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A. STEFANIK[1*], P. SZOTA[1], S. MRÓZ[1]

ANALYSIS OF THE EFFECT OF ROLLING SPEED ON THE CAPABILITY TO PRODUCE BIMODAL-STRUCTURE AZ31 ALLOY BARS IN THE THREE-HIGH SKEW ROLLING MILL

A numerical analysis of the process of single-pass rolling of AZ31 magnesium alloy bars in the three-high skew rolling mill has been carried out in the study. Based on the obtained investigation results, the effect of rolling speed on the band twist and the state of stress and strain occurring in the rolled band has been determined. From the obtained results of the numerical studies it has been found that with the increase in rolling speed the unit band twist angle θ, increase, which translates into an increase in the value of tangential stress in the axial zone of the rolled bar. This contributes directly to an increase in redundant strain in the rolled bar axial zone, which brings about a structure refinement. To verify the effect of rolling speed on the flow pattern and the stress and strain state, experimental tests were carried out. It has been found from the tests that the band twist (flow pattern) contributes to obtaining a bimodal structure in the bar cross-section.

Keywords: three-high skew rolling mill, radial-shear rolling, magnesium alloys, bimodal-structure bars, FEM

1. Introduction

The intensification of research on the possibility of manufacturing products of a refined, often ultrafine-grained, and bimodal structure, both of steel and lightweight metals, has resulted in the development of a number of manufacturing methods, such as high-pressure torsion, equal channel angular pressing, multiaxial deformation, twist extrusion, etc. [1-4]. Implementing severe plastic deformation methods (SPD) in production may result in obtaining a finished product of enhanced strength, compared to products made by traditional metal forming methods. Moreover, SPD methods may also result in an improvement in other properties of finished products, such as fatigue strength [5], wear resistance [6], corrosion resistance [7], electric conductivity [8], as well as obtaining a bimodal structure [9-10]. However, the use of SPD methods in the technological process is often limited by constructional considerations. One of the metal forming processes, which enable a fine-grained structure to be obtained in finished product, is the process of rolling on modified skew rolling mills. Screw rolling is a process in which a workpiece is deformed plastically by drive rollers rotating in the same direction, whose axes are inclined to the rolling axis and cross it at the same point. The screw rolling technology has found industrial application in three major areas: production of seamless pipes [11], production of rolled parts [12], production of solid billets and bars [13,23,24]. The aim of the screw rolling process to production of the bars with special properties is severe shear deformation and metal densification over the entire cross section of the rolled product, in which unique structure and enhanced properties are realized. The process is based on the scientific principle advanced by I. Potapov and P. Polukhin in the 1970s [14], according to this process, increasing the roll skewing angle up to a range of 18-24º (in the case of classic applications of three-high skew rolling mills, the roll skewing angle is merely 4-6º) leads to the occurrence of additional radial tangential stresses in the material being deformed. Research on the application of the process of rolling aluminum alloys [15] and magnesium alloys [16-18] in the three-high skew rolling mill has shown that it is possible to obtain bars of improved mechanical properties, compared to other manufacturing methods, thanks to a strongly refined bimodal microstructure. The investigation carried out within work [23] has shown that in order to obtain an ultra-fine structure in copper bars rolled on the three-high skew rolling mill, several rolling passes are needed to be used. An extensive discussion of the possibility of manufacturing AZ61 magnesium alloy bars of the bimodal structure is covered in study [10], where, in five passes with an incrementing unit deformation, 56 mm-diameter bars were rolled into a final diameter of 15 mm. The

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[1] CZĘSTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF MATERIAL PROCESSING TECHNOLOGY AND APPLIED PHYSICS, DEPARTAMENT OF METALLURGY AND METAL TECHNOLOGY, 42-200 CZĘSTOCHOWA, 19 ARMII KRAJOWEJ AV., POLAND

[*] Corresponding author: stefanik.andrzej@wip.pcz.pl

presented structure examination results have shown that, with an initial grain size of 16.9 μm, an average grain size of 1.5 μm was achieved after the rolling process at the surface, and 3.5 μm on average in the rolled bar axis, with the structure in the axis being much more diverse than that at the surface. While work [24] has demonstrated that by using the three-high skew rolling mill rolling process it is possible to obtained bars with a refined gradient structure from a new type of high-strength aluminium alloy in series 7000. Studies [10,16,24] report only experimental testing results, while work [23] covers a considerably limited numerical analysis of the three-high skew rolling mill rolling process. Therefore, it is justifiable to extend the conducted research by numerical analysis, especially using the cylindrical coordinate system.

