

K. LABER^{*,#}, A. KAWAŁEK^{*}, S. SAWICKI^{*}, H. DYJA^{*}, J. BOROWSKI^{**}, D. LEŚNIAK^{***}, H. JURCZAK^{****}**INVESTIGATIONS OF PLASTICITY OF HARD-DEFORMED ALUMINIUM ALLOYS OF 5XXX SERIES USING TORSION PLASTOMETER**

This paper presents the results of the study aimed at determination of plasticity of selected grades of hard-deformed aluminium alloys of 5xxx series in terms of parameters characteristic for the process of extrusion. The examinations were carried out for 5083 and 5754 alloys in the torsion test using STD 812 torsion plastometer. Using the empirical tests, the study evaluated yield stress of alloys depending on strain, strain rate and temperature and the results were approximated and mathematical models of rheological properties of the aluminium grades studied were determined within the range of parameters of deformation and temperature.

Keywords: hard-deformed materials, examination of plasticity, formability limit, torsion test

1. Introduction

Aluminium alloys with content of up to 5% of magnesium are the materials used for metal forming. As results from the data presented in a study [2], aluminium alloys of 5xxx series are the most resistant to corrosion of all aluminium alloys. Furthermore, they demonstrate a very good mechanical processing and welding properties [2, 3]. An insignificant decline in tensile strength was only found in the welded structures made of these alloys compared to the structures made of full material [1, 3]. Examinations of alloys of 5xxx series showed that these alloys exhibit medium strength. The increase in content of magnesium leads to improvement in strength properties of plastically formed AlMg alloys [1], which is connected with limited plasticity (formability) of these alloys and lower susceptibility to hot plastic deformation [4].

Therefore, it becomes justified to carry out the research in order to determine rheological properties and formability of aluminium alloys of 5xxx series in terms of opportunities of forming them using methods of metal forming, also through extrusion.

The basic parameter that characterizes susceptibility of material for plastic forming is yield stress σ_p , which, under conditions of uniaxial state of stress, is a function of strain (ε), strain rate ($\dot{\varepsilon}$), temperature (T) and strain history [5-8].

Determination of rheological properties, with particular focus on yield stress, is particularly difficult for conditions of hot plastic processing since the processes that result from the mechanism of plastic deformation, processes of material strengthening and heat-activated processes, depending on the

time of the phenomenon occur simultaneously in the structure of the material, leading to its weakening [4, 8-10].

Proper determination of metal properties in the form of stress-strain diagrams that take into consideration the effect of material temperature and strain rate ensures improved accuracy of calculations during using the empirical equations as well as during numerical calculations that employ finite elements methods [6-7, 11].

There are a number of research methods that are used for evaluation of yield stress, among which the most popular are tensile testing, compression strength testing and torsion testing. These methods were described in detail in e.g. [5, 8].

According to numerous authors, the most convenient method to determine flow curve for high temperatures is torsion test. This test allows for determination of yield stress in an indirect manner, using the hypothesis of material effort. The main benefits of the test include no friction, constant state of stress, with high accuracy that corresponds to pure shear and opportunities to achieve substantially greater strain compared to other tests [5, 8, 12]. The method of hot torsion test is particularly advantageous during examinations of hard-deformed and brittle materials for conditions of hot plastic forming. The test allows for creation of more reliable conditions for achievement of constant strain rate and offers the best way to model multi-level strain [13].

2. Aim and scope of study and test methodology

The aim of the study was to determine rheological properties for two grades of hardly deformed aluminium

* CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, FACULTY OF PRODUCTION ENGINEERING AND MATERIALS TECHNOLOGY, INSTITUTE OF METAL FORMING AND SAFETY ENGINEERING, 19 ARMII KRAJOWEJ AV., 42-200 CZĘSTOCHOWA, POLAND

** INOP METAL FORMING INSTITUTE, 14 JANA PAWŁA II STR., 61-139 POZNAŃ, POLAND

*** AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, AL. ADAMA MICKIEWICZA 30, 30-059 KRAKÓW, POLAND

**** ALBATROS ALUMINIUM SP. Z O.O., 1/27 CZARTORIA 1 STR., 61-102 POZNAŃ, POLAND

Corresponding author: laber@wip.pcz.pl

TABLE 1

Chemical composition of 5083 and 5754 aluminium alloys [%]

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
5083	0.229	0.145	0.004	0.553	4.44	0.120	0.024	0.018	R
5754	0.224	0.140	0.007	0.465	3.44	0.002	0.022	0.018	R

alloys of 5xxx series in 5083 and 5754 grades. The scope of the study also included determination of the function of yield stress of the alloys studied based on the results of empirical examinations which can be used during numerical modelling of extrusion processes.

