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APPROXIMATION MODEL OF THE STRESS-STRAIN CURVE FOR DEFORMATION OF ALUMINIUM ALLOYS

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The main purpose of this paper is to give a mathematical description of flow stress of examined aluminium alloys on the basis of upsetting tests performed in a servohydraulic plastometer. Deformation curves have been described by means of the Sellars-Tegart-Garofalo equation, with the aid of linear regression analysis and by the neural network method implemented in the NEUREX program.

Key words: alloys, regression analysis, neural networks, stress-strain curves, compression test

Približni model naprezanje-brzina deformacije krivulje za oblikovanje aluminijskih legura. Glavni cilj članka je dati matematički opis toka naprezanja ispitivanih aluminijskih legura na temelju testa opterećenja proveden na servohidrauličkom plastometru. Krivulje deformacije su opisane pomoću Sellars-Tegart-Garofalo jednadžbe, uz podršku linearnih regresionih analiza te metodom neuralne mreže ostvarene u NEUREX programu .

Ključne riječi: aluminijske legure, regresivne analize, neuralne mreže, krivulje naprezanje-brzina deformacije, tlačni test

INTRODUCTION

In view of current development of novel advanced technological processes and deployment of wider range of materials, knowledge of energy and forces in forming is important for defining optimum processing conditions leading to the best possible economic effect. Knowledge of the flow stress of materials in relation to forming parameters is a key to calculation of deformation forces and deformation work and resulting technical parameters for an effective process and higher product quality. The shape of the stress-strain curve enables to draw a conclusion on formation of microstructure and thus on properties of the product.

The purpose of the experimental section of the paper is to give a mathematical description of flow stress of examined aluminium alloys on the basis of upsetting tests performed in a servohydraulic plastometer. Stress-strain curves have been described with the aid of Sellars-Tegart-Garofalo equations and by means of linear regression analysis. An identical set of results was also processed using neural networks methods in NEUREX software.

COMPRESSION TEST

In a compression test, there is an additional tangential force acting on the specimen during deformation, which results from the friction between the tool and specimen. Where this friction force is not eliminated, it leads to an increase in the flow stress of 7 – 12 % in comparison with flow stress values obtained without the effect of friction. That is why there is an effort to reduce the friction in the deformation process by means of suitable lubricants (e.g. melted glass). For the purpose of rolling investigation, however, it is recommended to measure the flow stress in compression a test due to a similar deformation arrangement. Evaluation of the experiment should take into account the impact of the temperature increase in the process and the strain-time relationship. The evaluation is based on the assumption of a uniaxial compression stress state within the strain range of $0 \leq e \leq 0,7$ [1].

EXPERIMENTAL

A computer-controlled servohydraulic compression plastometer has been used as a testing machine for the upsetting test. This testing system by the company Servotest, converted into a fully digital instrument, performs compression testing at strain rates between 0,01 and 40 s^{-1} and at the testing force of up to 400 kN. It requires standard specimens with an initial height exceeding 10 mm and 10 mm diameter. This system also offers multi-stage testing with variable height reductions and holding times. For hot upsetting tests the system offers an integrated upsetting furnace which encloses the entire testing space (the specimen and the upsetting tool) to provide isothermal conditions until the start of testing.

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The set of experimental materials consisted of specimens of four aluminium alloys with the dimensions of ϕ 10 × 12mm, which had been heat-treated at 280 °C/2 hours and cooled-down slower than 50 °C/hour. Experiments were carried out at three temperatures: 360, 400 and 440 °C and at three strain rates: 0.1; 1; 10 s^{-1}. The shapes of the testing curves, as shown in Figure 1, indicate that beyond the peak stress dynamic restoration takes place, where recovery can be expected to occur in aluminium alloys. In Figure 1 the diagram shows the curves for the 2014 alloy. Chemical compositions of individual alloys are given in Table 1.

Table 1 **Chemical compositions / wt %**

alloy	sample	mark	Si	Fe	Cu
AlCu4Mg1	C	**2124**	0,19	0,21	4
AlCuLiMg	4	**2091**	0,03	0,08	1,71
AlCuLi	5	**2090**	0,02	0,09	2,59
AlCu4SiMg	7	**2014**	0,9	0,5	4,4
	Mn	Mg	Zr	Li	
AlCu4Mg1	0,71	1,36	-	-	
AlCuLiMg	-	0,99	0,06	1,81	
AlCuLi	-	0,04	0,11	2,05	
AlCu4SiMg	0,3	0,6	-	-	

The curves obtained at the temperature of 360 °C and strain rate of 1 s^{-1} are indicated in . Curves for other temperatures and strain rates have been obtained as well [2].

