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RESEARCH INTO FLOW STRESS OF Al-Mg-Si ALLOY DURING THE ABRUPT CHANGE OF THE STRAIN RATE AT ELEVATED TEMPERATURES

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Abstract

In industrial practice of bulk forging, e.g. extrusion, abrupt changes in strain rate during material's deformation occur. For accurate prediction of the material flow during a forging process and characterisation of the plastic deformation, the experimental investigation of the effect on the transient change in strain rate (CSR) on plastic material flow behaviour is necessary. The present paper deals with an investigation of this effect on the flow stress of an AD 31 aluminium alloy, ordered to the Al-Mg-Si aluminium alloys system, during its deformation within the temperature range of 300 – 510°C. During continuous uniaxial compression loading of a cylindrical specimen, the strain rate was abruptly increased or decreased from its initial value at engineering strain of ~35 %. The results of the experimental investigations were used to determine the isothermal flow stress-strain curves of the AD 31 alloy. On the basis of these curves, the strain rate sensitivity index *m* as a function of true strain as well as temperature was determined.

Key words: hot forging, extrusion-type forging, aluminium alloy, AD 31, AW 6063, transient CSR, QForm, FEM, flow curve, strain rate sensitivity index

1. INTRODUCTION

The effect on the transient change in strain rate (CSR) is an additional effect which can be observed during the severe material flow when such parts as ribs, vertical walls, flanges, spurs etc. are formed. It implies that a loading path of any material point near the die cavity is unique. Figure 1 illustrates the strain rate-time relationship of a backward extrusion process of an impeller.

The abrupt increase/decrease of the deformation loads was investigated by e.g. Baxter et al. (1999) and Petrov et al. (2010, 2011). Abrupt increasing of the load corresponds the changing of material flow direction due to the complex geometry of the die cavity.

For the numerical simulation of metal flow during industrial hot working operation of near net-shape parts' production the accurate mathematical model description of flow stress is required both for each point within the deforming volume and also for surface points with velocity discontinuity. It results that the flow curves should be determined within a defined temperature - strain rate range.

Usually, the determination of such flow curves is based on the results of the laboratory tests, e.g. uniaxial compression or tension test, under different values of strain rate as well as temperature.

The present paper is the continuation of the investigations carried out earlier for aluminium alloys V95 (analogue to AA 7075) and AW 6082 (Petrov et

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al., 2010, 2011), which were aimed for data verification regarding the flow stress at elevated temperatures for aluminium alloys. The abrupt decrease in strain rate allows to predict material softening during the hot plastic deformation. The effect of the strain rate on the flow stress should be also considered when the optimal conditions during the industrial isothermal near net-shape forging processes of aluminium alloys is selected.

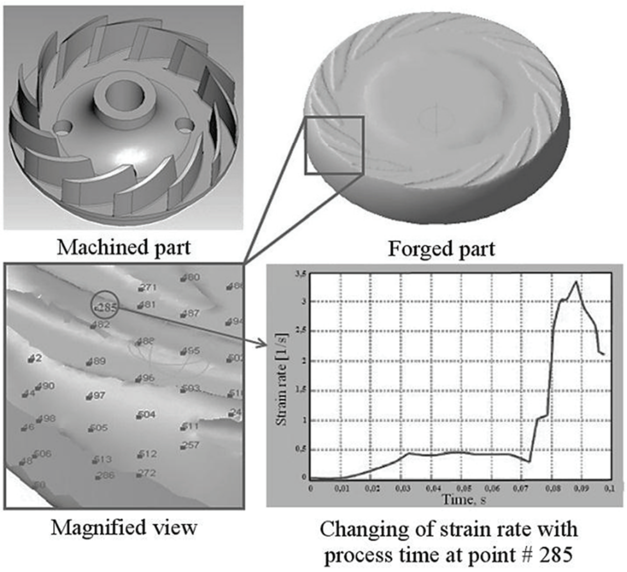


Fig. 1. *Backward extrusion of the impeller researched by Grinberg et al. (2010).*

This can be characterized in terms of strain rate sensitivity index *m*. It differentiates the superplastic and non-superplastic state of the material flow and was originally described by Enikeev (1997) and Testani et al. (2000) by the equation (1):

$$m = \left.\frac{\partial \log \sigma_i}{\partial \log \dot{\varepsilon}_i}\right|_{\varepsilon, T} \tag{1}$$

where σ_i – flow stress corresponding to a strain rate $\dot{\varepsilon}_i$, strain ε and temperature *T*.