Metal forming of magnesium alloys is complicated, due to the specific arrangement of atoms in crystallographic lattice, which is the reason of low ductility caused by a limited number of slip planes allowed at ambient temperature [19]. The application of the skew mill rolling process for the production of magnesium alloy bars enables the activation of additional deformation mechanisms resulting from the influence of radial tangential stress.

The aim of the investigations undertaken within this study was to determine the effect of the speed of rolling magnesium alloy AZ31 in the three-high skew rolling mill on the stress and strain state (increase in the share of tangential stress and redundant strain) occurring during rolling, which would bring about a strong refinement of the microstructure. The numerical analysis was conducted for a single rolling pass, in which feedstock of an initial diameter of 25 mm was rolled into a diameter of 20 mm. The theoretical studies were verified in rolling tests carried out on an RSP 14/40 three-high skew rolling mill.

2. The properties of materials used in the research

The material used for the tests was magnesium alloy AZ31, which is widely used in metal forming for the production of, e.g., plates and bars, and whose chemical composition is shown in Table 1. The other physical properties of the alloy tested were assumed based on relevant literature data [20].

TABLE 1

Chemical composition of AZ31 magnesium alloy /wt %

	Mg	Al	Zn	Mn	Si	Cu
AZ31	ballance	2.5	1.0	0.12-0.14	0.08	0.03

The application of the computer program Forge2011® using the thermo-mechanical models that it contains requires the definition of boundary conditions which are decisive to the correctness of numerical computation. The accuracy of numerical modelling highly depends on the accurate determination of the properties of materials used for simulations. The yield stress σ_p dependence of strain ε, strain rate $\dot{\varepsilon}$ and temperature T used for the theoretical research is approximated by extended Hensel-Spittel [21] formula expressed as:

$$\sigma_p = A \cdot e^{m_1 \cdot T} \cdot T^{m_9} \cdot \varepsilon^{m_2} \cdot e^{\frac{m_4}{\varepsilon}} \cdot (1+\varepsilon)^{m_5 \cdot T} \cdot \\ \cdot e^{m_7 \cdot \varepsilon} \cdot \dot{\varepsilon}^{m3} \cdot \dot{\varepsilon}^{m_8 \cdot T}, \text{MPa} \tag{1}$$

where: A, m_1, m_2, m_3, m_4, m_5, m_6, m_7, m_8, m_9 – coefficients of the function.

In order to determine the coefficients of the equation (1) performed approximation results of the plastometric test results made on the Gleeble 3800 system in Institute of Metal Forming and Safety Engineering Czestochowa University of Technology. Plastometric tests were performed, using strain rate of: 0.1 s^{-1}, 1.0 s^{-1}, and 10.0 s^{-1} for the temperature range from 350°C to 450°C. The coefficients of function (1) were developed based on the plastometric test results by mean-square approximation using an exponential function. Coefficients used in equation (1) are given in Table 2. Example flow curves for the AZ31 magnesium alloy for the temperature 400°C (initial temperature of the stock in rolling process) are presented in Fig. 2. The solid lines with full markers denote the actual curves (obtained from plastometric tests), while the solid lines with hollow markers denote the curves determined based on the results of approximating with function (1).

The behavior of the plastic flow curves (Fig. 1) determined from the plastometric tests confirms that during metal forming of magnesium alloy AZ31 at low deformation speeds, recovery and recrystalisation processes take place in the alloy [19,22]. A characteristic lowering of the flow stress is observed after exceeding a strain value of approx. 0.4. The maximum flow stress values were obtained for a true strain value not exceeding 0.2.

3. Numerical modelling of the AZ31 magnesium alloy in three-high skew rolling mill

A computer program Forge2011® has been repeatedly used in the modelling of forming processes with appropriate selection of the initial parameters, obtained results were characterized by a high compatibility with experimental research [15,17,18].

