Study of friction stir welding of aluminum

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A half-cold hardening aluminum plate were friction-stir welded at various rotation speeds (850–1860 rpm) and travel rates of 30 to 160 mm/min with welding forces ranging between 2.5 and 10 MPa using different dimension welding heads. Experimental results show that the dimensions of the welding head are critical to produce sound welds. The microstructure of the weld is characterized by its much finer and equiaxed grains as contrasted with the coarse and band-like structure of the parent aluminum plate. Tensile strength of the welds is about 20% lower than that of the hardening aluminum plate, but about 10% higher microhardness is demonstrated by the welds in comparison with that of the aluminum plate in annealing condition. Moreover, travel rate of the welding head pin has a strong effect on microhardness and tensile strength of the FSW welds, and the ratio of rotation speed and travel rate of the head should be in a reasonable range to obtain high performance welds. The variables of the welding process are also discussed in terms of heat balance and energy input of the welds.

1. Introduction

Friction stir welding (FSW) is a solid phase welding technique that has recently been developed [1, 2]. This technique was developed primarily for welding metals and alloys that heretofore had been difficult to weld using more traditional fusion techniques [3]. Aluminum and aluminum alloys, in particular, are difficult to weld, requiring weld pool shielding gas and specialized heat sources, and require the oxide layer to be stripped prior to or during the welding process. In addition, aluminum and its alloys are subject to voids and solidification cracking defects when they cool from a liquid [4, 5]. One particular benefit of FSW is that the formation of the weld joint is autogenous and is created by the solidification of the plasticized parent materials rather than a filler material. Therefore, the properties of FSW has exceeded those traditionally attributed to conventional fusion welding techniques [6].

FSW technique uses a rotating shouldered cylindrical tool with a projecting distal pin. During FSW, the welding pin spins rapidly and travels along the interface between the faying work piece surfaces while urging the work pieces together and forcing the shoulder of the cylindrical tool in close contact with the upper surface of the metal. The rotation of the welding pin between the opposing faces of the work pieces creates friction that generates sufficient heat energy to plasticize the work piece material in the weld zone, the plasticized metal of the work pieces is extruded to the back face of the pin while confined from above by the pressure exerted on the metal by a shoulder on the stir weld head, and joins the work pieces together in a unitary assembly as the plasticized regions of the work pieces flow together and solidify in the weld zone. The quality and property of the welds are controlled by the welding parameters for the technique, such as pin rotation speed, diameters of the pin and shoulder, pressure and rate of translation of the pin.

The current work was conducted to study the FSW process on a half-cold hardening aluminum with the focus on the effects of welding parameters on FSW welds. Microstructural examination and mechanical test were also carried out to evaluate the quality and the properties of the welds.

2. Experimental procedure

Nominally 3 mm thick plate of L2Y2 aluminum (0.01% Cu, 0.22% Si, 0.25% Fe, balance Al in weight per cent) was used for the FSW study. The L2Y2 aluminum plate was in half-cold hardening condition. FSW experiments were carried out using the aluminum plate in half-cold hardening condition and the same material after annealing treatment in a resistance furnace at 300°C for 0.5 h. The welding experiment was conducted in a reconstructed milling machine with a pressure-loading unit. The pressure (P) to force the shoulder of the welding head in the milling chuck against the upper surface of the work piece was varied from 2.4 to 10 MPa. The welding head shown in Fig. 1 was made of carbon-steel with the pin diameters (ϕ) varying from 2.7 to 3.9 mm and the shoulder diameters (Φ) from 6 to 13 mm. The head pin was shortened slightly ($\sim$0.2 mm less than the thickness of the aluminum plate so as to avoid contacting with the backing surface and bringing debris to the welds). The rotation speeds of the welding

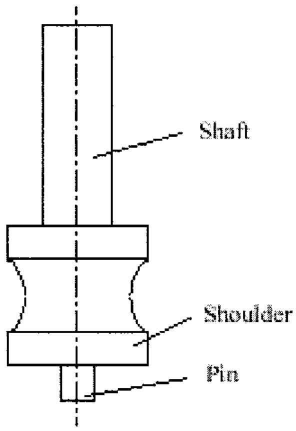

Figure 1 Schematic illustration of the welding head.

