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Influence of FSW parameters on formation quality and mechanical properties of Al 2024-T351 butt welded joints

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Abstract: The influence of *R*/*v* ratio on joint quality in 2024-T351 aluminum alloy was studied. Specimens were subjected to friction stir welding with the rotation rates of 750, 950 and 1180 r/min and welding speed between 73 and 190 mm/min, providing *R*/*v* ratio between 5.00 and 10.27. The welded joints were tested by means of both non-destructive (visual, penetrant and X-ray inspection) and destructive (metallographic, tension and hardness) testing. In all specimens typical zones are revealed, with corresponding differences in grain size. Tensile efficiency of the joints obtained is in the range of 52.2% to 82.3%. The results show that the best quality is obtained at *R*/*v* ratio of 8.06, 10.17 and 10.27. This behavior is attributed to the assumption that the material flows around the pin with an optimal speed, i.e. sufficient amount of material is available to fill the gap and prevent tunnel formation. *R*/*v* ratio also showed influence on hardness distribution, onion features and crack initiation/propagation zones.

Key words: Al 2024 alloy; friction stir welding; welding parameters; heat input; weld quality

1 Introduction

Heat treatable 2xxx series aluminum alloys with high strength level, favorable strength to mass ratio and good damage tolerance, are widely used for structural applications. Extensive use of the age hardenable 2xxx series aluminum alloys was hampered by limitations imposed by joining techniques. The loss of strength in the components fabricated from these alloys, using conventional, high heat input, fusion welding techniques such as TIG or MIG, introduced a serious limitation in their exploitation due to the presence of porosity, slag inclusion, solidification cracks, distortion, etc. Gap between the strength values of the fusion joint and the parent material is more than 40%, resulting in the fact that mechanical joints are preferred. In order to solve this difficulty a solid state joining process, named friction stir welding (FSW), was invented. At present, FSW is increasingly applied to the aerospace, automotive, marine and military industries [1−9].

FSW offers several advantages over conventional fusion welding process because of its low heat input and absence of melting and solidification process, enabling welding of materials that are extremely difficult to weld by conventional fusion welding processes, such as 2xxx and 7xxx series aluminum alloys. The benefits therefore include low distortion and residual stresses, no loss of alloying elements, no arc, no fume and no filler wire. Thus FSW becomes a very suitable process for joining high strength aluminum alloy such as 2024 [10−15].

Compared with the conventional fusion welding, different zones are formed during FSW due to friction heat and plastic deformation. Frictional heat causes metal softening and thus allows the tool move along the joint line. Under the driving of the welding tool (shoulder and pin), structure of weld, due to severe mechanical stresses experienced by material, shows three distinct microstructural zones on the transverse cross section of the FSW joint, i.e., nugget zone (NZ), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). The NZ is a region through which tool pin passes and thus experiences both high deformation and heat treatment. It generally consists of very fine equiaxed

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grains, due to full recrystallization, and characterized by the presence of so-called onion rings. Adjacent to the nugget zone is a TMAZ. This region experienced a severe thermo-mechanical alteration, though it has been not directly subjected to pin or shoulder action due to internal shear stresses. In TMAZ metal is plastically deformed as well as heated, but this is not sufficient to cause recrystallization. Beyond TMAZ there is part of material that experiences only a heating effect, with no mechanical deformation. This zone is referred as HAZ. The thin zone subjected directly to the action of tool shoulder is referred as flow arm [16−21]. Semicircular rings on the top of weld surface are referred as banded microstructure. Distance between semicircular rings depends on tool advance per revolution. Spacing between bands will increase as this ratio (welding speed/ rotation speed) grows, resulting in a less homogenous structure within the weld [22−25]. Several parameters, such as rotation rate (R), welding speed (v), axial force, tool and pin geometry, tool tilt angle and its penetration into the blanks (plunge depth) affect FSW process. Among these parameters, rotation rate and welding speed strongly influence the thermal cycle and are the two most important welding parameters [26−46].

The aim of this work is to establish the influence of R/v ratio on joint quality and elucidate defects formation mechanisms in 2024-T351 aluminum alloy.

2 Experimental

The rolled plates of 8.0 mm thickness, made of commercial aluminum alloy Alclad 2024-T351, were used in this work as the base metal. The plates were machined on both sides to remove the Alclads and get the final thickness of 6.0 mm. The chemical composition and mechanical properties of the machined plate are listed in Tables 1 and 2. The dimensions of single welded plates were 260 mm×65 mm×6 mm. The sides of plates were machined and had stiff contact with supporting plate, and were butt-welded along the rolling direction using adopted conventional milling machine. The welding length was around 210 mm on each pair of plates. The used FSW tool was made of 56 NiCrMoV7 tool steel, with spiral thread on the 5.5 mm length and concave profiled head on the 25 mm diameter cylindrical shoulder. The tool details are listed in Table 3. The tool was heat treated to HRC51. The tool tilt angle was 1.0° and was kept constant. An equal axial (welding) force was obtained by controlling the plunge depth of welding tool, since all the specimens had the same thickness. The plunge depth of tool shoulder was 0.2 mm. All welded joints were in “hot” condition, according to R/v ratio criterion suggested by VILAÇA at al [5,47]. The welding parameters used in this study are summarized in Table 4, where ratio R^2/v represents the pseudo heat index suggested by ARBEGAST and HARTLEY [48].

Table 1 Chemical composition of base metal (mass fraction, %)

Cu	Mg	Mn	Fe	Zn
4.70	1.56	0.65	0.17	0.11
Si	**Ti**	**Zr**	**Ni**	**Cr**
0.046	0.032	0.011	0.006	0.004

Table 2 Mechanical properties of base metal

YS/MPa	UTS/MPa	A_5/%	Hardness (HV)
370	481	18	145

Table 3 Geometry of used FSW tool

Pin description	Pin diameter/mm		Pin angle/(°)	Thread slope/(°)	Pitch of pin/mm
	Root	Head			
Taper screw thread pin	10	4	20	5	1.5

Table 4 Welding parameters

Sample	Rotation rate, R/(r·min^{-1})	Welding speed, v/(mm·min^{-1})	R/v	R^2/v
A	750	73	10.27	7700
B		93	8.06	6050
C		116	6.46	4850
D		150	5.00	3750
E	950	93	10.21	9700
F		190	5.00	4750
G	1180	116	10.17	12000
H		150	7.87	9280

In order to reveal the presence of surface and/or volume defects, the welded joints were first subjected to visual, penetrant, X-ray and ultrasonic examination. Further examination was performed only on the welded joints that had no defects. Complete testing procedure is given in Table 5. All the welded samples were naturally aged at room temperature for more than 20 d and the specimens were cross-sectioned perpendicular to the welding direction (Fig. 1).

Metallographic observation was carried out by optical microscopy (OM). The specimens for OM were ground, polished and etched using Tucker’s and Barker’s reagent for macro and microstructure, respectively. Electro polishing and etching technique was used on the specimen for microstructure examination. Much care was