Material for the study was obtained from cast ingots with diameter of 102 mm after homogenization. The detailed description of the specimens was presented in the study [1].

Chemical composition of the alloys analysed in the study is presented in Table 1.

Parameters for which the rheological properties of the AlMg alloys were carried out are presented in Table 2. Three tests were performed for each variant. The examinations were carried out under conditions of non-free torsion until reaching the value of true strain of 5.

TABLE 2

Test parameters for 5083 and 5754 aluminium alloys [%]

Mean strain rate, $\dot{\epsilon}$ [s ⁻¹]	Temperature, T [°C]				
0.1	400	440	480	520	560
0.5	400	440	480	520	560
1	400	440	480	520	560

Torsion tests were carried out using STD 812 torsion plastometer that was an equipment of the Institute of Metal Forming and Safety Engineering at Częstochowa University of Technology. The general design of the test chamber is illustrated in Fig. 1, whereas its most important technical specifications are presented in Table 3.

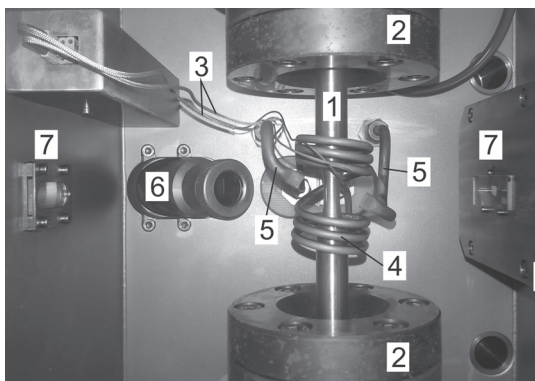


Fig. 1. Specimen during examination in the chamber of STD 812 torsion plastometer: 1 - specimen, 2 - holders, 3 - thermocouples type S, 4 - induction solenoid, 5 - cooling system jets, 6 - pyrometer, 7 - sensors for laser measurement of specimen diameter

The tests were carried out in vacuum at constant temperature of the specimen and at constant strain rate. Plastometric examinations used cylindrical specimens with diameter of $d = 8$ and length of measurement base of $l = 20$ mm. A thermocouple type K welded with the lateral surface of specimens was used to record and monitor temperature changes. The specimens were induction-heated at constant speed of $5\text{ }^{\circ}\text{C/s}$ until they reached the set temperature, maintained at this temperature for 10 s and finally deformed. Overall view of the specimen in the device for welding thermocouples is presented in Fig. 2.

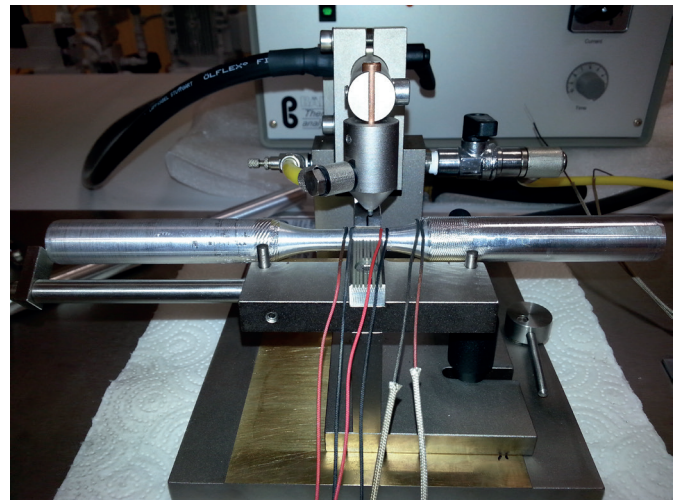


Fig. 2. Example specimen during welding of thermocouple with lateral surface.

TABLE 3

Basic specifications of STD 812 torsion plastometer

Heating:	induction
Maximum testing temperature	1500 °C
Heating and cooling rate	up to 100 K/s
Minimum time between strains:	60 ms
Medium: Vacuum 10^{-4} mbar, neutral gas, air	
Torsion	
Rotational velocity:	up to 500 rpm
Number of rotations:	up to 30
Torque:	up to 50 Nm
Strain rate:	up to 60 s^{-1}
Tension and compression	
Change in length:	ca. 15 mm
Strain rate:	up to 30 mm/s
Strain force:	up to 25kN
Strain rate:	up to 1.0 s^{-1}
True strain: dependent on specimen dimensions	
The device allows for torsion with tension or compression	

