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THE EFFECT OF AZ31 ALLOY FLOW STRESS DESCRIPTION ON THE ACCURACY OF FORWARD EXTRUSION FE SIMULATION RESULTS

WPŁYW FUNKCJI NAPRĘŻENIA UPLASTYCZNIAJĄCEGO STOPU MAGNEZU AZ31 NA DOKŁADNOŚĆ WYNIKÓW SYMULACJI MES WYCISKANIA WSPÓŁBIEŻNEGO

Hot compression tests of the AZ31 magnesium alloy, performed for wide ranges of temperature and strain rate, revealed two different flow curve types for the material investigated. At higher strain rates and lower temperatures, flow curves exhibit a distinct peak. At lower strain rates and higher temperatures, flow stress values change less rapidly. This makes it difficult to find a single function able to accurately describe the deformation behaviour of AZ31 alloy in the entire forming range.

The present study discusses an effect of the AZ31 magnesium alloy flow stress description on the accuracy of extrusion force prediction by means of FE simulation. A number of forward extrusion trials were carried out in order to acquire experimental data on AZ31 alloy deformation behavior in various forming conditions. Cylindrical billets of 40 mm in diameter and the tooling were initially heated to temperatures in the range of 200 to 400°C and placed in the working space of the 1500 kN hydraulic press to produce extruded rods of 12 mm in diameter. Numerical models for conducting corresponding extrusion simulations were prepared in Forge 2009 software and the selected form of Hensel-Spittel function was applied for the material flow stress description. Function coefficients were calculated both for the entire forming range of AZ31 alloy as well as for the ranges of parameters specific to a certain extrusion trial conditions. The numerical results were compared to the experimental ones and the accuracy of both approaches were estimated. It was found that the selected flow stress function, determined for the wide ranges of temperature and strain rate, allows to achieves a tis factory accuracy of AZ31 alloy extrusion force prediction by FE simulations.

Keywords: magnesium alloy, AZ31, flow stress, extrusion, FE simulation

Dwa różne rodzaje krzywych płynięcia uzyskano w próbach ściskania na gorąco stopu magnezu AZ31, prowadzonych dla szerokiego zakresu temperatury i prędkości odkształcenia. Dla wyższych prędkości odkształcenia i niższych temperatur krzywe płynięcia wykazują wyraźne maksimum naprężenia uplastyczniającego. Dla niższych prędkości odkształcenia i wyższych temperatur zmiany wartości naprężenia uplastyczniającego są mniej gwałtowne. Z tego względu trudno jest znaleźć jedną funkcję opisującą zależność naprężenia uplastyczniającego dla całego zakresu warunków odkształcania stopu magnezu AZ31.

W artykule przedstawiono wpływ zastosowanej funkcji naprężenia uplastyczniającego stopu AZ31 na dokładność wyznaczania siły wyciskania poprzez symulacje MES. Przeprowadzono szereg prób wyciskania współbieżnego w celu uzyskania danych doświadczalnych charakteryzujących zachowanie się stopu AZ31 w różnych warunkach kształtowania. Próbki walcowe o średnicy 40mm wraz z przyrządem do wyciskania były nagrzewane do temperatury w zakresie od 200 do 400°C i umieszczane w przestrzeni roboczej pionowej prasy hydraulicznej o nacisku 1500kN. Następnie wyciskano z nich pręty o średnicy 12mm. Próby wyciskania zostały zamodelowane w programie FORGE2009, a do opisu zmian naprężenia uplastyczniającego badanego stopu w zależności od warunków odkształcania wykorzystano wybraną postać funkcji Hensla-Spittla. Współczynniki funkcji zostały obliczone zarówno dla całego zakresu kształtowania stopu AZ31, jak i dla warunków występujących podczas określonej próby wyciskania. Wyniki obliczeń porównano z badaniami eksperymentalnymi, co pozwoliło na ocenę poprawności wyników symulacji numerycznych. Z badań wynika, że wybrana funkcja naprężenia uplastyczniającego, która została opracowana dla szerokiego zakresu temperatury i prędkości odkształcenia, pozwala na poprawne wyznaczanie siły wyciskania stopu magnezu AZ31 za pomocą symulacji MES.

