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Environmental cracking and impact investigations after short – term temperature treatments: 7050-T7451 friction stir weld

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Abstract

The influence of short-term heat treatments on the environmental cracking and impact properties of a 7050-T7451 friction stir weld were investigated. Prisms, cut transverse to the welding direction, were exposed for minutes at temperatures between 100 ^oC and 800 ^oC in an oven or exposed to a propane torch flame and/or water / air quenched. A significant increase in the environmental cracking resistance (ductility ratio from 0.2 to 0.9) was observed for samples exposed to temperatures below the solutionizing limit, but between 240 ^oC and 280 ^oC. The fracture location changed from the "soft" heat affected zones to the nugget. Furthermore, the weld exhibited a decrease in the Charpy impact adsorbed energy as compared to the weld unaffected parent metal. An increase in the temperature improved the adsorbed energy, while a temperature decrease promoted the brittleness and reduced the adsorbed energy. The flow contours, also called onion ring bands, present within the nugget, represented a preferential fracture path during impact. The high temperature treatments followed by water quenching did not significantly improved the resistance to impact.

INTRODUCTION

The temperature developed during the friction stir welding (FSW) of high strength 7-xxx series aluminum alloys promotes a coarsening of precipitates and a widening of the precipitate-free zones, in particular within the heat affected zones of the weld [1, 2]. These latter weld zones appear to be the most corrosion susceptible regions [3, 4]. Recently, the effect of natural, artificial and RRA aging on the properties and structure of 7-xxx series aluminum alloys [5, 6], and on the mechanical and corrosion properties of 7249 and 7075 aluminum alloys [7, 8] as well as the effect of temperature and exposure on precipitates morphology, strength and plasticity [9] were investigated. In this concern, conventional post-weld heat treatments have been used to partially restore the properties of the welds. These treatments often reached solutionizing temperatures and the samples were subsequently subjected to re-aging processes [10, 11, 12]. A non-conventional post-weld heat treatment was also applied to AA 7075-T651 [13], obtaining an increase in the corrosion properties. This was mainly due to the local dissolution of precipitates, in particular along the grain boundaries. Nevertheless, short-term heat treatments that might modify the properties of the welds are currently on an initial investigation stage.

Like the corrosion, the resistance to impact is an important property of engineering components subjected to dynamic loading. The temperature also control the fracture behaviour. The fracture proceeds, for ferritic alloys, through microvoid coalescence (ductile behaviour), adsorbing energy, or through cleavage, for brittle behaviours. In this latter case, the energy adsorbed decreases with a reduced toughness of the material [14]. The influence of notch severity and temperature on the impact were also tested for AA 7055. The fracture toughness of 45^o notched samples for AA 7055-T7751 increases when the test temperature increases [15]. Nevertheless, a lack of information exists on the influence of the temperature and of short-term heat treatments on the environmental cracking and impact of high strength aluminum alloys friction stir welds.

EXPERIMENTAL PROCEDURES

Material and welding

Aluminum alloy 7050 -T7451 plates with 10 mm thickness were friction stir welded at a travel speed of 140 mm/min and a rotation speed of 240 rpm. The welding direction was parallel to the rolling direction of the aluminum alloy.

Short-term heat treatments

To study the influence on the environmental cracking, short-term heat treatments were applied to welded prisms (120 x 10 x 10 mm) cut transverse to the welding direction. A propane torch flame was applied at a distance of 30 mm for 1, 2, 4, 7 minutes. Prisms were also placed in an oven for 1 minute at 600 ^oC and 800 ^oC. The temperature of the samples was measured with a thermocouple (Table 1). Prisms were water or air quenched at room temperature. To verify the influence of the temperature on the impact, welded cross section prisms (8 x 8 x 60 mm) were exposed to the torch flame at a distance of 30 mm for 4 minutes (sample T 330 ^oC). Other treatments consisted of placing the samples in an oven for 1 minute at 800 ^oC (sample T 230 ^oC), for 15 minutes at 480 ^oC and for 1 hour at 120 ^oC (Table 1). The prisms were tested at the peak temperature. As a comparison, prisms were also immersed for 1.5 minutes in liquid nitrogen (T = -190 ^oC) and tested. To determine the influence of short-term heat treatments on the impact, samples were exposed to the torch treatment for 1 and 2 minutes (sample T 204 ^oC and 285 ^oC), for 1 minute at 600 ^oC (sample T 200 ^oC) and 800 ^oC (sample T 230 ^oC) (Table 1). At the peak temperature, the samples were water quenched and tested.

