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The mathematical model of the mean flow stress for MgAl3Zn1Mn magnesium alloy

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ABSTRACT

Purpose: The presented paper deals with method for determination of mean flow stress (MFS) which contributes to better knowledge of forming processes of hot formed magnesium alloys.

Design/methodology/approach: An experiment leading to obtaining the model of the mean flow stress (MFS) of magnesium alloy AZ31 was realized in laboratory rolling mill. It resulted from mathematical and statistical processing of MFS values that these could be described by a simple function of just two independent variables – temperature (200 to 450°C) and equivalent height strain (approx. 0.2 to 0.7). The methods of the light microscopy for metallographic analyses were used.

Findings: The increasing strain resulted in decreasing deformation resistance. The effect of equivalent strain rate (approx. 10-80 1/s) was negligible. The model describes the given relationship with good accuracy; a relative error of calculated MFS values does not exceed ±10%.

Research limitations/implications: In future work an important relation between the MFS, the Zener-Hollomon parameter and the grain size will be determined. A significant influence of the deformation temperature on the average grain size after recrystallization was identified, while observing lower sensitivity of this parameter to an increased strain rate.

Practical implications: The results of structural studies along with the devised thermomechanical model will be used to design the foundations of rolling technology for this group of alloys. The results of this paper are determined for research workers deal by development new exploitations of magnesium alloys.

Originality/value: These results describe complex evaluation of properties magnesium alloys namely for determination of the values of mean flow stress (MFS) which contributes to better knowledge of forming processes of hot formed magnesium alloys and explain the structure developed used magnesium alloys after forming.

Keywords: Metallic alloys; Hot rolling; Metallographic analysis of structure; Mathematical model of mean flow stress

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MATERIALS

1. Introduction

At the contemporary stage of the development of the engineering thought, and the product technology itself, material engineering has entered the period of new possibilities of designing and manufacturing of elements, introducing new methods of melting, casting, forming, and heat treatment of the casting materials, finding wider and wider applications in many industry branches. Engineers whose employment calls for significant expenditure of labour and costs strive to reduce material consumption. Therefore the development of engineering aims at designs optimizing, reducing dimensions, weight, and extending the life of devices as well as improving their reliability. One of that's materials appears magnesium and its alloys. Scope of utilisation of foundry magnesium alloys is continuously being extended, so if we want to operate as competitive producers, it is necessary to investigate very actively properties of individual alloys, optimise their chemical composition, study issues of their metallurgical preparation, including heat treatment and forming methods [1-6].

Magnesium and magnesium alloys are primarily used in aeronautical and automobile industry in wide variety of structural characteristics because of their favourable combination of tensile strength (160 to 365 MPa), elastic modulus (45 GPa), and low density (1 740 kg/m^3), which is two-thirds of that of aluminium). Magnesium alloys have high strength-to-weight ratios (tensile strength/density), comparable to those of other structural metals.

A potential development direction of magnesium alloys is shown in Fig. 1 [3].

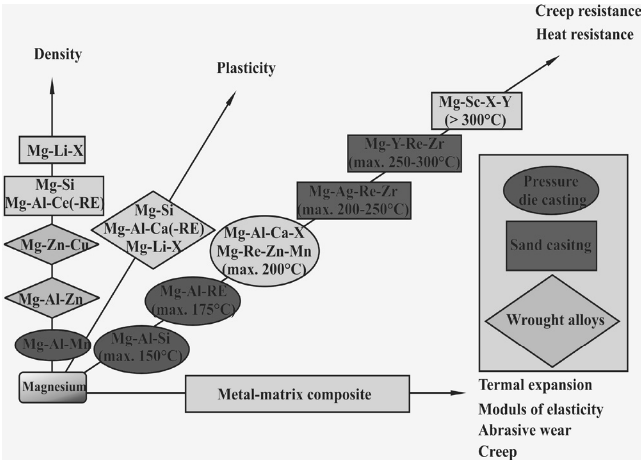


Fig. 1. Potential development directions of new magnesium

Magnesium alloys are subjected to heat treatment mostly for the purpose of improvement of their mechanical properties or as an intermediary operation, to prepare the alloy to other specific treatment processes. The type of heat treatment depends namely on the chemical composition of the alloy. A change of the heat treatment basic parameters has an influence on a change of the properties. Annealing significantly decreases the mechanical properties and causes improvement of plastic properties, thus facilitating further treatment. Complex evaluation of magnesium alloys requires very often knowledge of elastic and plastic properties at elevated temperatures.