1. Introduction

There's an increasing demand of the automotive and aerospace industries to produce lighter components which exhibit sufficient stiffness and strength. Due to their lightweight potential, wrought magnesium alloys are one of the most attractive materials for such ap-

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plications. A number of papers on various aspects of magnesium alloys forming technologies have been published recently. Metal forming operations are commonly designed on the basis of numerical analysis, therefore many studies are based on the results of FE simulations. Some of them are concerned with numerical modeling of AZ31 magnesium alloy extrusion, for instance these reported in [1÷ 4].

Correctness and reliability of metal forming FE simulations depend, among other factors, on accurate description of the flow stress in specific forming conditions. A number of advanced material models has been presented recently, allowing to predict the microstructural changes in a material subjected to forming. However, dedicated simulation software offers simpler models which are convenient for fast calculations, conducted for instance to predict load required to perform a metal forming operation in certain process conditions.These relatively simple functions allow to describe the initial increase of flow stress followed by its fall until the steady state stress is reached. Such a deformation behaviour is characteristic for many metallic materials under hot working conditions – also for magnesium alloys. It has been noticed that even simple Hollomon's equation, neglecting softening phase, wasused for modeling hot deformation behaviour of AZ31 alloy as well [4,5].

The aim of the present study was to assess the accuracy of extrusion force prediction by FE simulations using less and more precise flow stress models of AZ31 alloy.Validation of the models applied was made by comparing the numerical results to the experimental ones achieved in the laboratory forward extrusion trials.

2. Hot compression test results

Two specific types of flow curves were obtained from the plastometric tests of AZ31 magnesium alloy, subjected to uniaxial hot compression on the Gleeble thermo-mechanical simulator in the wide ranges of temperature and strain rate. According to Kuc at all. [6], slip is the dominant plastic deformation mechanism of the investigated alloy in deformation conditions for which Zener-Hollomon parameter Z is lower than $6{,}1 \times 10^{11}$ s^{-1}. In this case, flow curves (continuous lines on Fig. 1) exhibit relatively smooth hardening and softening phases, while the maximum flow stress value moves – together with the strain rate increase – towards greater equivalent strain values. In deformation conditions for which Z value is greater than $6{,}1 \times 10^{11}\,s^{-1}$, twinning dominates as the deformation mechanism, and the corresponding flow curves (dotted lines on Fig. 1) exhibit distinct flow stress maximum at similar strain values (approx. 0,25).These differences make it difficult to find a single function able to accurately describe the deformation behaviour of AZ31 alloy in the entire forming range.

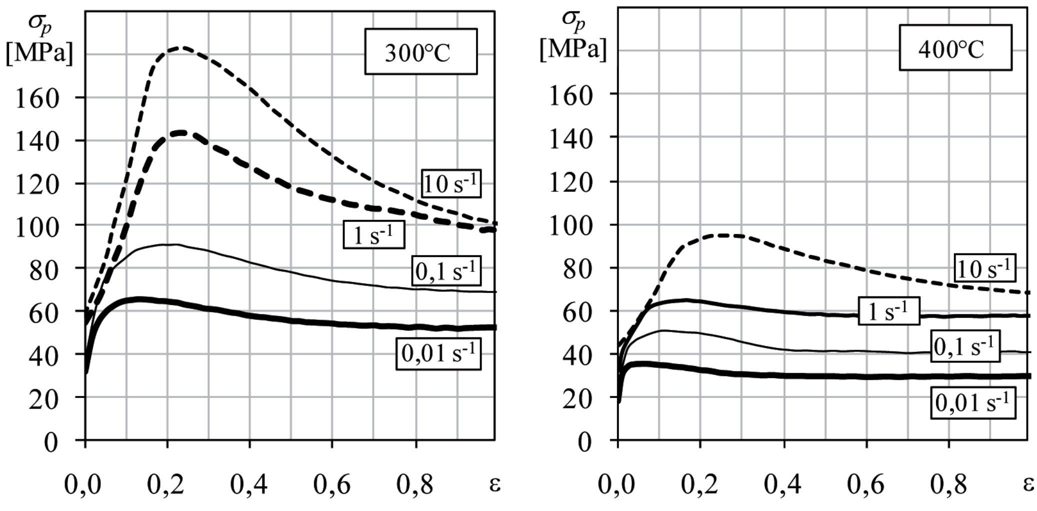

Fig. 1. Flow curves of AZ31 magnesium alloy hot-formed at temperature of 300°C and 400°C with the strain rates of 0,01, 0,1, 1 and 10 s^{-1}