Heat exposition type and time		**Sample Temperature [^oC]** Prisms (120 x 10 x 10 mm)	**Sample Temperature [^oC]** Prisms (8 x 8 x 60 mm)
Torch	1 minute	190 ^oC	204 ^oC
	2 minutes	240 ^oC	285 ^oC
	4 minutes	280 ^oC	330 ^oC
	7 minutes	380 ^oC	
Oven	1 minute (600 ^oC)	200 ^oC	200 ^oC
	1 minute (800 ^oC)	225 ^oC	230 ^oC

Table 1. Heat exposition type and time vs. sample temperature.

Mechanical tests, microstructure and fractography

The constant extension rate tests were carried out using M-CERT™ load frame [16] on tensile specimens oriented transverse to the weld in air and in aerated 3.5 wt % NaCl solution. Tests were conducted at an extension rate of 2.5 x 10^{-5} mm/s. The strain was measured as a $\Delta L / L_o$ ratio, (ΔL: effective elongation, L_o: initial gage length). The strain ratio was the ratio $\varepsilon_{environment} / \varepsilon_{air}$. The samples were tested 3 weeks after the heat treatments. The Charpy tests were carried out with a conventional machine according to the ASTM A 370 standard [14] on 3 weld cross section prisms pro condition (8 x 8 x 60 mm). The notch was located in the upper part of the weld and in the center of the weld nugget. The microstructure and fractography were observed with an XL 30 FEG field emission SEM at 10-15 kV and with a FEI Tecnai F20 TEM at 200 kV equipped with a HAADF STEM detector. TEM 3 mm foils were prepared and thinned by electropolishing at 15V, -20 ^oC, in a 25% nitric acid /75 % methanol solution.

RESULTS AND DISCUSSION

The stress-strain development after the heat treatments

The weld exhibits an ultimate tensile strength (UTS) of ca. 440 MPa, while the weld unaffected parent metal ca. 520 MPa. A reduced strain is observed for the weld (ca. 3 %), as compared to the parent metal (ca. 5.4 %). The short-term heat treatments do not significantly increase the UTS. The parent metal exhibits microvoids along the grain boundaries (Fig. 1). The weld fails within the heat affected zones and exhibits grain facets and dimples along the grain boundaries. The samples exposed to the short-term heat treatments, exhibit microvoids and tounge-like features. A significant change in the fracture, located within the nugget, is seen for the samples exposed 2 minutes to the torch treatment (T = 240 ^{o}C). Cracks, present along the nugget grains, indicate an intergranular fracture, while the dimples on the nugget grains indicate a duptile rupture (Fig. 1).

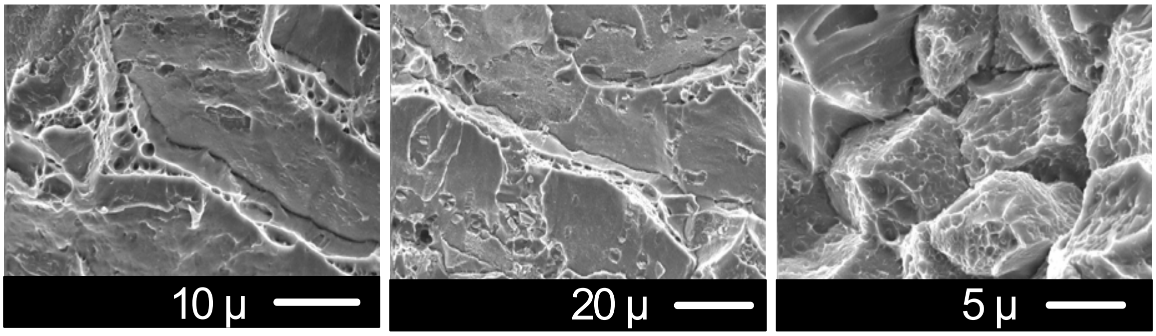

Fig. 1 Fracture surface of the parent metal, the weld and the samples exposed to the torch treatment for 2 minutes and water quenched.

Heat treatment and environmental susceptibility

A significant increase in the environmental cracking resistance is observed for the torched samples ((4 min.) - T sample 280 ^{o}C) (Table 1). The ductility ratio (DR) of the weld not affected by heat treatments is 0.2, while for the 4 minute torched samples, the DR becomes 0.9, similar to the parent metal (0.9) (Fig. 2). The decrease in the environmental susceptibility, observed after the treatments at ca. 300 ^{o}C and natural aging, appears to be caused by the dissolution of precipitates [12, 13]. In this case, no solutionizing temperatures or artificial aging appeared necessary [5, 10, 11, 12].