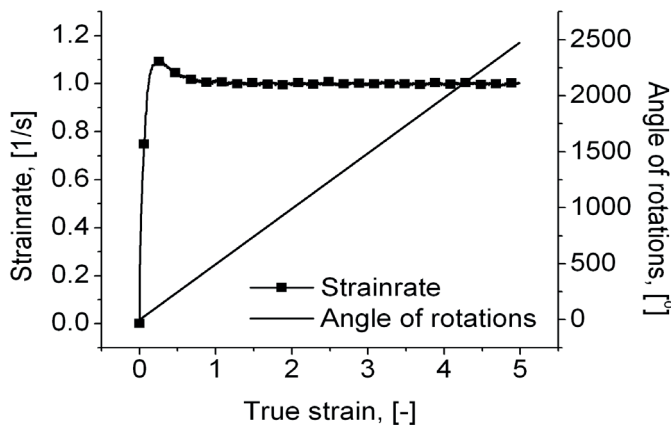


Fig. 3. Diagram of strain rate and changes in the angle of torsion for alloy 5083: temperature 400 °C, strain rate 1.0 s⁻¹

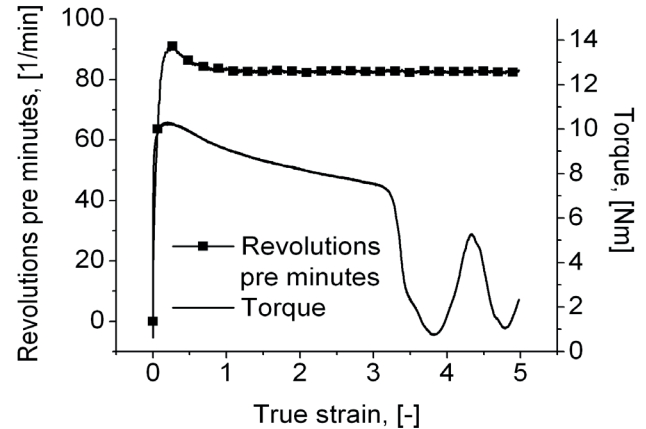


Fig. 4. Diagram of rotational velocity and changes in angle of torque for alloy 5083: temperature 400 °C, strain rate 1.0 s⁻¹

Coupling of PC with servomotors and sensors in the chamber allowed for continuous recording of the parameters analysed during plastometer tests.

The equation (1) was used to determine true strain during torsion tests, whereas true strain rate was evaluated based on (2). Yield stress was evaluated based on (3) [5, 8]:

$$\varepsilon = \frac{2 \cdot \pi \cdot r \cdot N}{\sqrt{3} \cdot L} \quad (1)$$

$$\dot{\varepsilon} = \frac{2 \cdot \pi \cdot r \cdot \dot{N}}{\sqrt{3} \cdot 60 \cdot L} \quad (2)$$

$$\sigma_p = \frac{\sqrt{3} \cdot 3M}{2\pi r^3} \quad (3)$$

where: r - specimen radius, L - specimen length, N - number of torsions (revolutions) of the specimen, \dot{N} - torsion rate (rotational velocity), M - torque.

Function (4) [11] was used to describe the value of yield stress σ_p during approximation of the results of empirical studies:

$$\sigma_p = A \cdot e^{m_1 T} \cdot T^{m_2} \cdot \varepsilon^{m_3} \cdot e^{\frac{m_4}{\varepsilon}} \cdot (1 + \varepsilon)^{m_5 T} \cdot e^{m_6 \dot{\varepsilon}} \cdot \dot{\varepsilon}^{m_7} \cdot \dot{\varepsilon}^{m_8 T}, \text{MPa} \quad (4)$$

where: σ_p - yield stress, T - temperature, ε - true strain, $\dot{\varepsilon}$ - strain rate, $A, m_1 \div m_9$ - coefficients of the function.

The software developed in the the Institute of Metal Forming and Safety Engineering at Czestochowa University of Technology was used for approximation of the results [14].

3. Analysis of the results

Fig. 3 presents the example diagram of changes in the strain rate and changes in the angle of torsion as a function of strain for 5083 alloy at the temperature of 400 °C and strain rate of 1.0 s⁻¹. Example diagram of rotational velocity and changes in torque vs. strain is showed in Fig. 4.

The data presented in Fig. 3 show that the device allows for very fast achievement of the set strain rate and ensures maintaining this rate at a constant level. The angle of rotation (torsion) for the specimens used that corresponds to true strain 5 was 2468 °. The number of rotations required for achievement of the set strain rate was 82 rpm, whereas maximum torque was slightly over 10 Nm and reduced for increasing strain (Fig. 4).

Fig. 5 presents the results of experimental studies of the effect of temperature on value of yield stress for 5083 aluminium alloy for the range of strain rate studied.

Due to very low formability of 5083 alloy at temperature of 560 °C (Fig. 5e), which caused almost immediate loss of coherence of the material studied (Fig. 6), the study was also carried out at temperature of 550 °C (Fig. 5f).



