STRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELD JOINTS OF MAGNESIUM ALLOY AZ31

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Abstract

The applicability of friction stir welding to hot rolled sheet of commercial magnesium alloy AZ31 plates has been investigated. Friction stir weld joint showed mechanical strength comparable to that of base material, though the ductility remained at one half of that of the latter. The results are consistent with the microstructure which is characterized by a fine grained bond layer bounded by intermediate grained base metals. It is found that both anodizing treatment and insertion of aluminum foil between batting faces do not degrade the joint properties at all. The results suggest that friction stir welding can be potentially applied to magnesium alloy.

Introduction

A revolutionary method of solid phase welding, which permits a wide range of parts and geometries to be welded, and called friction stir welding (FSW), was invented by W. Thomas and his colleagues of The Welding Institute (TWI), UK, in 1991[(1)].

Friction stir welding is a relatively simple process[(2)] (see Fig.1); a specially shaped cylindrical tool with a profiled probe, made from a hard and wear resistant material relative to the material being welded, is rotated and plunged into the abutting edges of the parts to be joined. After entry of the profiled probe to almost the thickness of the material and to allow the tool shoulder to just penetrate into the plate, the rotating tool is transitioned along the

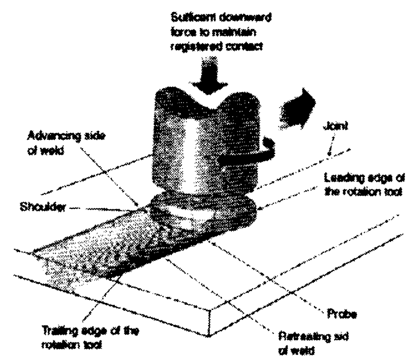

Figure 1: A schematic illustration of friction stir welding[(2)].

joint line. The rotating tool develops frictional heating of the material, causing it to plasticize and flow from the front of the tool to the back where it cools and consolidates to produce a high integrity weld, in the solid phase.

Subsequent improvement mainly accomplished in the tool design brought the technology forward for application especially to commercial aluminum alloys such as 2219, 2014, 6083, 6082 and 7075[(2)-(9)].

The process proves predominance for welding non-heat-treatable or powder metallurgy aluminum alloys, to which the fusion welding can not be applied. Thus fundamental studies both on the weld mechanism and on the relation all arrow ship between microstructure, properties and process parameters, have recently been started[(10)-(21)].

On the other hand, very limited information has been obtained about the feasibility of the process for welding commercial magnesium alloys, though they have the potential ability to substitute conventional light weight materials such as aluminum alloys or engineering polymers.

Thus the aim of this study is to examine experimentally the applicability of friction stir welding to commercial magnesium alloy AZ31. The results obtained here are compared with those of other researchers.

Procedure

Materials

The materials tested are hot-rolled plates of commercial magnesium alloy AZ31 of 6mm thick, supplied by Osaka Fuji Kougyo Inc., the nominal composition of which is 3.0%Al, 0.9%Zn, 0.3%Mn, 0.003%Fe, 0.002%Ni, 0.002%Cu, 0.2%Si and balanced Mg (dimension in mass%). A number of rectangular workpieces of 100mm width and 200mm length were machined out of the plates and submitted for FSW.

Welding Equipment

FSW was carried out according to the following sequence. A pair of workpieces free from oil films were abutted along a longitudinal section and fastened rigidly on the cast iron backing bar, which was mechanically fixed on the bed of a vertical type milling machine. A specially designed rotating tool, the details of which are shown in Fig.1, was vertically inserted along the abutted joint until the shoulder face came in touch with the top face of the workpiece. In this case, the height and diameter of pin was 5.8mm and 5.0mm, respectively.

In this paper, tool rotation speed and transition speed was held constant at 1750rpm and 88mm/min, respectively, though it is confirmed by the preliminary tests that the process can be successfully applied at the rotation speed ranging from 44 to 246mm/min and at the translating speed ranging from 980 to 1750rpm.

Evaluation of the Performance of Joints

In order to evaluate the performance of friction stir weld joint of AZ31 alloy plate, several methods were employed.

Thermal History: The change in temperature with time at three points on the lower surface of workpiece, the one (point A) just on the joint face and the other two (points B and C) 5mm distant from the joint, was monitored with a themocouple during the welding.

Metallography: Microstructure observation of weld joint was made on the two planes, one parallel to and the other perpendicular to the tool transitioning direction. Prior to the observation, the mechanically polished surface was chemically etched with an agent, the standard composition of which is 0.4g of picric acid, 13ml of ethanol, 3ml of glacier acetic acid and 3ml of boiled water.

Mechanical Tests: A series of 2mm thick sheets were cut out of the welded joint so that the longitudinal rolling direction of the sheet was parallel to the tool transitioning direction. Tensile test pieces, the gauge section of which was located within the welded zone and had a size of 30mm long, 4mm wide and 2mm thick, were cut out of the sheets. In order to discuss the fracture mechanism, local strain profile was obtained by measuring the change in length between preliminarily stamped points. Sharpy impact tests were carried out on the specimen having a cross section of 6mm x 6mm in which U-notch of 2mm depth was cut through the weld so that its edge laid perpendicular to the plate.

