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Ductilization of aluminium alloy 6056 by friction stir processing

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The ductility of Al alloys is dictated by the nucleation, growth and coalescence of small internal voids originating from intermetallic particle fracture and from the presence of pre-existing porosity. The ductility is degraded when intermetallic particles are large and clustered. A low ductility adversely impacts both forming operations and the integrity of structural components. Local stirring using a friction stir processing (FSP) tool is shown here to very significantly increase the fracture strain of the Al alloy 6056 sometimes by more than a factor of two while making it more isotropic. Three reasons for the ductilization are unravelled based on 3D microtomography: (i) FSP breaks the large intermetallic particles into smaller, and thus stronger, fragments, (ii) FSP closes the pre-existing porosity; (iii) FSP randomizes the particle distribution. Hence, FSP positively impacts three of the main causes of ductility loss in metallic alloys. From an applicability viewpoint, this method has the potential to locally improve ductility of sheets at locations where forming involves large strains or of structural components at stress concentration points.

1. Introduction

Ductile fracture is characterized by the nucleation of microvoids, followed by stable growth until coalescence of neighboring voids [1–6]. The accumulation of void linkage leads to the formation of a macroscopic crack that finally propagates until final failure. Micron-sized iron-rich intermetallic particles constitute the main source of damage in Al alloys. These particles fracture or undergo interface decohesion [4–8]. Additionally, voids may be already present from processing or from hydrogen or can also nucleate, usually at large strains, on smaller size dispersoïds [4]. Factors like particle clustering, particle morphology and size have a first order impact on the fracture strain [6,9]. It remains an important scientific and technological challenge to improve the ductility of Al alloys especially in high strength condition resulting from peak aging heat treatments.

Friction stir welding (FSW) is a solid-state welding process developed to bypass limitations associated with local melting and solidification involved in most conventional welding processes. It is particularly suitable for high strength Al alloys [10,11]. Friction stir processing (FSP) is a process derived from FSW [12–39], involving a non-consumable tool with complex features to locally modify the microstructure through solid state mixing. The rotating tool penetrates the material until the shoulder gets into contact with the upper surface and is then displaced along the surface at a controlled velocity and rotation speed (see Fig. 1a). The heat generated by friction and deformation leads to a malleable state that promotes material flow from the front to the back of the tool and around the pin. The strain level during FSP is in the 5 to 10 range and the strain rate level is on the order of 10–400 s^{-1} [19]. FSP leads to a decrease of the grain size by dynamic recrystallization [20]. Kumar et al. [21] have shown a grain size reduction by a factor close to 40 in an Al-Mg-Sc alloy. These fine grains tend to be unstable during subsequent solution heat treatment, typically above 450 °C in Al7010 [22]. Abnormal grain growth is likely to occur at high temperature in grains free of dislocations or free of pinning phases [22,23]. Grains as large as a few millimeters have been reported in FSPed 7xxx series [22,23] and cast Al alloys [24].

FSP has already been applied to cast Al alloy for the sake of improving properties. Cast Al alloys present large amount of porosities due to gas involved in the molten state, or due to solidification shrinkage defects. FSP has been shown to decrease the microporosity [12,25–32] owing to the large pressure applied by the tool at high temperatures, e.g. 0.1%–0.02% in A356 [26]. Such

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porosity reduction significantly improves the ductility [26,31,33]. The cast microstructure is also homogenized and refined by FSP due to the redistribution, erosion and breakage of large particles [26,28,34] improving the strength and ductility [31,35], e.g. a total elongation improvement from 1.1% to 20% in Al-7Si-0.5 Mg [31]. The fatigue performances of FSPed cast materials are also impressively improved [12,36–38], e.g. 80% increase of fatigue stress level in a cast A356 alloy [12].

The application of FSP to improve wrought Al alloy has not yet been widely studied. In wrought alloy the amount of initial porosity is much smaller than in cast alloys, but the potential for improvement could come from the impact on the intermetallic particles. Cavaliere [39] has shown a promising increase in fatigue resistance for a 2014 Al alloy. Nevertheless, to the best of the authors knowledge, no detailed analysis is available yet in the literature about the impact of FSP on damage resistance of wrought Al alloys. In a previous study [6], we characterized and modelled the ductile failure process of three 6xxx series Al alloys (6005A, 6061 and 6056). The key element controlling the magnitude of the fracture strain in these alloys was the effect of particle size distribution and spatial distribution on the void nucleation and coalescence process. The presence of pre-existing voids has also been shown to have a first order effect on the fracture strain.

The goal of the present study is to investigate, based on microtomography and detailed image analysis, the potential of friction stir processing (FSP) to improve the ductility of Al 6056 plates through the fracture of the large second phase particles into smaller and more resistant fragments, the closing of the existing initial porosity and the homogenization of the particle spatial distribution.

