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INVESTIGATION OF FUNCTIONS CHARACTERIZING THE FLOW CURVES OF CAST MAGNESIUM ALLOY MgAl9Zn1

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The article presents the results of testing the flow curves of cast magnesium alloy MgAl9Zn1. Experimental tests were carried out on a deformation dilatometer in a compression test of cylindrical specimens heated to 380 °C, 400 °C, 420 °C at strain rates of 0,1 s-1, 1 s-1, 10 s-1. The experimental curves were described by functions used in programs for simulating metal forming processes based on the finite element method. The Generalized Reduced Gradient optimization method (GRDM) implemented in Microsoft Excel was used to determine the function coefficients. Based on the results obtained, the best functions characterizing the flow curves were selected for use in describing the material models used in numerical simulations of cast magnesium alloy MgAl9Zn1.

Key words: cast, MgAl9Zn1, plastometric tests, strain rate, flow curves.

INTRODUCTION

Modern technology design is associated with numerical simulations, in which the material model is an important factor determining the accuracy of the calculations [1-2]. Its main element is the relationship between stresses and strains at different forming conditions, called flow curves. In connection with ongoing research work on the forming technology of sand-cast magnesium alloy AZ91, the authors of the study determined such flow curves in compression testing and presented them in this article. The registered parameters of the process were the value of the force as a function of the path of the compression tool. The experimental curves obtained from the compression tests were described by three function equations used in metal forming process simulation programs

RESEARCH METHODOLOGY

Magnesium alloy AZ91 is one of the most popular magnesium alloys, which belongs to the Mg-Al-Zn group [3]. It is widely used in hot metal forming. Due to this application, it was chosen for the study. The chemical composition of the AZ91 magnesium alloy cast into sand molds is shown in Table 1.

Table 1 **Chemical composition of AZ91 magnesium alloy cast / wt. % [3]**

Chemical element	Mass / %
Al	8,1 – 9,3
Zn	0,40 – 1,0
Mn	0,13 – 0,35
Si	0,3
Cu	0,1
Ni	0,01
Mg	Balance

AZ91 magnesium alloy castings made in sand molds were homogenized at 415 °C for 24 hours with argon as the shielding gas [4-5]. Plastometric tests for sand-cast AZ91 magnesium alloy were performed in compression test on a DIL 805 A/D strain dilatometer. The dilatometer has the ability to attach a plastometer attachment, which makes it possible to conduct physical simulations of the forging and rolling processes and obtain real flow curves. Figure 1 shows the dilatometer chamber used for plastometric experiments.

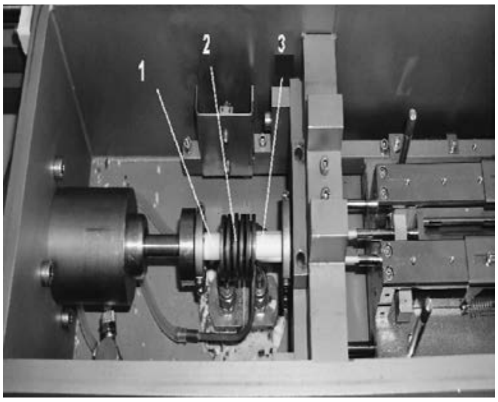

Figure 1 Dilatometer chamber used for plastometric experiments: 1 – movable tool, 2 – induction coil, 3 – non-movable tool

Cylindrical specimens of the following dimensions were used: diameter 5 mm, height 10 mm (Figure 2), which were cut from the castings. An induction coil was used to heat cylindrical samples. In order to determine

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the effect of strain rate on the value of plasticizing stresses, considering the technical capabilities of the test device used, three strain rates were planned: 0,1, s-1, 1 s-1, 10 s-1. The tests were conducted at temperatures: 380 °C, 400 °C, 420 °C. At each parameter, three times measurements were used, and the results were averaged. During testing at 420 °C and a strain rate of 10 s-1, cracks occurred, and due to this, the data for this parameter range were not considered for further analysis.

Figure 2 Example cylindrical samples used in the study

ANALYSIS OF THE RESULTS

The flow curves determined from the experiment for the applied strain rates and temperatures are shown in Figures 3÷8. The results obtained are described by functions that depend the value of flow stresses on the strain parameters. In the case described here, functions containing such parameters as strain, strain rate and temperature were chosen. Three forms of flow stress functions, also known as constitutive equations, were selected for analysis. These functions are described by the following formulas [6-8]:

$$\sigma_p = A\cdot\varepsilon^B\cdot\dot{\varepsilon}^C\cdot\exp(D\cdot t) \qquad (1),$$

and

$$\sigma_p = A\cdot\varepsilon^B\cdot\exp(C\cdot\varepsilon)\cdot\dot{\varepsilon}^D\cdot\exp(E\cdot t) \qquad (2),$$

and

$$\sigma_p = A\cdot\varepsilon^{B+C\cdot T}\exp(D\cdot\varepsilon)\cdot\dot{\varepsilon}^{E+F\cdot T}\cdot\exp(G\cdot T) \qquad (3),$$

where:

σ_p – flow stress,
ε – equivalent strain,
$\dot{\varepsilon}$ – strain rate, s-1,
t – test temperature, °C,
T – test temperature, K,
A, B, C, D, E, F, G – constant coefficients.