The favourable properties of magnesium account for the fact that it is applied not only in cast structural components but also in those subjected to plastic working. Investigations of materials and production process of semi-finished products from magnesium alloys formed via plastic deformation methods are now in a phase of intensive development.

The most frequently used magnesium alloys are represented by the type Mg-Al-Zn, containing 3-9% Al, 0.2-1.5% Zn and 0.15-0.5% Mn. Aluminium increases significantly strength, hardness and it also improves castability. Zinc also enhances strength properties and possibly also toughness. Manganese increases corrosion resistance and improves weldability.

Alloys containing 9% of Al are used thanks to their properties namely for casting, while alloys with lower content of Al (3-6% Al) are suitable also for forming.

Due to its hexagonal structure magnesium and its alloys are characterised by limited cold formability. Forming technologies are therefore dominantly based on hot forming [7-9].

The presented paper deals with method for determination of the values of mean flow stress (MFS) which contributes to better knowledge of forming processes of hot formed magnesium alloys [10-13]. An experiment leading to obtaining the model of the mean flow stress (MFS) of magnesium alloy AZ31 was realized in laboratory rolling mill. It was based on the measurement of forces during hot rolling of flat samples with varying thickness. Samples with thickness graded in size were used for gaining data on MFS at various rolling conditions. It resulted from mathematical and statistical processing of MFS values that these could be described by a simple function of just two independent variables - temperature (200 to 450°C) and equivalent height strain (approx. 0.2 to 0.7). The increasing strain resulted in decreasing deformation resistance. The effect of equivalent strain rate (approx. 10 - 80 1/s*)* was negligible. The model describes the given relationship with good accuracy; a relative error of calculated MFS values does not exceed ±10%.

In the following paper there have been the structure and properties MgAl3Zn1Mn alloy marked AZ31 after ASTM under elevated temperatures presented.

2. Used material and methodology

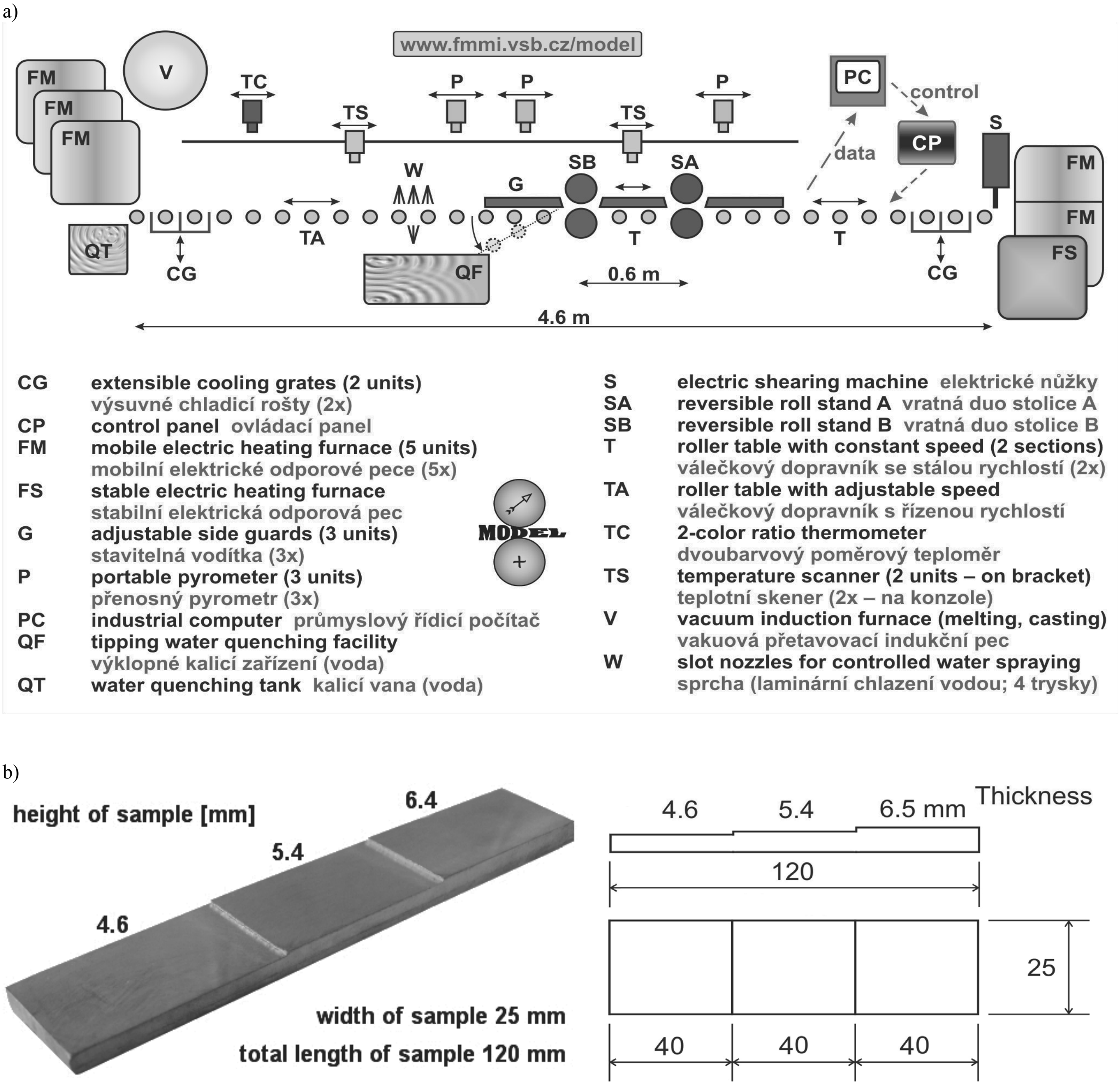
Chemical composition of used alloy shows Table 1. Model of the forming factor for mill stand A was developed from values measured in rolling of flat products in the laboratory rolling mill Tandem (see Fig. 2a) [14].

