Microstructure and texture of asymmetrically rolled aluminium and titanium after deformation and recrystallization

M Wronski¹, K Wierzbanowski¹, S Wronski¹ and B Bacroix²
¹AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Kraków, Poland
²CNRS, Université Paris 13, 99, av. J.B. Clement, 93 430 Villetaneuse, France

E-mail: mwronskii@gmail.com, krzysztof.wierzbanowski@fis.agh.edu.pl, wronski.sebastian@gmail.com, brigitte.bacroix@univ-paris13.fr

Abstract. Asymmetric rolling is used to modify material properties and to reduce forces and torques applied during deformation. This geometry of deformation is relatively easy to implement on existing industrial rolling mills and it can provide large volumes of a material. The results of the study of microstructure and crystallographic texture in asymmetrically rolled aluminium 6061 and titanium (grade 2) are presented in this work. These characteristics were determined using the EBSD technique and X-ray diffraction. The rolling asymmetry was realized using two identical rolls, driven by independent motors, rotating with different angular velocities. It was found that asymmetric rolling leads to microstructural refinement and texture rotation (around the transverse direction). The impact of asymmetric rolling on microstructural refinement appears also in recrystallized samples of both materials. On the other hand, texture rotation, caused by asymmetric rolling, persists after annealing in titanium but not in aluminium samples.

1. Introduction
Asymmetric rolling (AR) is a promising deformation process, which can have many practical applications. It reduces the applied rolling forces and torques, changes the rolled plate shape and modifies the microstructure and crystallographic texture (e.g., [1-5]). The rolling asymmetry was realized in the present work using two identical rolls driven by independent motors, rotating with different angular velocities: \( \omega_1 \) and \( \omega_2 \). Therefore, the degree of process asymmetry is defined as: \( A = \omega_1/\omega_2 \) (asymmetry ratio). The main goal of this work was to study the influence of AR on crystallographic texture and microstructure of aluminum (6061 type) and titanium (grade 2). Two experimental techniques were used: electron backscatter diffraction (EBSD) and X-ray diffraction. The material characteristics were studied for the rolled samples and also for the recrystallized material in order to check, which modifications of material parameters persist after recrystallization.

2. Microstructure of asymmetrically rolled aluminium
The selected material was the 6061 type Al alloy (containing 2.4% Mg). The initial samples were prepared from as-delivered sheet of material (sample were not annealing before deformation). Rolling deformation was performed in one pass up to 36% reduction. The following degrees of rolling asymmetry were considered: \( A=1 \), \( A=1.1 \), \( A=1.3 \) and \( A=1.5 \). Two sets of samples were examined: the
rolled samples and the samples rolled and annealed in air at 450°C for 15 minutes. The microstructure was examined by the EBSD technique using a Cambridge S360 (W-GUN) electron microscope. The presented Inverse Pole Figures (IPF) maps for ND were determined on the RD-TD plane (where: RD - rolling direction, TD - transverse direction and ND - normal direction). They were determined in the central sample layers. For initial and deformed sample the maps of the size 700x400 μm² with the step of 1 μm were measured. On the other hand, for the deformed and annealed samples the maps of the size of 650x650 μm² with the step of 1.2 μm were determined. The maps for the initial material, for the sample after symmetric rolling (SR) and for the sample rolled and then annealed - are presented in figure 1.

![Figure 1. EBSD maps for the initial material (a), for the sample rolled symmetrically(A=1) to the reduction of 36% (b), and for the sample annealed after symmetric rolling at 450°C for 15 minutes (c). IPF maps of the size 450x450 μm² for centre layers are shown.](image_url)

Based on the measured maps the characteristic microstructural parameters like: average grain size and Kernel average misorientation (KAM) were calculated and are presented in function of asymmetry ratio (A) in figure 2. The following definition of grain was used in our analysis: a grain is defined as a set of points with misorientation angles between neighbouring measurement pixels smaller than some threshold value (15° in the present case) and it has to contain at least 5 measurement points. After AR we observe fragmentation of grains, which is reflected in the increase of KAM vs. A (figure 2a). It should be noted that in the case of the annealed sample the grain structure was rebuilt and one observes equiaxed grains (figure 1c). The grain refinement in the annealed state, caused by AR, is reflected in the decrease of the average grain size with A - figure 2b.

