Through-thickness variations in recrystallization behavior in an Al-based ARB composite sheet

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Abstract. A composite sheet of commercially pure aluminum and an Al-0.3 wt.% Sc alloy (in the supersaturated solid solution condition) was produced by accumulative roll bonding at 200°C. The material was then subjected to isothermal annealing at 300°C for 1-30 minutes and cold water quenched. The transverse section was investigated by electron back-scatter diffraction (EBSD) to investigate the variations in microstructure and texture within Al layers through the sheet thickness. A faster spheroidization of the highly elongated lamellar band deformation structures was observed in the surface aluminum layer as compared to the mid- and quarter-thickness layers. In the quarter thickness aluminum layer so-called continuous recrystallization occurred and, thus, the β-fiber rolling texture was retained. Further growth in this layer led to secondary recrystallization of cube orientations. In contrast, in the surface aluminum layers the recrystallization and grain growth texture were relatively random. Intermediate behavior was observed in the mid-thickness aluminum layer.

1. Introduction
Accumulative roll bonding (ARB) was first developed by Saito, et al. [1]. It is an advantageous method among other major severe plastic deformation (SPD) processes since it is semi-continuous. In ARB the large plastic strains achievable produce ultra-fine grains (UFG) in malleable metallic materials. ARB processing occurs in cycles and each cycle involves stacking, rolling, cutting and mechanical polishing. At the end of a cycle, the sheet thickness is typically reduced to half and after several cycles (normally 3 to 5 cycles) sub-micron grains are usually generated. Consequently, the final product exhibits considerably improved mechanical properties without changing the product’s geometrical dimensions [1, 2].

Grain refinement and preferred crystallographic orientation, known as texture, are two important phenomena that affect material properties. Due to the high rolling reduction in a given cycle there is significant influence from friction forces: between the rolls and the outer layers of the sheet as well as between sheets themselves. This leads to generation of friction-driven shear strain and in-plane shear strain, respectively. In subsequent ARB cycles, the surface sheared layers are placed inside of the sheet and, hence, heterogeneity in microstructure and crystallographic orientation is produced. This texture inhomogeneity thus affects plastic anisotropy. Therefore, post-deformation annealing processes are required for optimizing rolled material formability. Understanding of texture evolution during annealing of highly deformed materials is limited, as such this study aims to examine the recrystallization texture inhomogeneity throughout the sheet thickness of a composite sheet comprising layers of commercially pure Al and an Al-Sc alloy subject to ARB following up to 5 cycles of deformation [3-5].
2. Experimental
Commercially pure (99.8%) aluminum (hereafter termed Al) with a uniform grain size of ~50 μm and an aluminum-scandium (Al-0.3wt.%Sc.) alloy (hereafter termed Al(Sc)) in a supersaturated solid solution (SSSS) condition with a coarse grain microstructure were accumulative roll bonded (after mechanical polishing and wire brushing) at 200°C and without lubrication. The ARB process was carried out up to 5 cycles (5C). Approximately 50% reduction in thickness was applied in each cycle. As a result, an alternatively-layered composite sheet was generated [6]. The Al layers of the composite sheet were characterized and found to contain lamellar bands that had formed under the application of intense strain [6]. The product was then isothermally heat treated at 300°C for 1, 3, 5 and 30 minutes followed by cold water quenching. Longitudinal (RD-ND) sections were examined by electron backscatter diffraction (EBSD) for microstructural investigations in Al layers located at different positions through the sheet thickness. Using a field emission scanning electron microscope (FESEM) having an Oxford HKL EBSD data acquisition system, Al layers at the surface, quarter and center of the specimen were examined. Orientation maps and pole figures were obtained using Channel 5 post-processing software. Annealing-induced inhomogeneity through the thickness of the material was analyzed.