Fig. 6. Parts of aluminium alloy specimens after losing the coherence - temperature of 560 °C.

Analysis of the results of rheological properties of 5083 aluminium alloy revealed that yield stress in the range of strain parameters decreases monotonically after reaching maximum value. The data presented in Fig. 5 show that the decline in the value of yield stress intensifies only insignificantly as a result of the increase in the strain rate.

Analysis of the results (Figs. 3 and 4) reveals that the increase in strain rate in the range of from 0.1 s⁻¹ to 1.0 s⁻¹ causes an increase in the value of yield stress of the material studied to ca. 15 to 30 MPa at the beginning of the strain process. With the increase in the value of strain, the differences in yield stress resulting from the increase of strain rate are becoming smaller, from 5 to 20 MPa. In the range of temperatures of 400 °C ÷ 520 °C, values of yield strain for 5083 aluminium alloy for strain rates of 0.5 s⁻¹ and 1.0 s⁻¹ are similar. Yield stress of the alloy studied rises noticeable with the increase in strain rate at the temperatures of 550 °C and 560 °C (Figs. 4c and 4d).

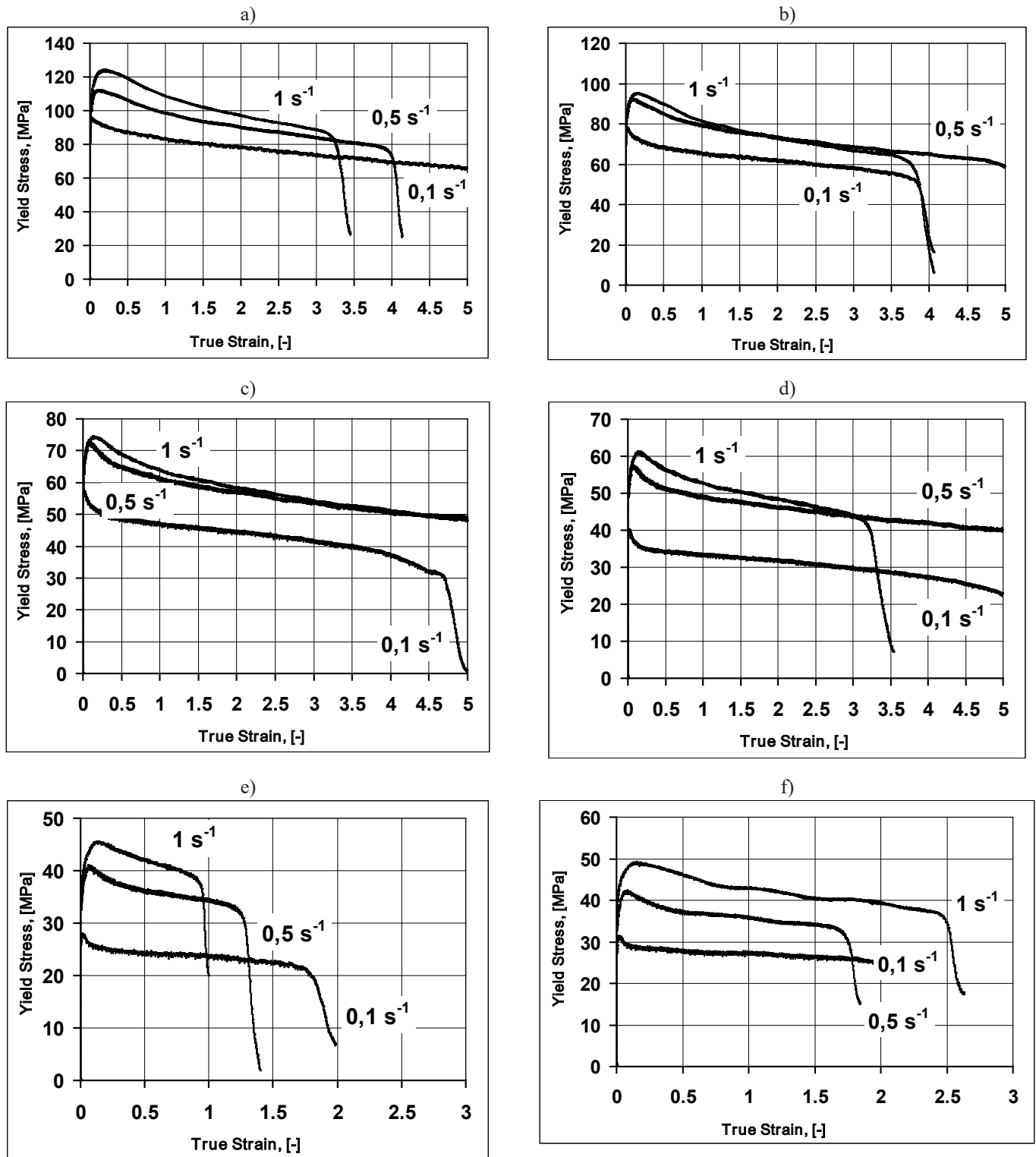


Fig. 5. Effect of actual strain and strain rate on distribution of yield stress for 5083 alloy: a) at temperature of 400 °C; b) at temperature of 440 °C; c) at temperature of 480 °C; d) at temperature 520 °C; e) at temperature 560 °C; f) at temperature 550 °C