Hardness: The microstructure of welded joints was evaluated by measuring hardness distribution along a central line drawn on a plane perpendicular to the tool transitioning direction.

Effect of Surface Finish:

FSW should in principle be insensitive to the morphology of the surface to be welded. To confirm this prediction, three kinds of weld specimens were prepared: the first was anodized before abutting and then welded, and had oxide films of 12μm thickness. The second was welded after aluminum foil of 15μm thickness was inserted into a butt plane. The third was a single plate which was friction stirred under the condition described in the previous section. Thereafter, the mechanical properties were measured by the conventional tensile tests.

Results and Discussion

Thermal History

Figure 2 shows the change in temperature with time at three points just beneath the lower surface of abutted plate, i.e., point A just upon the abutted plane, points B and C 5mm distant from the

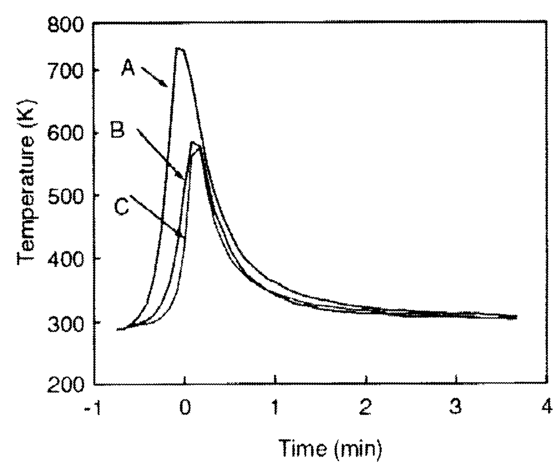

Figure 2: Change in temperature with time, at three points just beneath the lower surface of abutted plate. Point A: Upon the abutted plane, points B and C: 5mm distant from the plane.

plane. The fact that the material is heated up to 733K demonstrates that that FSW proceeds in the solid state. The fact that the material is held above 573K for 30s at point A suggests that the recrystallization occurs during friction stir welding. On the other hand, the peak temperature at points B and C are about 573K . There exists between points A and B (or C) a temperature gradient as large as 30Kmm^{-1}, meaning that only the material within a narrow range adjacent to the abutted plane is heated and softened.

Microstructure

In Fig. 3 are shown both macroscopic and microscopic (c, d, e) structures observed on the plane perpendicular to the tool translation direction. It is obvious that the nugget is well developed at the center of the weld (a, b). This contains an annual ring type inner structure, consisting of concentric ovals (a, d). The characteristic structure demonstrates that the materials plastcized by frictional heat flow not only horizontally but also vertically describing spiral loci. A similar structure has often been observed in some aluminum alloys[2-6]. Appendages to the nugget are seen at the upper surface of the weld and extend to the edges of the tool shoulder.

Considerably uniform and recrystallized grains of about 16μm in diameter are seen in the weld (Fig. 3e), in contrast to the coarse grains of about 56μm in the base metal (Fig. 3c). The heat-affected zone often observed in the friction stir weld joint of aluminum alloy plate is not observed in the present case. This is probably because the grains in the base metal have been recrystallized during hot rolling and hence insensitive to the thermal disturbance.

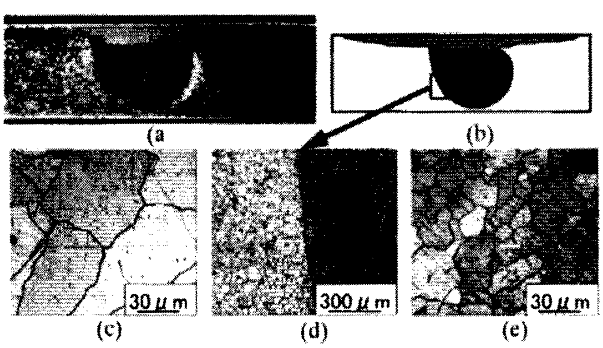

Figure 3: Macroscopic (a, b) and microscopic (c, d, e) structures observed along the same longitudinal rolling direction of the sheet as the tool transition direction.

Hardness Distribution

Figure 4 shows the hardness profile measured along a central line on the transverse plane perpendicular to the welding direction. No difference in the hardness is observed between the base metal and the weld. The result is in contrast to that in the welds of some wrought aluminum alloys that the hardness decreases drastically in the stirred region, and may be explained by the above mentioned fact that both the base metal and the weld consist of recrystallized grains[5].

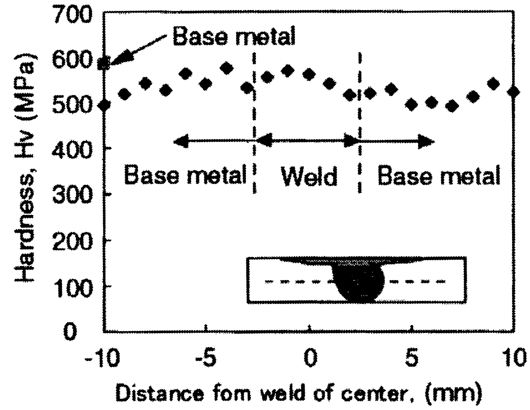

Figure 4: Hardness profile measured along a central line on the transverse plane perpendicular to the welding direction.