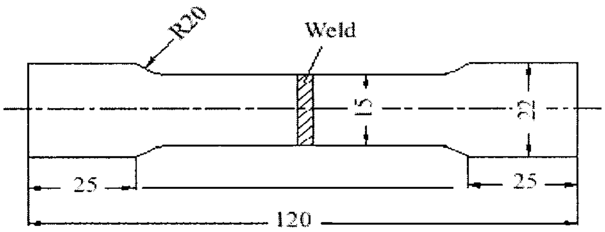

Figure 2 Tensile test specimen of the FSW weld.

head (R) were varied at 850, 1560 and 1860 rpm while the pin travel rates (V) were varied from about 30 to 160 mm/min.

The quality of the FSW welds was first visually inspected to both upper and bottom surfaces for weld smoothness and distortion, and then examined under microscope for microstructure and internal defects. Vickers microhardness of the work pieces was measured through the weld zone after FSW with an HVA-10A Hardometer using a 50 N load. The samples for microstructure observation were sectioned from the FSW zones and etched with Keller's reagent (150 ml H_2O, 3 ml HNO_3, 6 ml HCl, 6 ml HF). The dimensions of the specimens for tensile test of the FSW welds are shown in Fig. 2. Tensile and bending tests were carried out using a WE-10A universal test machine.

3. Experimental results

3.1. Welding

Among the numerous FSW experimental trials at the three rotation speeds, the welding conditions which can obtain fairly good welds are listed in Table I. In general, the welding heads with small shoulder diameters of Head 1, 2, 4, 6, 9 and 11 cannot join the work pieces together to form a weld at the lowest rotation speed of 850 rpm even under high pressure due to the insufficiency of heat generation, but make successful welds at higher rotation speed and very slow travel rate with relatively high pressure.

Contrarily, the heads with large dimensions of the welding Head 8, 11 and 12 are unable to make welds at the highest rotating speed even under low pressure due to excessive heat generation by the welding head. The reduction of the rotating speed and the increase in travel rate can accomplish the welding of the aluminum assembly. However, the weld surfaces are usually depressed, uneven and full of voids and barbs.

TABLE I Results of welding experiment in various conditions

Welding head						
No.	Diameter (mm) pin	shoulder	Pressure (MPa)	Rotation speed (rpm)	Travel rate (mm/min)	Weld quality
1	2.7	6	9.3	1860	45–70	Fair
2	2.7	8	5.0	1860	45–72	Good
				1560	30–45	
3	2.7	10	3.9	1860	72–128	Fair
				1560	59–128	Good
				850	30–90	Fair
4	3.0	6	9.9	1860	45–72	Fair
				1560	30–59	
5	3.0	9	4.0	1860	53–128	Best
				1560	42–110	
				850	30–90	
6	3.3	7	7.0	1860	45–90	Fair
				1560	30–60	
7	3.3	10	3.5	1860	72–136	Good
				1560	45–128	
				850	30–72	
8	3.3	13	2.4	1560	110–158	Fair
				850	72–128	
9	3.6	8	6.5	1860	90–136	Fair
				1560	72–110	
10	3.6	11	3.2	1560	90–158	Fair
				850	45–90	Good
11	3.9	8	5.8	1860	90–158	Fair
				1560	59–128	
12	3.9	12	2.9	1560	110–136	Fair
				850	59–90	

Figure 3 Welding specimen using Head 5.

No matter lager or small the pin diameters were used, most of good welds always come from the welding heads with pin and shoulder diameters in the proportion of 1:3, such as Head 2, 5, 7 and 10 as listed in Table I. The best welds with very smooth surface and pore-free structure are obtained by using Head 5 at all the rotation speeds with broader ranges of travel rates. A typical welding specimen is shown in Fig. 3.

