Welding Aluminum Alloy 6061 with the Opposing Dual-Torch GTAW Process

A modified welding system achieves good joint penetration and controlled heat input with the gas tungsten arc process

BY Y. M. ZHANG AND S. B. ZHANG

ABSTRACT. Cracking is a major concern in welding aluminum alloys. Although weld solidification cracks can be eliminated through the addition of filler metal, the additives modify the alloy or base metal constituents and may not always be desirable. High-energy beam processes, such as electron beam welding, that result in minimal heat input reduce crack sensitivity, but their high cost limits their applications. In this study, the conventional gas tungsten arc welding process is modified by disconnecting the workpiece from the power supply and placing a second torch on the opposite side of the workpiece. Such a modification changes the direction of the current flow, improves the weld penetration and reduces the heat input. Using this modified process, 6061-T651 alloy was welded without filler metals. Analysis suggested the reduced heat input, the changed direction of the current flow and the symmetric heating were responsible for the observed reduction of the cracking sensitivity.

Introduction

Cracking is a major concern in welding aluminum alloys. This is due to the relatively high thermal expansion of aluminum, the large change in volume upon solidification and the wide solidification-temperature range (Ref. 1). High heat inputs, resulting from high currents and slow welding speeds, increase the thermal stress, solidification shrinkage and partially melted region, thus contributing to both the weld solidification cracking and HAZ liquation cracking. Although weld solidification cracks can be effectively controlled using selected filler metal (Refs. 2–5), the additives modify the alloy or base metal constituents and may not always be desirable (Ref. 2).

High-energy beam processes reduce the overall heat input. The high thermal gradient from the weld into the base metal creates limited metallurgical modifications and is least likely to cause intergranular cracking in butt joints when no filler metal is added (Ref. 1). The electron beam welding process can weld aluminum alloys without the addition of filler metal (Refs. 1, 6, 7). However, due to the strong reflection, laser welding of aluminum alloys is less effective (Refs. 8–10).

The authors developed a new GTA welding process that can increase the weld penetration by using two torches on the opposite sides of the workpiece and connecting them to the power supply in series (Refs. 11, 12). The connection between the power supply and the workpiece in a conventional arc welding system is removed. As a result, the welding current flows from the power supply to a torch, then through the work more or less normally, then to another torch and finally returns to the power supply. Such a current flow concentrates the arcs and improves the weld penetration, thus resulting in a reduction in the heat input. This process may provide a method to weld aluminum alloys without filler metal and to generate positive effects on productivity, cost and weld quality. In this study, the dual-torch gas tungsten arc welding (GTAW) process will be used for welding aluminum.

KEY WORDS

Gas Tungsten Arc
GTAW
Aluminum
Solidification Cracking
Dual Torch
HAZ
Heat Input
6061-T651

Experimental Procedure

Figure 1 illustrates the configuration of the experimental system used to perform the proposed arc welding method, referred to as opposing dual-torch gas tungsten arc welding (ODT-GTAW). The two terminals of the square wave, constant current, AC power supply were connected to two regular GTAW torches. The polarity ratio was 15 ms to 15 ms. The maximum current of the power supply is 150 A at the arc voltage of 50 V.

Due to its popularity and high crack sensitivity, 6061 aluminum alloy was used as test material. Test plates 6.4 mm and 9.5 mm thick, 6061-T651, 50 mm in width and 250 mm in length, were employed. Uphill (vertical) welds were made in butt joints with a shielding gas of pure argon from both sides at the flow rate of 12 L/min. The plates were clamped during welding.

For comparison, AC GTAW was also conducted. The polarity ratio and the flow rate of the shielding gas (argon) were also 15 ms to 15 ms and 12 L/min, respectively.

Y. M. ZHANG and S. B. ZHANG are with Welding Research and Development Laboratory, Center for Robotics and Manufacturing Systems, University of Kentucky, Lexington, Ky.