3. Flow stress functions of AZ31 alloy

One of the most frequently used flow stress functions, implemented in the bulk metal forming simulation software (e.g. Forge, FormFEM), are based on the Hensel-Spittel model [7].These functions are relatively simple relations of the flow stress on three variables, such as temperature, strain and strain rate. They can be used to describe hot deformation behaviour of many alloys, due to theirability to consider a characteristic peak of the flow stress and subsequent material softening – a result of dynamic recrystallisation. The following

Hensel-Spittel equation was selected in order to determine the flow stress approximation function of AZ31 alloy:

$$\sigma_p = A\exp(m_1 T)\varepsilon^{m_2}\dot{\varepsilon}^{m_3}\exp\left(\frac{m_4}{\varepsilon}\right) \tag{1}$$

where:

ε – equivalent strain,

– strain rate, s^{-1},

T– temperature, °C,

A, m_1, m_2, m_3, m_4 – coefficients determined on the basis of plastometric tests of a material investigated.

The Newton's method was applied to determine the coefficients of equation (1) for the AZ31 alloy. A selected goal function–the normalized root mean square deviation between calculated and measured flow stress values–is given by the formula:

$$\varphi = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\sigma_{p_{ci}} - \sigma_{p_{mi}}}{\sigma_{p_{mi}}}\right)^2} \tag{2}$$

where:

σ_{pci},– flow stress value calculated by means of equation (1) for point i,

σ_{pmi},– flow stress value calculated on the basis of hot compression test measurementsfor point i,

n – a number of the points taken to comparison.

The coefficients of equation (1) for AZ31 alloy were determined both for the wide ranges of temperature (200 ÷450°C) and strain rate (0,01÷ 10 s^{-1}), as well as for the narrower ranges of temperature and strain rate that were recorded during forward extrusion simulations and experiments (described later in sections 4 and 5). Calculated coefficients are given in Table 1. Comparison of the corresponding approximation functions and the experimental flow curves is presented in Figs. 2 and 3.

The function A (determined for the wide ranges of temperature and strain rate) quite correctly describes flow curves without distinct peak stress (curves obtained at 350°C, 400°C and 450°C for strain rate of 1 s^{-1}). In the other cases, flow stress values are mostly underestimated, especially in the equivalent strain range of 0,15 to 0,5.The discrepancy of approximated and experimental data reaches up to 20%. It's evident that approximation functions determined for the narrower ranges of temperature and strain rate fit better to the experimental flow curves. Although flow stress values still remain underestimated, maximum difference at lower temperatures is considerably reduced (to12%at 350°C and the strain rate of 10s^{-1}). At temperatures of 400 to 450°C, the function B is not able to come closer to the peak stress noticed at strain rates of 10s^{-1}. However, it accurately predicts the steady-state stress values.

TABLE 1

The values of coefficients in equation (1), determined for different ranges of temperature and strain rate

Function designation	Temperature range,°C	Strain rate range, s^{-1}	A	m_1	m_2	m_3	m_4
A	200÷450	0,01÷10	709,4	-0,0065	-0,1538	0,1202	-0,0261
B	400÷450	1÷10	712,9	-0,0064	-0,1097	0,1098	-0,1399
C	300÷350	1÷10	819,5	-0,0069	-0,6006	0,0949	-0,1393
D	200-250	1÷10	242,9	-0,0020	-0,6417	0,03328	-0,1521