The objectives of the present paper are: (i) to examine the behaviour of an alloy from Al-Mg-Si system during its deformation under transient loading conditions within the temperature range of 300 – 510°C and to construct the mathematical model of strain rate sensitivity index *m* of the material as a function of true strain and temperature.

2. EXPERIMENTAL PROCEDURE

The cylindrical specimens were machined from a bar of ∅10 mm of aluminium alloy AD 31 and had height of 10 mm. This alloy is produced in accordance with the Russian standard GOST 4784-97. The chemical composition of the investigated alloy under study is given in table 1 referencing to the European analogue EN AW 6063 (according to DIN EN 573-3:2003 „Aluminium und Aluminiumlegierungen“).

The uniaxial compression tests on the high-speed testing machine Instron VHS – 8800 (with a nominal capacity of 400 kN) under isothermal conditions up to a true strain of 0,60 and installed at IFUM (Institute of Forming Technology and Machines, An der Universität 2, 230823 Garbsen, Germany) were carried out at following temperatures: 300°C, 350°C, 430°C and 510°C.

Three strain-rate histories were investigated: 1) constant strain rate of 50, 10, 1 and 0,1 s^{-1}; 2) abrupt strain-rate increasing from 1 to 10 s^{-1}; 3) abrupt strain-rate decreasing from 10 to 1 s^{-1}. The changes in strain rate were performed at a true strain of 0,4 – 0,5. Subjected to the upsetting with transient CSR specimens were processed at the temperatures of 350°C and 430°C.

3. NUMERICAL SIMULATION

The aim of the numerical simulation is to proof the isothermal flow stress-strain curves obtained in accordance with the technique published by Behrens et al. (2008). The numerical simulation was performed in FE-code QFORM-2D/3D® (Quantor-Soft LLC., Russia). It is allowed to compensate the deviation of the instantaneous cross-section area of a specimen from the mean value of 1 due to the friction influence.

Here, the mean value of the cross-section area refers to the frictionless deformation conditions. The material model for numerical simulation was described by the isothermal flow curve as a function of strain, strain rate and temperature. For one point (# 285) the strain rate – time function is presented in

Table 1. *Chemical composition of investigated alloy.*

Alloy	Mass concentration of elements, %								
	Al	Zn	Mg	Cu	Si	Fe	Mn	Cr	Ti
AD 31	rest	0,01	0,74	0,10	0,49	0,19	0,05	0,01	0,03
EN AW 6063	rest	0,10	0,45-0,90	0,10	0,20-0,60	0,35	0,10	0,10	0,10

figure 1. It is clearly seen, that the strain rate peak due to the impeller blade formation can be observed at a time point of 0,08 second so the transient CSR occurs.

4. RESULTS AND DISCUSSION

4.1. Strain rate sensitivity index

The strain rate sensitivity index *m* was determined from the equation (1) based on the isothermal flow curves at constant strain rates of 0,1 s^{-1}, 1 s^{-1} and 10 s^{-1}. It was calculated for all boundary conditions at a fixed values of a true strain within the range of 0 – 0,6. So the relationship between the index *m* and a true strain as well as temperature was determined.

To generalize the effect of strain on the value of index *m* expression (2) can be applied:

$$m = A_2\varepsilon^2 + A_1\varepsilon + A_0 \quad (2)$$

where A_i – temperature depended coefficients.

The relationship between the index *m* and both strain and temperature is presented in figure 2. During the deformation the index *m* was varying and the maximum strain rate sensitivity index was observed at a strain of 0,455 at 430°C and at a strain of 0,555 at 350°C. With the temperature growth the increase of the index *m* within the whole strain range occurs. The data presented in the figure 2 corresponds to the strain rate range of 0,1 – 50 s^{-1}.

