Study of texture, microstructure and mechanical properties of asymmetrically rolled aluminium

M Wronski[1,2], K Wierzbanowski[1], S Wronski[1], B Bacroix[2], M Wróbel[3] and A Uniwersał[3]
[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 13, 99, av. J.B. Clément, 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*

Abstract. Asymmetric rolling is a promising forming technique offering numerous possibilities of material properties modification and the improvement of technological process parameters. This geometry of deformation is relatively easy to implement on existing industrial rolling mills. Moreover, it can provide large volume of a material with modified properties. The study of microstructure, crystallographic texture and mechanical properties of asymmetrically rolled aluminium 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. It was found that asymmetric rolling leads to microstructure refinement, texture homogenization and decreasing of residual stress.
E-mails: mwronskii@gmail.com, wierzbanowski@fis.agh.edu.pl, wronski@fis.agh.edu.pl, brigitte.bacroix@univ-paris13.fr, mwrobel@agh.edu.pl, auniwers@agh.edu.pl

1. Introduction

Symmetric rolling (SR) is commonly used in industrial practice and a huge majority of materials is formed in such a way. Asymmetric rolling (AR) presents some alternative - in this deformation mode the peripheral velocities of the top and bottom rolls are different [1-5]. 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, ω_1 and ω_2 (the bottom roll turned with 10 rpm). The rolling process asymmetry was defined as: $A=\omega_1/\omega_2$. AR is of potential importance for industrial applications, because it reduces the applied rolling forces and torques and modifies the rolled plate shape and its microstructure. In particular, it can lead to grain refinement. The associated strong shear deformation offers also a possibility of tailoring deformation and recrystallization textures and resulting mechanical properties. In the present work we study microstructure, crystallographic texture and mechanical properties of asymmetrically rolled aluminium 6061.

2. Microstructure of asymmetrically rolled aluminium

The material microstructure was examined by EBSD technique using Cambridge S360 (W-GUN) electron microscope located in LSPM laboratory, University Paris 13. The presented EBSD maps were determined in the RD-TD plane and they show topology of the orientation distribution of normal direction, ND, in the crystal reference frame. They were determined in the central sample layers. The maps for the initial material and for samples rolled symmetrically ($A=\omega_1/\omega_2=1$) and asymmetrically (A=1.1 and A=1.5) are shown in Figs. 1a and 1b, respectively. After AR we observe elongated grains, which are strongly fragmented in their interiors (Fig. 1b). The enhanced grain fragmentation after AR is confirmed by a systematic increase of the *Kernel average misorientation* vs. degree of rolling asymmetry (Fig. 2a).
It is common industrial practice that an annealing is applied after rolling in order to recover material properties. Therefore, we examined the microstructure of the material rolled to 36% reduction and annealed during 1 h at the temperature 500 °C. The obtained EBSD maps are shown in Fig. 1c. We observe equiaxed grains with decreasing size vs. rolling asymmetry. This


Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

result is quantitatively confirmed in Fig. 2b, where one observes a decrease of the average grain area vs. rolling asymmetry ratio (for its two measures :*'number'* and *'area'* - according to *OIM TSL* software). The grain boundary was defined under condition of misorientation higher than 15°.