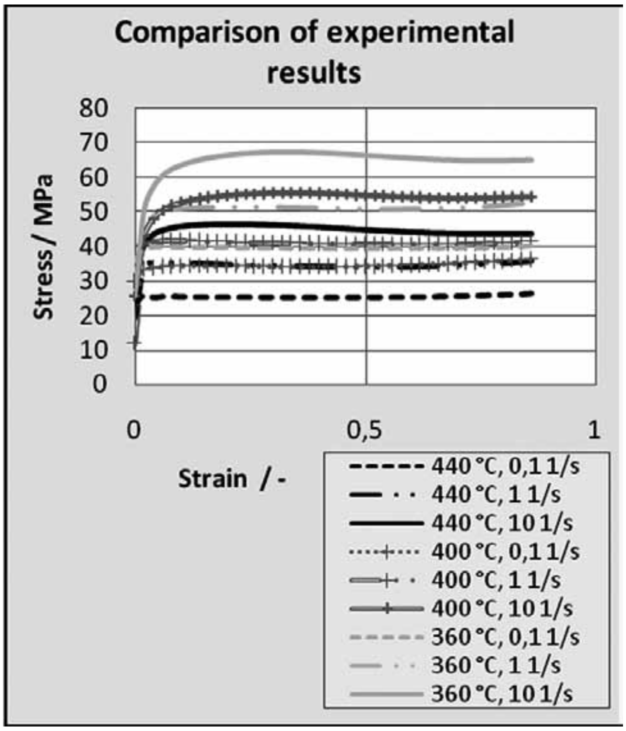

Figure 1 Experimental results of flow stress measurement in dependence on temperature and strain rate for the 2014 alloy

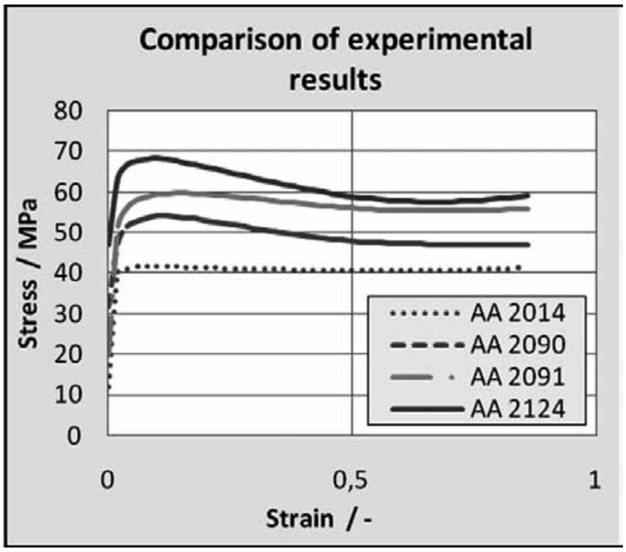

Figure 2 Comparison of experimental results obtained at 360 °C and the strain rate of 1 s^{-1}

EVALUATION OF MEASUREMENT RESULTS

Data obtained from the plastometer has been used as the basis for evaluation.

The first method used involved finding the coefficients of the Sellars-Tegart-Garofalo equation through calculation of peak strain values ε_{p-c} and σ_{p-c} peak stresses and substituting them in the equation:

$$\sigma_c = \sigma_{p-c}\left[\frac{\varepsilon}{\varepsilon_{p-c}}\exp\left(1-\frac{\varepsilon}{\varepsilon_{p-c}}\right)\right]^c \tag{1}$$

Resulting curves are shown in the Figure 3 below. These particular ones indicate the stress in the AA 2014 alloy at the strain rate of 1 s^{-1} and temperatures of 360, 400 and 440°C. Their graphical comparison with experimental data is indicated for better clarity as well.

Another method applied was an evaluation with the aid of linear regression analysis. Simple forms have been taken into account first (2 - 3) in accordance with

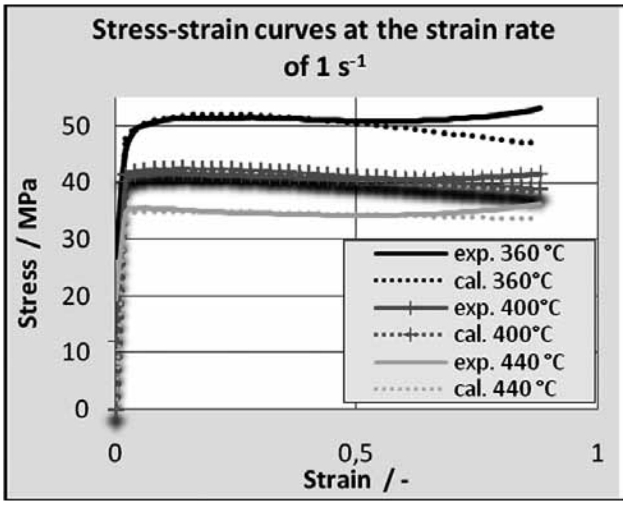

Figure 3 Comparison of experimental and calculated results according to Sellars-Tegart-Garofalo equation

equations proposed by Spittel et al [3] in the following form:

$$\sigma_p = \sigma_{po} \cdot A_1 \cdot \exp(-m_1 T) \cdot A_2 \varepsilon^{m_2} \cdot A_3 - \dot{\varepsilon}^{m_3} \quad (2)$$

leading to the particular conclusion relevant for the AA2014 alloy:

$$\sigma_p = 41{,}7 \cdot 6{,}284 \cdot \exp(-0{,}00456T) \cdot \cdot 1{,}066 \cdot \varepsilon^{0{,}02512} \cdot 1{,}014 \cdot \dot{\varepsilon}^{0{,}0926} \quad (3)$$

