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Influence of deformation conditions on the rheological properties of 6xxx series Al alloy

Wpływ warunków odkształcenia na własności reologiczne stopu Al serii 6xxx

Abstract
Knowledge of the characteristics describing the technological properties of the material is the basis for correct numerical simulation and the design of new technological processes or the modernization of existing ones. For each technological process of plastic forming, a set of features should be defined that correctly describe the susceptibility of the material to its shaping in a given process.
The paper presents the results of rheological tests of 6xxx series Al alloy, obtained for deformation parameters corresponding to the process of the extrusion of large-size profiles. The effect of deformation conditions on changes in yield stress was determined. Next, the true values of the mathematical model coefficients describing the rheological properties of the tested material were determined using the inverse method, which is the basis for conducting numerical tests.

Keywords: plastometric tests, yield stress, strengthening curves, 6xxx series Al alloys

Streszczenie
Dobra znajomość charakterystyk opisujących własności technologiczne materiału jest podstawą do prawidłowego przeprowadzenia symulacji numerycznych oraz projektowania nowych bądź modernizacji istniejących procesów technologicznych. Dla każdego procesu technologicznego przeróbki plastycznej można określić zestaw cech, które dobrze opisują podatność materiału do jego kształtowania w danym procesie.
W pracy przedstawiono wyniki badań reologicznych stopu Al serii 6xxx, uzyskane dla analizowanych parametrów odkształcenia odpowiadających parametrom procesu wyciskania profili wielkogabarytowych. Określono wpływ warunków odkształcenia na zmiany granicy plastyczności. Następnie określono wartości rzeczywiste współczynników modelu matematycznego opisującego właściwości reologiczne badanego materiału metodą odwrotną, który to model jest podstawą przeprowadzenia badań numerycznych.

Słowa kluczowe: badania plastometryczne, granica plastyczności, krzywe umocnienia, stopy aluminium serii 6xxx

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1. Introduction

The wide range of 6xxx series Al alloys in various industries requires the determination of its mechanical properties for specific technological conditions. The application of aluminum profiles when creating constructions such as cars provides the potential to reduce the vehicle's own weight by about 10%, which translates, among other things, into lower exhaust emissions. Another challenge faced by today's enterprises is the reduction in the number of connections in favor of manufacturing complex shapes that additionally have fixing functions. In order to realize such complex products, it is necessary to carry out the process of technological design in order to reduce the time of launching the production of newly created elements.

In order to carry out the correct numerical analysis and design of technological processes, it is necessary to know the characteristics describing the technological properties of the material. For plastic working processes, the basic feature characterizing the material workability is the yield stress σ_p and the limit strain ε_g [1–4]. The correct determination of 6005 Al alloy properties in the form of stress-strain diagrams, taking into account the influence of material temperature and deformation velocity, allows exact results to be obtained using both empirical formulas and numerical calculations in which the finite element method is used [4].

The advantage of the uniaxial compression test at an elevated temperature is the fact that data concerning the actual stress in relation to the actual strain can be obtained in a much wider range of deformations compared to the received data e.g. from the tensile test [5–7].

The aim of the research was to determine the effect of strain, strain rate and temperature on the changes in yield stress, for 6005 aluminum alloy for the conditions of plastic forming occurring in industrial practice. The conditions of plastometric tests were selected in such a way that after their implementation it was possible to determine the functions used to the yield stress determination and the calculation their coefficients, for specific deformation conditions during the extrusion process.

2. Material and methodology

The test material was 6005 aluminum alloy. The chemical composition of the alloy is shown in Table 1.

Table 1. The chemical composition of the tested alloy Al, %; R – Al content

Alloy	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Al**
6005	0.246	0.146	0.004	0.567	5.54	0.002	0.026	0.019	R

The analysis of alloy properties under specific deformation conditions was conducted. The first stage of the research was to determine the characteristic temperatures on the basis of dilatometer tests on the DIL 805A/D device. Next, plastometric tests were carried out for selected temperature ranges (350–450°C) and strain rates (0.1–100 s^{-1}). The compression tests were carried out in a vacuum chamber at a constant temperature of the deformed sample.

3. Test results

The first stage of the study was to carry out dilatometric tests to determine the optimal temperature range for the extrusion process. In addition, the dilatometric tests allowed the determination of the linear coefficient of thermal expansion at elevated temperatures. Dimensional changes of the solid body are represented by changing one of the dimensions of the body being examined, most often the length, when it is subjected to a variable temperature effect. The heating and cooling rate was 3°C·s^{-1}. The obtained results of the studies on dependence of the relative elongation on the temperature are shown in Figure 1a, while the dependences of the linear expansion coefficient are shown in Figure 1b.

