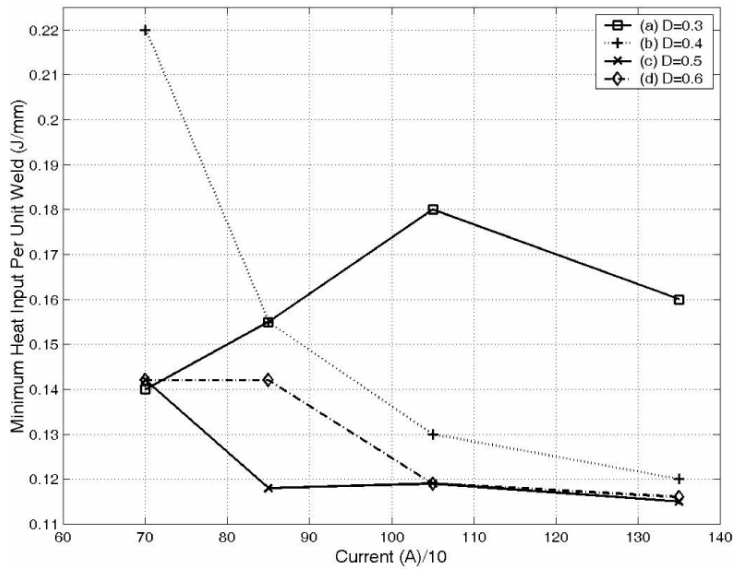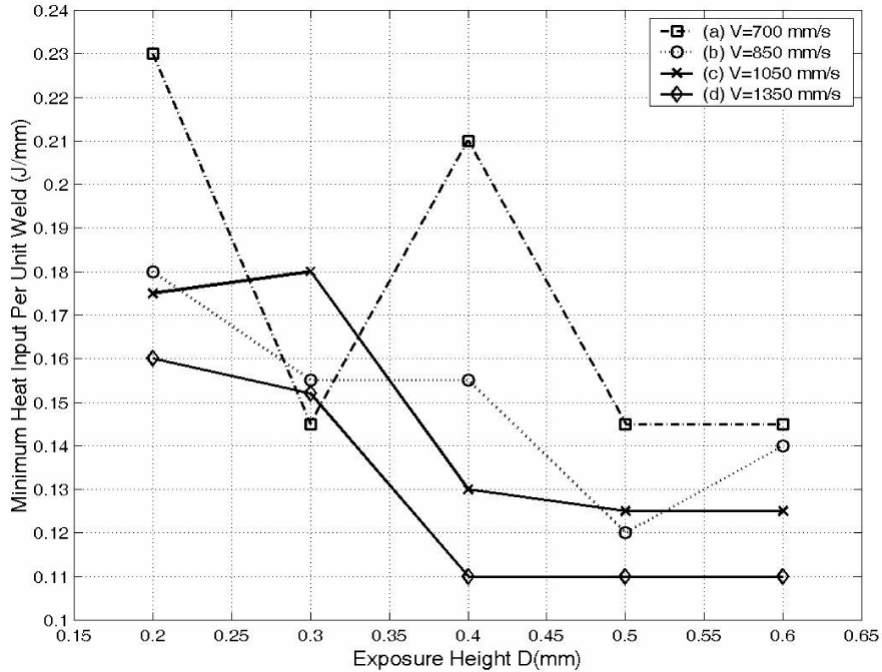**Figure 11**   Minimum heat input for sufficient strength

Figure 12 Effect of exposure height on heat input

4 Conclusion

The extensive use of microplasma welding in industrial applications, is handicapped by the difficulty of choosing proper process parameters. Production of quality welds requires knowledge on the role of each major welding parameter, on their interconnection and dependence and on the way in which they are coupled. This study explores the possibility and suitability of the microplasma arc welding to be used in microfusion welding.

In this study, a series of experiments has been conducted to investigate the effects of welding parameters on the weld strength. The major parameters include welding current, travel speed and workpiece exposure height. Experiment results on thin stainess steel plates (SUS 304) showed:

- Strength does increase with the current before the strength becomes sufficient or approximately 98 MPa. After the strength exceeds the sufficient level of 98 MPa, the strength may reduce or vary, but in the sufficient range when the current increases. When the penetration is insufficient, an increase in the penetration can significantly increase the strength. When the penetration reaches a certain level, the strength saturates with increasing penetration. The strength may fluctuate, but it is still within the sufficient range because of sufficient penetration.

- As travel speed increases, the minimum heat input per unit weld needed to produce the sufficient strength decreases.

Acknowledgement

References

Auto/Steel Partnership (A/SP) (1997) *Weld Quality Test Method Manual*, Standardized Test Method Task Force.

Bashenko, V.V. and Sosnin, N.A. (1988) 'Optimization of the plasma arc welding process', *Welding Journal*, pp.233s–238s.

Bertrand, C., Le Petitcorps, Y., Albingre, L. and Dupuis, V. (2001) 'The laser welding technique applied to the non precious dental alloys procedure and results', *British Dental Journal*, Vol. 190, pp.255–257.