Mechanical Properties of FSW Joint

Figure 5 shows nominal tensile stress-nominal strain curves of the weld joint compared to that of the base metal. Both yield stress and ultimate tensile strength of the joint is almost at the same level as that for the base metal. The weld joint has an elongation of about 12%, which is sometimes sufficient for many practical applications, though the base metal exhibits ductility much higher than that of the joint. A remarkable dimple structure is observed on the fracture surface in each case, as shown in Fig. 6.

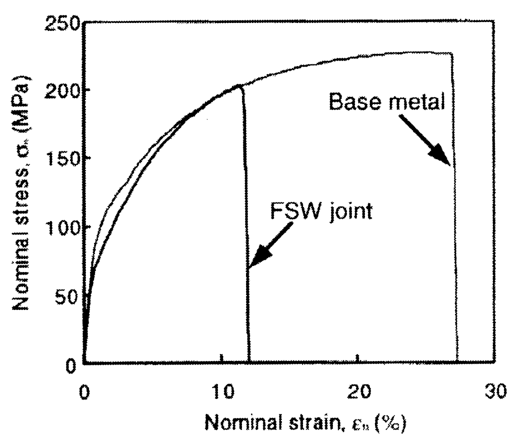

Figure 5: Nominal stress vs. nominal strain curve of the weld joint compared to that of base metal.

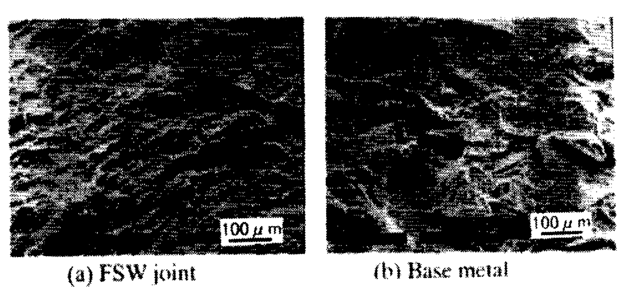

Figure 6: SEM micrographs showing fracture surface of the weld and the base metal.

The Sharpy impact value of the weld was 7.7J, while the base metal showed 6.1J. The superior toughness of the weld should be attributed to the fine and uniform grain structure brought about by FSW.

Effect of Surface Finish

Figure 7 shows nominal tensile stress-nominal strain curves for the specimens prepared by various preliminary treatments described earlier and through subsequent welding. It is seen that both strength and ductility of the welds are affected neither by the surface oxide films, nor by the absence of a butt plane. A separate experiment proved that the surface roughness of the plate to be welded has no effect on the mechanical properties of joint. In summary, FSW is a process quite insensitive to the extent of surface finish.

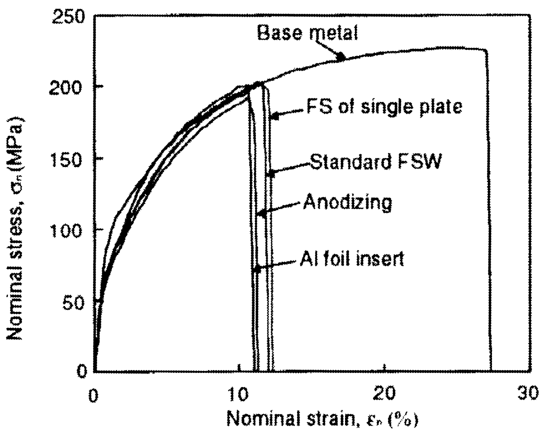

Figure 7: Nominal tensile stress-nominal strain curves of the specimens prepared by various preliminary treatments. (See text.)

Comparison with the Previous Results

To the best of our knowledge, no other comprehensive paper has been published regarding the FSW of magnesium alloys except one by Shimizu and his colleague[22]. As in this case, they also had observed fine and recrystallized grain structure and as well as the flat profile of hardness. However, both the strength and the ductility of FSW joint are much lower than those of the base metal in comparison to our results. This is probably because of their peculiar probe with a V-profile which would be inadequate to stir the lower half material of the plate to be welded, and would hence be apt to cause crack-like weld defects called "kissing bond"[2].

Conclusions

The applicability of friction stir welding in air to hot-rolled plate of magnesium alloy AZ31 has been investigated. The results obtained at a fixed set of rotation speeds and tool transition speed are summarized as follows:

(1) The friction stir weld joint of hot rolled plate of magnesium alloy AZ31 has the strength comparable to that of the base metal. This is because fine and recrystallized grain structure is established during the welding.

(2) An annual ring structure observed on a plane in line with to the welding direction strongly suggests that the flow lines of the material, plasticized by the frictional heat, have vertical components as well as horizontal ones, resulting in the effective mixing of materials.

(3) The mechanical performances of the welds are fairly insensitive to the morphology of the base metal sheet.

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