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Impact toughness improvement of high-strength aluminium alloy by intrinsic and extrinsic fracture mechanisms via hot roll bonding

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A multilayer aluminium laminate comprising 10 layers of Al–Zn–Mg–Cu alloy (82 vol.%) and nine layers of pure aluminium (18 vol.%) has been processed by hot rolling. The rolled laminate was characterized by electron backscattering diffraction, Charpy impact and shear tests. The multilayer laminate showed an outstanding Charpy impact toughness, which was 18 times higher than that for the as-received Al–Zn–Mg–Cu alloy. The improvement in damage tolerance was due to the high volume fraction of the high-strength aluminium and extrinsic fracture mechanisms.

Keywords: Aluminium alloys; Multilayer; Interfaces; Impact behaviour; Delamination

The highest strengths attained in wrought aluminium alloys correspond to the Al–Zn–Mg–Cu alloys (7xxx-serie) [1]. However, these heat-treatable aluminium alloys exhibit low fracture toughness, which limits their wider application.

In recent years, metallic multilayer composites have received attention due to their striking characteristics [2,3]. In particular, from a mechanical point of view multilayer materials are able to achieve an optimized combination of strength and toughness [4]. Hot rolling is capable of producing good bonds between metallic layers, improving toughness and refining the microstructure [5–9]. The interfaces that may delaminate are responsible for the high fracture resistance of the multilayer materials, and contribute to increasing the extrinsic toughening by different mechanisms [10]. Multilayer laminates based on aluminium alloys have been developed by hot roll-bonding, resulting in materials with improved impact toughness [11]. In Ref. [11], the aim was to optimize the rolling strain in two multilayer laminates with similar volume fraction of high-strength Al 7075 and Al 1050.

In the present study, a hot-rolled aluminium multilayer laminate based mainly on Al 7075 alloy (82 vol.%) with high strength and outstanding impact toughness has been processed. Since Al 7075 alloy exhibits a high work hardening rate, which may be problematic during processing, thinner Al 1050 layers than in previous works [10,11] have been placed among the Al 7075 to facilitate bonding between sheets and to contribute to the intrinsic toughness. Therefore, the objective of this work is to improve the intrinsic and extrinsic fracture mechanisms, which are involved in the improvement of the impact toughness of Al 7075-based composite. Hence, a high-strength multilayer material based on alternating layers of Al 7075 (82 vol.%) and Al 1050 (18 vol.%) has been processed and characterized.

The aluminium alloys used were rolled Al 7075-T6 alloy (termed "D") 2 mm thick and foils of Al 1050-H24 (termed "H") 0.5 mm thick. The main alloying elements of the Al 7075 are Zn (5.95 wt.%), Mg (2.52 wt.%) and Cu (1.36 wt.%). Ten Al 7075 layers (D) and nine Al 1050 (H) layers were stacked alternately, making up a bundle 24.5 mm thick, 60 mm wide and 150 mm long, referred to as ADH19, with a Al 7075:Al 1050 volume ratio of 82:18. The stacked multilayer material was welded by tungsten inert gas (TIG) and then hot-rolled at 465 °C in four series of four passes of about 4–8% reduction per pass, corresponding to an equivalent true strain of $\varepsilon = 0.85$ (von Mises criterion) (reduction of 2.1:1). The diameter of the rolls was 130 mm and the rolling speed was 346 mm s^{-1}. The laminate was rolled parallel to

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the rolling direction of the as-received sheets. After hot rolling, a T6 heat treatment was carried out [11]. The resulting laminate was a plate about 11.5 mm thick, 350 mm long and 60 mm wide. The final thickness of the Al 7075 layers in the ADH19 laminate was ~990 μm and that of the Al 1050 layers was ~270 μm.

The microstructure in the normal direction (ND)–rolling direction (RD) sections of the as-received materials and the laminate material was observed by scanning electron microscopy (SEM), using a JEOL JSM 6500F equipped with a field emission gun. Microtexture information was obtained by electron backscattering diffraction (EBSD), operating with an accelerating voltage and working distance of 20 keV and 15 mm, respectively. The data processing was carried out using HKL Channel 5 software. Orientation mapping was performed with a step size of between 0.3 and 0.6 μm depending on the magnification. A low-angle grain boundary (LAB) was defined by a misorientation between adjacent grains of $2° < \theta < 15°$, and a high-angle grain boundary (HAB) was defined by $\theta > 15°$. HABs and LABs are shown as black and white lines, respectively, on the maps. The laminate impact toughness was measured by Charpy tests on a pendulum impact tester with a maximum capacity of 294 J. Two millimetres V-notched Charpy type testing samples were machined with dimensions of $10 \times 10 \times 55\ mm^3$ from the as-received monolithic alloys and the roll-bonding laminate, and were tested in the crack arrester orientation. The rolled microstructure in the as-received aluminium materials, with elongated grains in the rolling direction, enable the two different orientations to be distinguished. Thus, for the as-received materials, in the so-called crack arrester orientation, the notch tip is parallel to the plane and rolling direction. For the laminate materials, in the crack arrester orientation, the crack is forced to pass through each layer sequentially—this is the natural configuration for an aluminium panel in an airplane. Selected fractured specimens were examined by SEM to evaluate deformation micromechanisms during crack propagation. The interface mechanical properties were measured by shear tests in a Servosis universal test machine at a cross-head rate of $0.005\ mm\ s^{-1}$, using specimens $\sim 10 \times 10 \times 3\ mm^3$. The shear stress, τ, and the shear strain, γ, are given by the expressions $\tau = p/ae;$ $\gamma = tan(\alpha) = d/l_{gap}$ [12], where a and e are the initial width and thickness of the sample, respectively, p is the force applied on the sample, d is the midspan displacement of the sample, α is the shear angle and l_{gap} is the span length between the supports and the mobile punch, corresponding to 0.35 mm in this study. A scheme of the shear test performed was shown elsewhere [13].

