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Incipient Melting and Corrosion Properties of Friction Stir Welded AA2024-T3 Joints

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The effect of welding speed on strength and corrosion behavior of FSW 2024-T3 joints was investigated in the present study. For both strength and corrosion, the transition from the thermo-mechanically affected to the heat affected zone (TMAZ/HAZ) turned out to be the most critical site. Higher welding speeds produced both a smaller hardness drop in the TMAZ/HAZ and a smaller width of the softened zone. Thereby, tensile strength could be improved and the intergranular corrosion attack localized to the overaged TMAZ/HAZ could be reduced. Paradoxically, at lower heat input (i.e. at higher welding speed), the weld nugget region also suffered enhanced intergranular corrosion. SEM examinations of the top surface of FSW 2024-T3 joints revealed the presence of constitutionally melted Al_2MgCu (S-phase) particles in that region. The S-phases were mainly localized to the advancing side of the joint, and their volume fraction increased with growing welding speed. Hence it is suggested that a focalization of the thermal source resulted in incipient melting. Eutectic S-phases were formed and served as preferential corrosion sites lowering corrosion resistance of the weld nugget.

Keywords: *Friction Stir Welding, Incipient melting, Corrosion*

1. Introduction

Friction Stir Welding (FSW) [1], is a solid state welding technique which allows for producing high quality welds without solidification cracking, porosity, from aluminum alloys not recommended for fusion welding [2] . Although the overall temperatures occurring during the Friction Stir Welding process are well below the melting point, they are still high enough to generate microstructural changes even outside the stirred zone which decreases the mechanical performance of the joint [3]. With respect to corrosion, the microstructural variations represent galvanic couples producing corrosion damage when FSW joints are exposed to corrosive environments. The microstructure and, consequently, the corrosion behavior of FSW joints are strongly dependent on welding parameters. Lower heat input (i.e. lower rotational and/or higher travel speed of the weld tool) can reduce the susceptibility to corrosion, but concurrent change in strength may also take place. Usually, lower heat inputs are preferred in order to obtain the best compromise between mechanical and corrosion performance of the joints. The objective of this study is to investigate the effect of welding speed on strength and corrosion behavior of FSW 2024-T3 joints.

2. Experimental

The material used was 4 mm thick unclad sheet of the alloys 2024-T3. Butt joints were produced using the DLR FSW equipment operated under position control mode following the TWI patent [1]. The welding parameters are and peak temperature at a distance of 15 mm from the weld center at retreating side (RS) are listed in table 1.Welding direction was always parallel to the rolling direction of the parent sheet. Vickers hardness measurements were made on the cross section of the welds along the half thickness line with a load of 9.81 N. The corrosion potential across the weld region was measured using rod-like specimens with a cross-section of 4×4 mm taken at different distances of the weld center. The through thickness plane normal to the weld direction was immerse 24 hr into an aqueous solution of 1 M NaCl with addition of hydrogen peroxide according to the ASTM G110 standard.

Table 1 Welding parameters and welding peak temperature of the parent plate recorded at retreating

Specimen	Rotational Speed [RPM]	Welding Speed [mm/min]	Temperature at RS [°C]
Slow	850	100	-
Mid speed	850	200	202
Standard	850	300	160
Fast	850	400	154

Results and Discussion

The increment of welding speed produced several changes in the hardness profiles of the FSW 2024-T3 weld joints (*Fig. 1*). At center of the welded joints, an increase in hardness was induced. The hardness values of the coldest FSW 2024-T3 weld nugget was higher than that of the base metal. From literature, it is well known that the thermo mechanical process applied during friction stir welding produce dissolution of the strengthening phases followed by a natural aging process [3,4]. Therefore, hardness values close to the natural aged 2024-T3 aluminum alloy were expected. However, the values of the slowest FSW-joint were just below compared to those of the base metal, while those of the Fast-joint attained values close to those of a AA 2024-T851 (146 HV). According to the temperatures registered at the surface of the welding shoulder and the hardness values of the weld nugget, the microstructure of the FSW joints might present some degree of precipitation. An increase of hardness of the overaged TMAZ/HAZ also took place. Hardness values of 110 to 130 HV1 were measured for the hottest and coldest FSW-joints respectively. The position of these low hardness regions moved closer to the center line of the weld nugget as welding speed increased as a result of lower peak temperatures and faster thermal transients.