The criterion of temperature selection for the dilatometric test was based on the phase equilibrium system of the alloy.

a) b)

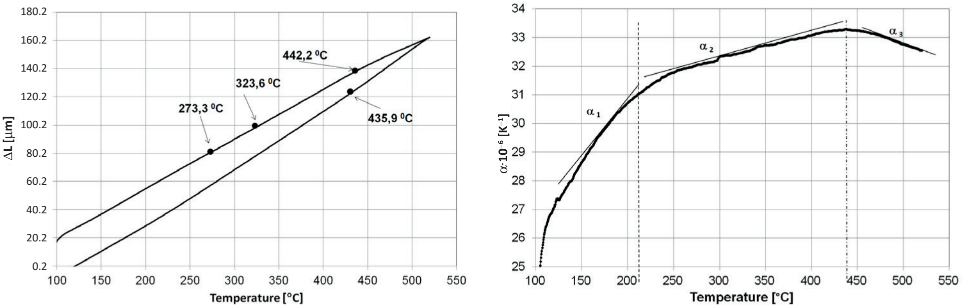

Fig. 1. Dependency: a) changes in length from temperature; b) change in coefficient of expansion from temperature for 6005 aluminum alloy

The results of dilatometric tests for the 6005 aluminum alloy in the temperature range of 20–520°C presented in Figure 1a and Figure 1b show changes in the dimensional parameters of the tested samples. During the heating process of the tested material, the coefficient of linear thermal expansion changes, as shown in Figure 1b. The difference in the slope of the curve occurs after exceeding the temperature of 420°C, proving the initiation of changes in the structure of the material being tested. Dilatometric testing allowed the determination of the temperature ranges most advantageous for carrying out plastic working processes (Fig. 1a).

On the basis of the specified temperature ranges, the other parameters of the analysis were selected. For the determination of rheological properties of the material used to define the parameters of forming processes such as extrusion, rolling, pressing, it is necessary to determine the $\sigma - \varepsilon$ relationship. After the compression test of the 6005 aluminum alloy, experimental and approximated relationships of the yield stress and true strain were determined for the investigated three temperatures and six different strain rates. The test results are shown in Figures 2 and 3.

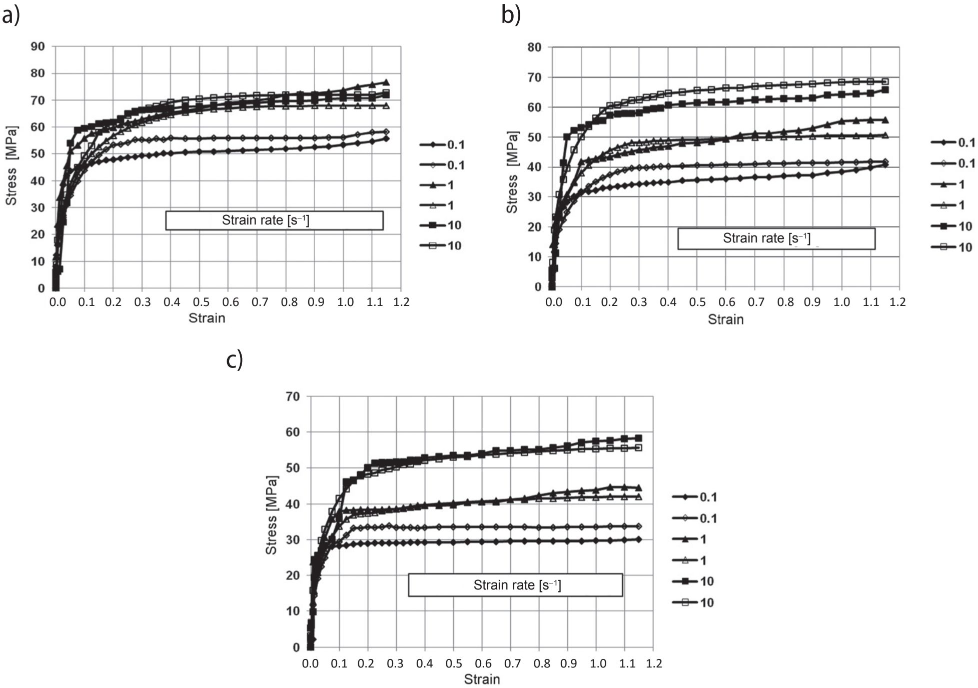

Fig. 2. Strengthening curves of Al 6005 alloy for the strain rate range of 0.1–10 s^{-1}: a) at 350°C; b) at 400°C; c) at 450°C; full symbols – experimental curves, blank symbols – approximated curves