Table 1.
Chemical composition of alloy (weight %)

Al	Zn	Mn	Si	Zr	Sn	Rest
2.82	0.80	0.37	0.037	0.003	0.01	Mg

Samples with thickness graded in size (see Fig. 2b) were used for gaining data on MFS at various rolling modes [13].

Each sample was carefully measured and then heated in the furnace at the temperature 450°C for 30 minutes to homogenize the structure. After taking out of the furnace, the sample was cooled down in the air to deformation temperature 200 to 450°C. After partial cooling, each sample was inserted for 5 minutes into the furnace heated to forming temperature. After discharging the furnace, the heated sample was immediately rolled in the two-high stand A of the mill Tandem [14] (see Fig. 2a). Adjustment of the roll gap and revolutions of rolls were changed (2.8 to 3.5 mm and 40 to 160 rpm, respectively) at various temperatures (200 to 450°C). The temperature was changed with particular samples as well as the adjustment of the roll gap (and hence the total reduction corresponding to specific grades of each sample) and nominal revolutions of rolls N. Under the influence of previously specified factors, the achieved mean equivalent strain rate γ [s^{-1}] is given.



sample view schematic draft

Fig. 2. a) Scheme of rolling mill Tandem [14], b) Initial shape of the sample with thickness graded in size

The registered total roll forces *F* [N] and actual revolutions of rolls, as well as dimensions of the rolled products, serve for automatic calculation of height strain $e_h = \ln(H_0/H_1)$, mean strain rate γ and mean flow stress σ_m [MPa] for each element of the rolled sample. For the calculation the following formulas are used [15]:

$$\gamma = \frac{2}{\sqrt{3}} \cdot \frac{v_r}{\sqrt{R \cdot (H_0 - H_1)}} \cdot e_h \qquad (1)$$

Where H_0, or H_1 [mm] is entry or exit thickness of the rolling stock in a given location; v_r [mm/s] is real circumferential speed of rolls with radius *R* [mm]. Mean flow stress is calculated as follows [15]:

$$\sigma_m = \frac{F}{Q_{Fv} \cdot \sqrt{R \cdot (H_0 - H_1) \cdot B_m}} \qquad (2)$$

Where Q_{Fv} is a forming factor, corresponding to a specific rolling mill stand, and B_m [mm] is mean width of the rolling stock in a given place (an average value of the width before and after rolling). The factor $\sqrt{R \cdot (H_0 - H_1)}$ represents contact length of the roll bite, i.e. l_d [mm].

Credibility of calculation of MFS is influenced most of all by an exact estimate of the forming factor, which - as matter of fact - transfers deformation resistance to values of equivalent flow stress (i.e. of that which corresponds to a defined uniaxial stress state). Values of Q_{Fv} for both stands of the rolling mill Tandem were obtained by previous research and they are described in relation to aspect ratio l_d/H_m by equations of type [15]:

$$Q_{Fv} = A - B \cdot \exp\left(-C \cdot \frac{l_d}{H_m}\right) + \exp\left(D \cdot \frac{H_m}{l_d}\right) \qquad (3)$$

Where *A* - *D* are constants for a given facility, verified e.g. by comparison of power/force parameters determined during laboratory rolling, torsion test, or industrial rolling; H_m [mm] is mean thickness in a given location.