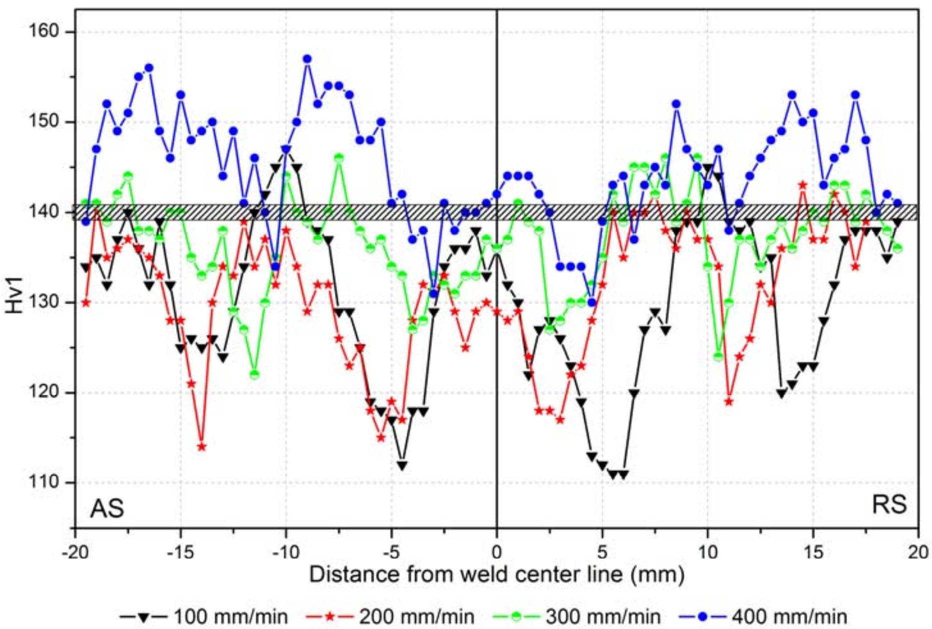

Fig. 1 *Hardness profiles of FSW 2024-T3 joints produced using different welding speeds*

Fig. 2 shows the corrosion potential measured according to ASTM G69 across the friction welded 2024-T3 joints produced with the lowest and fastest welding speed. Values of the 2024-T3 and 2024-T8 base alloys are also indicated. In both FSW-joints, the weld nugget region exhibited the more active potentials. The open circuit potential increased through the thermo-mechanically affected and heat affected zones. In the case of the coldest joint the potential at HAZ was quite similar to the value of the base alloy 2024-T3 (-0.608 V_{sce}), while the potentials of the HAZ of hottest weld were still more active than the base metal. The highly active corrosion potentials of the weld nuggets of both "slowest" and "fastest" FSW 2024-T3 joints might be attributed to precipitation of Cu containing phases (i.e. S'(S) phases) in these regions. The quantity of such Cu containing particles is affected by the welding thermal cycle. At higher heat inputs (i.e. slower welding speeds) more material is exposed to the precipitation temperatures allowing for higher degree of overaging. Conversely, at higher welding speeds more localized thermal cycles are produced, and therefore, less material is affected.

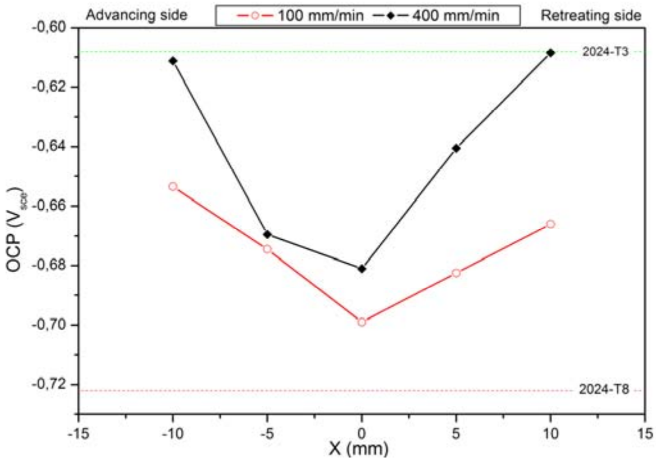

Fig. 2 *Corrosion potential profiles across friction stir welds of alloy 2024-T3 produced with different travel speeds*

