THE EVALUATION OF MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELDEDAL-MG-SI ALLOY

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ABSTRACT

The microstructural change associated with the hardness profile in friction stir welded, age-hardenable 6005 Al alloy had been evaluated. Frictional heat and plastic flow during friction stir welding created the fine recrystallized grain (Stir Zone, SZ), the elongated and recovered grain (Thermo-Mechanical Affected Zone, TMAZ) in the weld zone. Heat affected zone (HAZ), which could be only identified by hardness test because there is no difference in the grain structure compared with that of the base metal, was formed beside the weld zone. A softened region had been formed near the weld zone during friction stir welding process. The softened region was characterized by the dissolution and coarsening of the strengthening precipitate during the friction stir welding. The sound joints of 6005 Al alloys were successfully formed under a wide range of the friction stir welding conditions.

KEYWORDS

Friction stir welding, age hardenable Al alloy, precipitate

1.Introduction

Al alloys were characterized by high strength to weight ratio, low density, corrosion resistance, relative ease of forming and machining, good cryonic properties, ductility and non-magnetic.[1,2] There have been increased demands for the wider low distortion Al alloys sheet and plate in the fabrication industry, for example, the streamlined production of bridge decks, ship panels and other transportation applications like train and airplane components. Larger extrusion presses and rolling mills causing the production cost to be high are recently utilized in this fields of part, but the problem associated with extrusion presses is that they are limited in size and capacity.[3] Therfore, the welding thechnique acquired good quality must be applied to the joining of wrought Al alloys.

Friction stir welding is a new, solid-state welding technique which was invented by The Welding Institute (TWI) in 1991.[4] It has enabled us to join the long butt Al alloys, which are often difficult to be joined by fusion welding without void, cracking, or distortion. Basically, FSW process is that a non-consumable tool with a specially designed rotating pin is inserted into the abutting edges of the sheet or plate to be welded. Once entered, the rotating tool produces the frictional heat and plastic deformation in the weld zone. The tool is then translated along the joint to complete the joining process.[5]

Microstructural changes of friction stir weld zone have been the main subject of some recently published papers. However the effects of friction stir welding parameters, especially welding speed, on microstructural change, mechanical properties of friction stir welded Al alloy have not been well known.

The objective of the present study is to evaluate the microstructure of near weld zone and the distribution of strengthening precipitate regarding the hardness profile and effects of the friction stir welding parameter and post welding aging treatment on microstructural change and mechanical properties.

2.Experimental procedure

The material used in this study was the 6005-T6 Al alloy with 140 mm in length, 70 mm in width and 4 mm in thickness. Its chemical composition is shown in table 1.

Table 1 Chemical composition of the 6005-T6 alloy.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
6005Al	0.779	0.514	0.001	0.031	0.459	0.006	0.005	0.007	Bal.

The details of the FSW codition were that welding speed varied from 87mm/min to 567mm/min and other parameters were fixed at 3° tool angle, 1600rpm tool rotation speed. Microstructural change of the welded specimens was examined with OM (optical microscopy) and TEM (Transmission Electron Microscopy). The echant used in this experiment was Keller solution which consists of 150 ml water, 3 ml nitric acid, 6 ml hydrofluoric acid and 6mL hydrochloric acid for 180 s.

Thin disk specimens were cut with 3 mm in diameter from various locations in the weld zone. To avoid the thermal degradation it was used by an electrical-discharge machine. Much care was taken for locations to locations correspondence between observation and hardness measurement. A twin-jet electropolisher was used to produce electron-transparent thin section in this slice disc. This process was performed in a nitric acid/methanol solution at 223K.

Vickers hardness was measured at the cross section perpendicular to the weld center and was used a microvickers hardness tester with 100 g for 10 s. The tensile test was carried out at the room temperature used by Instron type testing machine with crosshead speed of 1.67×10^{-2}mm/s.

3. Results and discustions

The transverse macroscopic changes of FSWelded 6005 Al alloy were shown in figure.1. Macroscopic examination of the weld revealing a relative non-symmetric stir zone was mainly associated with the angle of tool and relation between rotation direction between welding direction.[6]

It was apparent that the weld itself exhibited a high degree of continuity and no porosity. The area of the weld zone decreased with increasing welding speed. The weld zone showed wider near the upper surface than lower surface because the upper surface experienced extreme deformation and frictional heat caused by contacting with a cylindrical tool shoulder during the welding. Each weld zone exhibited a sharp (shearing side) and diffused (flowing side) transition region between the TMAZ and the SZ. These regions were formed as a result of the relation between rotation of the tool and the welding direction. The difference of two regions was confirmed by OM and hardness test.