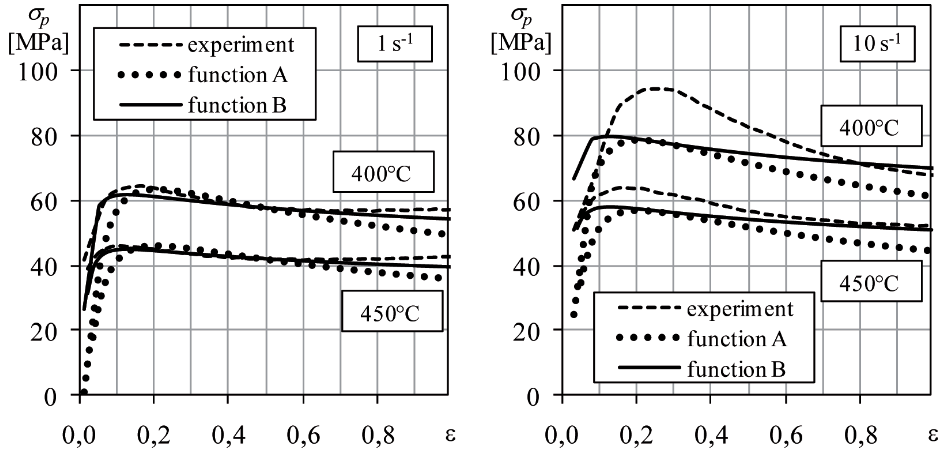

Fig. 2. Comparison of the corresponding experimental flow curves and approximation curves for AZ31 alloy compressed at temperature of 400°C and 450°C and strain rate of 1 and 10s^{-1}

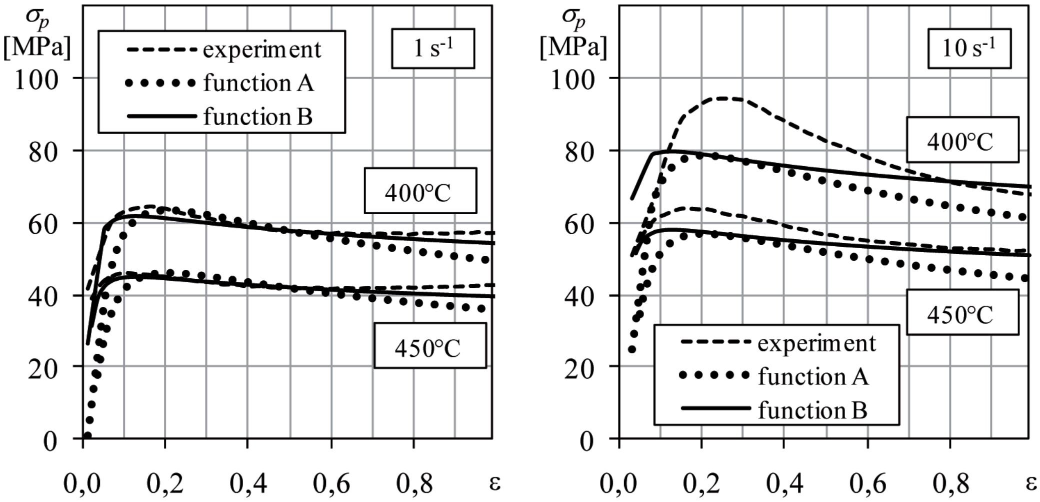

Fig. 3. Comparison of the corresponding experimental flow curves and approximation curves for AZ31 alloy compressed at temperature of 300°C and 350°C and strain rate of 1 and $10s^{-1}$

4. Numerical simulations of AZ31 alloy forward extrusion

A numerical model of any metal forming process consists of several elements, which in combination create are presentation of the real process. It includes geometric models of a billet and tools, a material model and a set of boundary and initial conditions.The proper selection of all these elements, in terms of their compatibility with the real process, is a prerequisite for proper function ing of the numerical model and obtaining results consistent with the physical examinations.

A geometric model of the forward extrusion was prepared on the basis of CAD documentation of the laboratory extrusion device used for conducting corresponding physical tests. The model, which consists the tools that have direct contact with a billet during deformation (punch, recipient, die and base), is shown in Fig. 4.

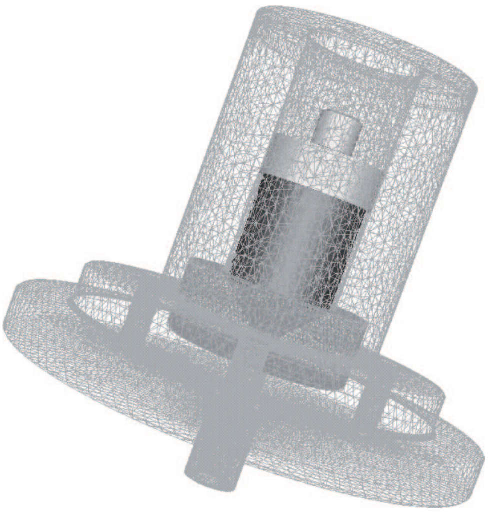

Fig. 4. A geometric model of the laboratory device for extrusion tests

The following thermo-physical properties of AZ31 alloy were used in simulations [3,8]: density ρ = 1770 kg/m^3, specific heat c = 1050 J/kgK and conductivity k = 96 W/mK. The heat transfer coefficient between a billet and the tools was set to 11kW/m^{2}K [3,8].