An important issue in numerical modelling of the three-high skew mill rolling process is to correctly define the geometry and the axis of rotation of the rolls. Based on the technical documentation of the RSP 14/40 three-high skew rolling mill, a three-dimensional model was made in a CAD program, containing the rolling mill's body with inserts moving relative to

TABLE 2

Parameters of function (1) for the AZ31 magnesium alloy

A_0	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9
0.684788	–0.00721633	0.342418	0.02864	0.000230534	–0.00439388	–0.08198	0.0002181	1.41094

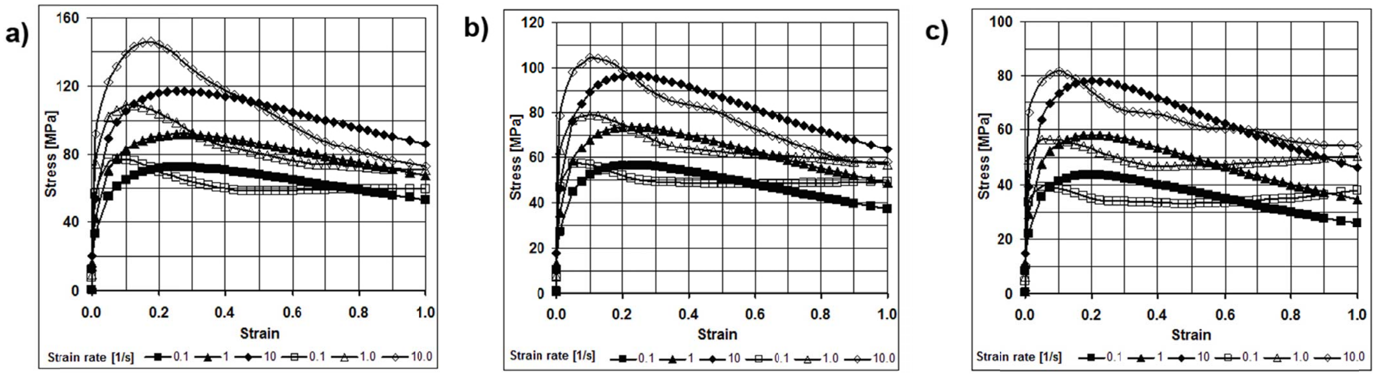

Fig. 1. Plastic flow curves for the AZ31 magnesium alloy for temperatures: a) 350°C, b) 400°C, c) 450°C

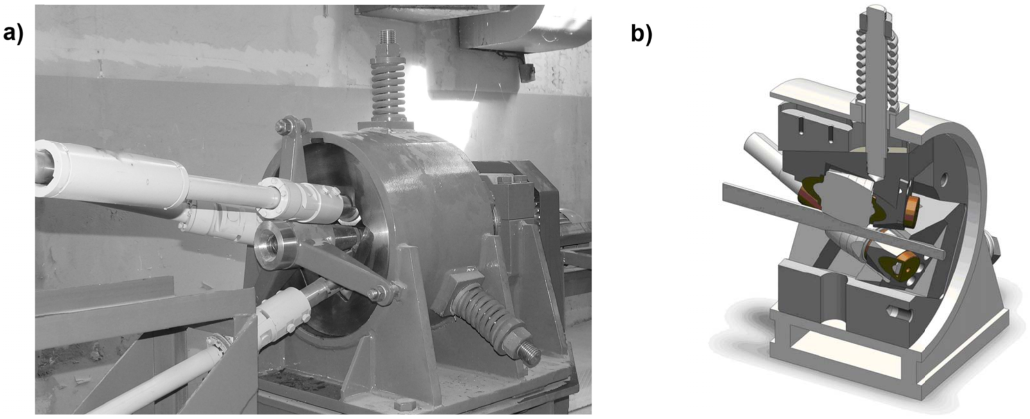

Fig. 2. View of three-high skew rolling mill (a), and CAD model used for the numerical modelling (b)

each other, on which the rolls are mounted (Fig. 2). This provided the capability to map the mutual position of the rolls and to determine the skewing angles and the axis of rotation of the working rolls. The models made were then implemented in the Forge2011® program.

The process of rolling bars in the three-high skew rolling mill can be regarded as an axially symmetrical process, whose essential feature is the forced flow of metal following the torsion lines. To facilitate the analysis of the process, it is advantageous to adopt a cylindrical coordinate system which will be oriented in such a manner that the z axis will coincide with the axis of the rolled bar. The remaining directional coordinates are denoted as follows: r – radial coordinates, and ρ – angular coordinates.

An initial diameter of the stock was 25 mm. The diameter of the final bars was set up to 20 mm. Elongation in this case during the magnesium alloy bar rolling in three-high skew rolling mill was equal to 1.56. The theoretical analysis was performed for the real rolling conditions: working rolls diameter – 90 mm, friction factor – 0.8, coefficient of heat exchange between the material and the tool α – 5 000 W/(Km^2); coefficient of heat exchange between the material and the air αair – 10 W/(Km^2), working rolls temperature – 30°C; ambient temperature – 20°C and the stock temperature – 400°C. The theoretical studies were carried out for three variants of rotational speeds (corresponding to the range of rolling speeds for the laboratory RSP 14/40 three-high skew rolling mill),i.e.: Variant I-V = 50 rpm; Variant II-V = 75 rpm; and Variant III-V = 100 rpm.