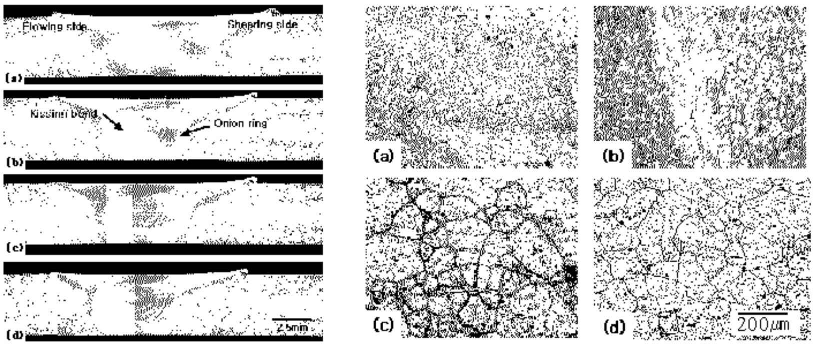

Figure 1. The macroscopic views(left side) of the weld zone with increasing welding speed.(a) 87mm/min, (b) 267mm/min, (c)342mm/min, (d) 507mm/min and the microstructure of weld zone(right side) (a) SZ, (b) TMAZ, (c) HAZ, (d) BM

Figure 1 also showed the microstructure of FSW zone by OM. Unlike that of the base metal, the SZ had a fine, equiaxed grain structure and its diameter was about 10㎛. That was produced by dynamic recrystallization, which was caused by the frictional heat and deformation, this region included the onion ring and the kissing bond concerning the trace of pin contacted with welded specimens. The formation mechanism of the kissing bond and onion ring had been exactly unknown. But according to the recently published paper from Hasanori et al[7]., it contained Al, Mg and Si based oxides dected by EDS analysis and they had no significant effect on the tensile strength of the joint. About the onion ring pattern, it would be discussed later in this paper.

The TMAZ was evident where the original grain structure was microscopically upsetting. The elongated and recovered grain structure was characterized in the TMAZ. The HAZ was only identified by hardness results, because the HAZ was no different in grain structure as compared with that of the base metal. The mechanical and temperature conditions in the HAZ were not sufficient to promote grain growth or macroscopically deform the metal.

The black spots were pits left from etching of 2nd phase dispersion (strengthening precipitate) and they were mainly presented in the base metal. The 2nd phase constituents presented in the base metal were less discernible in the SZ mainly due to the mechanical break up or resolution of the constituents during FSW process.

The feature called “onion ring or flow pattern” was visible in the weld nugget and corresponded to the variation in the friction stir welding parameters.[8] Onion rings were tied to the tread of the tool and these were seen as a sign of good quality. This ring pattern apparently represented the plastic deformation increments as the pin of the rotating tool moved through the joints.

The feature of onion ring and width of the weld bead showed a special relation with the welding speed. The number of onion rings decreased as the weldig speed increased. However, the gap of onion rings and the width of bead increased with increasing welding speed (seen in figure 3).

The FSW process generated heat by contacting cylindrical rotating tool with the weld specimens. The lower welding speed (87mm/min), the more the heat quickly spread around the weld due to a long duration time and the original high thermal conductivity of Al alloy. Therefore, the wider heat affected region was formed than that of the high welding speed.

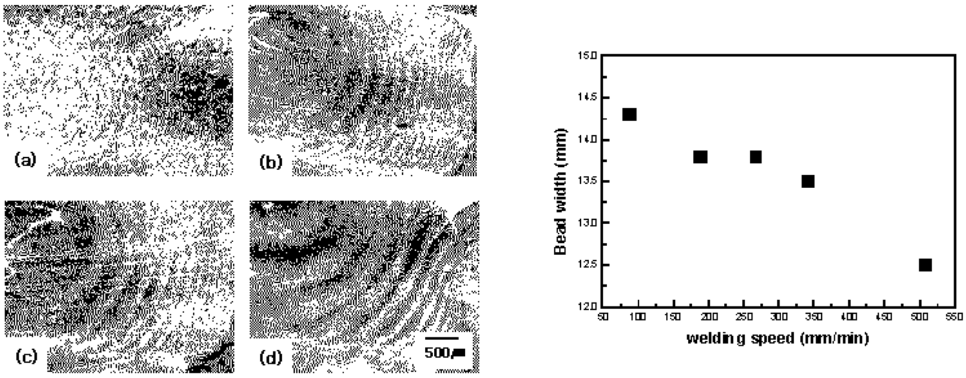

Figure 3: The variations of onion ring pattern(left side) in the weld zone, (a) 87mm/min, (b) 267mm/min, (c)342mm/min, (d) 507mm/min and the relation between welding speed and welding bead width(right side)

The horizontal hardness profile in the weld zone along the center line was shown in figure.4. There was a considerable softened region relative to the base metal, which had a scattered hardness a range of 100-120HV. The total softened range was 14mm and the minimum hardness was near HAZ located at about 5mm-6mm away from the weld center. The shearing side showed a slightly wider softened region than that of the flowing side.

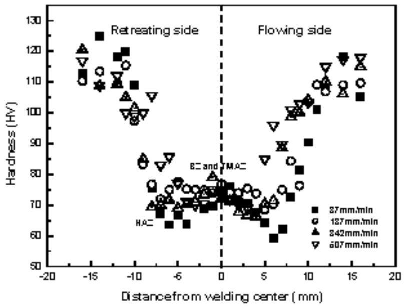

Figure 4 :Horizontal hardness profile in the weld zone along the center line with increasing welding speed.