3.2. Morphology change of microstructure

The microstructure of the L2Y2 aluminum plate in half-cold hardening condition is characterized by its coarse, long and band-like structure, as shown in Fig. 4. However, friction stir welding creates a severely deformed, but highly refined grain structure in the weld, as illustrated in Fig. 5 where the coarse and zonal structure of the original aluminum plate becomes much finer and equiaxed grains due to the mechanical stir and dynamic recrystallization effects of FSW. Further, friction stir

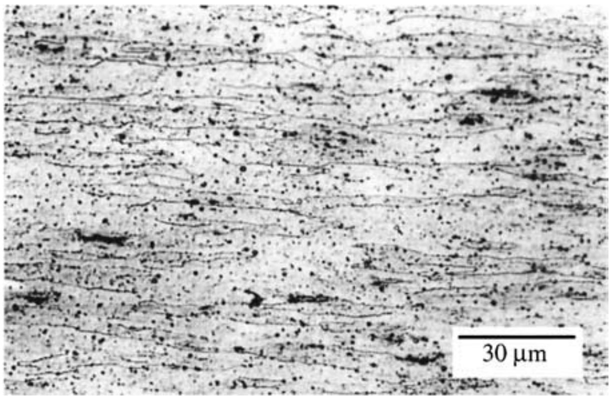

Figure 4 Microstructure of the L2Y2 aluminum plate in half-cold hardening condition.

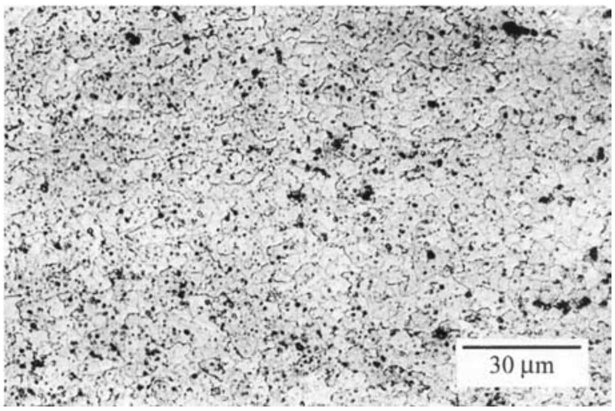

Figure 5 Microstructure of the FSW weld.

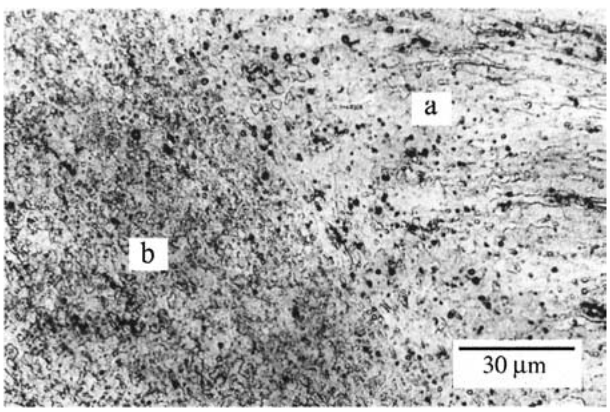

Figure 6 Microstructure of the FSW welding joint. (a) Heat-affected zone, (b) weld.

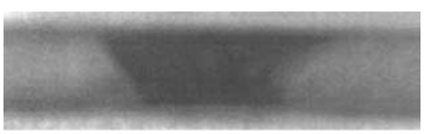

Figure 7 Cross section of the FSW joint.

welding results in a much more narrow heat-affected region when compared to fusion welding processes where the temperature of the weld reaches beyond its melting point. Fig. 6 shows the microstructure of the heat-affected zone, and the maximum width of the heat-affected zone is about 200 μm for all of the welds prepared by using Head 5. Fig. 7 shows the macrostructure