![Figure 2. Influence of rolling asymmetry (A=1, A=1.1, A=1.3 and A=1.5) on: a) Kernel average misorientation for samples rolled to 36% reduction, b) average grain areas (μm²) for samples rolled to 36% reduction and annealed at 450°C for 15 minutes. Results for central layers are shown.](image_url)
3. Texture variation in asymmetrically rolled aluminium

Crystallographic textures were determined in the centre layers of the rolled samples using the X-ray diffraction technique (INEL goniometer with Co radiation). The texture of the initial material depicted in figure 3 is very sharp and contains Brass (B) and Cube (W) orientations. This material was next rolled symmetrically ($A=1$) and asymmetrically ($A=1.5$). The orientation distribution function (ODF) [6] sections at $\phi_2=0^0$ presenting rolling textures, are shown in figure 4. A full analysis showed that the texture of the SR sample contained the following components: W (dominant one), B, rather weak C orientation and traces of S and G orientations [4]. A strengthening of W component is somewhat surprising. However, the shifts of B orientation are essential in the present study and we will focus our attention on this effect.

Characteristic effects appearing during SR and AR can be followed examining the B component which is visible in $\phi_2=0^0$ section. In the case of the SR material four equivalent B component maxima lie on the horizontal blue line drawn at $\Phi=45^0$ (figure 4a). In the case of the AR material one observes the shifts of B component maxima. Namely, the first two maxima of the B component (in the $[0^0, 180^0]$ range of $\phi_1$) are shifted up and the next two maxima - are shifted down (figure 4b). Graphical explanation of this texture modification after AR is depicted in figure 4c. It was checked that the observed shifts of texture maxima result from a texture rotation around TD [5].

![Figure 3](image1)

**Figure 3.** The crystallographic texture of the initial aluminium sample determined by X-ray diffraction. $\phi_2=0^0$ sections are shown and orientations W (■) and B (▲) are marked.

![Figure 4](image2)

**Figure 4.** Textures of (a) symmetrically ($A=1$) and (b) asymmetrically ($A=1.5$) rolled samples determined in central material layers. $\phi_2=0^0$ sections are shown and blue lines are located at $\Phi=45^0$. W (■) and B (▲) orientations are marked and (c) graphical explanation of texture modification after asymmetric rolling is shown. Textures were determined by X-ray diffraction and are presented using levels: 2.40, 8.00, 12.22, 17.61, 22.00, 35.00

The rolled aluminium samples were annealed next at 450 °C for 15 minutes. The recrystallization textures corresponding to SR ($A=1$) and AR ($A=1.5$) are shown in figure 5. They both contain only Cube (W) component. Therefore, we do not observe an influence of the rolling asymmetry ratio, A, on the annealing textures.
4. Microstructure of asymmetrically rolled titanium
The second examined material was commercially pure titanium (Ti grade 2). The samples were prepared from as-delivered sheet of material (without annealing). Two set of samples were examined: after low deformation (20% rolling reduction) and after higher deformation (60% rolling reduction) and annealing in air at 550 °C for 1 h. Rolling deformation was performed in many passes with 5% reduction per pass. For deformed sample (20%) the maps of the size 350x300 μm² with the step of 0.3 μm were measured. On the other hand, for the deformed (60%) and annealed samples the maps of the size of 400x200 μm² with the step of 0.5 μm were determined.

The EBSD maps for the initial material and for the samples rolled up to a 20% reduction are shown in figure 6. The maps for symmetric (A=ω₁/ω₂=1) and asymmetric rolling (A=1.5) are shown in this figure.

It is already visible that the microstructure is finer in the AR case. This is confirmed by the average grain size vs. A plot - figure 7a; the results for three degrees of asymmetry are shown: A=1, A=1.3 and A=1.5. It is visible that the grain size decreases with asymmetry ratio. The other factor, namely KAM, which characterizes the fragmentation of the microstructure, is also presented in this figure. Similarly, like in the case of aluminum, KAM increases vs. the degree of rolling asymmetry - figure 7b. In can be therefore concluded that AR produces smaller and more fragmented grains.
Figure 7. Influence of rolling asymmetry (A=1, A=1.3 and A=1.5) on: a) average grain size ($\mu m^2$) and b) Kernel average misorientation. Results for 20% rolling reduction and for central titanium layers are shown.

It is common industrial practice that an annealing is applied after rolling in order to recover some material properties, e.g., ductility. Therefore, the microstructural characteristics were determined for titanium samples rolled to 60% reduction and then annealed for 1 h at 550 °C. The EBSD maps measured in the central layers of SR and AR samples are presented in figure 8a,b. Based on the measured maps the average grain size for the cases $A=1$, $A=1.3$ and $A=1.5$ was calculated and is presented in figure 8c. The conclusion is that the average grain size of titanium samples decreases with asymmetry ratio ($A$).