Fig. 3 shows the course example of the measured roll force, together with values of the actual height reduction, strain rate, dimensions of the sample before and after rolling, and MFS values calculated from these values in particular parts of the sample.

3. Determination of the forming factor

For calculation of MFS, knowledge of the forming factor of the mill stand is necessary. The forming factor Q_{Fv} highlights the influence of the mean stress exerted on the contact surface between the rolled metal and work rolls in the roll bite and in the rolling direction on the roll force size. The experiment was carried out before [16] with samples from low-carbon steel grades ČSN 11 523, 12 040 and Cr-Ni austenitic steel grade ČSN 17 251. For each of these materials, a model of flow stress σ in the expression according to Equation (4) was derived, based on continuous torsion tests. Values of mean flow stress σ_{m-t} may be calculated from these torsion tests using the integration and then compared with values of mean deformation resistance σ_{d-r}, obtained by rolling in analogous conditions.

$$\sigma = G \cdot e^J \cdot \exp\left(-J \cdot \frac{e}{e_p}\right) \cdot \gamma^{K - \frac{M}{T}} \cdot \exp(-N \cdot T) \qquad (4)$$

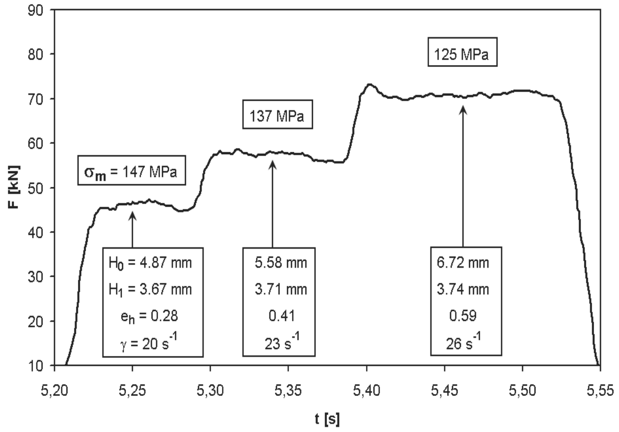


Fig. 3. Example of measured roll force in rolling of the graded in thickness specimen at temperature 340°C

Where *e* is true strain [-], e_p is strain to peak [-], γ is strain rate [s^{-1}], *T* is temperature [K] and *G* - *N* are material constants.

Pertinent material constants for three investigated steels were achieved in the statistical program Unistat by non-linear regression. Mean flow stresses σ_{m-t} corresponding to parameters of rolling of particular samples are reached by integration of the specific flow stress curve - see Equation (4) - from initial to final deformation e_1:

$$\sigma_{m-t} = \frac{1}{e_1} \cdot \int_0^{e_1} \sigma_e(e)\,de \qquad (5)$$

Flat samples were rolled with a various reduction size at various forming temperatures. The initial height of individual samples varied in the range of 4 - 30 mm. To reach a wide range of the aspect ratio l_d/H_m, height reductions in the range of 10 - 50 % were realized according to power possibilities of the laboratory mill TANDEM [14]. In this way, values of mean deformation resistance σ_{d-r} for each sample were reached, in accordance with the equation:

$$\sigma_{d-r} = \frac{F_v}{I_d \cdot B_m} \qquad (6)$$

The value of the forming factor Q_{Fv} for each sample was calculated by means of the mean deformation resistance achieved from roll forces σ_{d-r} and mean flow stress σ_{m-t}.

$$Q_{Fv} = \frac{\sigma_{d-r}}{\sigma_{m-t}} \qquad (7)$$

A final equation for the forming factor with evaluated constants according to Equation (3) and corresponding to the mill stand A of the rolling mill Tandem has the following expression [15]:

$$Q_{Fv} = 4.0483 - 4.7198 \cdot \exp\left(-0.0842 \cdot \frac{I_d}{H_m}\right) + \exp\left(0.2475 \cdot \frac{H_m}{I_d}\right) \tag{8}$$

In Fig. 4, values of the forming factor related to aspect ratio for particular types of steel are seen as well as dependence of Q_{Fv} based on the Equation (8).