Bertrand, P., Smurov, I. and Grevey, D. (2000) 'Application of near infrared pyrometry for continuous Nd:YAG laser welding of stainless steel', *Applied Surface Science*, Vol. 168, pp.182–185.

Efimov, V.M. and Zuev, I.V. (1977) 'Determination of depth of penetration in sealing of integrated-circuit packages by microplasma welding', *Welding Production*, Vol. 24, pp.37–39.

Evans, D.M., Huang, D., McClure, J.C. and Nunes, A.C. (1998) 'Arc efficiency of plasma arc welding', *Welding Journal*, pp.53s–58s.

Fuerschbach, P.W. and Knorovsky, G.A. (1991) 'A study of melting efficiency in plasma arc and gas tungsten arc welding', *Welding Journal*, pp.287s–297s.

Halmoy, E., Fostervoll, H. and Ramsland, A.R. (1994) 'New applications of plasma keyhole welding', *Welding in the World*, Vol. 34, pp.285–291.

Hand, D.P., Fox, M.D.T., Haran, F.M., Peters, C., Morgan, S.A., McLean, M.A., Steen, W.M. and Jones, J.D.C. (2000) 'Optical focus control system for laser welding and direct casting', *Optics and Lasers in Engineering*, Vol. 34, pp.415–427.

Ilin, B.I. and Mironov, E.P. (1974) 'Semiautomatic microplasma welding of bodies of micro-circuits', *Welding Production*, Vol. 21, p.73.

Ivanov, G.V., Makovetskii, A.M. and Raisin, I.B. (1985) 'Microplasma welding disk windings of electrical machines in pulsed regime', *Welding Production*, Vol. 32, pp.11–12.

Lu, W., Zhang, Y.M. and Lin, W.Y. (2004) 'Nonlinear interval model control of quasi-keyhole arc welding process', *Automatica*, Vol. 40, No. 5, pp.805–813.

Lugscheider, E., Bobzin, K. and Lake, M.K. (2001) 'Deposition of solder for micro-joining on M.E.M.S. components by means of magnetron sputtering', *Surface and Coatings Technology*, Vols. 142–144, pp.813–816.

Martikainen, J. (1995) 'Conditions for achieving high-quality welds in the plasma arc keyhole welding of structural steels', *Journal of Materials Processing Technology*, Vol. 52, pp.68–75.

Martikaimen, J.K. and Moiso, T.J.I. (1993) 'Investigation of the effect of welding parameters on weld quality of plasma arc keyhole welding of structural steels', *Welding Journal*, Vol. 72 pp.329s–340s.

Metcalfe, J.C. and Quigley, M.B.C. (1975a) 'Heat transfer in plasma arc welding', *Welding Journal*, pp.99s–104s.

Metcalfe, J.C. and Quigley, M.B.C. (1975b) 'Keyhole stability in plasma arc welding', *Welding Journal*, pp.401s–404s.

Nunes, Jr., A.C. and Bayless, E.O. (1984) 'Variable polarity plasma arc welding on the space shuttle external tank', *Welding Journal*, Vol. 63, pp.27–35.

Santos, M.L., Acciari, H.A., Vercik, L.C.O. and Guastaldi, A.C. (2003) 'Laser weld: microstructure and corrosion study of Ag–Pd–Au–Cu alloy of the dental application', *British Dental Journal*, Vol. 57, pp.1888–1893.

Tomsic, M. and Barhorst, S. (1984) 'Keyhole plasma arc welding of aluminum with variable polarity power', *Welding Journal*, Vol. 63, pp.25–32.

Tzeng, Y.F. (2000a) 'Effects of operating parameters on surface quality for the pulsed laser welding of zinc-coated steel', *Journal of Materials Processing Technology*, Vol. 100, pp.163–170.

Tzeng, Y.F. (2000b) 'Parametric analysis of the pulsed Nd:YAG laser seam-welding process', *Journal of Materials Processing Technology*, Vol. 102, pp.40–47.

Viswanath, R., Wakharkar, V., Watwe, A. and Lebonheur, V. (2000) 'Thermal performance challenges from silicon to systems', *Intel Technology Journal*, Vol. 3, pp.1–16.

Woodard, L.D. (1989) 'Microplasma arc welds switches', *Welding Design and Fabrication*, pp.67–69.

Zhang, Y.M. and Liu, Y.C. (2003) 'Modeling and control of quasi-keyhole arc welding process', *Control Engineering Practice*, Vol. 11, No. 12, pp.1401–1411.

Zhang, Y.M. and Ma, Y. (2001) 'Stochastic modelling of plasma reflection during keyhole arc welding', *Measurement Science and Technology*, Vol. 12, No. 11, pp.1964–1975.

Zhang, Y.M., Zhang, S.B. and Liu, Y.C.A. (2001) 'Plasma cloud charge sensor for pulse keyhole process control', *Measurement Science and Technology*, Vol. 12, No. 8, pp.1365–1370.