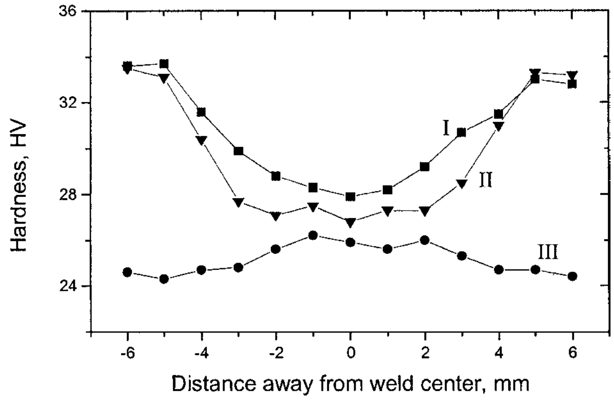

Figure 8 Microhardness variations throughout the weld zones at $\Phi = 9.0$, $\phi = 3.0$ and $R = 1560$ rpm for the half-cold hardening aluminum plate at (I) $V = 70$ mm/min and (II) $V = 110$ mm/min and for the annealed at (III) $V = 70$ mm/min.

of a FSW weld joint where the black region is the FSW weld. From the measurement of the black regions, the top and bottom widths are slightly larger (~0.20 mm) than the diameters of the shoulder and the pin for all of the welding heads with different dimensions.

3.3. Microhardness

Fig. 8 demonstrates the microhardness variations throughout the weld zones at a constant pin rotation speed of 1560 rpm. The microhardness of the welds is much lower (Curve I and II) than that of the parent material when the aluminum in half-cold hardening condition is used for the welding assemblies. By comparison of the Curve I and II in Fig. 8, it can be seen that pin travel rate has a great effect on the microhardness of the welds. The microhardness of the welds decreases as the pin travel rate increases. However, the microhardness of the weld is about 10% higher than that of the parent material when the weld assembly is made of the aluminum in annealed condition (Curve III in Fig. 8), which is attributed to the grain refinement of the FSW weld shown in Fig. 5.

3.4. Mechanical properties

Tensile strength of the half-cold hardening aluminum is 123 MPa with a specific elongation of 11.8%. For the tensile tests of all the welded specimens of the half-cold hardening aluminum, the fracture occurs always in the welds, as shown in Fig. 9. This material property degradation is attributed to the elimination of work-hardening effect in both the weld zone and the heat-affected region, as illustrated by their microhardness in Fig. 8. Although bending tests have shown uniform deformation of the FSW specimens (Fig. 10), the

Figure 9 Fracture of the tensile specimen at weld of the half-cold hardening aluminum plate.

Figure 10 Bending test of the FSW weld.

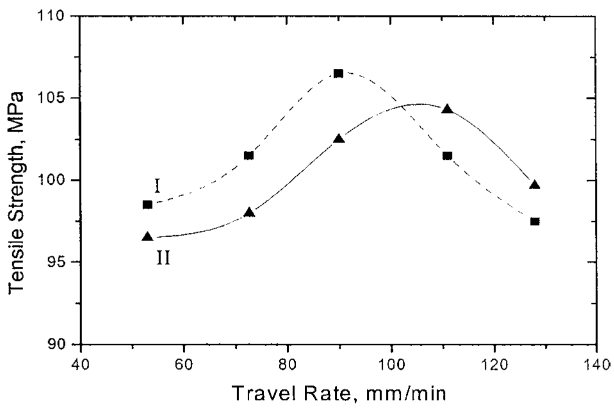

Figure 11 Relation of tensile strength and pin travel rate for the FSW welds at $\Phi = 9.0$, $\phi = 3.0$ and $P = 4$ MPa for (I) at $R = 1560$ rpm and (II) at $R = 1860$ rpm.

extensibilities of the welds are little lower, about 10.5% for all the tensile specimens at different FSW conditions. However, the tensile strength of the FSW welds has shown a strong dependency on pin travel rate, as shown in Fig. 11. At both pin rotation speeds of $R =$ 1560 rpm and $R = 1860$ rpm, the tensile strength of the welds increases first, reaches a maximum and then decreases with increasing travel rate of the welding head pin.