4. Deformation resistance models

Based on previous experience, [15, 16] a simple model was chosen to describe MFS of the investigated material in relation to strain, temperature and strain rate [13]:

$$\sigma_m = a \cdot e_h^b \cdot \exp(-c \cdot e_h) \cdot \gamma^d \cdot \exp(-g \cdot T) \tag{9}$$

Where σ_m is MFS which is predicted (calculated according to the developed model) and a - g are calculated material constants which were determined on the basis of methods of the multiple non-linear regression with use of the statistical program Unistat.

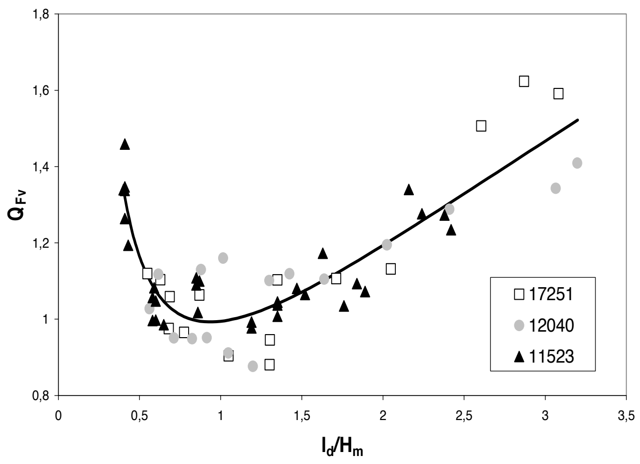


Fig. 4. Graphic expression of the relationship between the Forming factor of the stand A of laboratory mill Tandem and aspect ratio ld/Hm (the curve corresponds to Equation [8]

The basic form of Equation (9) includes members for hardening, softening, speed and temperature. However, its further simplification is desirable for practical use to accelerate prediction of MFS. It was found by mathematical processing that the effect of strain rate (in range of ca 10-80 s^{-1}) is statistically insignificant in the given case, and that is why a simplified equation in the following form was derived:

$$\sigma_m = 357.5 \cdot e_h^{0.006} \cdot \exp(-0.30 \cdot e_h) \cdot \exp(-0.00234 \cdot T) \tag{10}$$

Further investigation revealed that influence of deformation expressed only by one member is sufficient and the subsequent simplification of the mathematical model has no significant influence on the value of gained MFS calculated according to this equation. A final, totally simplified form of the mathematical model with quantified constants looks like this:

$$\sigma_m = 352.2 \cdot \exp(-0.28 \cdot e_h) \cdot \exp(-0.00232 \cdot T) \tag{11}$$

A graphic confirmation of the possible simplification of the equation of type (9) can be observed in specific graphs in Fig. 5 that show relative deviations Δ of values MFS calculated according to Eqs. (10) and (11) from values determined in experimental way. The deviation Δwas calculated as a quotient of the residuum and the MFS value which was found out in the experimental way.

5. Metallographic analysis

The examined magnesium alloy after casting was characterized by a single-phase coarse-grained structure with a flat grain average area of 80µm (see Fig. 6). The alloy grains were equiaxed and no structure anisotropy was found. The detail SEM analyzes show non homogenous content of aluminium through grain. The homogenous structure after heat treatment T4 (after ASTM) and hot pressing was reached [17]. After deformation within the applied range of deformation parameters, changes corresponding to different stages of structural reconstruction processes were observed.

Evaluation of the structure was performed on the specimens after rolling (see above for the parameters) and water quenching. The structure of the alloy after rolling was analyzed on perpendicular microsections. The metallographic investigation was performed on an Olympus light microscope in the range of magnifications 100 to 1000×. A quantitative analysis was made by surface method, using the "MET-ILO" computer program. Methodological problems in the analysis of the obtained structural images, consisting in the occurrence of artefacts, were solved by application of appropriate image transformations. During the quantitative analysis, twin boundaries were partly removed in an automatic way. A number of stereological parameters were determined [17,18], of which the following are presented: mean diameter of grain plane section and fraction of recrystallized grains.

After deformation at temperature of 200 to 250°C, elongated grains with a large number of twinning regions with initial state of dynamic recrystallization (Fig. 7) were observed for low strain values, which testify to a considerable effect of this mechanism in the process of magnesium alloy AZ31 deformation.

In case of higher strain values, the process of continuous dynamic recrystallization was observed, with new grains occurring initially at primary grain boundaries, to proceed towards the centre of elongated primary grain (Fig. 8).

The degree of recrystallization advancement depended on the applied parameters of the rolling process. Based on quantitative studies of the structure, the fraction of recrystallized grains in the structure was calculated. The size of new grains after deformation at temperature of 200 to 300°C fluctuated within the range of 5 to 12 μm. At temperature of 350°C and higher, a fully recrystallized structure was identified already for low strain values (Fig. 9).