The increase in strain temperature causes the decline in the value of yield stress of the alloy studied by ca. 60÷70 MPa at initial stage of strain. At further stages of the process, this decline is ca. 50÷60 MPa.

The examinations of rheological properties point to a substantial effect of temperature and strain rate of the alloy on its plasticity, with particular focus on forming limit. During

deformation of 5083 alloy with the strain rate of 0.1 s^{-1} , the material was characterized by the greatest formability at temperatures of 400 °C and 520 °C. At temperatures of 440 °C and 480 °C, the alloy showed reduced plasticity. The lowest formability (forming limit) for 5083 alloy and strain rate of 0.1 s^{-1} , at the level of around 2 was observed for temperatures of 550 and 560 °C.

Analysis of the data for strain rate of 0.5 s^{-1} found that the alloy studied was characterized by the highest formability at temperatures of 440°C , 480°C and 520°C . The lowest formability (forming limit) for 5083 alloy and this strain rate (1.3) was recorded for the temperature of 560°C .

During the test with strain rate of 1.0 s^{-1} , the material studied was characterized by the highest formability at

temperature of 480°C . The lowest formability (forming limit) for the material studied and strain rate of 1.0 s^{-1} (0.9) was recorded at the temperature of 560°C .

The results of plastometer testing of 5083 alloy showed that the increase in the strain rate causes a decline in formability of the alloy studied.

Effect of strain temperature on the value of yield stress of 5754 alloy was presented in Fig. 7.