2. Materials and experimental methods

2.1. Materials and FSP

Cold rolled 6 mm thick plates of Al 6056 were used in T4 initial condition. Up to six overlapping FSP passes (see Fig. 1(a)), were performed with a tool rotation rate of 500 rpm and a traverse speed of 200 mm/min along the rolling direction (RD) (except for the case of six passes performed also in the transverse direction (TD)). The tool was composed of a 20 mm diameter scrolled shoulder prolonged by a 5 mm long cylindrical M6 threaded Triflat pin, see Ref. [34]. After FSP, all samples were kept at room temperature for at least 1 month to allow natural ageing. The as-FSPed samples were then heat treated at 180 °C, and some of them at 350 °C as well. Heat treatments were systematically followed by water quenching.

2.2. SEM and X-ray microtomography

Cross-sectioning of the weld along a plane perpendicular to the FSP direction was performed for metallographic observations (Fig. 1). After standard polishing, the intermetallic particles were characterized based on images taken with a Field Emission Gun Scanning Electron Microscope (FEG-SEM) operated at 15 kV under electron backscattered mode and analyzed using the software ImageJ [40]. X-ray synchrotron microtomography were performed at the TOMCAT beamline of the Swiss Light Source [41]. The sample is probed by X-ray beam tuned to 20 keV using a double crystal multilayer monochromator. 2160 projections were recorded in absorption mode using 16 bit PCO.edge CMOS detector coupled with a 40X optical magnifying lens to a 5.9 μm thick LSO:Tb scintillator. The observed region is cuboid in shape, with dimensions 265 μm × 265 μm × 160 μm, and isotropic voxel size of $160 \times 160 \times 160$ nm^3. Intermetallic particles and cavities observed in the reconstructed volume were segmented by manual thresholding. Labelling and parameters measurement was then performed using a dedicated image processing plugin implemented in ImageJ [42].

The shape and the orientation of the particles are defined based on the best-fitting ellipsoid with its three semi-axes R_1, R_2, R_3 ($R_1 \geq R_2 \geq R_3$). The particle aspect ratio W_p is defined as $W_p = R_1/\sqrt{R_2 R_3}$ and the orientation of the particle is defined by the angle between the major semi-axes R_1 and TD (see Fig. 1(a)).

2.3. Uniaxial tensile tests

Uniaxial tensile tests were performed on a screw-driven universal machine under displacement control with 1 mm/min velocity. Cylindrical specimens, 4 mm in diameter, were machined along the FSP direction and along RD and TD for the base material (BM), see Fig. 1(a). The initial gauge length was equal to 30 mm. The initial yield stress σ_0 is extracted from the stress-strain curves. The true fracture strain defined as $\varepsilon_f = \ln(A_0/A_f)$ is determined from broken specimens, with A_0 and A_f being respectively the initial and final cross-section area.

A number of tensile tests on specimens extracted from the BM and from the six passes FSPed material were interrupted prior to necking and polished down to mid-thickness along the transverse section in order to analyze the fraction of damaged particles. If the particle is broken, its surface is reconstructed by manually merging all fragments together. Approximately 2000 particles have been analyzed for each interrupted test.

One interrupted tensile test of the BM loaded in RD and one of the FSPed material (6 passes) have also been characterized by microtomography. These tensile tests where both interrupted at a stress level of approximately 400 MPa. The samples have been extracted in the center of the specimens, see Fig. 2. A method for reconstruction of broken particles observed within the 3D images is proposed in order to quantitatively study the fragmentation of each particle, see Fig. 2. After segmentation of the particles, a second segmentation of the cracks appearing in the broken particles was performed. These cracks are then dilated and any particles which are connected though a crack, i.e. particles which share at least one voxel with one same crack, were merged into a single particle. However it has only been possible to apply the reconstruction algorithm on the sample extracted from BM. Indeed, it was not possible to perform such segmentation for the broken particles in the FSPed material due to the very small size of the particles and hence, of their cracks.

3. Results and discussion

3.1. Intermetallic particles

Fig. 3 shows 3D perspective of intermetallic particles as observed by microtomography[1] The volume fraction of particles F_p is always ~0.5%. Indeed, FSP breaks-up the intermetallic particles but does not dissolve them. The BM contains some very large particles and the particles are preferentially aligned with RD. After 1 FSP pass, some large particles still remain intact but their spatial distribution is modified. After 3 and 6 passes of FSP, the mean particle size is clearly reduced and the spatial distribution gets more homogeneous.

[1] The color code will be explained later and can be ignored at present time.