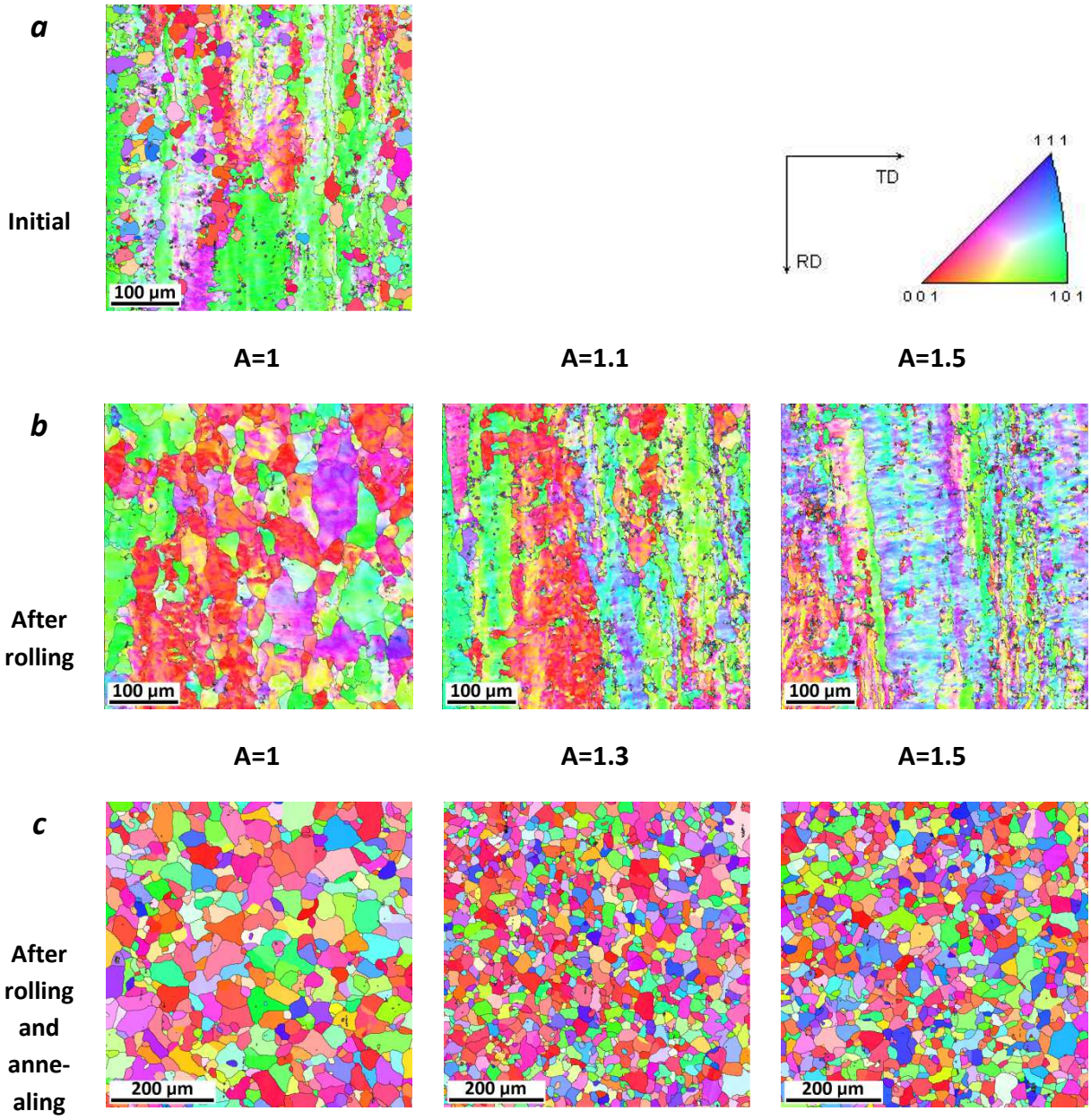


Fig. 1. *EBSD maps for the initial material (a), for the samples rolled symmetrically (A=1) and asymmetrically (A=1.1 and A=1.5) to the reduction of 36% (b), and for the samples annealed after rolling (with A=1, A=1.3 and A=1.5) at 500 °C for 1 h. Topology of ND orientation is shown.*