4. Discussion

A FSW process welds two pieces of metal together through frictional heating, plasticizing, mixing, and forging of the plasticized metal into a uniform weldment. The ultimate requirement for a FSW process is to create a certain amount of friction heat which can keep the welding material in a well-plasticized state with a suitable temperature, so that a sound weld can be produced.

The heat generation in FSW is in direct proportion to friction coefficient and friction area between the welding head and work piece surfaces, rotation speed of the welding head pin and the pressure applied to the welding head shoulder. The heat loss includes the heat to raise the temperature of the weld material to the plasticized state, the heat to conduct through the welding head, work piece and backing surface into the ambient environment and the heat to create a heat-affected region around the weld zone. The main source of the friction heat generation comes from the pin. The increase in pin diameter increases the heat generation by increasing friction area and peripheral velocity at constant rotation speed, while broadens the FSW weld and the heat-affected zone, which means more energy is needed to heat up the weld material to the plasticized state. The pin travel rate is mainly determined by the rotation speed of the welding head. A high rotating speed allows for the increase in the travel rate of the head pin.

Apart from faying welding assembly surfaces on the opposite side from the backing surface to prevent plasticized material from extruding out of the welding joint, the welding head shoulder also has a great contribution to friction heat which, if excessive large, causes overheating of the upper surface and invites welding defects such as barbs, pores and distortion when the shoulder diameter is larger. The study found that the good welds are produced when the ratio of pin and shoulder diameters is 1:3. Other work [7] reported that the reduction of the shoulder diameter from 20 to 10 mm permitted of a doubled travel rate achieving high quality pore-free welds and exhibiting reduced heat-affected zone. As a consequence of the shoulder diameter reduction, a reduced downward force applied on the shoulder resulted in distortion-free welded structures [8]. Therefore, the design of the welding head is critical to the success of FSW process, which is important to control heat gain and loss of the process and the quality of the welds. The variation of tensile strength versus traveling rate shown in Fig. 11 is closely correlative to the heat absorption of the welds during FSW process that alter the weld structures, resulted in the difference in tensile property.

Once the parameters of a FSW process are chosen, such as material, welding pressure and the design of the welding head, the total energy input, E, of the weld is determined by [9]

$$E = \pi \mu P R \frac{\Phi^2 + \Phi\phi + \phi^2}{45(\Phi + \phi)} \tag{1}$$

where μ denotes friction coefficient between the welding head and the work pieces, P presents the downward force on the shoulder, R expresses the rotation speed of the welding head, and Φ and ϕ stand for the shoulder and pin diameters of the welding head respectively. Then, the energy input per unit length of the weld can be expressed as

$$e = C \cdot \frac{R}{V} \tag{2}$$

where C is a constant, and V is the travel rate of the head pin. Obviously, the magnitude of energy input is associated with the rotation number of the welding head in unit length. The variation of either R or V changes the input of the friction energy. However, the study found that increasing the travel rate excessively to control the friction heat input leads to the formation of pores along one side where the rotating surface is moving in the same direction as the travel along the joint, which is also proved by Thomas *et al.* [5]. Therefore, a suitable range of the R:V ratio should be kept to obtain high quality FSW welds. For example, high visual quality welds with tensile strength over 100 MPa shown in Fig. 11 were achieved for the pin rotation at 1560–1860 rpm in the R:V ranging from 14 to 23.

5. Conclusions

1. The microstructure of the FSW weld consists of very fine and equiaxed grains instead of the coarse and band-like structure of the half cold-hardening aluminum plate, and the heat-affected zone is very small.

2. Tensile strength of the welds is about 20% lower than that of the hardening aluminum plate, but about 10% higher microhardness is demonstrated by the welds in comparison with that of the aluminum plate in annealing condition. Both of the microhardness and tensile strength of the FSW welds are affected by travel rate of the welding head pin.

3. Good welds can be produced when pin and shoulder diameters of the welding head are in the proportion of 1:3, and the best visual quality welds with tensile strength over 100 MPa are obtained by using the head with ϕ3 mm pin and Φ 9 mm shoulder rotating at 1560–1860 rpm in R:V ranging from 14 to 23 under a downward force of 4 MPa.

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