Figure 8. EBSD maps of the size 150x150 $\mu m^2$ for the titanium grade 2 rolled to 60% reduction and annealed for 1 h at 550°C: (a) after SR ($A=1$), (b) after AR ($A=1.5$). Figure (c) presents a bar chart showing the average grain size ($\mu m^2$) vs. A relation for the rolled ($A=1$, $A=1.3$ and $A=1.5$) and annealed samples.

5. Texture variation in asymmetrically rolled titanium
Crystalllographic textures of SR and AR titanium samples rolled to 40 % were examined. The measured pole figures (determined from EBSD maps) were not symmetrised and the orientation distribution functions (ODFs) were calculated. The $\phi_2=0$ ODF sections for the initial material and for the symmetrically ($A=1$) and asymmetrically ($A=1.3$) rolled samples are presented in figures. 9a and b. We note that the main texture maximum of the initial material as well as of the SR material has a symmetric position with respect to the line plotted at $\phi_2=30^\circ$ (blue dashed line). In contrast, the AR process leads to a shift of the main texture maximum to the right - figure 9b. This effect is related again to a texture
rotation around TD and is caused by an occurrence of a strong shear stress component, \( \Sigma_{13} \), in the sample during the AR process (\( x_1 = \text{RD}, \ x_2 = \text{TD} \) and \( x_3 = \text{ND} \)). This result was confirmed by texture modeling using the Finite Element Method [7] with an implemented crystalline model [8]. It should be mentioned that AR also leads to texture homogenization across the sample thickness [7]. Moreover, the residual stresses determined by diffraction method (see e.g., [9,10]) are generally lower in the AR samples [7,11]. The ODF section for the titanium sample rolled asymmetrically (\( A=1.3 \)) and then annealed for 1h at 550 \(^\circ\text{C} \) is shown in figure 8c. One finds that the characteristic shift of the main texture component, appearing after AR, persists after annealing.

![Texture of titanium grade 2 determined by the EBSD technique](image)

**Figure 8.** Texture of titanium grade 2 determined by the EBSD technique: a) initial material, b) SR (\( A=1 \)) and AR (\( A=1.3 \)) samples rolled 40% reduction, c) textures of SR and AR samples annealed at a temperature 550 \(^\circ\text{C} \) for 1h; \( \phi_1=0 \) sections are shown.

**6. Conclusions**

The results presented, obtained for asymmetrically and symmetrically rolled aluminium 6061 and titanium grade 2 samples, lead to the following conclusions:

- average grain size is smaller and grains are more fragmented after asymmetric rolling (compared with the symmetric rolling mode),
- an impact of asymmetric rolling on the average grain size appears also after recrystallization of titanium and aluminium samples,
- textures after asymmetric rolling are rotated around the transverse direction; this rotation leads to characteristic shifts of maxima in aluminium and titanium textures,
- in the case of titanium samples - the shift of the texture maximum, caused by asymmetric rolling, persists also after recrystallization.

Acknowledgements
This study was financed by the Polish National Centre for Science (NCN) under decision numbers: DEC-2011/01/D/ST8/07399 and DEC-2013/11/B/ST3/03787.

References
[1] Gao H and Chen G 1998, Iron and Steel 33 63
[2] Lee S H and Lee G N 2001, Int. J. Mech. Sci. 43 1997
[3] Chhann S, Solas D, Etter A L, Penelle R and Baudin T 2007, Mater. Sci. Forum 550 551
[4] Wronski S, Ghilianu B, Chauveau T and Bacroix B 2011, Mater. Charact. 62 22
[5] Wronski S, Wierzbanowski K, Bacroix B, Wróbel M, Rauch E, Montheillet F and Wronski M 2009, Arch. Metall. Mater. 54 89
[6] Tarasiuk J, Wierzbanowski K and Baczmanski A 1998, Cryst. Res. Technol. 33 101
[7] Wronski M, Wierzbanowski K, Wronski S, Bacroix B and Lipinski P 2014, Int. J. Mech. Sci., 87 258
[8] Wierzbowski K, Baczmanski A, Lipinski P and Lodini A 2007, Arch. Metall. Mater. 52 77
[9] Baczmanski A, Wierzbowski K, Tarasiuk J, Ceretti M and Lodini A 1997, Rev. Metall-Paris, 94 1467
[10] Baczmanski A, Tidu A, Lipinski P, Humbert M, and Wierzbowski K 2006, Mater. Sci. Forum, 524-525 235
[11] M. Wroński, K. Wierzbowski, M. Wrobel, S. Wronski, B. Bacroix 2015 Met. Mater. Int., 21 (5) - to appear