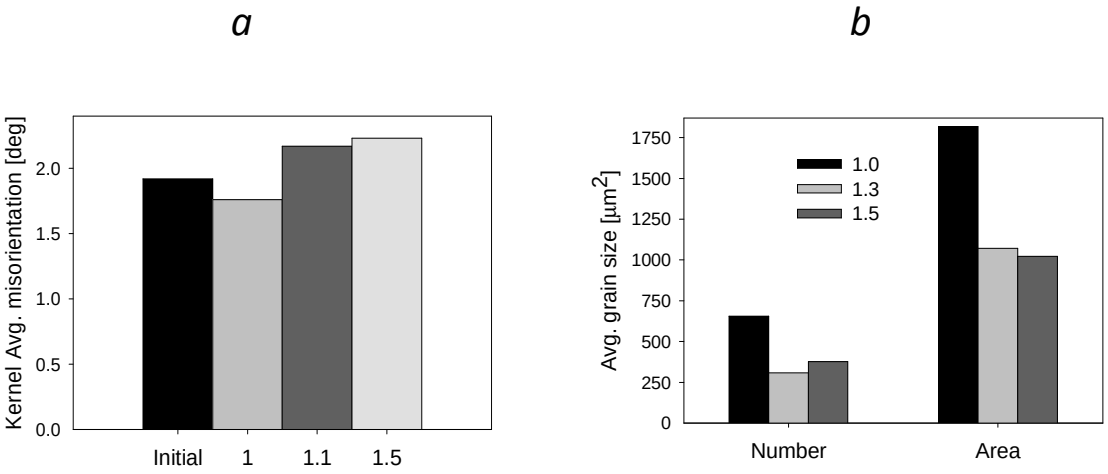


Fig.2. *Influence of rolling asymmetry (A=1, A=1.1, A=1.3 and A=1.5) on: a) Kernel average misorientation of samples rolled to 36% reduction, b) average grain area of samples rolled to 36% reduction and annealed at 500 °C for 1 h, calculated as 'number' and 'area' averages (µm²). Results for centre layers are shown.*

3. Texture variation

Pole figures were determined in three regions of the rolled samples, i.e. in the top, bottom and central layers, using X-ray diffraction. ODFs were calculated with WIMV method using popLA calculation package [6] (cf. also [7]). The crystallographic texture of the initial material was very sharp and contained Brass (*B*), Cubic (*W*), *S,* and Copper (*C)* orientations. This material was rolled symmetrically (*A*=1) and asymmetrically (*A*=1.5). The ODF sections at φ_2=*0°*, presenting the rolling textures, are shown in Fig. 3. A full analysis showed that the texture of SR sample contained the following components: *W* (dominating one), *B*, rather weak *C* orientation, and traces of *S* and *G* orientations. Characteristic effects appearing during SR and AR can be followed examining *B* component which is visible in φ_2=0° section. In the central layer of SR material all equivalent B component maxima lie on the horizontal red line drawn at Φ=45° (Fig 3c-left). In the surface layers of SR material one observes slight shifts of these maxima. In the top layer the first two maxima of B component (in the [0°, 180°] range of φ_1) are shifted up while the next two maxima are shifted down (Fig. 3b - left). All discussed textures are expressed in the same coordinates system: RD, TD, ND. The opposite shifts appear in the bottom layer of the material (Fig.3d - left). Another behaviour is observed in AR material - the shifts of *B* maxima are the same in the three examined layers (the first two maxima are shifted up while the next two maxima are shifted down) as seen in Fig. 3b-d - right. It was checked that the discussed shifts of maxima are caused by corresponding texture rotations around TD. In the case of AR they are of the same sign in the three material layers. Therefore we conclude that the texture becomes more homogeneous after AR process as compared to the SR process.

The aluminium samples were recrystallized after rolling (at 500 °C for 1 h). The recrystallization textures from the centre layer which are corresponding to SR (*A*=1) and AR (*A*=1.5) are shown in Fig.4. They contain only Cube (*W*) component. We do not observe any qualitative influence of the rolling asymmetry ratio, *A*, on the annealing textures.