From the data presented in Figure 2, it follows that the flow stress increases with increasing true strain. Analyzing the test results obtained, it can be noticed that for the temperature of 350°C and the strain rate 0.1 s^{-1} after achieving the strain value of 0.2, the stress value does not increase. For the strain rate equaled 1 s^{-1} and 10 s^{-1}, after the true strain exceeds the value of 0.4 the yield stress value is stabilized. An increase of the specimen temperature for about 100°C caused a 40% decrease in the yielded stress value for a strain rate of 0.1 s^{-1}. In the case of the higher strain rate (10 s^{-1}), the decrease in the yield stress of about 20% was observed. In the analyzed temperature range, the increase in the strain rate of 0.1 s^{-1} to 1 s^{-1} causes the increase in the flow stress by 30%. An increase of the temperature causes the movement of the stabilization point on the stress-strain curve to lower values of the true strain.

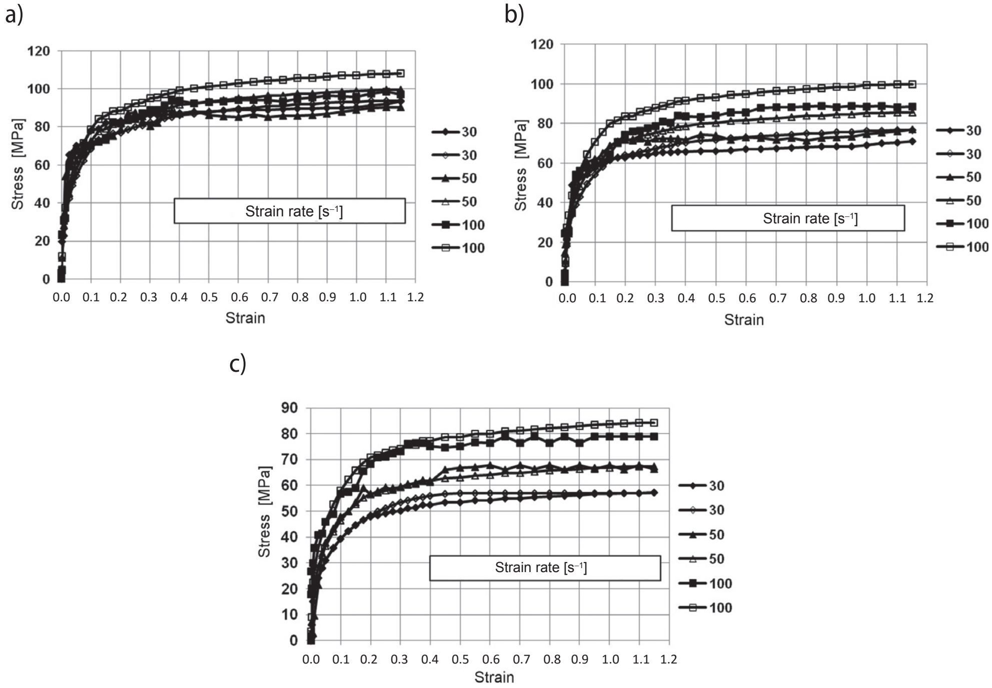

Fig. 3. Strengthening curves of 6005 aluminum alloy for the strain rate range of 30–100 s^{-1}: a) at 350°C; b) at 400°C; c) at 450°C; full symbols – experimental curves, blank symbols – approximated curves

The data presented in Figure 3 show that a significant increase in the strain rate range causes changes in the characteristics of the stress-strain curve. For a strain rate of 100 s^{-1} the influence of the thermal effect on the strengthening factor (movement of the yield stress value to the higher values of the true strain) can be seen. The strain rate increase from 30 s^{-1} to 100 s^{-1} at the temperature of 350°C results in a slight growth (about 5%) in yield stress. An increase of the sample temperature for about 100°C causes a decrease in the yield stress by approx. 40% for the strain rate of 30 s^{-1} and 10% for the strain rate of 100 s^{-1}. Therefore, it can be concluded that the thermal effect is closely related to the change in the deformation temperature. With increasing temperature, the thermal effect of plastic deformation is smaller. Data confirming the validity of the conducted analysis are presented in Figure 4.