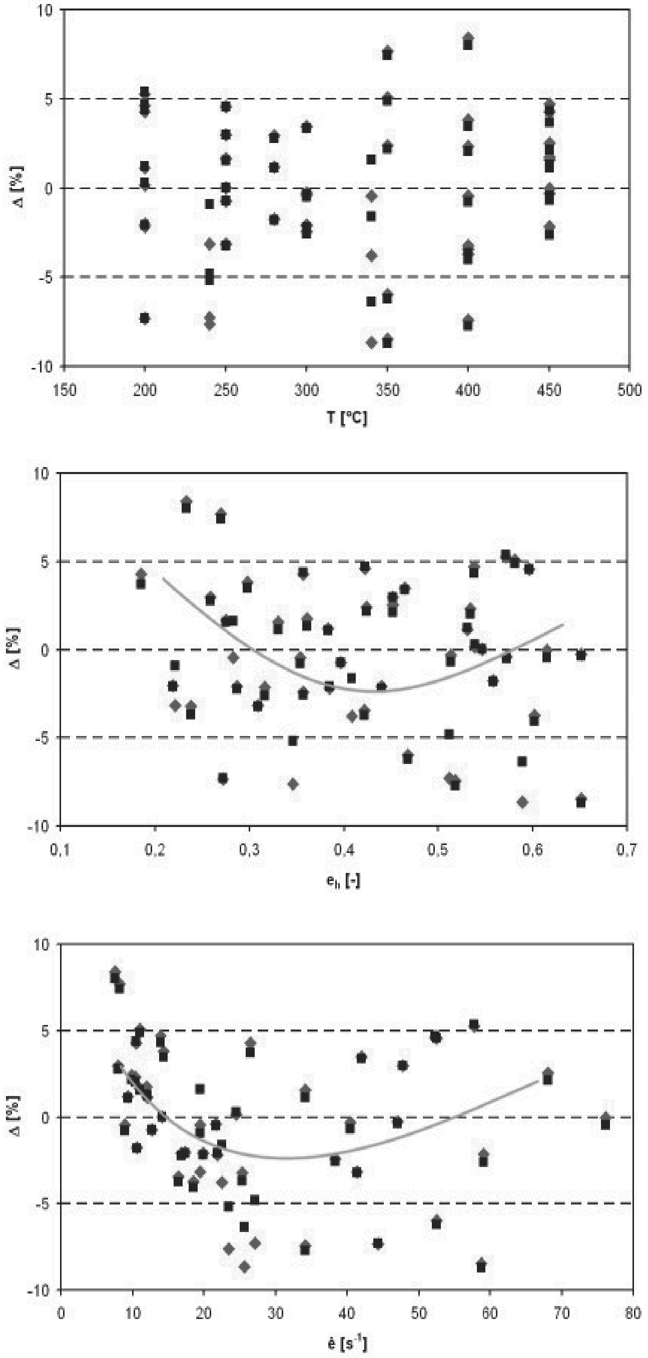


Fig. 5. Relative errors of the MFS values calculated according to Eqs. (10) ● and (11) ■ in comparison with the values obtained experimentally [16]