Fig. 3 shows the transversal sections of the specimens of FSW 2024-T3 joints welded with different welding speeds after 24hr immersion in an aqueous chloride-peroxide solution according to ASTM G110. The vertical line indicates the center of the weld nugget. The location of the maximum corrosion attack was found at both sides of the fine grain zone nugget in the TMAZ/HAZ. Closer examination of these zones indicates a high susceptibility to intergranular corrosion. A direct relation between the welding speed (heat input) and maximum depth of corrosion of the TMAZ/HAZ was not observed. All FSW 2024-T3 joints displayed depths of corrosion between 230 to 290 µm. Nevertheless, the width of the corroded zones and its distance from the weld center decreased as the travel speed increased. The decrement of width of the corroded zones at TMAZ varied in the same mode as the peak temperature at shoulder did.

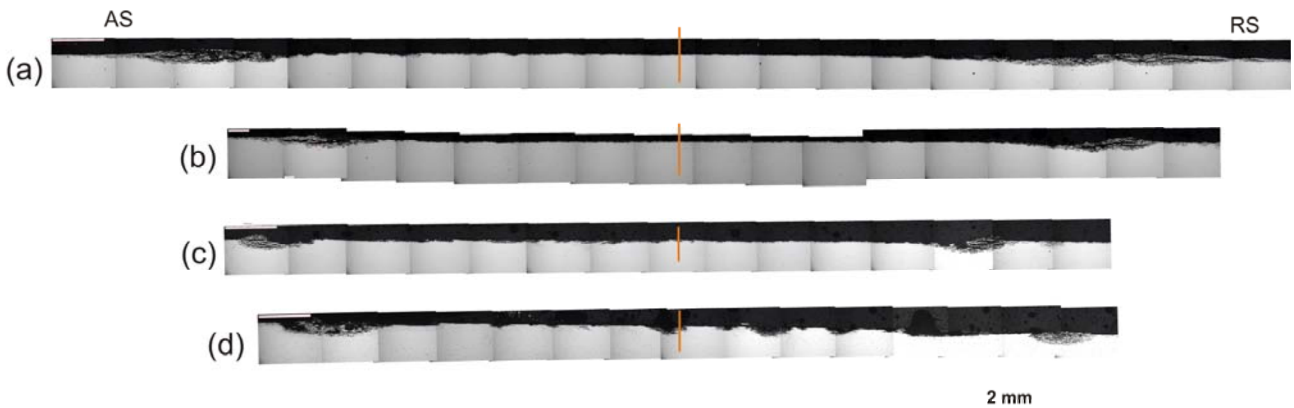

Fig. 3 *Cross transversal sections of FSW 2024-T3 after 24hr immersion in chloride-peroxide solution (a) 100 mm/min, (b) 200 mm/min, (c) 300 mm/min, (d) 400 mm/min*

Conversely, the weld nugget region became more susceptible to corrosion at higher welding speeds than at lower travel speed being basically immune to intergranular corrosion (*Fig 4*). This corrosion behavior is in disagreement with the thermal conditions measured at welding shoulder. It has been expected that with lower thermal regimens (i.e. faster welding speeds) better corrosion resistance would have been produced. The depth of the corrosion attack in this zone reached similar values to those of the overage TMAZ/HAZ, about 200 µm.

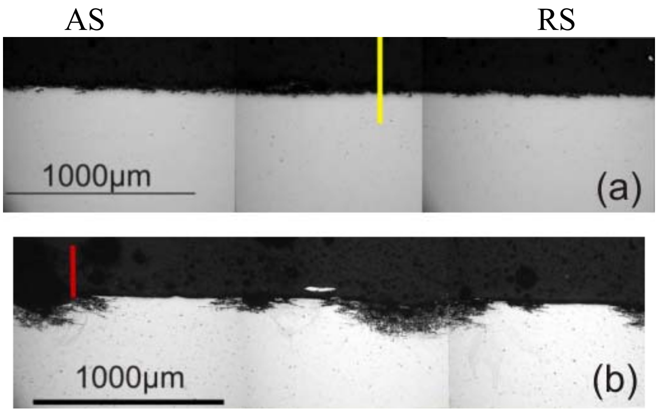

***Fig.4** Effect of welding speed on corrosion behavior of FSW 2024-T3 weld nugget region at the face side (a) 100 mm/min, (b) 400 mm/min*