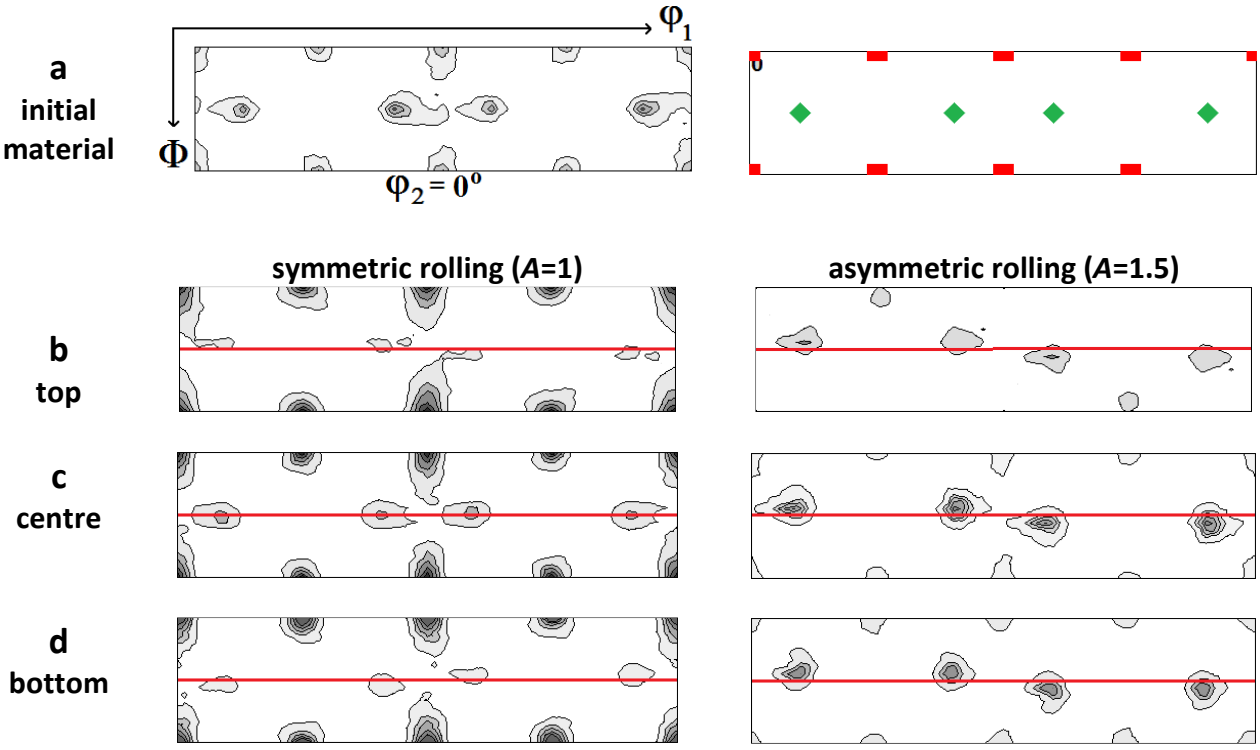


Fig. 3. *Textures of: homogeneous initial material (a) and of symmetrically and asymmetrically rolled samples determined in top (b), centre (c) and bottom (d) material layers. φ_2=0° sections are shown and red lines are located at Φ=45°. W (■) and B (◆) orientations are marked. Textures are presented using levels: 2.40, 8.00, 12.22, 17.61, 22.00, 35.00.*