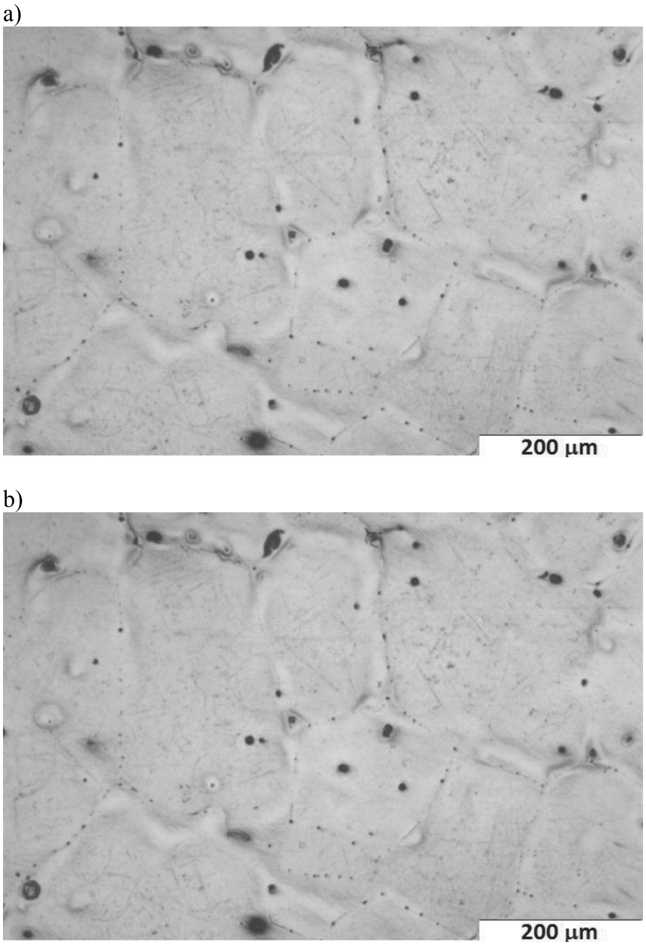


Fig. 6. Magnesium alloy after casting: a) as cast b) after heat treatment and hot pressing

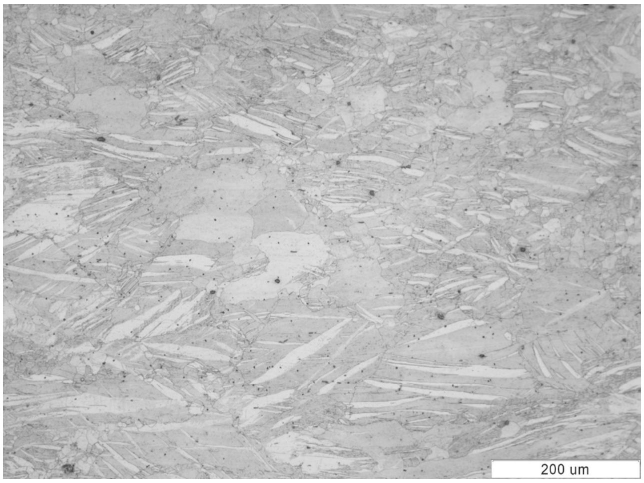


Fig. 7. Microstructure after rolling at T = 200°C, e_h = 0.22, $\gamma = 17\ s^{-1}$

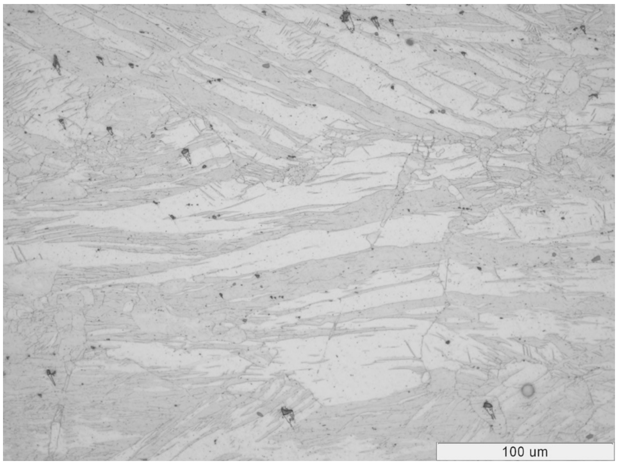


Fig. 8. Microstructure after rolling at T = 250°C, e_h = 0.45, $\gamma = 48\ s^{-1}$

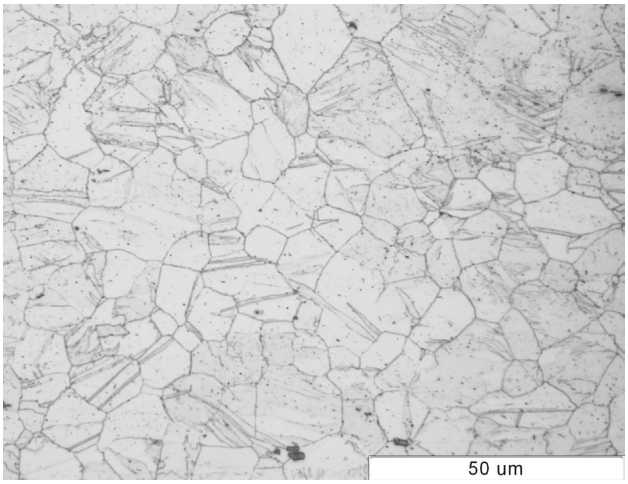


Fig. 9. Microstructure after rolling at T = 400°C, e_h = 0.30, $\gamma = 14\ s^{-1}$

A significantly lower fraction of twins was detected in the dynamically recrystallized structure, in comparison with an increased number of twin boundaries observed during rolling at low temperatures (Fig. 10). An increase in the average grain size was observed as the forming temperature rose, whereas the influence of a changing strain rate was less significant. In the analyzed temperature range, the size of dynamically recrystallized grain fluctuated from about 10 to 40 µm after rolling, at temperature of 350 and 450°C, respectively.