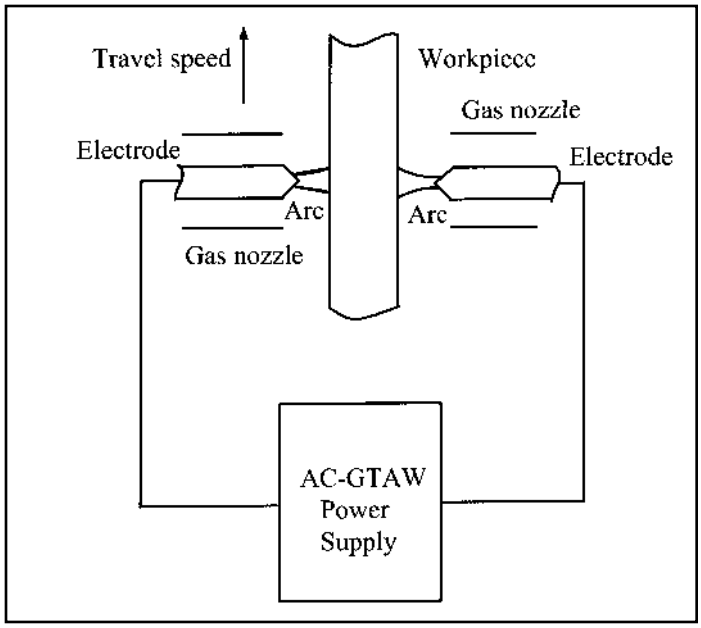

Fig. 1 — Experimental setup.

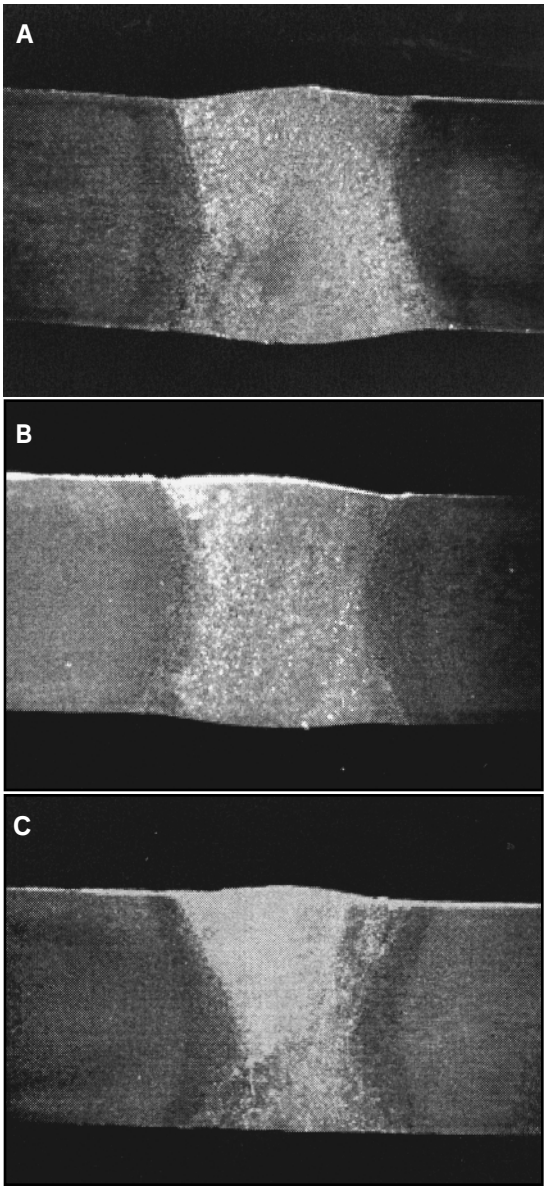

Fig. 2 — Cross-sectional photos of double-sided arc welds in butt joints. Thickness 6.4 mm, material 6061-T651, welding current 145 A, arc voltage 47 V. A — Welding speed 4.2 mm/s; B — welding speed 6 mm/s; C — welding speed 7.5 mm/s.

Experimental Results

Experimental results showed, although no filler metal was added, ODT-GTAW made no cracks — Figs. 2 and 3. However, regular AC GTAW made cracks. Figure 4 shows the weld face appearance of the welds made using the two different methods.