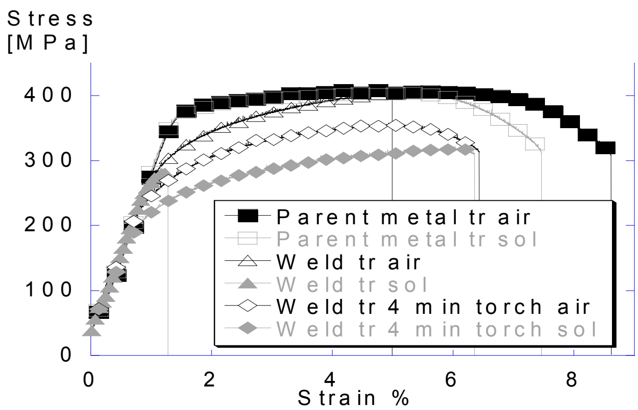

Fig. 2 CER tests for the parent metal, the weld and the weld after exposure to a torch flame for 4 minutes and water quench. Tests in air and in a 3.5 wt. % NaCl solution.

Impact behaviour

The fracture propagates for all samples along the 2-3 μ equiaxed nugget grains. A relatively high presence of 10 nm intragranular precipitates is observed and locally the grain boundaries exhibit a slight sensitization (Fig. 3).

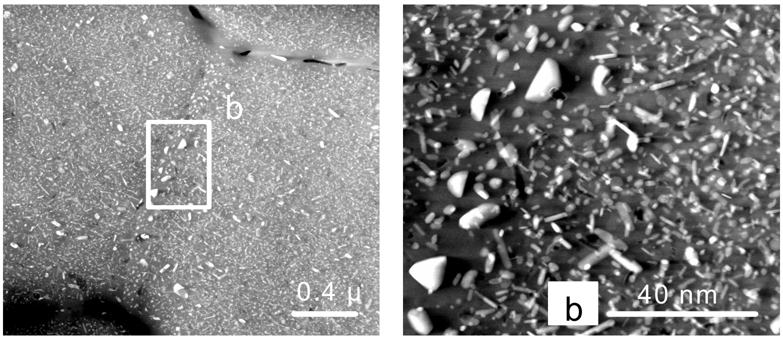

Fig. 3 Nugget microstructure of the 7050-T7451 friction stir weld.

The weld exhibits lower Charpy adsorbed energy as compared to the parent metal (Fig. 4). The elongated grains of the parent metal are oriented transverse to the crack propagation direction and may act as crack barrier. On the contrary, the cracks may easily find a path through the equiaxed grains of the nugget. The samples exposed to high-low temperatures exhibit energies from 25 J to 2.5 J (Fig. 4). A temperature increase from 120 ^{o}C to 800 ^{o}C promotes higher adsorbed energies during the impact, increasing the fracture toughness [15].

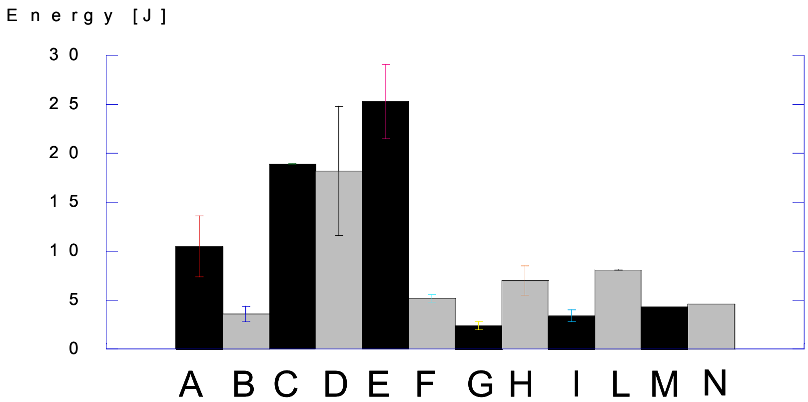

Fig. 4 Charpy impact energy of the samples with the standard deviation bars. **A**: parent metal, **B**: weld transverse (wt), **C**: wt – 1 min / 800 ^{o}C, **D**: wt - 4 minutes torched, **E**: wt - 15 min / 480 ^{o}C, **F**: wt - 1h / 120 ^{o}C, **G**: wt - liquid nitrogen, **H**: parent metal liquid nitrogen , **I**: wt - 1min / 600 ^{o}C / H_2O Quench, **L**: wt - 1min / 800 ^{o}C / H_2O Quench, **M**: wt - 1 minute torched / H_2O Quench, **N**: wt - 2 minutes torched / H_2O Quench.