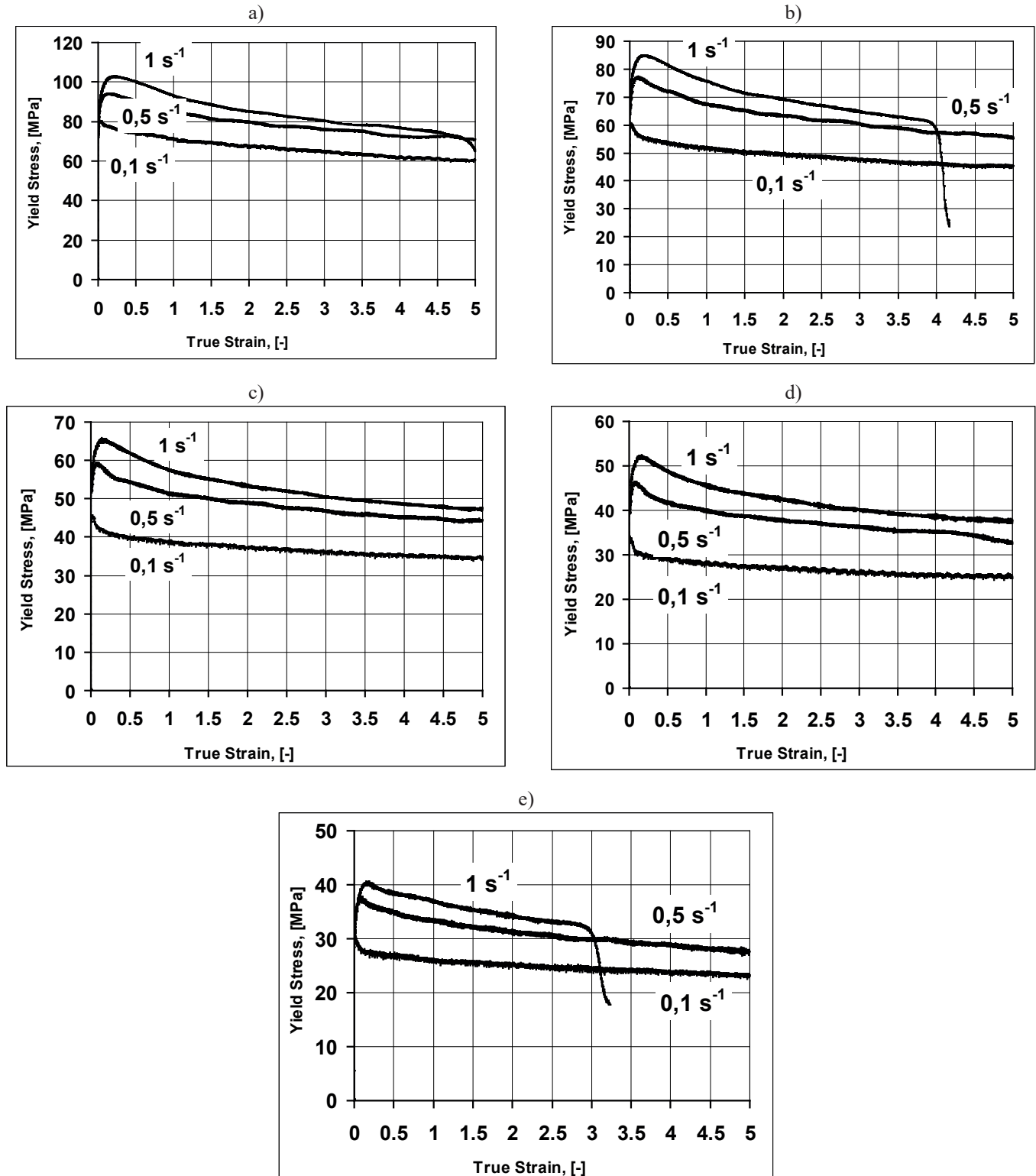


Fig. 7. Effect of actual strain and strain rate on distribution of yield stress for 5754 alloy: a) at temperature of 400°C ; b) at temperature of 440°C ; c) at temperature of 480°C ; d) at temperature 520°C ; e) at temperature 560°C

Analysis of the results of rheological properties of 5754 aluminium alloy revealed that yield stress in the analysed range of strain parameters decreases in the most of cases after reaching maximum value. Only for the strain rate of 0.1 s^{-1} and temperatures of 520°C and 560°C (Figs. 7d and 7e), yield stress of the aluminium alloy studied, after reaching the maximum value, showed insignificant decline and then remained steady at the level of ca. $22\div 24 \text{ MPa}$. Analysis of the data presented in Fig. 7 revealed that the increase in strain rate from 0.1 s^{-1} to 1.0 s^{-1} causes the increase in the value of yield stress of the material studied at initial stage of deformation process by ca. $10\div 30 \text{ MPa}$. At further stage of deformation, the increase in the value of yield stress of the aluminium alloy 5754 caused by increased strain rate ranged from 5 to 15 MPa. With the increase in the value of strain, the differences in yield stress resulting from the increase of strain rate are smaller. The increase in the yield stress of the alloy studied, resulting from the increase in the

strain rate is greater in the range of strain rates of $0.1 \text{ s}^{-1} \div 0.5 \text{ s}^{-1}$ compared to the range of $0.5 \text{ s}^{-1} \div 1.0 \text{ s}^{-1}$.

Increase in the temperature of the specimens tested (Fig. 7) causes the decrease in the value of yield stress of the alloy studied at the beginning of strain by ca. $50\div 60 \text{ MPa}$. At further stages of deformation, this decline is ca. $40\div 50 \text{ MPa}$.

Effect of temperature and strain rate of 5754 alloy (Fig. 7) on its plasticity, with particular focus on forming limit, is lower than for 5083 alloy (Fig. 5). During process of deformation of 5754 alloy at the strain rates of 0.1 s^{-1} and 0.5 s^{-1} , this material was characterized by good formability over the whole temperature range.

During the test with strain rate of 1.0 s^{-1} the material studied was characterized by the highest formability at temperatures of 480°C and 520°C . The lowest formability (forming limit) for the material studied and strain rate of 1.0 s^{-1} (3) was recorded at the temperature of 560°C .