Experiments also showed that the ODT-GTAW process improved the weld penetration. It is known that in order to weld 3.2-mm-thick aluminum plates, regular AC GTAW needs one to two passes with 110–140 A current and 4 mm/s welding speed (Ref. 1). For 6.4-mm-thick plates, two passes are needed at 200–240 A current and 3–4 mm/s welding speed (Ref. 1). As can be seen in Fig. 2, ODT-GTAW significantly penetrates 6.4-mm-thick plates in a single pass with 145 A current and 7.5 mm/s welding speed. For 9.5-mm-thick plates, with preheating to 177°C (350°F), regular AC GTAW needs three passes at 260–300 A current and 3–4 mm/s welding speed. For the ODT-GTAW, 9.5-mm-thick plates can be sufficiently penetrated in a single pass with 150 A current at a welding speed of 2 mm/s, without preheating. The improvement in the weld penetration is quite significant. Due to the improvement in the weld penetration capability, the heat input and fusion zone are reduced. Lower heat input and no preheat decrease the width of the HAZ (Ref. 1). Such decreases should help increase the weld strengths for 6061 alloys and other aluminum alloys (Ref. 1).

Table 1 gives the test results for the mechanical properties of the welds made using ODT-GTAW. The samples were tested as welded. The results are average readings from three samples for each condition. It can be seen that when the welding speed is 4.2 or 6 mm/s, the ultimate strength of the ODT-GTA welds is 199 MPa or higher, slightly better than that of the regular gas shielded arc welds (186 MPa or higher, Ref. 1). Also, the joint ductility measured over a 50.8-mm gauge length (12.4% or higher) is better than that of the regular gas shielded arc welds (8% or higher, Ref. 1), although the yield strength (103 MPa) is lower than that of the regular gas shielded arc welds (124 MPa or higher, Ref. 1). Furthermore, the mechanical properties of the ODT-GTA welds are independent of filler metals. Hence, when the welding speed is appropriate — 4.2 or 6 mm/s in the experiments — the ODT-GTAW process demonstrates some characteristics that may better meet some particular requirements. When the welding speed is 7.5 mm/s, porosity is increased and the resultant weld strength is reduced.

Test results reveal that ODT-GTAW can achieve acceptable mechanical strengths if the welding speed is 4 to 6 mm/s. When the welding speed increases, porosity in the weld will increase and the resultant strength degrades (Table 1). For aluminum welding, the recommended maximum welding speed is 5 mm/s (Ref. 1). Hence, the welding speed associated with ODT-GTAW is acceptable.

Discussion

Experimental results reveal that the proposed ODT-GTAW method is a potential arc welding process to weld 6061 alloy, and possibly other aluminum alloys, without filler metal. To understand

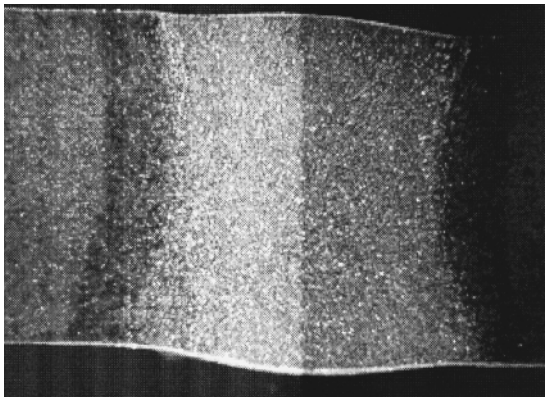

Fig. 3 — Cross-sectional photo of double-sided arc weld in a butt joint on thick plate. Thickness 9.5 mm, material 6061-T651, welding current 150 A, welding speed 2 mm/s, arc voltage 48 V.

the principle of the proposed approach, the process and its mechanism in reducing the crack sensitivity should be discussed.

Process

The majority of the welding current in regular arc welding, such as in plasma arc welding (Ref. 13), grounds through the top surface of the base metal. In the proposed method, the welding current is through the workpiece — Fig. 5. Such a difference in the direction of the welding current generates a difference in the resultant forces.

