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Modification of stress and texture distributions in asymmetrically rolled titanium

M. Wronski[1,a], K. Wierzbanowski[1,b], A. Baczmanski[1,c], S. Wronski[1,d], B. Bacroix[2,e], M. Wróbel[3,f], A. Lodini[4,g]

[1] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Kraków, Poland,
[2] LSPM-CNRS, Université Paris XIII, 99, av. J.B. Clement, 93 430 Villetaneuse, France
[3] AGH University of Science and Technology, Faculty of Metals Engineering and Industrial Computer Science, al. Mickiewicza 30, 30-059 Kraków, Poland.
[4] LISM, UFR SEN, Université de Reims Champagne Ardenne, Moulin de la Housse BP1039, 51687 Reims, France

[a] mwronskii@gmail.com, [b] krzysztof.wierzbanowski@fis.agh.edu.pl, [c]andrzej.baczmanski@fis.agh.edu.pl, [d]wronski.sebastian@gmail.com, [e] brigitte.bacroix@univ-paris13.fr, [f]mwrobel@agh.edu.pl, [g]alain.lodini@univ-reims.fr

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Abstract. Asymmetric rolling can be used in order to modify material properties and to decrease 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 study of microstructure, crystallographic texture and residual stress in asymmetrically rolled titanium (grade 2) is presented in this work. The above characteristics were examined using EBSD technique and X-ray diffraction. The rolling asymmetry was realized using two identical rolls, driven by independent motors, rotating with different angular velocities ω_1 and ω_2. It was found that asymmetric rolling leads to microstructure refinement, texture homogenization and lowering of residual stress.

Introduction

Symmetric rolling is commonly used in industrial practice and a huge majority of materials is formed in such a way. Asymmetric rolling presents some alternative - in this deformation mode the peripheral velocities of the top and bottom rolls are different [1-4]. The velocity difference can result from different angular velocities of rolls, their diameters or friction coefficients between rolls and a material. In the present study two identical rolls, of 180 mm diameter, were turning with different angular velocities (the bottom roll turned with 10 rpm) and the asymmetry ratio of the process, $A=\omega_1/\omega_2$, was defined. Asymmetric rolling is of potential importance for industrial applications, because it reduces the applied rolling forces, and changes the rolled plate shape. It also modifies material properties and microstructure. A strong shear stress, which is induced during this type of deformation, can lead to grain refinement, texture homogenization and reduction of residual stress. Asymmetric rolling can be used to tailor deformation textures and mechanical properties. In the present work the microstructure, crystallographic texture and residual stress of asymmetrically rolled commercially pure titanium were studied.

Microstructure of asymmetrically rolled titanium

The microstructure of titanium (grade 2) was examined by EBSD technique using Zeiss scanning electron microscope located in LSPM laboratory, University Paris 13. The presented EBSD maps show topology of the orientation distribution of normal direction, ND, in the crystal reference frame

([001] inverse pole figure). The maps for the initial material and for symmetrically ($A=\omega_1/\omega_2=1$) and asymmetrically ($A=1.5$) rolled samples are shown in Fig. 1. Samples rolled to 20 % reduction were examined in order to obtain good quality EBSD diffraction lines. It is already visible in Fig. 1 that microstructure is finer in the asymmetrically rolled material. This is confirmed in Fig. 2 a, where the average grain area determined from EBSD maps is shown for the central layer of material (the non-weighted arithmetic average for area was used in this work). The results for three degrees of asymmetry are presented: A=1, A=1.3 and A=1.5. We see that with increasing rolling asymmetry, the grain area is decreasing. Two other factors, which characterize fragmentation of the microstructure, are also presented in this figure. The *Kernel average misorientation* (Fig. 2 b) increases with the degree of rolling asymmetry, while the *average grain orientation spread* (Fig. 2 c) increases only slightly when passing from A=1.3 to A=1.5. The above three characteristics were obtained using OIM TSL software, attached to EBSD equipment. In conclusion we can state that asymmetric rolling produces smaller grains and more fragmented microstructure.

Initial material | *20 % rolling reduction* $A=\omega_1/\omega_2=1$ | *20 % rolling reduction* $A=\omega_1/\omega_2=1.5$