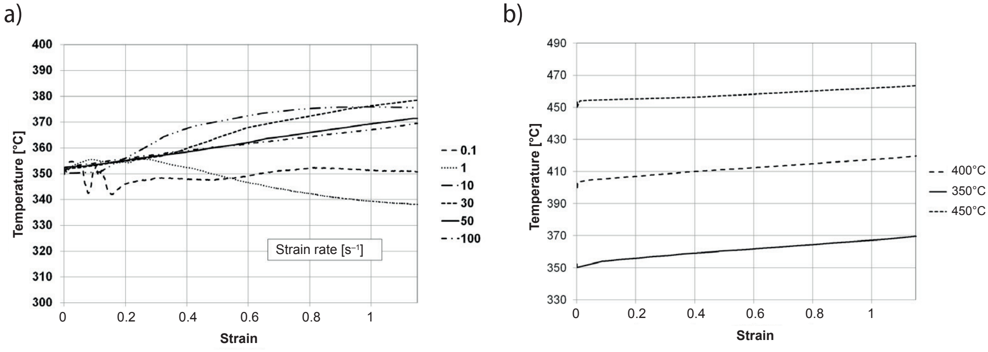

Fig. 4. The dependence of temperature change as a function of time T = f (ε) for the alloy deformed at 350°C at different deformation speeds (a), and for the alloy deformed at a deformation rate of 100 s^{-1} for different deformation temperatures (b)

On the basis of the data shown in Figure 4, it can be concluded that the 6005 aluminum alloy is sensitive to the changes in strain rate and temperature ranges for the tested parameters. An increase in the strain rate causes an increase in deviations from the selected temperature value (Fig. 4a), which for a strain rate of 100 s^{-1} is approx. 20°C (Fig. 4b).

Analyzing the character of real and approximated curves elaborated for the investigated alloy in the tested range of parameters, a high correspondence between the true values of the yield stress and the values obtained as a result of approximation can be observed. To describe the rheological properties of the tested alloy, the Hensel–Spittel [3, 8] function was used in the form of an Equation (1):

$$\sigma_p = A \cdot e^{(m_1 \cdot T)} \cdot T^{(m_9)} \cdot \varepsilon^{(m_2)} \cdot e^{\frac{m_4}{\varepsilon}} \cdot (1+\varepsilon)^{(m_5 \cdot T)} \cdot e^{(m_7 \cdot \varepsilon)} \cdot \dot{\varepsilon}^{(m_3)} \cdot \dot{\varepsilon}^{(m_8 \cdot T)} \quad (1)$$

where:

σ_p – flow stress [MPa],
T – temperature [°C],
ε – real strain,
$\dot{\varepsilon}$ – strain rate [s^{-1}],
A, m_1–m_9 – determined coefficients.

The values of the yield stress of the function coefficients determined for the two areas of tested strain rate: 0.1–10 s^{-1}, 30–50 s^{-1} and analyzed for the entire range of strain rates 0.1–100 s^{-1} The analysis was made for a temperature range of 350–450°C. The obtained values of the function coefficient is Equation (1) are shown in Table 2.

The choice of ranges of thermo-mechanical parameters of the process is very important since, analyzing the obtained data, it can be concluded that different values of yield stress are obtained in different ranges of research, confirming a certain average approximation error. For a wide range of tested parameters, the approximation error is 10%. It is assumed that the function coefficients in Equation (1) are sufficiently well matched if the average approximation error does not exceed 8–10%. Therefore, it can be concluded that with too broad a range of parameters, the analysis is carried out at the limit of the acceptable level. On the basis of the flow curves obtained for temperature range of 350–450°C and strain rate range of 0.1–100 s^{-1}, an ambiguous effect of increasing the strain rate on the flow stress value was observed. As a result, an increased error of approximation is obtained after increasing the strain rate range. To reduce the error, the function coefficients in Equation (1) for narrower strain rates ranges should be determined.

Table 2. Values of the function coefficients used to determine σ_p

Coefficient *A*	**Coefficients m_1–m_9**								**Average approximation error ΣA [%]**	**The range of strain rate [s^{-1}]**
	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9		
34992297335728	0.0099	0.425	−0.378	3.64 e^{-5}	−0.0043	0.333	0.0012	−5.075	6.5	0.1–10
1.5185 e^{-9}	−0.0275	0.373	−0.606	−6.2909	0.0017	−1.156	0.0021	5.923	7.1	30–50
0.0003037	−0.0108	0.399	0.0295	−1.32e^{-5}	−0.0013	−0.411	0.0002	2.856	10	0.1–100

4. Conclusions

The plastometric tests of the 6005 aluminum alloy dedicated to the extrusion process show that a very important point in the planning of the technological process is the appropriate selection of the range of input parameters.

Analyzing the true and approximated stress-strain curves for the tested alloy (6005) in the investigated range of parameters, there was agreement between the real values of yield stress and the values obtained as a result of approximation. For the strain rate ranges of 0.1–10 s^{-1} and 30–100 s^{-1} the approximation error for flow stress determined from the Hansel–Spittel Equation (1) does not exceed 6.5% and 7.1%, respectively.

The results obtained from the approximation of flow curves of the tested material can be used during numerical modeling of the plastic forming processes.

When planning the extrusion process of complex profiles, the material should have a good bonding ability, for example in the pocket dies, which requires proper selection of the process conditions.

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