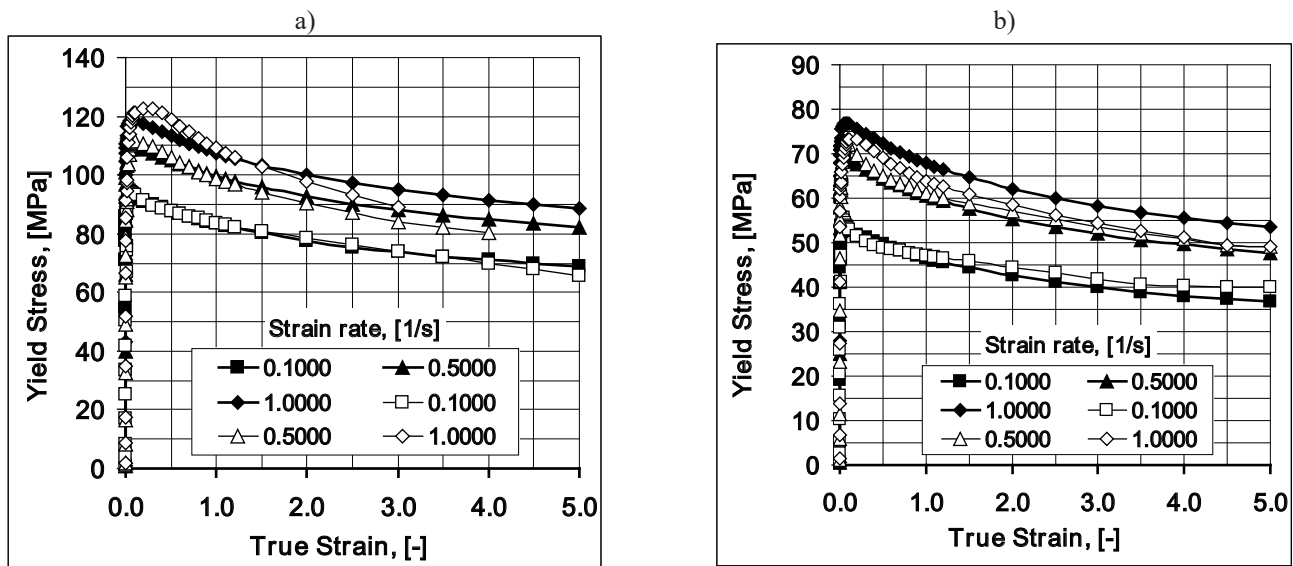


Fig. 8. Plastic flow rates for 5083 aluminium alloy: a) at temperature of 400°C , b) at temperature of 480°C ; empty symbols: data from plastometer testing, filled symbols: results after approximation

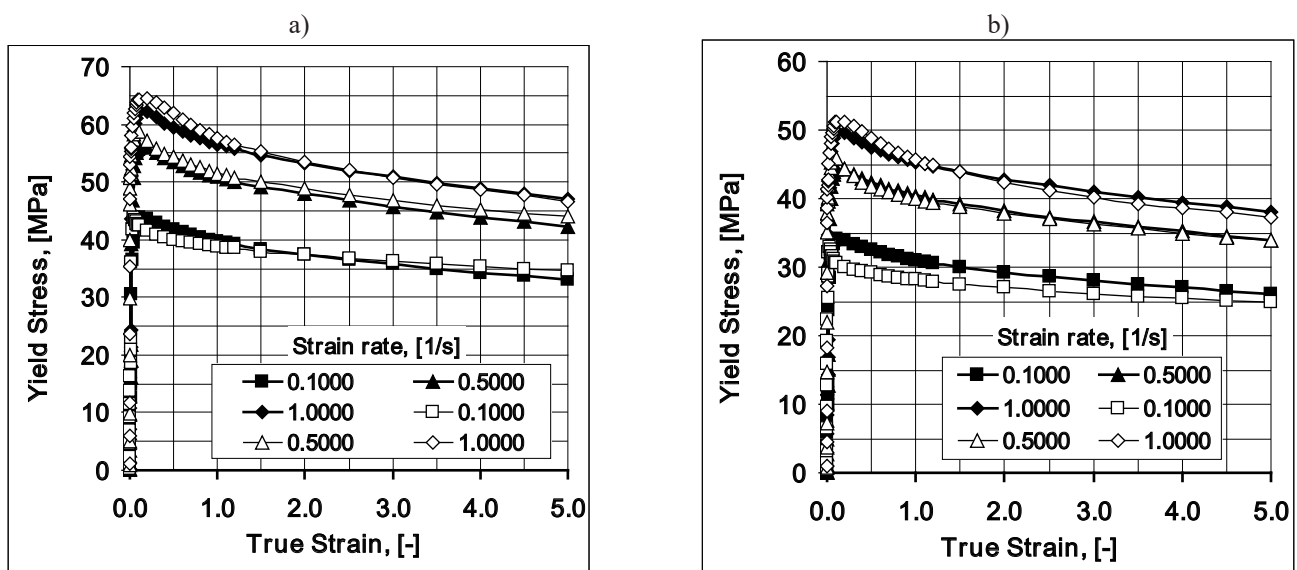


Fig. 9. Plastic flow rates for 5754 aluminium alloy: a) at temperature of 480°C , b) at temperature of 520°C ; empty symbols: data from plastometer testing, filled symbols: results after approximation

At the last stage of the study, the results of plastometer testing were approximated and the coefficients for the approximation equation (4) were determined. The example of actual and approximated patterns of changes in yield stress of 5083 and 5754 alloys are presented in Figs. 8 and 9, respectively.