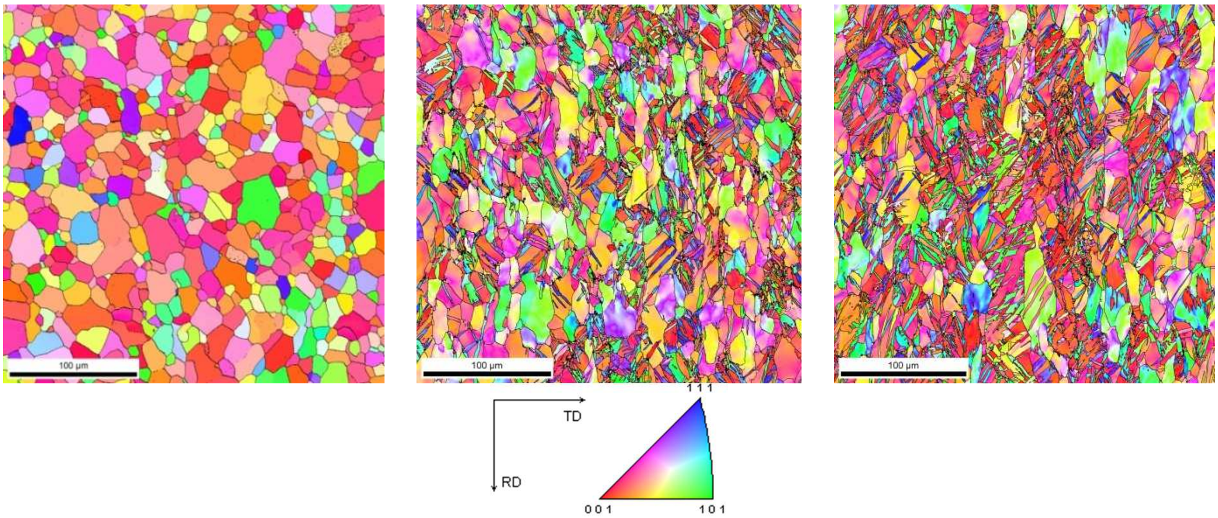

Fig. 1. *Maps of the orientation distribution for the initial material (titanium grade 2) and for the samples rolled symmetrically (A=1) and asymmetrically (A=1.5) to the reduction of 20 %.*

It is common industrial practice that annealing is applied after rolling in order to recover material properties. Therefore, we examined the microstructure characteristics of titanium samples rolled to a higher reduction (60 %) and annealed during 1 h at the temperature 550 C^0. In order to check the microstructure homogeneity, the EBSD study was done in three material layers: in the two surface layers (top and bottom) and in the centre layer. The results are presented in Fig. 3, where the average grain area in these material layers is shown for A=1, A=1.3 and A=1.5. The conclusion is that in each of the examined layers the average grain area decreases with increasing rolling asymmetry (A).

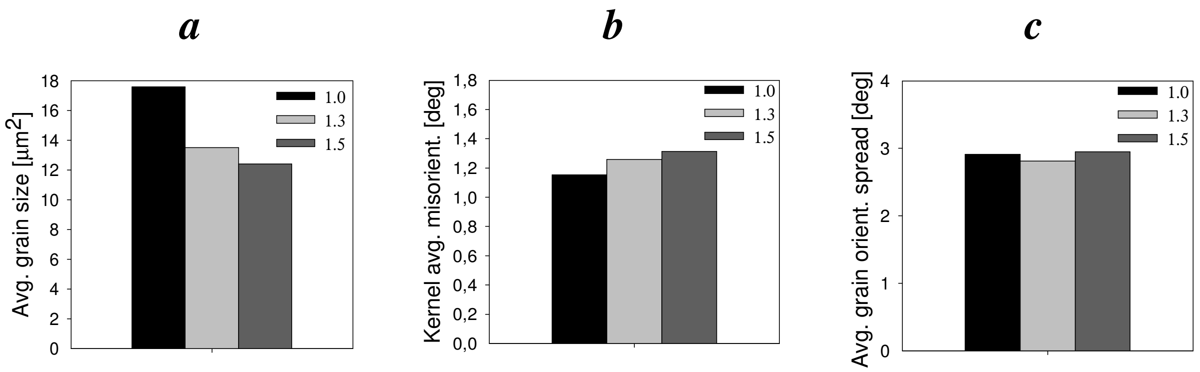

Fig.2. *Influence of rolling asymmetry (A=1, A=1.3 and A=1.5) on: a) average grain area (μm²), b) Kernel average misorientation, c) average grain orientation spread. Results for 20 % rolling reduction and for centre layers are shown.*

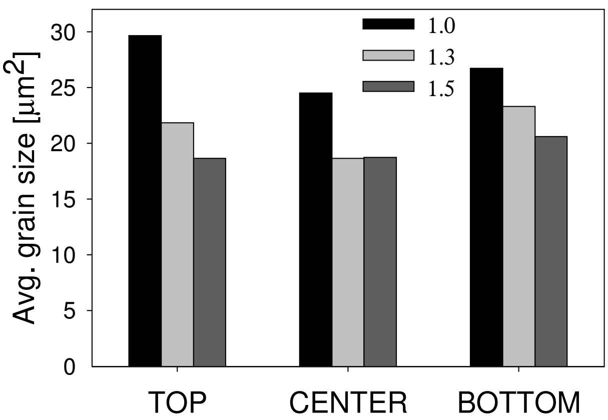

Fig. 3. *Influence of rolling asymmetry (A=1, A=1.3 and A=1.5) on grain area (μm²). Results for three material layers (top, centre and bottom) of titanium grade 2, rolled to 60 % reduction and annealed during 1h at the temperature 550 C, are shown.*