To determine the twist angle θ (the angle of band torsion in the roll gap), a coordinate grid was introduced, which was deformed along with the rolled material. The assumed coordination grid had dimensions corresponding to the dimensions of the feedstock used for the tests, namely: a height of 25 mm (corresponding to the initial diameter of the rolled stock) and a length of 150 mm (equal to the initial length of the rolled stock).

4. Results and analysis of theoretical studies

Based on the performed numerical studies, the changes in the shape of the coordination grids were determined for each of the examined variants. The deformed grids were analyzed and from the analysis results, the twist angle θ was determined for each grid (the angle of torsion in the deformation zone). The twist angle defines the torsion of the material between the arm occurring in the plane of entry to the deformation zone (spanned between the trace of the rolled bar axis and the point on the rolled bar perimeter) and the arm in the plane of exit from the deformation zone (defined by analogous points). The coordination grid shapes and the twist angles θ determined from the numerical studies for the examined rolling process cases are illustrated in Fig. 3. Fig. 3a-3c represent the planes of band entry/exit to/from the deformation zone. From the analysis of the obtained study results it can be found that with the increase in rolling speed, the value of the band twist angle increases. Fig. 3d il-

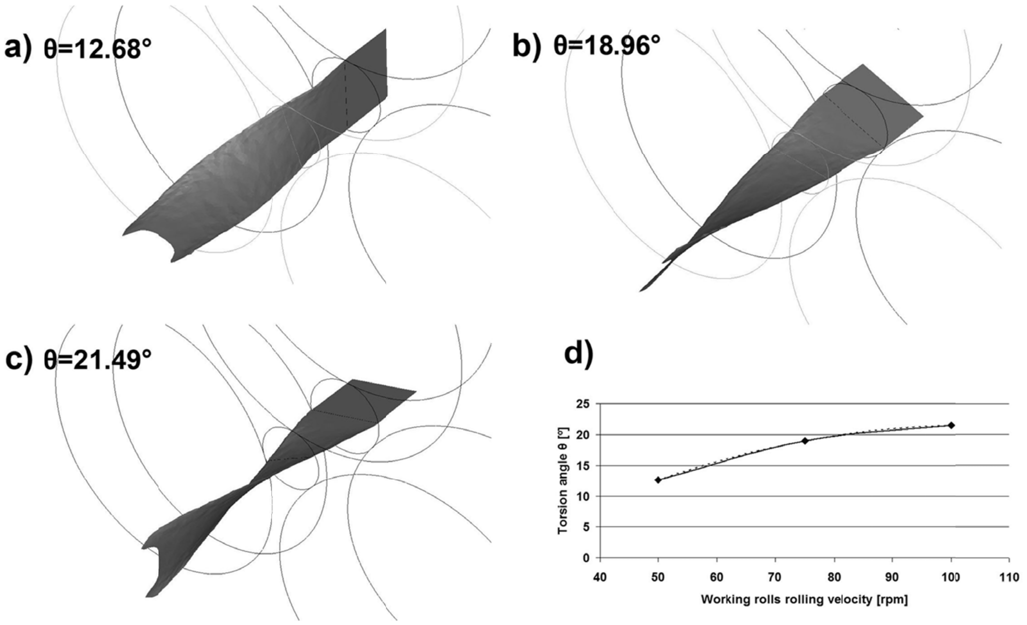

Fig. 3. View of deformed coordination grids: a) variant I, b) variant II, c) variant III d) dependence of torsion angle θ on rotational speed of rolls

lustrates the relationship of the magnitude of the twist angle θ versus roll rotational speed for the examined process. Based on the obtained results it can be stated that increasing the rolling speed has the effect of increasing the band twist angle. This is because the rotational speed in three-high skew mill rolling process translates directly into the linear speed of the rolled bad, as well as its rotational speed. Increasing the roll rotational speed causes, at the same time, an increase in band rotational speed, which results in an increase in deformed band twist [14]. The effect of increasing the band twist should be an intensification of tangential stress $\tau_{\rho z}$.

To determine the effect of roll rotational speed variation on the stress and strain state determining the possibility of activation of additional shear bands in the deformed material, the distributions of the component of $\tau_{\rho z}$ stress (tangential stress) tensor, strain intensity, and the component of $\gamma_{\rho z}$ strain (redundant strain) tensor were analyzed.