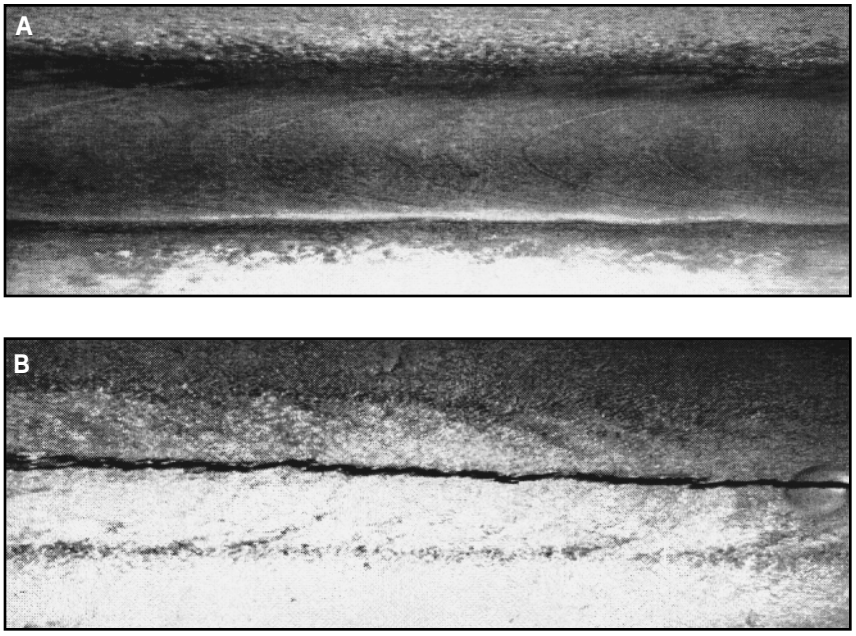

Fig. 4 — Weld face view of cracking of arc welds made using different processes. Material 6061-T651, filler metal none. A — Double-sided arc weld; thickness 6.4 mm, welding current 145 A, welding speed 6 mm/s, arc voltage 47 V, penetration full; B — AC GTA weld; thickness 6.4 mm, welding current 150 A, welding speed 2 mm/s, arc voltage 29 V, penetration partial.

Table 1 — Test Results of Mechanical Properties for 6061-T651 Double-Sided Butt Joint Welds

Welding Current (A)	Welding Speed (mm/s)	Ultimate Strength ksi	Ultimate Strength MPa	Yield Strength ksi	Yield Strength MPa	Elongation (percentage for 2 in.)	Failure Location
145	4.2	29.2	199	15.2	103	15.0	HAZ
145	6	29.5	201	16.4	112	12.4	HAZ
145	7.5	24.4	166	16.9	115	4.7	Weld[a]

(a) Porosity present.

It is known that the current is subjected to electric field force F_e caused by the difference of the electric potential between the electrode and work and electromagnetic force F_m (Fig. 5A) in the arc length area. These two forces can be calculated using the following equations (Refs. 14, 15):

$$\begin{cases} F_e = qE \\ F_m = J \times B \end{cases} \quad (1)$$

where q is the charge of the particle considered, E is electric field strength vector, J is current density vector and B is magnetic flux density vector. F_e has two components, $f_e^{(x)}$ and $f_e^{(y)}$. Component $f_e^{(x)}$, along the x direction, diverges the current and increases when the current approaches the work. Component $f_e^{(y)}$ along the y direction, accelerates the particles in the plasma toward the work. For F_m, its component $f_m^{(x)}$ along the x direction concentrates the current, but diminishes as the current reaches the work. The component along the y direction, $f_m^{(y)}$, also accelerates the particles in the plasma toward the work.

In ODT-GTAW (Fig. 5B), the current directly flows through the work. $f_e^{(x)}$ and $f_m^{(y)}$ are zero or negligible. This results in $f_m^{(x)}$, which converges the current being increased to its maximum, while the divergent force $f_e^{(x)}$ is zero. Hence, the current and the arc become much more concentrated than in regular arc welding.

For ODT-GTAW, the current in metal is subjected to the same forces as in the electrode-to-work distance due to its direction — Fig. 5B. The electromagnetic force will tend to converge the current, thus driving the fluid flow toward the axis of the current flow — Fig. 5B. Such flow tends to deepen the penetration. Due to the varying polarity, the direction of such fluid flow is subjected to periodical change. Such change may tend to generate a stirring effect in the weld pool. However, in regular arc welding, such a flow exists on the surface of the workpiece, but not inside the base metal.

In the proposed approach, the two arcs symmetrically heat the workpiece. The symmetric heating decreases the thermal distortion of the workpiece during the welding. The reduced thermal distortion should tend to decrease the thermal stress.

