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Original Research Article

On the influence of repetitive corrugation and straightening on the microstructure and mechanical properties of AA 8090 Al-Li alloy

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ABSTRACT

This paper reports on the improvements in the mechanical properties of AA8090 Al-Li alloy subjected to repetitive corrugation and straightening (RCS). AA 8090 Al-Li alloy sheets were processed using different corrugation profiles (semi-circular, flat-groove and V-groove) at 300 °C, with a pressing velocity of 2.5 mm/s. This study shows that a V-grooved die favors grain refinement, e.g. a reduction in the average grain size from 65 μm to 12 μm after eight passes is achieved. Grain size distribution and misorientation between grain boundaries were studied using EBSD and TEM. The microstructures also appear to have more high-angle grain boundaries in the case of the specimen processed using the V-grooved die. The tensile strength increases with the number of passes, but drops when surface cracks appear after the 16th pass for a semi-circular die, the 12th pass for a flat grooved die and the 10th pass for a V-grooved die. In contrast, the hardness continues to increase with increasing number of passes. Ultra-fine-/nano-grains were present after the eighth pass in a sheet that was processed using a V-grooved die.

1. Introduction

Enhancement of mechanical properties of metallic materials for multi-functional applications is an area of serious research [1]. Processes such as solid-solution strengthening, precipitation strengthening and strain hardening are employed to improve material properties by thermal/mechanical treatments. Severe plastic deformation (SPD) is a well recognized technique of relatively recent origin for producing ultrafine-/nano-grain structures in metallic materials. The generation of a high density of dislocations during severe plastic deformation leads to the formation of short to long range plastic strain bands, which eventually get converted into new grains. However, following SPD there is no significant overall dimensional change in the specimen [2]. In recent years, techniques such as equal channel angular pressing (ECAP) [3], high pressure torsion (HPT) [4], accumulated roll bonding (ARB) [5], multi-axial forging (MAF) [6], twist extrusion (TE) [7], repetitive upsetting extrusion (RUE) [8], rotary-die

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ECAP [9], cyclic extrusion and compression (CEC) [10], cyclic closed-die forging (CCF) [11], repetitive corrugation and straightening (RCS) [12] and some other integrated processes [13] are being used to improve the mechanical properties by the principal mechanism of grain refinement. Of these, ARB and RCS are suitable methods for producing ultrafine grain-/nano-structures in sheet materials. But, ARB has a limitation that during processing a good bonding between the stacked sheets does not always develop [14].

Al-Li alloys are used in several aerospace structural applications with a view to reducing the weight without compromising on engineering requirements, e.g. for use in the skin of aircraft wings [15]. The addition of 1 wt.% of lithium in aluminum reduces the weight of the component by 3% and increases the specific strength by 6% [16]. However, the strength of these alloys at high temperatures reduces as the metastable δ′ phase Al_3Li and Al_2Li_3 dissolve at higher temperatures and facilitate recovery and grain growth [17], i.e. the stability of the material at high temperatures is a matter for concern.

Llorca-Isern et al. [18] have reported a significant improvement in the hardness of AA8092 Al-Li alloy at the end of four ECAP passes, i.e. from 660 MPa to 1378 MPa. Gao et al. [19] have reported that pre-stretching and aging of 2A97 Al-Li alloy plates increases their UTS from 447.7 MPa to 534.3 MPa. Despite the improvement in the ECAP process being high, this process cannot be scaled up beyond intermediate levels of production. In addition, specimens can be produced only in batches and there is also a limitation on the maximum possible dimensions. Therefore, an alternate, continuous process, namely, repetitive corrugation and straightening was studied here. This process is continuous and allows a scale up for large scale industrial production, if other factors are also made favorable by suitable improvements from the present levels. While it is expected that material properties would be improved significantly in this process also, as in the other SPD processes, research reports on this process are rather limited, especially those involving Al-Li alloys. Therefore, figures on the different relevant features are missing. In view of the above, this study reports on the effects on microstructure and mechanical properties of AA8090 Al-Li alloy of the repetitive corrugation and straightening process carried out with dies of different corrugation geometries at 300 °C. A somewhat similar study was presented earlier [20]. The differences between the two investigations of different focus were as follows: The material studied earlier was the Al-Mg (AA5083) alloy and the present study considers the Al-Li (AA8090) alloy, and the microstructure-correlations in these alloys are not identical. Therefore, the issues considered are similarity of observations between the two alloys and the differences. The overall aim is to broad base the conclusions. It was seen that AA5083 is ductile and isotropic whereas AA8090 is stiffer and anisotropic. Moreover, the present study considers the failure strain as a function of the experimental conditions and the homogeneity of grain refinement by measuring the hardness distribution. Furthermore, for the understanding of grain refinement mechanism, this study discusses the step by step metallurgical changes due to every successive two passes for the samples processed through the optimal die (V-groove) using TEM analysis.

2. Material and processing

AA8090 sheets of composition Al-94.46%, Li-2.5%, Si-1.8%, Cu-.5%, Zn-.171%, Ni-0.165%, Pb-0.387% (determined by spark atomic emission spectroscopy ASTM E1251-11) were supplied by ALCOA, Germany. Samples of dimensions 61 mm × 21 mm × 2 mm were prepared for the RCS process. These specimens were processed on a 50 T hydraulic press using three different dies, viz. a semi-circular die (radius 10 mm), a flat groove die (flank distance 5 mm, flank height 3 mm and corrugating angle 30°) and a V-groove die (pitch 20 mm, corrugating angle 30° and curve radius 2 mm). The different dies used for the experiments are shown in Fig. 1. The hydraulic press used in this RCS process is facilitated with a heating chamber mounted over the bed of the press, where a thermocouple is connected with a PID controller which has an indicator to ensure the working temperature (Fig. 2). The influence of temperature was also considered in this study. The material could not be processed at room temperature (RT), 100 °C and 200 °C because in these cases surface cracks were observed even after the first pass. High temperature DSC was used to determine the recrystallization temperature of the material – Fig. 3. The results indicate that the recrystallization temperature is ~350 °C. Therefore, the RCS processing temperature was kept at 300 °C, clearly below the recrystallization temperature. The ram velocity was fixed as 2.5 mm/s. The imparted strain on the specimen was measured along the longitudinal direction. The strain values are presented in Table 1. A corrugation – straightening step is considered as one pass. On each corrugated die the specimens were processed up to the maximum possible number of passes before failure. The specimens were processed to a maximum of 16 passes using the semi-circular die, 12 passes using the flat groove die and 10 passes using the V-groove die.

The theoretical values of the strain (ε) imparted were calculated using the formulae given below.

For a semi-circular corrugated die [21], the strain imparted in each pass can be calculated using Eq. (1).

$$\varepsilon = n\frac{4}{\sqrt{3}}\left(\frac{r+t}{r+.5t}\right) \tag{1}$$

For a flat groove die (shear in lateral and transverse directions are assumed to be negligible) [22], the strain imparted in each pass is calculated using Eq. (2).

$$\varepsilon = \frac{\Delta x/d}{\sqrt{3}} \tag{2}$$

where n = number of passes, r = radius of semi-circular die, t = thickness of the specimen, Δx = flank width and d = flank height.

The theoretical strain imparted using a V-groove die was calculated trigonometrically, assuming uniform deformation. The actual strain imparted in each case was measured experimentally by the optical grid analysis method [20]. The difference between the actual and the calculated strain is due to the theoretical calculations not considering the material behavior, kinematic hardening, temperature effect and frictional forces at the interfaces of the metal sheet and the die profile. In contrast, the experimental values reveal the actual