Analysis of the actual and approximated material strengthening curves of the aluminium alloys studied (Figs. 8 and 9) reveals high concordance between the true values of yield stress of the materials analysed and values obtained as a results of approximation.

4. Conclusions

The examinations of plasticity of aluminium alloys of series 5xxx and analysis of the results obtained lead to formulation of the following results:

- plastometer testing of aluminium alloys of 5xxx series showed a substantial effect of strain, temperature and strain rate on the values of yield stress of these alloys,
- for the alloys studied, the increase in the strain rate caused simultaneous increase in the value of yield stress, whereas the increase in temperature of the materials studied resulted in a decline of yield stress.
- effect of temperature and strain rate of 5754, particularly on forming limit, is lower than for 5083 alloy.
- the examinations carried out in the study showed that higher plasticity in the range of parameters studied is observed for 5754 alloy.
- analysis of the actual and approximated material strengthening curves of the materials studied showed high concordance between the true values of yield stress and values obtained from approximation.
- the results of plastometer testing obtained in the form of equations allow for implementation of rheological properties of the alloys studied to databases of the most of computer pieces of software used for numerical modelling of metal forming processes,
- considering of actual rheological properties of the aluminium alloys of 5xxx series during numerical modelling will improve computational accuracy with respect to actual technological processes.

Acknowledgements

Financial support from National Centre of Research and Development under grant No: UOS-DEM-1-335/001 entitled "The development of innovative extrusion technology of hard-deformable AlMg alloys" (program DEMONSTRATOR+)

REFERENCES

- [1] D. Leśniak, A. Rękas, W. Libura, J. Zasadziński, Badania odkształcalności stopów serii 5xxx o wysokiej zawartości Mg w procesie półprzemysłowego wyciskania, *Obróbka Plastyczna Metali* **3**, 159-167 (2014).
- [2] ASM Handbook, Aluminium and Aluminium Alloys, 1993, ASM International.
- [3] H. Wiśniewska-Weinert, J. Borowski, J. Sulej-Chojnacka, D. Andrzejewski, Mechanical properties of TIG welded extruded aluminium profiles of 5xxx and 6063 alloys, VI *Mezhdunarodnyj Kongress Cvetnye Metally i Mineraly - Obrabotka Metallov Davleniem*, 1201-1206, 2014.
- [4] T. Shepard, On the relationship between extrusion conditions, mechanical properties and surface acceptability in some hard aluminium alloys", *Proc. 7th International aluminium extrusion technology seminar*, 307-320, Chicago 2000.
- [5] H. Dyja, A. Galkin, M. Knapiński, *Reologia metali odkształczanych plastycznie*, 2010, Wydawnictwo Politechniki Częstochowskiej, Częstochowa.
- [6] A. Gryc, T. Bajor, H. Dyja, S. Sawicki, K. Laber, Physical modelling of plastic deformation conditions for the rolling process of AZ31 bars in a three high skew rolling mill, *Metalurgija (Metallurgy)* **53** (4), 489-492 (2014).
- [7] H. Dyja, K. Sobczak, A. Kawalek, The influence of the shape of grooves on the behavior of internal material discontinuities in continuous S355J2G3 steel strands during rolling, *Metalurgija (Metallurgy)* **53** (4), 501-504 (2014).
- [8] F. Grosman, E. Hadasik, *Technologiczna plastyczność metali. Badania plastometryczne*, 2005, Wydawnictwo Politechniki Śląskiej, Gliwice.
- [9] A. M. Galkin, *Badania plastometryczne metali i stopów*, 1990, Wydawnictwo Politechniki Częstochowskiej, Częstochowa.
- [10] B. Koczurkiewicz, S. Mróz, H. Dyja, Modelowanie własności kształtowników łebkowych HP220 podczas walcowania na gorąco i regulowanego chłodzenia, *Inżynieria Materiałowa* **3** (151), 757-760 (2006).
- [11] S. Mróz, *Proces walcowania prętów z wzdłużnym rozdzieleniem pasma*, 2008, Wydawnictwo Politechniki Częstochowskiej, Częstochowa.
- [12] J. Sińczak, *Procesy Przeróbki Plastycznej*, 2003, Wyd. Naukowe Akapit, Kraków.
- [13] T. Drózd, H. Dyja, J. Mrozek, Pomiar i sterowanie plastometrem skrętnym przy zastosowaniu techniki komputerowej, *Metrologia i systemy pomiarowe* **16**, 335-342, (1993).
- [14] P. Szota, S. Mróz, A. Stefanik, R. Mola, Analysis of the AZ31 magnesium alloy bars rolling process in modified stretching passes, *Materialwissenschaft und Werkstofftechnik* **3** (46), 285-293 (2015).