Figure 1a shows the microstructure of the as-received Al 1050-H24. It presents an equiaxed (sub)grain structure with an average (sub)grain size of 2–3 μm. The as-received Al 7075-T6 (Fig. 1b) shows large grains (20–30 μm) that are elongated and flattened parallel to the rolling direction. Additionally, randomly distributed iron-rich intermetallic particles were observed in both as-received materials. The EBSD map of the as-received Al 1050 obtained at low magnification (Fig. 1c) shows a bimodal microstructure, highlighting a main lamellar structure composed of large grains elongated in the rolling direction containing fine subgrains (2–3 μm). Furthermore, small grain aggregates are observed along with the elongated grains. The EBSD map has been colour coded according to the inverse pole figure (IPF) shown in the inset, and the colours represent the crystallographic orientations parallel to ND. Thus, the spacing between HABs on the as-received Al 1050 presents a bimodal distribution with large grains 10–15 μm in thickness and small grains 2–3 μm in thickness. On the other hand, the HAB spacing in the normal direction (ND) for the as-received Al 7075 was about 5.8 μm (Fig. 1d). The {1 1 1} pole figure corresponding to the as-received Al 1050 (Fig. 1c) shows a β-fibre ideal texture in rolled face-centred cubic metals [14]. The as-received 7075 material is weakly textured, slightly highlighting the Cube component ({0 0 1}⟨1 0 0⟩), which is associated with partially recrystallized structures [15]. In general, the Al 7075 presents grains of a wide range of orientations (Fig. 1d).

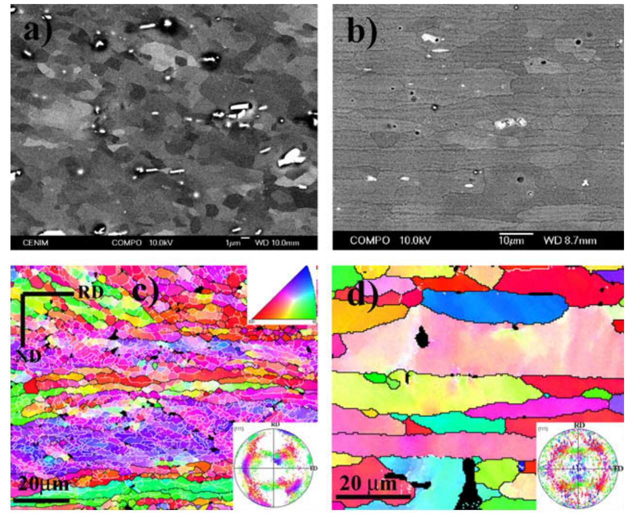

Figure 1. Backscattered electron micrographs and EBSD maps showing the microstructure and microtexture of (a and c) the as-received Al 1050-H24 (H), and (b and d) Al 7075-T6 (D) in the ND–RD section.

After rolling, the Al 7075 (D) in the ADH19-T6 laminate presents a RD-aligned lamellar microstructure separated by HABs (black lines) (Fig. 2a at low magnification; Fig. 2b at higher magnification). Figure 2a shows the EBSD map of the ADH19-T6 laminate, containing alternating layers of large grains in the Al 1050 layers (H) and smaller "pancake" grains in the Al 7075 layers (D).

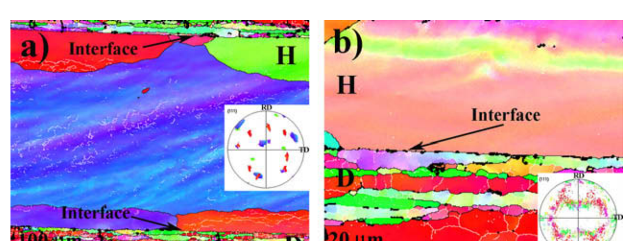

Figure 2. EBSD maps showing the microstructure and microtexture of the ADH19-T6 laminate in the ND–RD section.