More detailed inspection of the weld nugget region of the Fast weld (400 mm/min) revealed the presence of intergranular precipitates near to the top surface, being in more quantity in the flow arm on the advancing side of the weld. (*Fig. 5*) In some cases, these intergranular particles formed continuous lines, which were oriented parallel to the surface of the joint. The particles were rather equiaxed and exhibited a lamellar microstructure characteristic of an eutectic phase (see *Fig. 5d*). The size of these intergranular eutectic phases was 2-3 µm. The particles contain Al, Cu and Mg, as revealed by EDX analyses, suggesting to be S-phase (see Table 2).

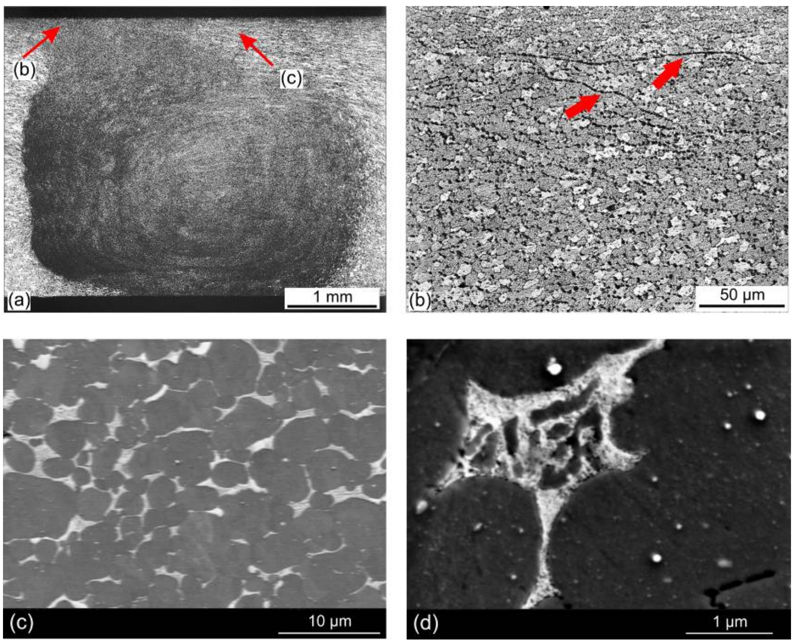

***Fig. 5** Intergranular precipitates found in the flow arm region near to the top surface of the FSW 2024 T3 revealed after etching with Keller's reagent. Arrows in (b-Advancing side) and (c-retreating side) indicate the location of the micrographs.*

The occurrence of these intergranular particles in the Fast-joint can be attributed to an incipient melting of the existing constitutional S phases during the welding process. The peak temperature measured at the weld center of FSW 2024-T3 joint was 507 °C before the pin arrived. This temperature is quite close to the eutectic temperature of the 2024 aluminum alloy [5]. It can be, therefore, expected that higher temperatures are reached at the interface between the shoulder and plasticized material due to the heating produced by plastic deformation [6]. These severe thermo mechanical conditions might cause fragmentation and melting of the constitutional S-phase particles, producing a partially liquid film. This film was subsequently redistributed by stirring of the welding tool. The higher temperatures generated by the larger deformation gradients under the shoulder close to the pin on the advancing side [6,7] might promote a more complete liquation of the S- phase constituents decorating the grain boundaries. On the other hand, the lower temperatures reached on the retreating side, as suggest by the partially recrystallized material at the top surface of the joint in this area, might have only caused the liquation of these Al_2CuMg constituents, which are situated much closer to the surface.

Once that the welded joint are exposed to a corrosive medium, the eutectic phases found in material flow arm at the top surface of the material flow arm act as corrosion damage site. As shown in *Fig. 6*, the SEM examination of the corroded surface revealed preferential dissolution of the matrix surrounding the liquated S phases. The regions contiguous to these constituent S phase particles corroded in form of pitting attack. The Al matrix around the S phase particles dissolved substantially leaving smaller particles spread over the corroded matrix (Figure 6b).EDX analyses of the original eutectic S-phase remnant (Figure 6) left behind after corrosive attack are summarized in Table 2. The change in chemical composition indicates that the eutectic Al_2CuMg particle experienced a severe de-alloying of Al and Mg during immersion. As a result, a nobler remnant (enriched in Cu) was left behind. The presence of oxygen may indicate the formation of a (hydr-) oxide layer on the surface of the S- phase remnant after corrosion.