The distribution of the $\tau_{\rho z}$ stress tensor component on the rolled bar longitudinal section has been shown in Fig. 4. When analyzing the data in Fig. 4 it can be noticed that for all examined variants, the maximum value of tangential stress $\tau_{\rho z}$ is at a similar level (in the range of 180÷200 MPa) and occurs in the of metal-roll contact regions. Increasing the rolling speed, on the other hand, results in an increase in the magnitude of the analyzed stress in the rolled bar axis direction. By comparing the obtained results it can be noticed that the magnitude of the analyzed stress increases by approx. 50 MPa in the zone from the rolled bar axis to the mid-radius for Variant III, compared to Variant I. Whereas, no change in $\tau_{\rho z}$ stress magnitude is observed in the axis of the rolled bar. It can, therefore, be assumed that the increase of the θ angle caused by increasing the rolling speed results in an increase in the magnitude of tangential stress in the inner zone of the rolled bar, but not in the rolled bar axis itself.

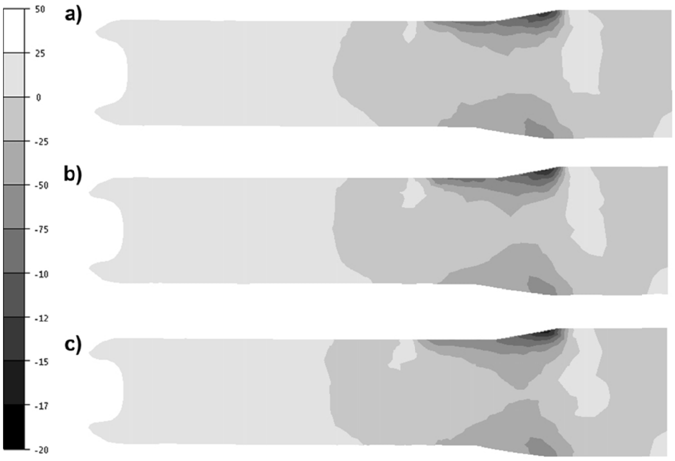

Fig. 4. Distribution of stress component $\tau_{\rho z}$ during the rolling of the 20 mm magnesium alloy AZ31 round bar in three-high skew rolling mill: a) Variant I, b) Variant II, c) Variant III

The distribution of strain intensity for the analyzed rolling process variants has been shown in Fig. 5. When examining the data in Fig. 5 one can notice that the effect of rolling speed on the magnitude of strain intensity is relatively small. It can also be noticed that with increasing roll rotational speed, the magnitudes of strain intensity in the rolled bar core zone increase. However, the maximum differences between Variant I (Fig. 5a) and Variant III (Fig. 5c) do not exceed a value of 0.4 for the axial zone, while in the sub-surface layers, the distribution character and strain intensity values are identical for all examined variants. For the examined cases, the maximum values of strain intensity in the sub-surface layers are contained in the range from 3.8 to 4.5, while in the core zone, from approx. 0.9 to 1.9. This causes considerable structure refinement, occurring, however, non-uniformly on the rolled bar cross-section. Even though the strain intensity distribution varies considerably between the outer zone of the rolled bar and its core zone, the obtained strain values confirm that the deformation penetrates to the axis of the rolled bar.

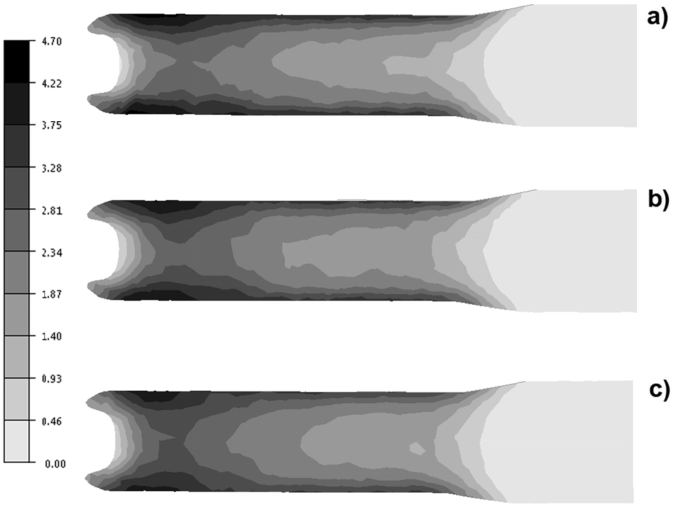

Fig. 5. Distribution of effective strain during the rolling of the 20 mm magnesium alloy AZ31 round bar in three-high skew rolling mill: a) Variant I, b) Variant II, c) Variant III

