Dependence of microstructure evolution on rolling conditions in AA1050 aluminum alloy

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Abstract. Cold rolling has often been employed to tailor the microstructure and to achieve desired mechanical properties. In this study, the formation of sub-grain and grain orientation evolution in cold rolling processed AA1050 aluminum was investigated by electron backscatter diffraction (EBSD) characterisation. The experimental results demonstrated that increasing rolling reduction facilitates the transformation from sub-boundaries to high angle boundaries within grains by accumulating misorientation, and asymmetric rolling could impose a higher equivalent plastic strain, accelerating the grain refinement. The formation of small and equiaxed grains demonstrates that asymmetric rolling with high reduction promotes the recrystallization in (112) grains and contributes to the formation of (110) fibre in aluminum.

1. Introduction
Rolling is the process of plastic deformation of materials by passing them through a set of rolls. During rolling deformation, metal is subjected to compressive stress in its normal direction. To produce large-scale sheets or plates with deformation homogeneity through thickness, asymmetric rolling has been proposed to uniformly impose intense plastic deformation in the sample [1]. Asymmetry in rolling can arise through inequality in roll radii, roll velocity and interface friction; inhomogeneous or anisotropic workpiece material; or bending end forces [2]. The strong shear strain resulted from asymmetric rolling can enhance the deformation homogeneity and promote its penetration into the middle layers of the processed sheets, so that the grains or microstructure at these areas can be effectively deformed or refined compared to that of the symmetrically rolled ones, be able to impose the strength and elongation of asymmetric processed sheets [3].

The formability of a metal sheet depends on its scheduling during the rolling process apart from its alloying elements. In other words, the microstructure evolution could result in the formation of different types of fibres or textures. Plastic anisotropy resulted from the formed texture can have both beneficial and detrimental effects on formability. In a strong textured sheet, the variation in yield stress can be observed along with the direction in the rolling plane as well as in the thickness. Such directional behaviour affects non-uniform material flow in the deep drawability of metals.
It has been demonstrated that the microstructural evolution generally depends on the formation of dislocations structure, which is crystallographic orientation-dependent. Changing deformation parameters, such as reduction, rolling speed ratio can result in variation of strain accumulation and deformation conditions. Therefore, the main purpose of this study is to explore the effects of rolling conditions (e.g. symmetric or asymmetric rolling, reduction) on the microstructure evolution in aluminum.

2. Experiments
Commercial AA1050 aluminum alloy strip (chemical composition as shown in Table 1) was homogenised at 500 °C for 2 h and then submitted to cold rolling with different rolling reductions: 30% and 70%, which corresponding to the reduction of the sample thickness from 1 mm to 700 μm and 300 μm. The dimensional change was conducted under symmetric and asymmetric cold rolling. The cold rolling was conducted on a rolling mill with a diameter of 50 mm of upper and lower work rolls.

Table 1. Chemical composition of AA1050 aluminum.

| Elements | Si | Fe | Cu | Mg | Zn | Ti | Al     |
|----------|----|----|----|----|----|----|--------|
| w/%      | 0.10 | 0.28 | 0.01 | 0.02 | 0.01 | 0.02 | Balance |

The samples were mechanically polished up to 4000 grit SiC paper. Following this, electro-polishing was undertaken at room temperature for 20 s each on a Struers Lectropol-5 operating at 20 V, ~250 mA using an electrolyte of 25% perchloric acid, 25% ethanol and 50% distilled water. The microstructural observations were conducted on a JEOL JSM 7001F field emission gun – scanning electron microscope operating at 15 kV accelerating voltage, ~6.1 nA probe current and 15 mm working distance. The Oxford Instruments Nordlys-II(S) EBSD detector interfaced with the OI AZtec acquisition software suite. Throughout the experiment, electron backscattering patterns were collected using 4×4 binning at ~25 ms exposure time and ~40.5 Hz acquisition rate.

Owing to the relatively large step size employed in this study, subgrain structures are defined by a minimum of ten pixels and are bounded by misorientations (θ) ≥ 5°. Misorientations between 5° ≤ θ ≤ 15° and 15° ≤ θ ≤ 57.5° are low angle grain boundaries and high-angle grain boundaries, respectively.

3. Results
The microstructure of the annealed aluminum sample is shown in Figure 1. The morphology of the grains indicates that almost equiaxed grains are generated after annealing. After inclined cold rolling at various reductions (30% and 70%), the microstructural morphology and orientations of the grains were characterized and shown in Figure 2. It is found from the EBSD orientation maps that the morphology of grains was slightly changed both for symmetric (Figure 2a) and asymmetric (Figure 2b) rollings with 30% reduction. The EBSD orientation maps show that grain orientation is observed in some grains under
symmetric rolling and the slip bands induced grain orientations can be observed in the grains. While in the asymmetric rolled sample, the grain orientation deviations are much more obvious and observed in almost all grains, demonstrate asymmetric rolling induces a much more homogeneous deformation in the sample.