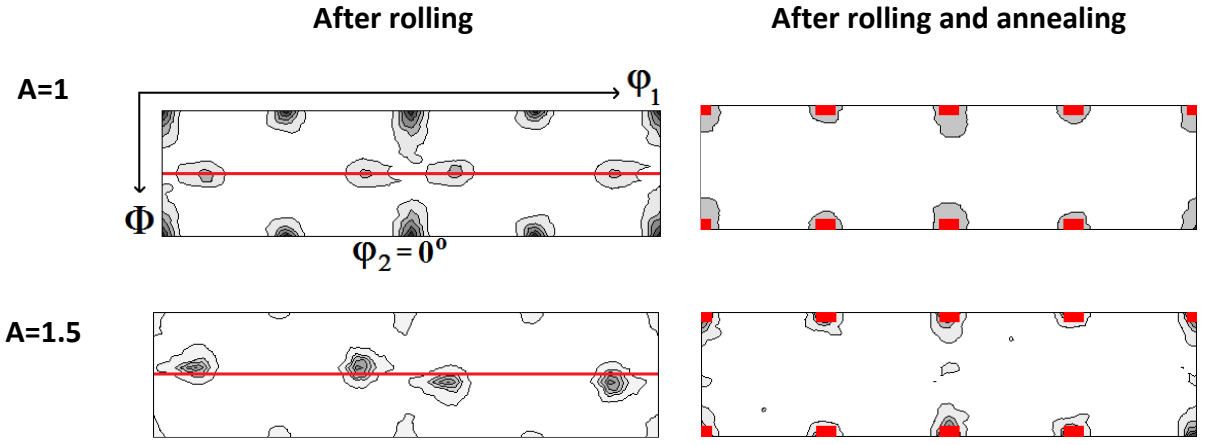


Fig.4. ODF sections ***(φ_2=0°)*** *for symmetrically and asymmetrically rolled and recrystallized aluminium 6061 samples (annealed at 500 °C for 1 h). Textures of centre layers are shown and W (■) component is marked. Textures were presented using levels: 2.40, 8.00, 12.22, 17.61, 22.00, 35.00.*

4. Selected mechanical characteristics

Asymmetric rolling has a noticeable influence on mechanical properties. The stress-strain curves from tensile test of samples with different ratios of rolling asymmetry are shown in Fig. 5. It can be noted that samples rolled asymmetrically have higher strength and are less ductile. This effect is caused by a stronger microstructure fragmentation.

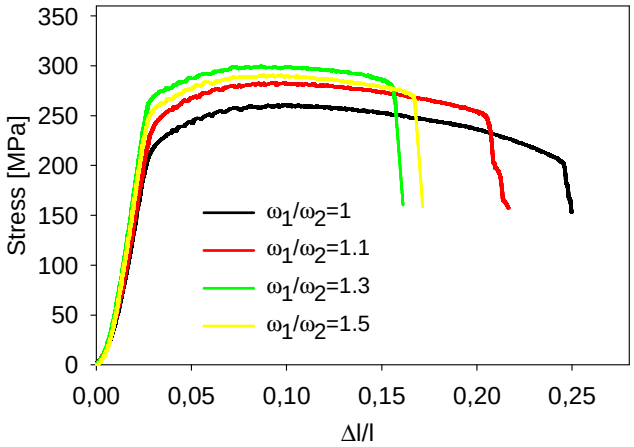


Fig.5. *Stress-strain curves from tensile test of samples rolled symmetrically (A=1) and asymmetrically (A equal to 1.1, 1.3 and 1.5).*