To determine in detail the effect of rotational roll speed on the deformation and the structure refinement capability, Fig. 6 shows the distribution of the component of $\gamma_{\rho z}$ strain tensor (corresponding to the redundant strain in the torsion direction). The data represented in Fig. 6 confirm that increasing the roll rotational speed causes an increase in the value of the $\gamma_{\rho z}$ strain tensor component in the axial zone of the rolled bar. While the obtained redundant strain values in the sub-surface zones are comparable, with the increase in roll rotational speed in the axial zone the values of the component under examination increase. It can also be noticed that for all examined variants, a characteristic sequential distribution (symmetric with respect to the rolled bar axis of symmetry) is observed. The observed sign change determines only the direction computing the $\gamma_{\rho z}$ strain tensor component value. The local zones of maximum $\gamma_{\rho z}$ strain values (in the range of absolute values from 0.2) are the natural locations of initiation of local shear band formation. As shown by previous studies, considerable structure refinement occurs in this region [10,18].

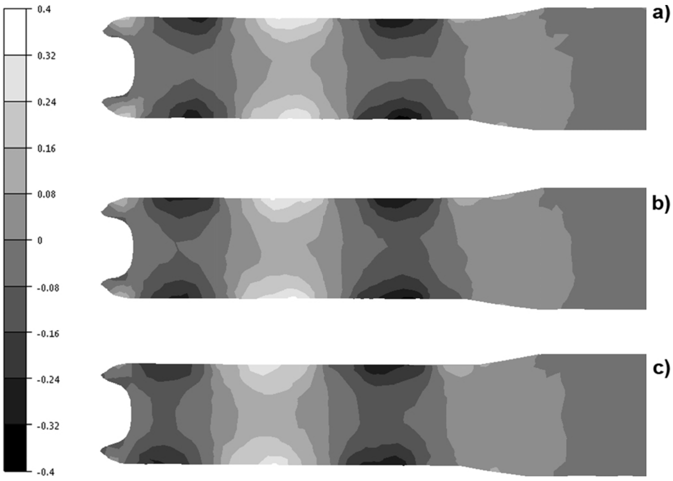

Fig. 6. Distribution of $\gamma_{\rho z}$ strain component during the rolling of the 20 mm magnesium alloy AZ31 round bar in three-high skew rolling mill: a) Variant I, b) Variant II, c) Variant III

5. Experimental verification of theoretical research

The experimental tests of the process of rolling AZ31 magnesium alloy bars were carried out on an RSP 14/40 laboratory rolling mill using process parameters corresponding to Variant III of numerical studies. For the experimental tests, Variant III was selected, as the one that most intensifies the band torsion, leading to the occurrence of considerable tangential stress and redundant strain. Test specimens of an initial length of 150 mm were made of 25 mm-diameter bars. Degreased specimens were then heated up to a temperature of 400ºC and rolled in a single rolling pass into a final diameter of 20 mm. From rolled bars, templates were taken for structural examination. Specimens for observations with an optical microscope were etched in a reagent with the following composition: 10 ml $C_2H_4O_2$, 6g $C_6H_3N_3O_7$ and 100 ml C_2H_5OH. The specimens were taken in longitudinal section of the rolled bars. The macro photograph taken for a specimen prepared for microstructure observation (the arrow indicates the rolling direction) has been shown in Fig. 7.

When examining the data in Fig. 7 one can notice a characteristic shape of the deformed metal flow lines, which is caused by both the linear displacement in the rolling direction, as well as the torsion of the rolled band in the deformation zone. It can be noticed that the revealed flow lines are coincident with the distribution of the redundant strain component, shown in Fig. 6. The shape of the torsion lines in the sub-surface layer, obtained from the analysis of the experimental tests, is inclined to the rolled bar axis. It can also be noticed that in the region at the bar axis, the pattern of metal flow is mainly linear (longitudinal). This is due to the fact that the influence of tangential torsion strain is smaller here (as per the data in Fig. 6). By contrast, in the sub-