A friction model has significant impact on the results of the extrusion process simulation. Different values of friction coefficients and factors used during numerical modeling of AZ31 alloy extrusion can be found in the literature [1÷3]. Therefore, selection of the appropriate friction coefficient values is difficult. In this study, Tresca friction model was applied and the values of friction factor m were calculated by means of the equation proposed by Flitta and Shepard [9] and presented in Fig. 5. They concluded that the friction factor linearly depends on the initial billet temperature.

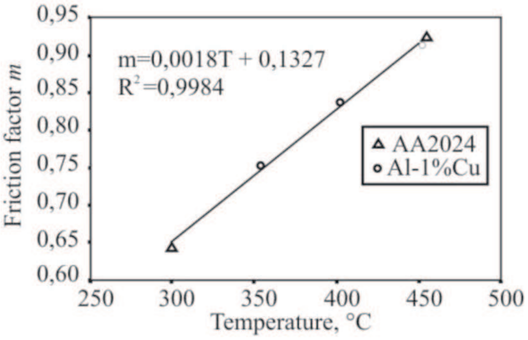

Fig. 5. The effect of initial billet temperature on friction factor m during extrusion of aluminum alloys [9]

The flow stress model was introduced din the form of the Hensel-Spittel equation described in the preceding section. Two simulations with different set of equation coefficients were used for every corresponding experimental trial (functions A and B at temperature of 400°C, functions A and C at temperature of 300°C and functions A and D at temperature of 200°C). It was also assumed, that for the equivalent strain greater than 1, the steady-state flow stress values are calculated.

As expected, due to the same initial temperature of abillet and the tooling, significant temperature increase (approx. 40°C) was observed in the extruded rod (Fig.6). The ram velocity of 2 mm/s and extrusion ratio higher than 11 resulted in achieving the strain rates higher than 1 s^{-1} near the exit plane. It proves that ranges of temperature and strain rate taken into account for determining coefficients of approximation functions were selected accurately.

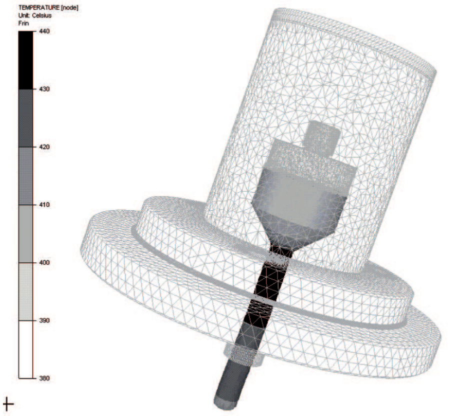

Fig. 6. The temperature distribution on a surface of the rod extruded at initial temperature of 400°C

5. Verification of the numerical simulation results

In order to verify the accuracy of the applied flow stress models, physical extrusion trials were conducted by means of the laboratory two-column hydraulic press with vertical action. The maximum press load is 1500kN, although the construction is likely to achieve maximum force 2000 kN. Thanks to two columns leading the ram,the press has large working space, allowing to conduct research for various forming processes, such as extrusion, forging and stamping. The press is equipped with a computer control system that allows to adjust the test parameters and run fully automat ed tests. The system also enables to record the basic parameters, such as test duration time, press pump efficiency, ram travel displacement of working bench, ram velocity, press load.

A special tooling was developed and produced, in order to conduct the forward extrusion tests on the hydraulic press described above. The device allows to extrude billets with the initial diameter of 40 mm. Thanks to application of changeable dies, it is possible to obtain rods of 10, 12 and 14 mm in diameter. Tooling is made of hot-work steel. This solution allows to heat up the device to initial temperature of a billet in order to avoid rapid temperature changes in the billet's volume.

Extrusion of 12 mm dia. rods was conducted after heating the billet and the tools to 400°C, 300°C and 200°C in the chamber furnace. After heating all the element sup to the required temperature and placing the billet in the recipient, the device was installed in the press working area. To reduce friction, the high temperature resistant lubricant was used.The ram velocity was about 2 mm/s.

The test results were compared with the numerical simulations of extrusion carried out in the same temperature. Comparison of the recorded and calculated extrusion force courses is presented in Figs. 7-9.