6. Conclusions

Based on laboratory rolling of flat samples in the temperature range of 200-450°C, actual height reductions of ca 0.2-0.7 and strain rates ca 10-80 1/s, the MFS values of the magnesium alloy of type AZ31 were obtained after recalculation from roll forces. Model of the forming factor for mill stand A was developed from values measured in rolling of flat products in the laboratory rolling mill Tandem and from a model describing flow stress curves of these steels on the basis of hot torsion tests. The resulting equation accurately describes the function $Q_{Fv}=f(l_d/H_m)$ in the whole range of applied temperatures and deformations, regardless of friction coefficient. As far as accuracy of the developed models of deformation resistance of the AZ31 alloy is concerned, the root of mean square error 6.7 and value $R^2 = 0.958$ resulted from calculations for Equation (5), for Equation (6) the root of mean square error was 6.2 and value $R^2 = 0.964$. It means that the simplified Equation (6) describes the given relationship of deformation resistance even better than Equation (5). The satisfactory accuracy of calculation of MFS found according to both equations can also be seen from graphs in Fig.5. Dispersion variance of experimental deviations and deviations of MFS values which were found by recalculation according to Eqs. (5) or (6) are satisfactory in the whole range and relative errors do not surpass ±10%. Therefore, the model (6) would be suitable for implementation in the control system of the mill with rolls strips from the given alloy in operational conditions.

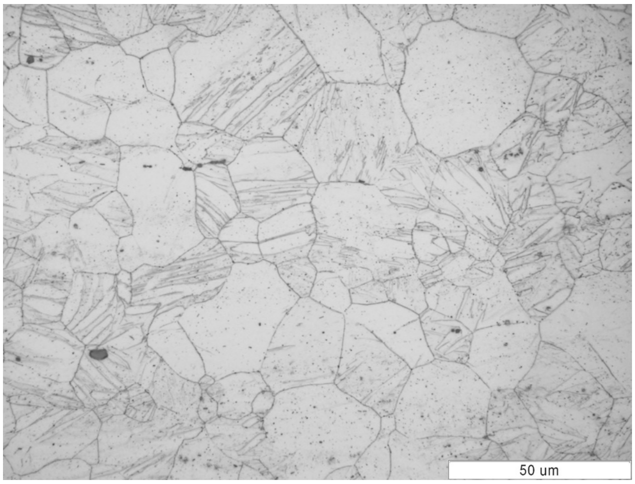


Fig. 10. Microstructure after rolling at T = 450°C, e_h = 0.36, $\gamma = 12\ s^{-1}$

Compared to previously published articles [19, 20-22] that used a similar mathematical model to describe MFS, a certain trend in the case of relative deviations Δ for strain and strain rate is apparent. In contrast with previous works, where this particular trend of deviations was apparent only in the case of temperature, the dispersion of these deviations in dependence on temperature is here very uniform.

Neglecting of the speed member in the resulting model of MFS was possible by a relatively narrow range of applied strain rates, and also by the fact that a relationship between variables e_h and γ exists - see Equation (1).

The unconventional description of deformation influence only by the softening member in Equation (6) can be justified only in the case of description of the mean flow stress; it would not be applicable for description of the stress-strain curve, mainly in initial phases of fierce increase in deformation resistance.

A final, totally simplified form of the mathematical model with quantified constants looks like Equation (11).

The developed models for MFS have strongly utilitarian character and therefore the needed experimental data were obtained only for actual height reductions e_h higher than ca 0.2.

The results of metallographic analyse describe the structural processes through the forming.

After casting, the AZ31 alloy has a coarse-grained single-phase structure. Alloys of this kind are characterized by hexagonal structure and for this reason, a small number of easy slide systems. Rolling at low temperatures contributes to a significant growth of deformation twins. The on-going process of dynamic recrystallization allowed a substantial refinement of the alloy structure. After rolling at temperature of 350 to 400°C, the structure was composed of fine recrystallized grains of an average size ranging from ca 10 to 20 μm. A significant influence of the deformation temperature on the average grain size after recrystallization was identified, while observing lower sensitivity of this parameter to an increased strain rate.

The results of structural studies along with the devised thermomechanical model will be used to design the foundations of rolling technology for this group of alloys. In future work an important relation between the MFS, the Zener-Hollomon parameter and the grain size will be determined.

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