Crack Sensitivity

Weld cracking in aluminum alloys may be classified into two primary categories based on the mechanism responsible for the cracking and the crack location (Ref. 1). Solidification cracking occurs within the weld zone and typi-

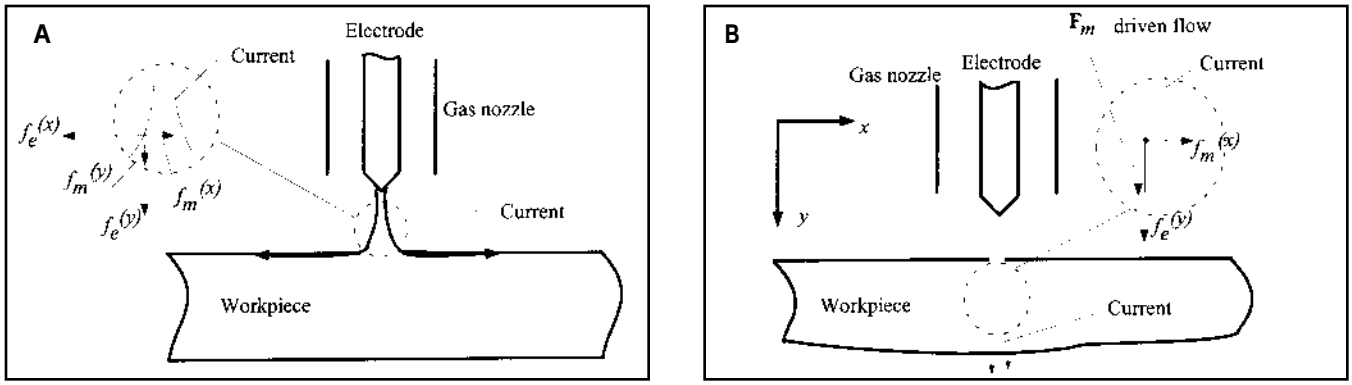

Fig. 5 — Forces acting on welding current. A — Regular GTAW; B — ODT-GTAW.

cally appears along the center of the weld or at the termination craters (Ref. 1). Liquation cracks take place adjacent to the fusion zone and may or may not be readily apparent.

Solidification cracking occurs when high levels of thermal stress and solidification shrinkage are present when the weld pool is undergoing solidification (Ref. 1). Due to the high coefficient of thermal expansion, the solidification shrinkage of aluminum alloys is almost twice that of ferrous alloys (Ref. 1). High heat inputs melt large amounts of base metal, thus intensifying the shrinkage. It is the increase in penetration for a given current that allows lower current and therefore lower heat inputs to be used with ODT-GTAW. For example, to weld a 6.4-mm-thick aluminum workpiece, the heat input into the workpiece in a unit length along the weld joint IU/v should be less than 145 A x $2U_0$ / (7.5 mm / s) = 38.7 U_0. Here I is the welding current, v is the welding speed and U is the arc voltage of the two arcs that is approximately twice U_0, the arc voltage in regular AC GTAW measured by volts. For regular AC GTAW, the heat input into the workpiece in a single pass is $200U_0$ / 3 = $66.7U_0$. (Two passes are needed to weld a 6.4-mm-thick aluminum workpiece by regular AC GTAW.) Hence, the ODT-GTAW reduces the shrinkage, thus positively contributing to the reduction of solidification cracking sensitivity.

Due to the reduced heat input, the thermal stress may decrease. Also, the symmetrical heating associated with the ODT-GTAW, which lowers the thermal distortion, may help decrease the thermal stress. The reduction in the thermal stress can decrease the solidification cracking sensitivity.

An important cause of the solidification cracking is the wide range of the solidification temperatures. The partial melted state of the metals during solidification blocks the flow of the melted metals. If the solidifying metals can be shaken, the flow of the unsolidified metals and the heat transfer may be improved. (We notice that magnetic stirring has been generated to reduce cracking sensitivity, Refs. 16–18.) In the proposed approach, the electromagnetic force-driven flow acts in the neighborhood of the central line of the weld and changes its direction according to the polarity of the AC welding current. Such a flow may tend to shake the solidifying metals at a frequency of the AC current. In our experiments, the frequency of the AC current is 33.3 Hz and is relatively high in comparison with the thermal process. Hence, the location and direction of the AC current flow in the ODT-GTAW may also be a factor that reduces the crack sensitivity. However, further studies will be needed in order to confirm this assumption.

Conclusions

The proposed ODT-GTAW appears capable of welding 6061 alloys without addition of filler metals under conditions used in this study. In addition to the reduction in the cracking sensitivity, the ODT-GTAW process also provides some other advantages, such as the reduction in the number of the passes. However, to actually apply the proposed ODT-GTAW method, both sides of the workpiece must be accessible.