The precipitation sequence during aging time of pseudo binary Al-Mg_2Si alloys is as followed : supersaturated solid solution → a needle-shaped precipitate(β˝) → a rod-shaped precipitate (β’) → a β-Mg_2Si.[9-12] It was known that the needle shaped precipitate act as the main strengthening element owing to a very fine size precipitate. The rod-shaped precipitate was featured by coarsening precipitate with a low strengthening effect relative to the needle-shaped precipitate.[13]

In order to examine the effect of precipitate distribution on the hardness profile, microstructures of each locations: (a) SZ, (b) LOW(lower hardness than base metal), (c) BM(base metal) were observed by TEM.

Figure.5 showed TEM images obtained from the three regions in the weld zone. The incident beam was parallel to a <100> zone axis of the matrix in each photograph. The two kinds of precipitate were observed in BM region. One kind was needle-shaped precipitate characterized by very fine size and the other was rod-shaped precipitate which is about 200nm length. However, any kinds of precipitate and dislocation couldn’t be observed in the SZ due to the resolution of precipitate and recrystallization. The LOW region included more rod-shaped precipitates than needle-shapesed precipitates because the fine precipitate was grew up to rod-shaped precipitates by welding heat. This caused the LOW to show lower hardness than that of the BM.

The grain size was not consistent with the horizontal hardness profile in the weld from the result of OM and hardness measurement, because the hardness profile in the age-hardenable aluminum alloy depended strongly on the precipitate distribution rather than the grain size .

The temperature of SZ ranged from 458℃ to 480℃ according to data released papers.[8] In 6005 Al alloy, these temperatures were sufficient to completely dissolve all precipitates and the cooling speed was sufficiently rapid to retain the solute in saturated solid solution. The temperature that corresponded with the lowest hardness in the HAZ was approximately 420℃. This temperature was nearly equal to the 413℃ annealing temperature for 6xxx alloy. At this temperature a rapid transition in the strengthening β″ phase to an essentially non-strengthening β' phase rapidly was occurred.

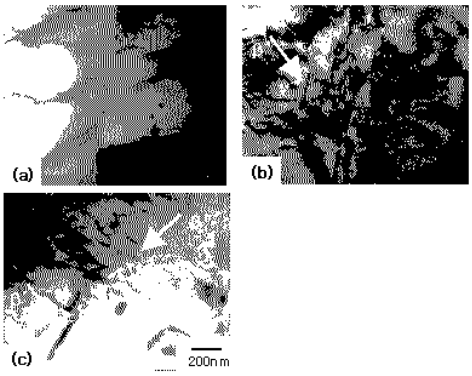

Figure 5: TEM images obtained from the three regions of the weld. (a) The SZ, (b) The LOW and (c) The BM

The welding travel speed had a high impact on productivity in streamlined production of Al alloys section. Fig.6 showed the effect of welding speed on the tensile strength. A significant increase in welding speed was achieved with high weld quality and the excellent joint property.

In the case of high welding speed, the softened area was narrower than that of low welding speed. Therefore, the tensile strength of as welded 6005 Al alloy had proportional relation with welding speed. The locations of failure were near HAZ and base metal in the whole welding speeds. This result means that the sound weld quality was acquired over a wide range of FSW conditions. The maximum tensile strength of as welded 6005 Al alloy was about 220MPa at 507mm/min welding speed, that was the 85% of the base metal (262.5MPa). The elongation was near the same value compared to that of base metal, which was presented a range of 8-9%.

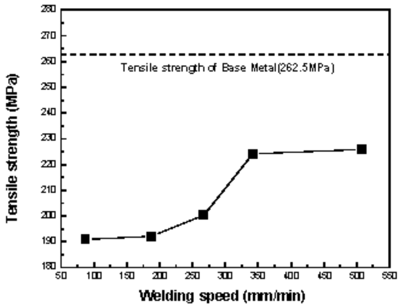

Figure 6: The relation between tensile strength and welding speed.

4.Conclusions

The present work examined the microstructure and mechanical properties of the as Friction Stir Welded and the results of this work were as followed:

1. The weld zone was divided into three regions as the grain structural variations: (1) SZ have the finely recrystallized and equiaxed grains in the weld zone , (2) TMAZ have the elongated and recovered grain structure beween SZ and HAZ, (3) the region(HAZ) is identified only by hardness results, because there is no difference in grain structure with respect to the base metal.
2. The onion ring pattern in the weld had a special relation with friction stir welding speed. The number of onion rings was decreased and the gap of onion rings was increased with increasing welding speed.
3. The friction stir welding process produced a softened region near the weld zone due to resolution of precipitate in the matrix. This area was almost 7-8mm away from the weld center.
4. The grain size was not consistent with the horizontal hardness profile in the weld. This was because the hardness profile in the age-hardenable aluminum alloy depends strongly on the precipitate distribution rather than on the grain size.
5. The tensile strength increased with increasing welding speed. The highest tensile strength was obtained at welding speed of 507mm/min.

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