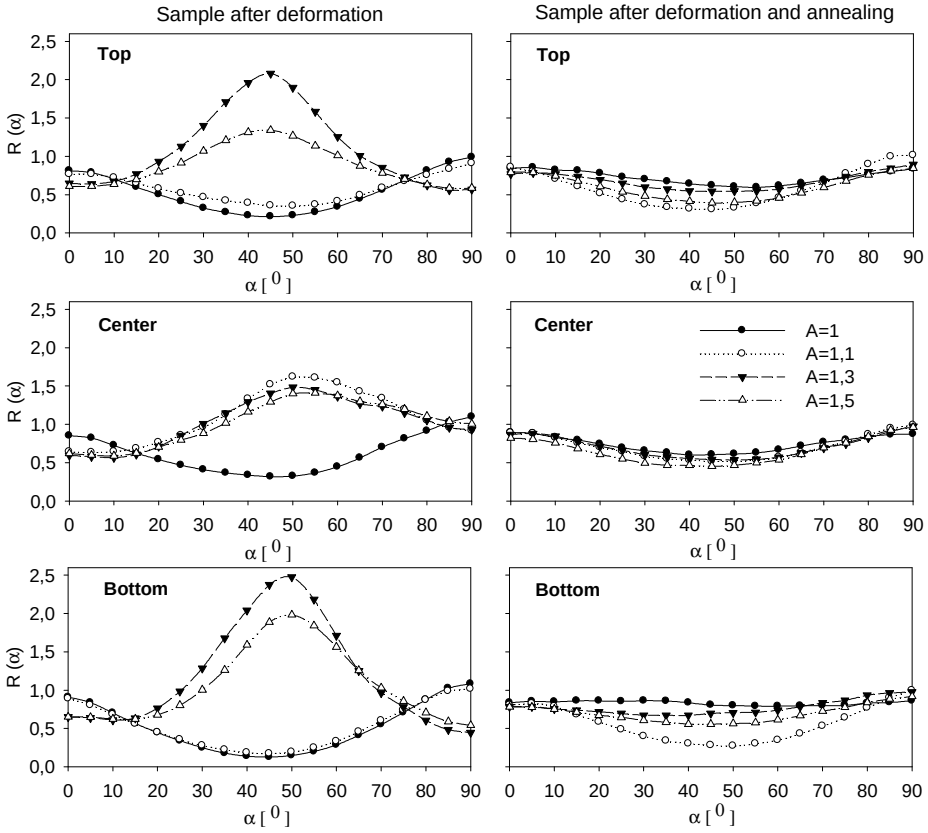


Fig.6. *Lankford coefficient, R(α), for rolled and annealed material in three sample layers (top, centre, bottom) for different ratios of rolling asymmetry, A. α is the angle between the tensile direction and rolling direction.*

The plastic anisotropy, defined by Lankford coefficient, was examined for the rolled and recrystallized samples (Fig. 6). This coefficient was calculated using deformation model and rolling textures of examined samples according to [8] (cf. also [9,10]). We observe an important increase of plastic anisotropy in the case of AR samples (compared to SR ones) in

the three considered material layers. In contrast, the influence of rolling asymmetry on plastic anisotropy is strongly reduced after recrystallization.
Determined by X-ray diffraction [11-13], residual stresses in the aluminum samples rolled to 70% reduction were considerable lowered after AR compared with SR. The σ_{11} residual stress component was reduced from -60 MPa to -23 MPa in the top surface layer, while for the bottom surface layer it was reduced from -90 MPa to -16 MPa (the experimental error was around 10 MPa), when passing from A=1 to A=1.5.

5. Conclusions

The obtained results show that asymmetric rolling of polycrystalline aluminium 6061 leads to the following changes in material properties:
- microstructure is more fragmented after AR than after SR,
- rolling textures are more homogeneous across the sample thickness after AR (they are homogeneously rotated around TD),
- recrystallization textures are similar after SR and AR and they contain only Cubic component,
- AR samples exhibit higher strength (visible in stress-strain curves from tensile tests) than SR,
- AR samples show much higher anisotropy of Lankford coefficient in the rolling plane (in three material layers) than the SR samples; this anisotropy is strongly reduced after recrystallization.

Acknowledgements

This study was financed by the Polish National Centre for Science (NCN) under decision numbers: DEC-2011/01/B/ST8/07394 and DEC-2011/01/D/ST8/07399.

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 et al. 2007, *Mat. Sci. Forum* **550** 551
[4] Wronski S et al. 2011, *Mater. Character.* **62** 22
[5] Wronski S et al. 2009, *Arch. Metall. Mater.* **54** 89
[6] Kallend J S et al. 1990 *Operational texture analysis, Report LA-UR-90-2852* (Center for Materials Science, Los Alamos National Laboratory, USA)
[7] Tarasiuk J et al. 1998, *Cryst. Res. Technol.* **33** 101
[8] Arminjon M and Bacroix B 1991, *Acta Mech.* **88** 219
[9] Wierzbanowski K et al. 2007, *Arch. Metall. Mater.* **52** 77
[10] Baczmanski A et al. 1995, *Zeit. Metallkd.* **86** 507
[11] Baczmanski A et al. 1997, *Revue de Metallurgie - Cahiers d'Informations Techniques* **94** 1467
[12] Baczmański A et al. 2006, *Mat. Sci. Forum* **524-525** 235
[13] Baczmanski A et al. 1999, *Archives of Metallurgy* **44** 39