Texture variation

Crystallographic texture variation in symmetrically and asymmetrically rolled titanium was also examined. In all examined cases the measured pole figures (determined from EBSD maps) were not symmetrised and the orientation distribution function (ODF) was calculated. The representative ODF sections for $\varphi_1=0$ are shown in all examined cases. The textures of the initial material and of the symmetrically ($A=1$) and asymmetrically ($A=1.3$) rolled samples are shown in Figs. 4a-c (rolling reduction was 40 %). We note that the main maxima of the initial material as well as of the material rolled symmetrically and located in the centre of the sample - have symmetrical positions with respect to the red line plotted at $\varphi_2=30^0$ (Fig. 4b). In contrast, in the case of asymmetric rolling the texture maxima in the top and bottom surface layers are shifted to the left and right, respectively (Fig. 4c). This result was confirmed by texture modelling using Finite Element Method with implemented crystalline model [5]. It can be shown that the observed maxima shifts in the surface material layers are related to rotations of texture around the transverse direction (TD) due to a characteristic distribution of the internal shear stress component Σ_{13} [5] (where: RD=x_1, TD=x_2 and ND=x_3; RD).

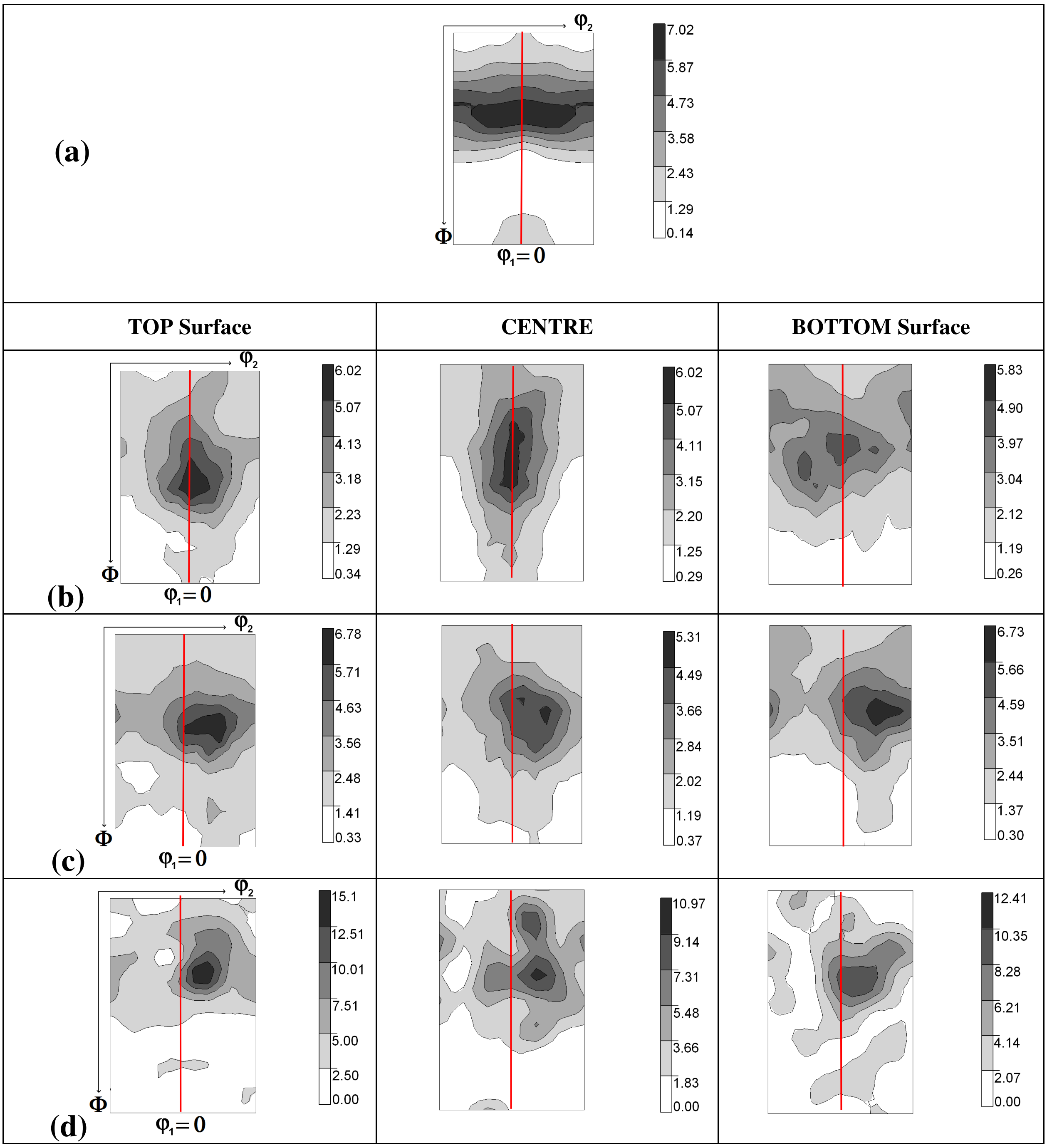

Fig. 4*.Textures of titanium (grade 2) determined by EBSD technique: a) texture of homogeneous initial material, b) textures in three material layers (top, centre, bottom) after symmetric rolling ($A=\omega_1/\omega_2=1.0$), c) textures after asymmetric rolling ($A=\omega_1/\omega_2=1.3$), d) textures after asymmetric rolling and annealing during 1 h at 550 ^0C .*

The rolling reduction was 40 %; $\varphi_1=0$ sections are shown and red lines are located at $\varphi_2=30^0$.

On the other hand, the asymmetric rolling leads to shifts of texture maxima of the same sign in three sample layers (Fig. 4c). In other words, the asymmetric rolling produces a nearly homogeneous texture, which is not the case of symmetric rolling ! This effect was also confirmed by the model calculations [5], though the maxima shifts are larger in the case of predicted textures. The resulting homogeneous texture is caused by a nearly homogeneous distribution of Σ_{13} internal stress component across the sample thickness during asymmetric rolling [cf. 5,6], and consequently by a homogeneous texture rotation around TD. Finally, the asymmetrically rolled samples were annealed (recrystallized) at 550 ^{0}C during 1 h and the resulting textures are shown in Fig. 4d. It is visible that the discussed shift of texture maxima in asymmetrically rolled sample persisted after recrystallizaton. Therefore, we conclude that asymmetric rolling has a strong influence both on rolling and recrystallization textures: it produces texture homogenisation across the thickness of the sample.