Functions (1), (2) and (3) include the effect of the parameters measured at the time of the experiment: strain, strain rate and temperature, on the value of flow stresses. The Generalized Reduced Gradient (GRG2) optimization method implemented in Microsoft Excel was used to determine the coefficients of the $A÷G$ functions [9-10]. The objective function was defined by the equation:

$$\Phi_\sigma = \frac{1}{k}\sum_{i=1}^{k}\frac{\left(\sigma_{pt}-\sigma_{pex}\right)^2}{\sigma_{pex}^2}\cdot 100\% \qquad (4)$$

where:

Φ_σ – objective function,

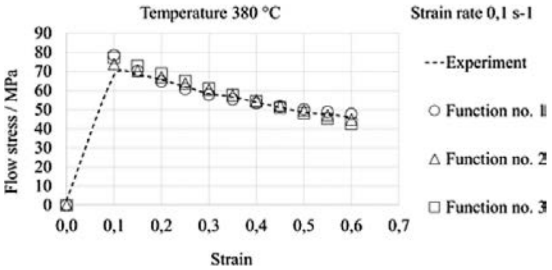

Figure 3 The comparison of flow curves obtained in experiment with theoretical ones determined by function (1), (2) and (3) at temperature 380 °C and strain rate 0,1 s-1

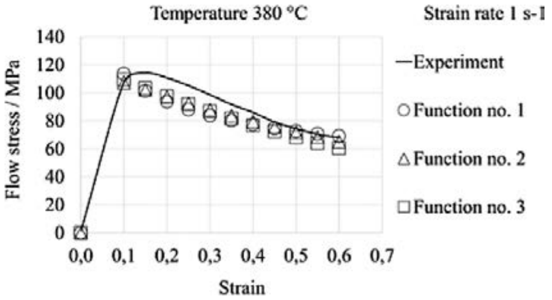

Figure 4 The comparison of flow curves obtained in experiment with theoretical ones determined by function (1), (2) and (3) at temperature 380 °C and strain rate 1 s-1

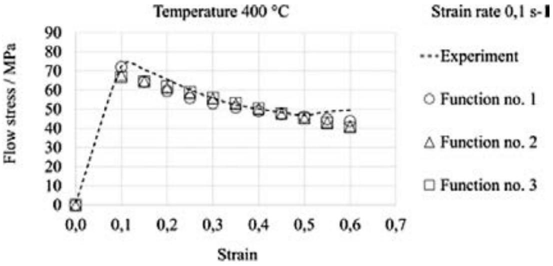

Figure 5 The comparison of flow curves obtained in experiment with theoretical ones determined by function (1), (2) and (3) at temperature 400 °C and strain rate 0,1 s-1

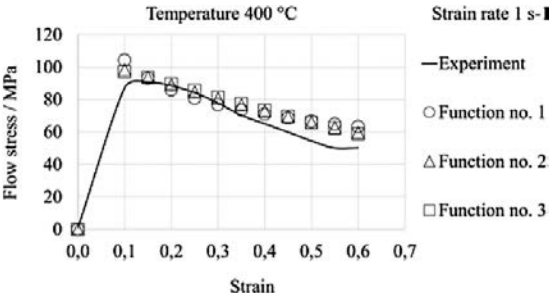

Figure 6 The comparison of flow curves obtained in experiment with theoretical ones determined by function (1), (2) and (3) at temperature 400 °C and strain rate 1 s-1

σ_{pt} – the value of flow stresses calculated based on functions (1), (2) and (3),
σ_{pex} – experimental value of flow stresses,
k – number of measurement points.

Based on preliminary calculations, it was found that the accuracy of the results is significantly affected by the large number of measurement points for a range of small

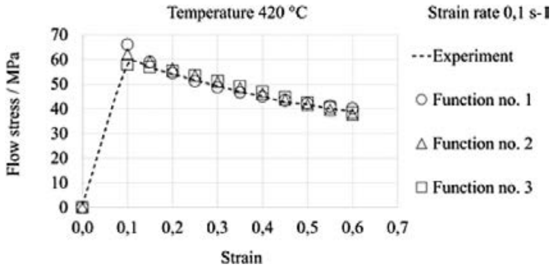

Figure 7 The comparison of flow curves obtained in experiment with theoretical ones determined by function (1), (2) and (3) at temperature 420 °C and strain rate 0,1 s-1