![EBSD orientation map of the annealed aluminum.](image)

**Figure 1.** EBSD orientation map of the annealed aluminum.

Figures 2c and 2d indicate that lamella grains are formed after rolled with 70% reduction. Under symmetric rolling, the applied load tends to facilitate the formation in the grain with orientation close to [100] pole, the misorientation is at a relatively lower level in the grains with orientation close to [111] pole. However, Figure 2d shows a different phenomenon after asymmetric rolling in comparison with symmetric rolling. In Figure 2d, the grains with orientation between [112] and [111] contain parallel low angle grain boundaries, which are correlated with the dislocations activities during cold rolling, and these boundaries tend to grow into high angle grain boundaries with further deformation. The [100] grains remain stable after rolling and grain orientation deviation is dominantly observed at boundaries, demonstrating a significant effect of grain interaction on grain orientation development.
Figure 2. EBSD orientation maps of aluminum after rolling with reductions of (a,b) 30% and (c,d) 70% under (a,c) symmetric and (b,d) asymmetric rolling.

Figure 3 shows the orientation developments of the grains under asymmetric rolling at different rolling reductions. It is shown that grain orientation rotates towards different directions in the grain and the magnitude of orientation shift is higher at grain boundaries (marked by red dash circle in Figure 3a). While grain under a higher level of deformation, high misorientation angles are recorded in the grains, where new grains are characterised. It is demonstrated in previous research [4] that grain orientation tends to rotate towards [110] pole during compression deformation. It can be seen from the inverse pole figure triangles that an obvious grain orientation spread from [112] pole to [110] pole, and the recrystallized grains resulted from higher rolling reduction (Figure 3d) exhibit an orientation close to the [110] pole, demonstrating asymmetric rolling tends to facilitate the grain rotation and the formation of (110) fibre.
4. Discussion

Grains have different shapes and ingrain misorientation development for symmetric and asymmetric rolling, which is associated with the initial grain orientations and level of deformation. It is seen that grains with initial orientation close to [112] pole tend to show higher grain orientation deviation than [111] grains (Figure 2). This difference is attributable to the orientation-dependent rotation, which follows Schmid law [4]. According to Schmid law, the [111] orientations are stable and reluctant to rotate during the deformation, while grains with orientation close to [112] pole are unstable, tend to rotate towards to [101] pole during compression. Additionally, interactions with neighboring grains prohibit the rotation and lead to complex rotation components of the lattice. Therefore, evident orientation deviations are obtained in the grain. The morphological change of the grains depends on the level of strain as elongated grains are dominantly obtained in the sample at a higher reduction.

The deformation process under symmetrical rolling and asymmetrical rolling can be approximated by a two-dimensional strain state of compressive strain along with normal dissection (ND) together with simple shear strain ($\gamma$). The amount of shear imposed during the asymmetrical rolling process can be characterized by shear coefficient $K$ and compressive strain $\varepsilon_N$,

$$K = \frac{\gamma}{\varepsilon_N}$$  \hspace{1cm} (1)

$$\varepsilon_N = \frac{2}{\sqrt{3}} \ln \left( \frac{h_i}{h_f} \right)$$  \hspace{1cm} (2)

The shear strain imposed by ASR processing could be approximated by the calculations reported by
Kang et al. [5], but their formulas were corrected because the asymmetric conditions in the current FE simulation and experimental rolling procedures were introduced by a rolling mill with the same diameters but different angular speeds. The shear angle was calculated as the difference of shear distance between the rolls at the same rolling time and obviously, the shear distance of roll with higher rotational speed is larger than that of roll with slower rotational speed. Considering the above assumption and a simple geometrical analysis, $\gamma$ was expressed as [6],

$$\gamma = \frac{1}{h_i + h_f} \cos^{-1} \left( 1 - \frac{h_i - h_f}{2R} \right) \left( 1 - \frac{v_2}{v_1} \right)$$

where $h_i$ and $h_f$ are the initial and final thickness of the rolled sheets, respectively. R is the roll radii, $v_1$ and $v_2$ represent the roll speed of the upper and lower rolls.

With the increase of rolling reduction, higher strain magnitude and grain rotations are obtained in the sample. Therefore, evident grain orientation spread is obtained in the sample under high strain level, due to the competitive rotation between adjacent grains, which causes a complex stress-strain state.

The evident orientation deviation in the grains is attributed to the deformation homogeneity under asymmetric rolling. High reduction during cold rolling results in obvious grain refinement. As previously indicated [7], the microstructure and crystallographic texture are the factors that determine the mechanical properties. The relative lower reduction (30%) results in a substructure rearrangement during plastic deformation, causing a misorientation increase across the dislocations walls. While deformed at a higher reduction, the dislocation rearrangement is observed with parallel bands were achieved in the sample. Additionally, the large strain facilitates the development of dislocation walls and substructures induced low angle boundaries to develop into high angle grain boundaries. Consequently, small and equiaxed morphology microstructures are observed as new grains in the material.

5. Conclusion

Symmetric and asymmetric rollings with different reductions were carried out on pure aluminum sheets. The effect of rolling conditions on the microstructural evolution are evaluated as follows:

- High rolling reduction causes an evident morphology evolution in the aluminum such that lamellar structures were formed.
- The ingrain orientation deviation depends on the grain orientation. Lower orientation deviations were obtained in grains with stable orientation ([111] orientation), while grains with unstable [112] orientation tend to rotate towards [101] orientation and a higher deviation is developed.
- The asymmetric rolling facilitates the development of substructure such that small and equiaxed microstructures are obtained in the material.
References

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