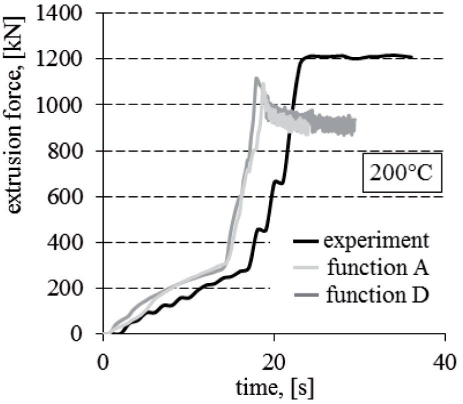

Fig. 7. Comparison of AZ31 alloy extrusion force courses obtained in experiments and numerical simulations conducted at temperature of 200°C

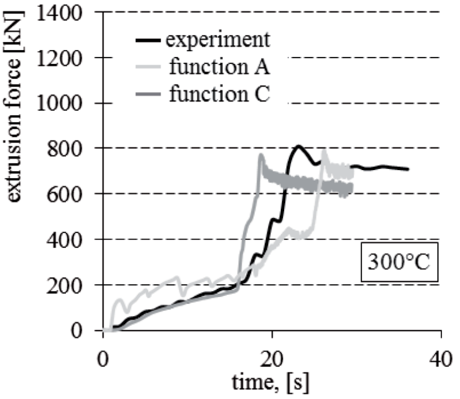

Fig. 8. Comparison of AZ31 alloy extrusion force courses obtained in experiments and numerical simulations conducted at temperature of 300°C

Considering the maximum extrusion force values and the curve shape describing the decrease in extrusion force after reaching the maximum, no significant difference can be observed between results obtained for the compared flow stress functions. Moreover, the simulations results are in good agreement with the results of the experimental tests carried out after heating the material to 400°C and 300°C.

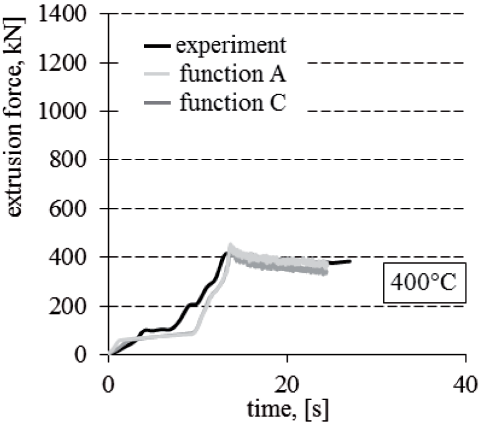

Fig. 9. Comparison of AZ31 alloy extrusion force courses obtained in experiments and numerical simulations conducted at temperature of 400°C

In the case of numerical simulations conducted at 200°C, the results differ from the results recorded in the laboratory test. The maximum measured value of extrusion force was about 8% higher than the corresponding values obtained in both simulations.This implies that other factors (probably friction definition) have a greater impact on extrusion force prediction than the flow stress description inaccuracies. A steady value of the measured force is probably related to the fact that due to low formability of the AZ31 alloy at this temperature (small cracks were observed on the surface of the extruded rod),load needed to carry out the extrusion trial was close to the maximum press load.

6. Summary

Depending on the type of dominant plastic deformation mechanism (slip or twinning) in certain forming conditions, two considerably different kinds of flow curve courses were obtained from plastometric tests of AZ31 magnesium alloy. Therefore, the accurate description of its deformation behaviour in the entire forming range by means of the Hensel-Spittel function is not possible. In order to increase the precision of AZ31 alloy flow stress model, the coefficients of the selected equation can be determined for conditions characteristic only for an analyzed processor operation. Such an approach were applied in the research presented in this paper. The extrusion force prediction accuracy was checked for FE simulations using both less and more precise flow stress models of AZ31 alloy. It was found that the approximation discrepancy (observed for the function determined in the wide ranges of temperature and strain rate) is of no significant importance for prediction of the extrusion force by FE simulations. Moreover, results of simulations conducted in 300°C and 400°C showed good agreement with the empirical results. Slightly worse accuracy was obtained for the extrusion case carried out in 200°C. It suggests that probably friction should be defined with greater care in further research.

Summing up the above considerations one can assume that the selected flow stress function, determined for the entire forming range of AZ31 alloy, allows to achieve sufficient accuracy of extrusion force prediction by FE simulations.

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