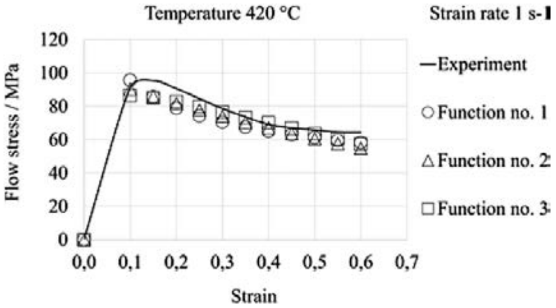

Figure 8 The comparison of flow curves obtained in experiment with theoretical ones determined by function (1), (2) and (3) at temperature 420 °C and strain rate 1 s-1

strain values, which are of limited importance from the point of view of metal forming processes. Considering the data for this range generates errors; it causes the difference between the measured and theoretical values to increase as the strain increases. It was verified that a significantly better fit (smaller value of the objective function) occurs when the function is determined for strains greater than 0,1. For this reason, the range of small strains was ignored in further calculations.

Table 2 **Determined values of coefficients of functions (1) – (3)**

Function no.	Function coefficients							Objective function Φ_σ
	A	*B*	*C*	*D*	*E*	*F*	*G*	
(1)	305,857	-0,278	0,161	-0,004	-	-	-	0,006
(2)	611,995	0,346	-1	0,162	-0,004	-	-	0,004
(3)	126,384	-1,664	0,003	-1,222	-0,206	0,001	0	0,005

The results of the optimization calculations performed are shown in Table 2 and Figures 3÷8. Based on the results obtained, it was found that for most of the cases considered, the use of function (2) results in better agreement with experimental results than the use of functions (1) and (3). Hence, it was assumed that function (2) would be used to describe the material model during numerical analyzing the metal forming processes of AZ91 magnesium alloy cast into sand molds.

CONCLUSION

On the basis of the results of plastometric experiments, the flow curves of AZ91 magnesium alloy cast into sand molds were determined. The obtained dependences of flow stresses on strains will be implemented into the material model in metal forming process simulation programs. Conducted compression tests also confirmed the ductility of this alloy for hot metal forming at temperatures ranging from 380 ºC to 420 ºC and strain rates of 0,1 – 1,0.

The AZ91 magnesium alloy cast in sand molds shows high sensitivity to strain rate over the entire temperature range used in plastometric experiments. This is most clearly observable at strain rates of 10 s-1 at which all specimens cracked at each of the temperatures tested. The forming processes of the analyzed alloy are therefore more favorable to be carried out using forging machines with low speeds of tool movement.

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REFERENCES

[1] P. Skubisz, Results of Thermomechnical Treatment Implementation in Hammer Drop Forging Industrial Process, Metalurgija 60 (2021), 1-2, 71-74

[2] A. Dziubinska, A. Gontarz, I. Zagorski, Qualitative research on AZ31 magnesium alloy aircraft brackets with a triangular rib produced by a new forging method, Aircraft Engineering and Aerospace Technology 90 (2018), 3, 482-488.

[3] A. Dziubinska, P. Surdacki, Numerical Analysis of the New Forming Process of the Aircraft Bracket Forging Made of AZ91 Alloy at Different Rates of Deformation, Tehnicki Vjesnik 29 (2022), 2, 201-205.

[4] E. Czekaj, T. Reguła, M. Bronicki, M. Lech-Grega, An Assessment of the Possibilities to Shape the Mechanical Properties of Cast AZ91 Magnesium Alloy Through Application of Proper Heat Treatment, Foundry Institute Works XLVIII (2008), 1, 39–45.

[5] C. Liu, J. Liang, J. Zhou, Q. Li, Z. Peng, L. Wang, Characterization and corrosion behavior of plasma electrolytic oxidation coated AZ91-T6 magnesium alloy, Surface and Coatings Technology 304 (2016), 179–187.

[6] A.M. Gałkin, Plastometric testing of metals and alloys, Publishing House of the Czestochowa University of Technology, Czestochowa, 1990, 1-139.

[7] A. Gontarz, W.S. Weronski, Forging of aluminum alloys, Publishing Lublin University of Technology, Lublin, 2001, 1-278.

[8] Z. Pater, G. Samolyk, Fundamentals of theory and analysis metal forming of metals, Publishing Lublin University of Technology, Lublin, 2011, 1-290.

[9] J. Abadie, Generalized reduced gradient and global Newton methods, Optimi-zation and Related Fields, Springer, 1984, Sicily, 1–20.

[10] C. L. Hwang, F.A. Tillman, W. Kuo, Reliability Optimization by Generalized Lagrangian-Function and Reduced-Gradient Methods, IEEE Transactions on Reliability, R-28 (1979), 4, 316-319.

Note: The responsible for English language is Tomasz Kuras, Lublin, Poland.