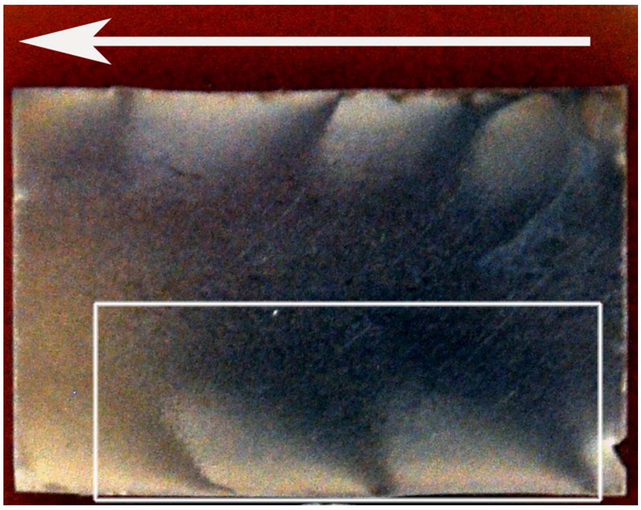

Fig. 7. A macro photograph of the revealed microstructure of a 20 mm-diameter AZ31 alloy bar rolled in a three-high skew rolling mill

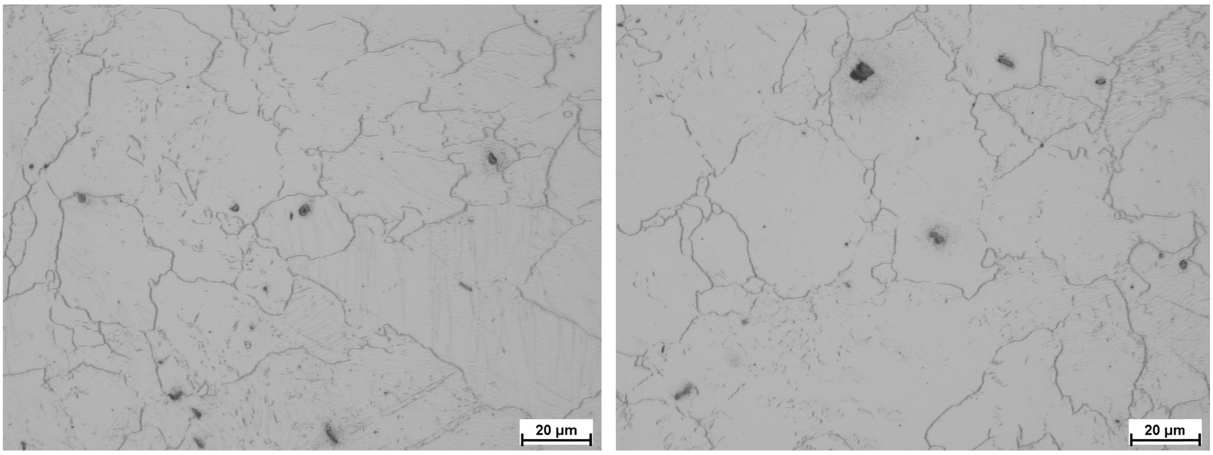

Fig. 8. Initial microstructure of the AZ 31 magnesium alloy bars used to three-high skew rolling process (magn. 500×)

surface zone, the values of this strain are greater. In the case of magnesium alloys, increasing the influence of tangential stress results in the activation of additional deformation mechanisms [19] causing the refinement of the structure; so, it is advantageous in this case to increase the rolling speed to obtain the greatest possible band twist in the deformation zone.

An initial microstructure defined for bars used as rolling feedstock has been shown in Fig. 8. Analyzing the data presented in the Fig. 8 it can be seen that the material are shown large grains, about 130 μm with visible deformation twins.

To determine the microstructure variations caused by the process of rolling using Variant III, an analysis was conducted in three characteristic areas, as shown in Fig. 7. The points denote the following, in succession: 1 – rolled bar sub-surface layer (about 0.1 mm from the surface), 2 – half radius (about 5 mm from the bar axis) and 3 – bar axis. The obtained microstructure photographs are shown in Fig. 9. When analyzing the data in Fig. 9 it can be noticed that, for the entire volume of the rolled bar, a refinement of the microstructure has occurred. The average grain size for the examined bar regions was, respectively: 1 – approx. 6 μm, 2 – approx. 21 μm and 3 – approx. 35 μm. At the same time, according to the previous theoretical study results, it can be noticed that the greatest refinement occurs in the sub-surface zone, while the least, at the bar axis. The obtained results confirm that the occurring additional tangential stress contributes to an intensive structure refinement (especially in the region from about the mid-radius to the bar surface). It can be observed at the same time that, both at point 1, as well as at point 2, regions with heavily refined grains, but also isolated larger grains, occur. This confirms the earlier observations that so-called "shear bands" are activated in this case, which markedly contribute to microstructure refinement [10,17÷19]. It can be presumed that applying subsequent rolling passes should result in a further refinement of the structure, its homogenization in individual regions, and a reduction of differences in grain size for the examined characteristic points [17]. So, the bar obtained from the rolling process has every features of a bimodal product with a considerable diversification of structure size within the entire volume.