3. Result and discussion
A pattern quality map and grain boundary map of a large area in the 30 minutes annealed recrystallized sheet is shown in Figure 1a. This image includes half of the specimen thickness containing 16 roll bonded Al and Al(Sc) layers. Al layers were found to contain large recrystallized grains separated by high angle grain boundaries (HAGBs, shown in black). In contrast, Al(Sc) layers retain prior deformation structures containing low angle grain boundaries (LAGBs: 2°<misorientation<15°, shown in red). Surface, quarter and central Al layers after 3 minutes annealing at 300°C are presented in higher resolution EBSD maps in Figures 1b-d respectively. It is noticeable that the surface microstructures are relatively more equiaxed than the quarter and central layers, where the spheroidization rate is less, and so elongated grains are still predominant. However, some recrystallized grains can also be observed in the center layer. After a 5 minute anneal, the microstructures in all the Al layers were almost fully recrystallized. In the quarter-thickness layers a clearer heterogeneity in grain size was evident in the form of a few highly coarsened grains in a fine lamellar matrix. Comparatively, there is less significant difference in the overall grain size in surface or central Al layers. After 30 minutes annealing, recrystallized grains in the quarter thickness layer are grown to full layer thickness (Figure 3).

Figure 2 shows the <111> pole figures of the Al layer at the quarter thickness layer as a function of annealing time. It is clear that the typical β-fiber FCC metal rolling texture developed during deformation is still retained after annealing. The β-fiber extends from copper {112} <111> through s {123} <634> to brass {011} <211>. Retention of the rolling texture after recrystallization is an indication of the involvement of a continuous recrystallization mechanism. With further annealing to 30 minutes significant grain growth occurs in the surface, quarter and center layers. The orientations of the larger grains in the quarter thickness layers are concentrated around the cube {001} <100> texture, whereas in the surface and mid thickness layers a diffused β-fiber texture is sustained.
Figure 1: (a): Pattern quality map of the specimen (30-minute annealed) labelled at S: surface, Q: quarter and C: central regions, 2°< misorientation<15°: LAGBs in red and 15°< misorientation: HAGBs in black. EBSD micrograph of the Al layers after 5 ARB cycles and annealing at 300 °C for 3 minutes at (b): surface (c): quarter and (d): center Al layer showing faster spheroidization of surface layer as compared to the quarter and central regions.

| Quarter | 3 min | 5 min | 30 min |
|---------|-------|-------|--------|
| ![Image](rd.png) | ![Image](td.png) | ![Image](nd.png) | ![Image](rd.png) |

Figure 2: <111> pole figure distribution for the Al layer at the quarter thickness layer at different annealing times indicating texture evolution with increasing annealing time.
100 µm

Figure 3: EBSD orientation maps of (a) surface (b) quarter and (c) central Al layers after annealing for 30 minutes. The HAGBs are defined by black lines where the misorientation is $>15^\circ$.

Figure 4: $<111>$ pole figures of the (a) surface, (b) quarter, (c) center layers of Al, from Figure 1a, showing the dominant texture after annealing at 300°C for 30 minutes. The surface layer shows relative randomization behavior, while in quarter layer the cube orientation is centered for well-grown grains. The center layer has maintained the $\beta$-fiber texture.

EBSD-generated higher resolution orientation maps of Al of the aforementioned areas i.e. surface, quarter and center regions in the 30 minutes annealed sample in Figure 1a, are presented in Figures 3a-c. These micrographs show the variation in recrystallized grain size as a function of layer location. In the quarter-thickness layer (Figure 3b) most grains were found grown to full layer thickness. Although the material was recrystallized in previous annealing stages, further annealing up to 30 minutes resulted in selective grain growth in this layer by a mechanism known as secondary recrystallization or abnormal grain growth [3]. The selective grain growth process was least, and only intermediately, observed in surface and center layers respectively (Figures 3a & c).
The large recrystallized grains within an area of ~ 934 x 19 µm in the surface, quarter, and central Al layers were plotted as <111> pole figures, as shown in Figures 4a-c, respectively. It is evident that the cube orientation is dominant in the quarter thickness as poles are mostly centered at cube component (Figure 4b). Whilst the orientation of large grains in the surface layer shows some degree of randomization (Figure 4a), the central layer maintains the β-fiber texture following a 30 minute anneal (Figure 4c).

4. Conclusions

A composite sheet of commercially pure aluminum (Al) and an aluminium-0.3 wt.% scandium alloy (Al(Sc)) was fabricated by accumulative roll bonding at 200°C. The product was then annealed at 300°C for various times. It was found that in the Al layers a texture gradient was developed through the sheet thickness that resulted to approximately randomly-oriented grains at the surface Al layer of the sheet and a retained β-fiber orientation at the central Al layer of the sheet. The Al layer of quarter thickness underwent secondary recrystallization to a cube-centered orientation.

5. References

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