The fracture abruptly changes the orientation at the bottom of the nugget and propagates almost vertical towards the notch, for the weld samples tested at room temperature, in liquid nitrogen, and exposed to the short-term heat treatments and water quenched. For the samples exposed to high temperatures, the fracture path is irregular and diffuse. The parent metal exposed to the liquid nitrogen, similarly to the samples exposed for 1 minute at 800 ^{o}C and water quenched, exhibits a through-thickness vertical fracture path (Fig. 5).

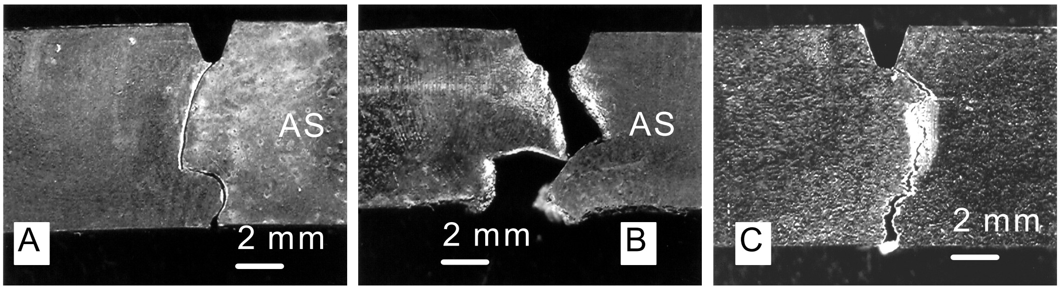

Fig. 5 Fracture paths through the weld cross section (A), (B) weld exposed for 1 minute at 800 °C, (C) parent metal exposed to liquid nitrogen. AS: advancing side of the weld.

The broken surfaces of the weld indicate the presence of the nugget flow contours, which describe the plastic deformation increments caused by the advancing movement of the rotating pin [17]. The flow contours of the nugget represent preferential shear fracture paths and are particularly present for samples tested at high temperatures (Fig. 6 A, B).

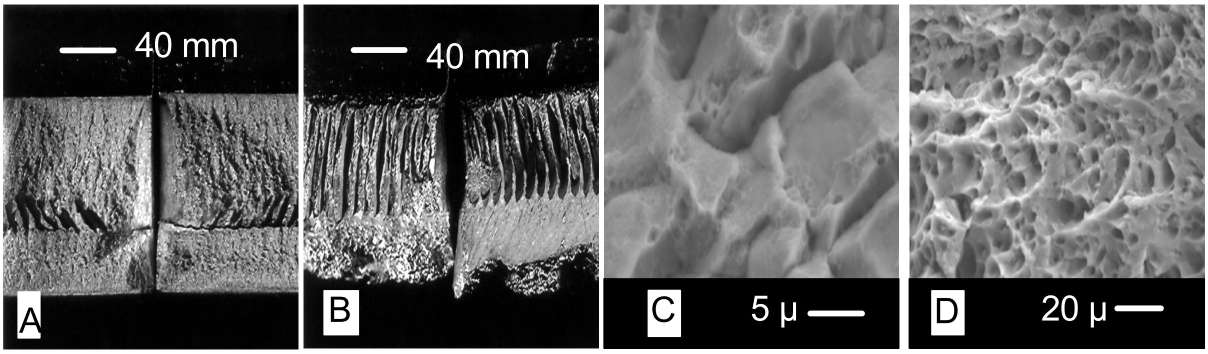

Fig. 6 Fracture surface of the weld (A, C) and the weld tested after the 4 minutes torch treatment (B, D). Dimples on the nugget grains (C) and macro-dimple enrichments (D).

The flow contours of the weld may control the fracture propagation in the central-bottom part of the weld cross section, where these macroscopic features are particularly marked. Cracks and dimples are present on the nugget grain boundaries (Fig. 6 C). The samples exposed at high temperature (4 minutes torch treatment), exhibit diffuse shear planes along the flow contours and deformed dimples with shear like-features (Fig. 6 D).

The short-term heat exposure, in particular the torch heat treatment, may significantly improve the corrosion properties of the weld. On the other hand, the impact tests cannot discriminate the homogenization and re-dissolution of precipitates, as it is for the tensile and corrosion tests, where even minute changes in the microstructure may affect the properties [13]. Nevertheless, a slightly higher adsorbed energy is observed at high temperature (+ water quenching) as compared to the weld tested at room temperature.

CONCLUSIONS

The FSW 7050-T7451 exposed to short-term heat treatments below solutionizing temperatures, but above 240 °C, exhibits a significant increase in the environmental cracking resistance. The weld exhibits lower adsorbed energies as compared to the parent metal. High temperatures increase the adsorbed energy, but heat treatments do not significantly improve the impact resistance. The macroscopic features (nugget flow contours), may represent preferential fracture paths when the weld is subjected to impact.

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