Three possible causes have been assumed to explain how the ODT-GTAW reduces the cracking sensitivity. It is evident further studies must be conducted to verify these causes.

Acknowledgments

This work is supported by the National Science Foundation (DMI-9812981) and the Center for Robotics and Manufacturing Systems at the University of Kentucky. The authors also thank NASA Marshall Space Flight Center, Huntsville, Ala.; The Lincoln Electric Co., Cleveland, Ohio; and Thermal Arc, Inc., Troy, Ohio, for technical input, equipment and materials.

References

1. J. R. Davis (ed). 1994. *ASM Specialty Handbook: Aluminum and Aluminum Alloys*, ASM International, Materials Park, Ohio.

2. Dudas, J. H., and Collins, F. R. 1966. Preventing weld cracks in high-strength aluminum alloys. *Welding Journal* 45(6): 241-s to 249-s.

3. Kim, H. T., Nam, S. W., and Hwang, S. H. 1996. Study on the solidification cracking behavior of high strength aluminum alloy welds: effects of alloying elements and solidification behaviors. *Journal of Materials Science*, Vol. 31, pp. 2859–2864.

4. Nakata, K., *et al.* 1994. Improvement of weld solidification crack susceptibility of Al-Zn-Mg ternary alloy by low frequency pulsed GMA with Zr added Al-high Mg welding wire. *Yosetsu Gakkai Ronbunshu/Quarterly Journal of the Japan Welding Society* 12(1): 108–114.

5. Katoh, M., and Kerr, H. W. 1986. Investigation of heat affected-zone cracking of GMA welds of Al-Mg-Si alloys using the varestraint test. *Proceeding of the International Conference on Trends in Welding Research*, pp. 759–761, ASM International, Materials Park, Ohio.

6. Tosto, S., Nenci, F., and Hu, J. 1996. Microstructure and properties of electron beam welded and post-welded 2219 aluminum alloy. *Materials Science and Technology*, Vol. 12, pp. 323–328.

7. Matsuda, F., and Nakata, K. 1982. New self-restrained solidification crack susceptibility test for electron-beam welding of aluminum alloy-taper-shaped hot cracking test. *Transactions of JWRI* 11(1): 141–143.

8. Guitterz, L. A., Neye, G., and Zschech, E. 1996. Microstructure, hardness profile and

tensile strength in welding of 6013 T6 extrusions. *Welding Journal* 75(4): 115–121.

9. Belforte, D. A. 1993. Laser materials processing — the next generation of application. *Proc. 5th International Conference on Welding and Melting by Electron and Laser Beams*, pp. 1–11, La Baule, France.

10. Mehmetli, B. A. 1996. Direct measurement of reflectance from aluminum alloys during CO_2 laser welding. *Applied Optics* 35(18): 3237–3242.

11. Zhang, Y. M., and Zhang, S. B. 1998. Double-sided arc welding increases weld joint penetration. *Welding Journal* 77(6): 57–61.

12. Zhang, Y. M., and Zhang, S. B. 1998. Method of arc welding using dual serial opposed torches. U.S. patent application, S. N. 9,049,191.

13. Dowden, J., Kapadia, P., and Fenn, B. 1993. Space change in plasma arc welding and cutting. *Journal of Physics (D): Applied Physics*, Vol. 26, pp. 1215–1223.

14. Lancaster, J. F. 1986. *The Physics of Welding*, 2nd edition, International Institute of Welding, Pergamon Press, Oxford, U.K.

15. Cao, Z. N., Zhang, Y. M., and Kovacevic, R. 1998. Numerical transition analysis of GTA weld pools. *ASME Journal of Manufacturing Science and Engineering* 120(1): 173–178.

16. Novikov, O. M. 1992. Efficient method for prevention of weld cracking during gas-electric arc welding of thin-walled constructions made of aluminum alloys by means of magnetic stirring. *Svarochnoe Proizvodstvo*, No. 6, p. 16.

17. Kou, S., and Le, Y. 1985. Alternating grain orientation and weld solidification cracking. *Metall Trans A* 16(10): 1887–1896.

18. Ohmae, T., Wakamoto, I., and Nagareda, M. 1985. Study on high quality welding process by magnetic stirring. *Yosetsu Gakkai Ronbunshu Japan Welding Society—National Meeting Spring* 3(1): 117–123.