There are more complex equations providing more adequate description of the curves beyond the peak stress (4 – 5):

$$\sigma_p = \sigma_{p0} \cdot A_1 \cdot \exp(-m_1 T) \cdot A_2 \varepsilon^{m_2} \cdot \exp\left(\frac{m_4}{\varepsilon}\right) \cdot \cdot (1+\varepsilon)^{m_s T} \cdot A_3 \cdot \dot{\varepsilon}^{m_s} \quad (4)$$

which leads to the expression, again for the AA2014 alloy:

$$\sigma_p = 41{,}7 \cdot 6{,}284 \cdot \exp(-0{,}00456T) \cdot 1{,}066 \cdot \varepsilon^{0{,}02512} \cdot \cdot \exp\left(\frac{-0{,}001}{\varepsilon}\right) \cdot (1+\varepsilon)^{-0{,}00112T} \cdot 1{,}014 \cdot \dot{\varepsilon}^{0{,}0926} \quad (5)$$

Values of parameters used for obtaining the above equations for all alloys in question are listed in the Table 2.

Table 2 **Table of material constants**

slitina	A1	A2	A3	m1
AA2014	6,284	1,066	1,014	0,00456
AA2091	9,199	1,091	0,954	0,00556
AA2090	14,768	1,142	0,95	0,00674
AA2124	3,788	1,012	0,94	0,00319
	m2	m3	m4	m5
AA2014	0,25119	0,09263	-0,001	0,00112
AA2091	0,03456	0,11821	-0,00143	0,00166
AA2090	0,05349	0,10814	-0,00217	0,00261
AA2124	0,00217	0,16785	-0,00018	0,00002

Another model which has been used (4) leads to a satisfactory description of curves, as indicated by the final comparison in Figure 4.

The last method applied was evaluation by means of neural networks. The application program NEUREX was used, offering the simulation of a feed-forward multi-layer neural network employing backpropagation teaching with user-defined parameters, such as synoptic weights [4-5]. The ability to alter the number of neurons in the hidden layer has been used to identify the optimum neural network for the problem in question. A network with two, three or up to five neurons in the hidden layer has been used for each alloy. After calculation it was observed that the best approximation was achieved with the five-neuron variant displayed in the final comparison in Figure 4.

Identical AA 2014 alloy has been used for torsion tests with lower strain rates but higher total true strain

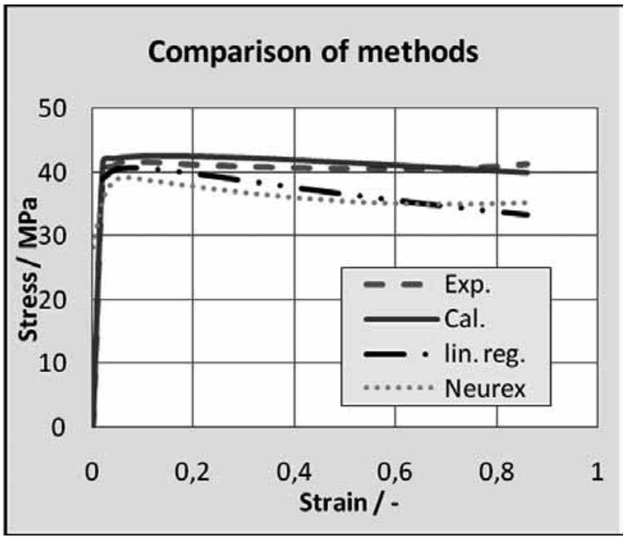

Figure 4 Comparison of methods used for the AA 2014 alloy at the temperature of 400°C and strain rate of 1 s^{-1}

[6]. The curves are of similar nature but the peak value is about 20 % higher. Moreover, they have been obtained at strain rates which had been several orders of magnitude lower than the previous ones. The explanation may lie in a different calculation algorithm and conversion of parameters (compression force, torque) to stress values.

CONCLUSION

On the basis of experimental results of upsetting tests on four types of aluminium alloys, models for calculation of flow stress were constructed via three methods [7-9].

Comparison of those methods leads to the conclusion that within a specific range of strain values they can be used for describing the measured curves. Values obtained by regression analysis are relatively accurate, particularly in the peak deformation stress region. At higher strains ($\varepsilon > 0{,}7$) the curves diverge more significantly and their shapes cannot be described by a single equation. Best results in the strain interval of $\varepsilon < 0{,}5$ were obtained by means of the model based on seeking Sellars-Tegart-Garofal equation coefficients. In this area, this model proved to be the most accurate one. Stress-strain curves constructed in the program NEUREX are an optimum match of the shape of the experimental curve. At lower strains,however, they fail to reach the same accuracy as the above methods. The final comparison of experimental and calculated curves is shown in Figure 4.

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Note: The responsible translator for English language is J. Drnek, Czech Republic