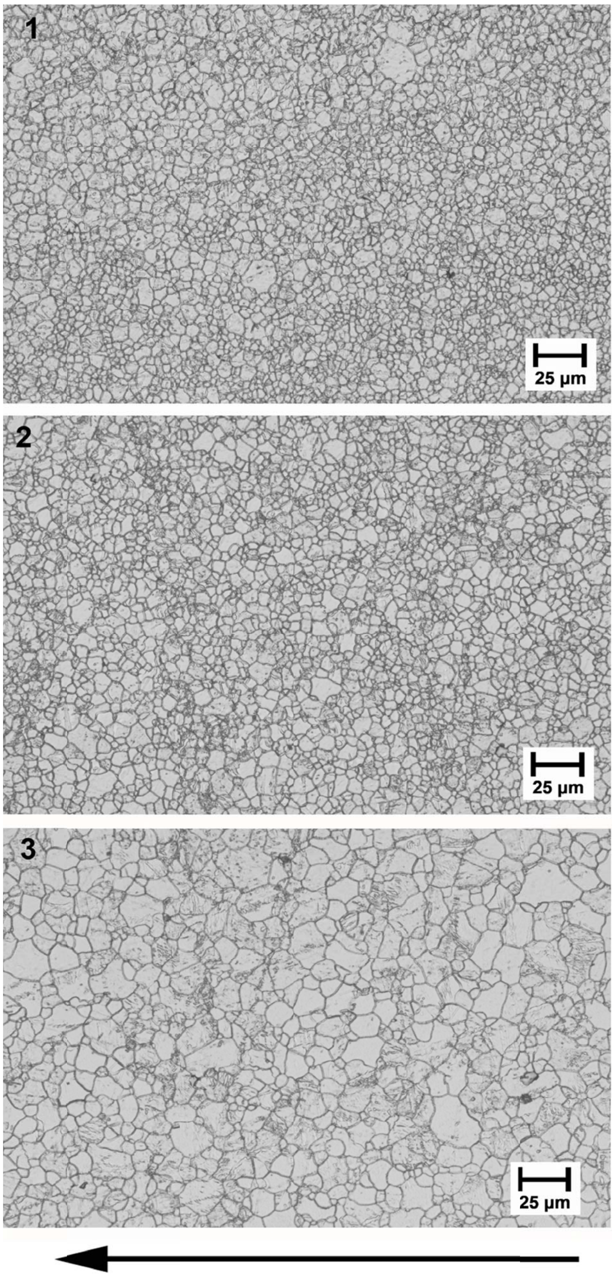

Fig. 9. Microstructure of the AZ31 bars with a diameter of 20 mm in the analyzed areas (magn. ×200)

5. Summary

From the theoretical and experimental studies carried out, the following can be concluded:

- the increase in roll rotational speed, it is observed an increase in unit twist angle θ in the deformation zone, which cause an intensification of tangential stress $\tau_{\rho z}$ in the rolled bar axial zone (from the axis to about the mid-radius), change in the magnitude of tangential stress $\tau_{\rho z}$ results in an increase in strain intensity, chiefly in the axial zone of the rolled bar;
- the component of redundant strain $\gamma_{\rho z}$, for all examined variants, has a characteristic sequential distribution (symmetrical with respect to the rolled bar axis of symmetry); moreover, with the increase in rolling speed, an increase in $\gamma_{\rho z}$ value can be noticed to take place in the axial zone;
- the macro analysis of the microstructure of bar rolled following variant III revealed characteristic torsion lines and a nearly linear flow of metal in the rolled bar axis, shape of the shape of the flow line revealed in experimental studies coincides with the distribution obtained for the component of redundant strain $\gamma_{\rho z}$ in heoretical studies;
- the microstructure analysis showed that a microstructure refinement occurred within the entire bar volume; whereas, the grain size was varying (from around 6 μm in the subs-surface layer to around 35 μm in the bar axis);
- the obtained results of the theoretical studies and experimental tests have confirmed that the use of the three-roll skew rolling mill enables bimodal bars to be produced, which are characterized by a non-uniform structure with a heavy grain refinement in the subs-surface layer, with the grain size increasing steadily towards the bar axis.

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