Residual stresses, coherent domain size and average lattice distortion

It is well known that residual stresses play an important role in mechanical and thermodynamic properties of materials (e.g., [7-10]). We examined residual stresses and also performed the analysis of diffraction peak shape. Residual stresses were measured on 'top' and 'bottom' sample surfaces using laboratory X-ray diffraction. Two titanium samples were examined: rolled symmetrically, $A=1$, and asymmetrically, $A=1.5$ (both to 80 % rolling reduction). Only two non-zero residual stress components were detected at sample surfaces: σ_{11} and σ_{22}. We note that two stress components are compressive in all presented cases. The important result is that the amplitudes of residual stress components are significantly lower in asymmetrically rolled samples. This tendency is especially visible in the bottom surface layer of material.

Table 1. *Residual stress components [MPa] in top and bottom surface layers of symmetrically and asymmetrically rolled titanium (A=1 and A=1.5). Rolling reduction was 80 %.*

	Top surface		Bottom surface	
	σ_{11}	σ_{22}	σ_{11}	σ_{22}
$A=\omega_1/\omega_2=1$	- 87.8 ± 18	-128.6 ± 18	-108.6 ± 18	-165.9 ± 18
$A=\omega_1/\omega_2=1.5$	- 60.4 ± 14	- 104.2 ± 14	- 37.7 ± 18	- 37.4 ± 18

The analysis of diffraction peak shape was done using Williamson-Hall method [11]. The average size of coherent domain, d, and the average lattice distortion, ε, were determined for two surfaces of the symmetrically and asymmetrically rolled titanium samples and they are presented in Table 2. We observe a clear tendency of reduction of d and ε when passing from symmetric to asymmetric rolling mode on each of the sample surfaces, though this effect is much stronger on the bottom surface, similarly like the behaviour of residual stress (cf., Table 1).

Table 2. *Average size of coherent domain, d [Å] and the average lattice distortion, ε, in the top and bottom surfaces of symmetrically and asymmetrically rolled titanium samples. The relative error of the measured quantities is about 30 % for d and 10 % for ε.*

	Top surface		Bottom surface	
	d [Å]	ε	d [Å]	ε
$A=\omega_1/\omega_2=1$	1890	0.40	2590	0.41
$A=\omega_1/\omega_2=1.5$	1160	0.38	640	0.34

Conclusions

The presented results show that asymmetric rolling of the polycrystalline titanium (grade 2) leads to the following modifications of material properties (compared to symmetric rolling):
- finer grains are obtained,
- microstructure is more fragmented,
- more homogeneous texture across the sample thickness is formed,
- residual stresses, coherent domain size and average lattice distortion in surface material layers are lowered; this effect is stronger in bottom sample surface (corresponding to slower roll).

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