Table 2 Chemical composition of the eutectic S-phase remnant after 4 h immersion in a 3.5% NaCl aqueous solution (concentration in wt %)

Condition	***Al***	***Cu***	***Mg***	***O***
Prior to corrosion	46	44.8	9.2	------
corroded	11.87	76.5	0.81	11

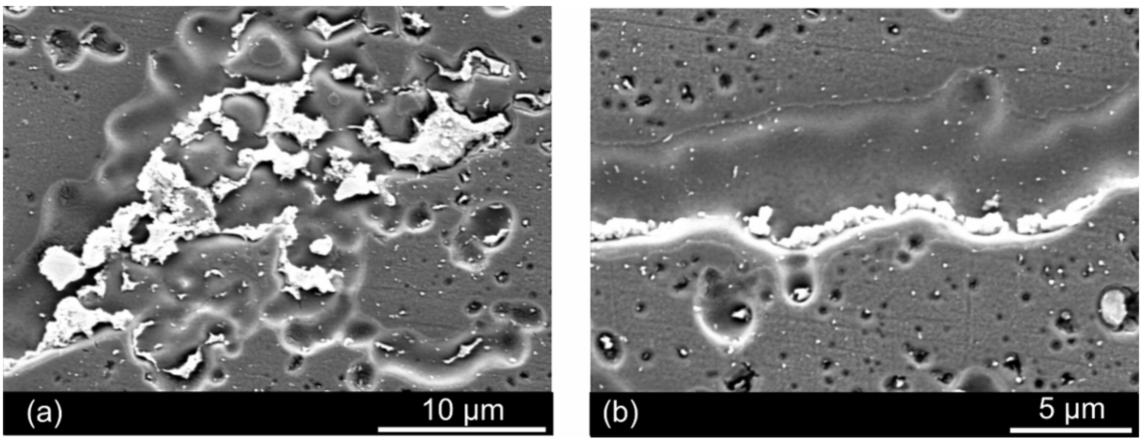

Fig.6 SEM micrographs of Al–Cu–Mg-containing eutectic phase particles in FSW 2024-T3 joint after 4h exposure to an aqueous 3.5 wt -% NaCl aqueous solution

The above observations indicate that the corrosion attack at the top surface of the FSW joint can be associated with galvanic coupling between the constitutionally melted S-phase particles and the aluminum matrix. The mechanism of localized corrosion may be comparable to that occurring between coarse constituent S-phase particles and the surrounding matrix in AA 2024-T3 base material [8-10]. In presence of chloride containing corrosive media, the S-phase precipitates are initially anodic to the aluminum matrix. Due to an unfavorable cathode-to-anode surface ratio, galvanic corrosion concentrates on the small anode, producing an accelerated attack of the particle. Preferential dealloying of Mg might occur. As dealloying continues, the intergranular S-phase precipitate remnants become richer in Cu turning into cathodes towards the adjacent Al matrix. Consequently, the opposed galvanic couple of "now" anodic aluminum matrix and cathodic Cu-rich S-phase remnant is activated, causing the preferential dissolution of the surrounding Al matrix.

Conclusions

- Better mechanical properties were attained in both heat affected zone and weld nugget. At the TMAZ/HAZ, the width of the low hardness zone as well as the hardness drop (hardness minimum) was reduced, corresponding with thermal history experienced by these zones. An increment in hardness was also observed in the weld nuggets of the FSW-joints. Post weld heat treatments indirectly revealed some degree of precipitation.

- FSW 2024-T3 displayed high susceptibility to intergranular corrosion of the TMAZ/HAZ and weld nugget after corrosion tests. The location of the attack was controlled by galvanic coupling between the different regions of the weld and was affected by the processing parameters. The TMAZ/HAZ corrosion susceptibility was reduced with increment of weld speed, corresponding to the thermal cycle experienced by these zones.

- The weld nugget region of the FSW-joints presented an unexpected increase of corrosion attack. The enhanced susceptibility to intergranular corrosion in the FSW joints was found to be caused by the incipient melting of copper-rich constitutional particles; most probably S-phase (Al_2CuMg).

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