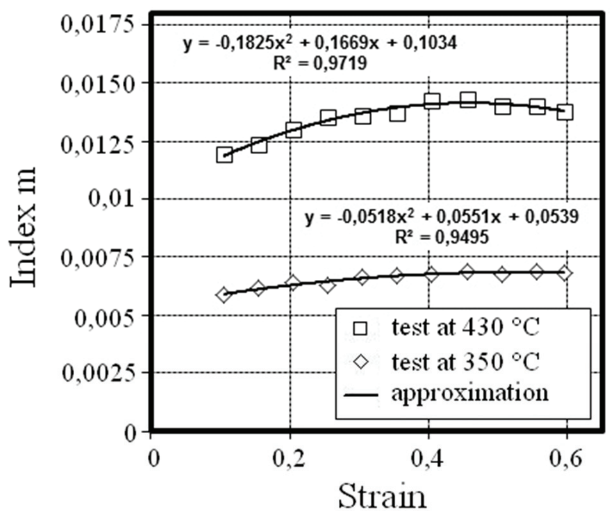


Fig. 2. *Index m vs. true strain for different temperatures.*

According the data obtained by Enikeev (1997) and Testani et al. (2000) the value of strain sensitivity index *m* is equal to 0,3 or more for a material in a superplastic state.

4.2. Affecting of changing strain rate

Figure 3 illustrates the comparison between the flow curves for constant strain rate histories and the transient change in strain rate histories. The time scale corresponds to the duration of the transient CSR only.

For the abrupt increase in strain rate shown in figure 3a, the strain-rate history was fitted with the Boltzmann type sigmoid function (figure 3c). The general formulation of the Boltzmann sigmoid can be found in the paper by Petrov et al. (2011). It was found out, that in case of the abrupt decrease in strain rate, represented in figure 3b, the variation of $\dot{\varepsilon}$ with time fits well the exponential descent from the figure 3c.

Specimens which underwent transient decrease in strain rate had reached the σ_s at true strain of 0,4775, which is higher then for a constant strain rate of 1 s^{-1}, shown in figure 4b. The confidential bound for fitting the flow curve for the transient increase or decrease in strain rate from 10 s^{-1} to 1 s^{-1} and from 1 s^{-1} to 10 s^{-1} were estimated at ± 2.5 %. The flow curve for the constant strain rate of 1 s^{-1} is app. 8,5 % lower than the confidential bound of the flow curve at the transient decrease in strain rate (see figures 3a and 3b).

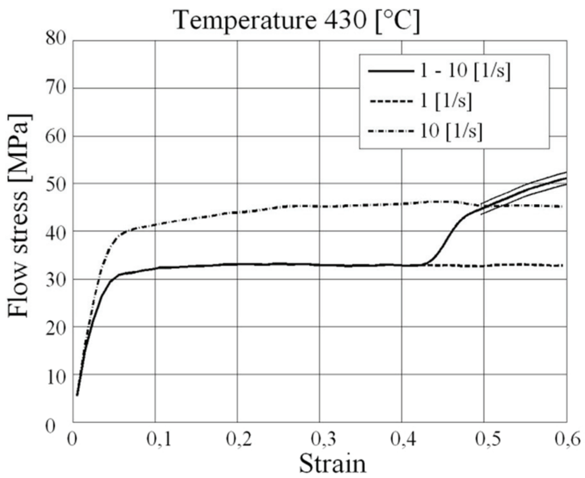
The variation of flow stress (σ_s) with time was fit by a complex function included the linear and sigmoid terms and shown in figure 4a.

In the decreasing strain rate history, the variation of the flow stress with time can be described by an exponential law, shown in the figure 4b. It corresponds to the dynamic softening stage of the alloy during the decreasing transient in strain rate.

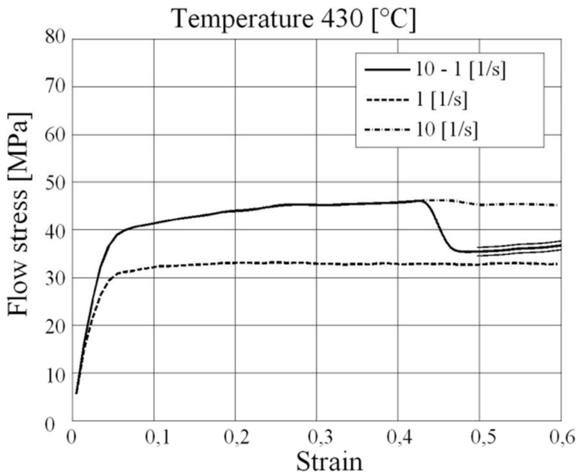
The similar behaviour of the flow stress as well as the tendency in strain rate and flow stress change during the transient strain rate history is observed at temperature value of 350°C.

5. CONCLUSIONS AND OUTLOOKS

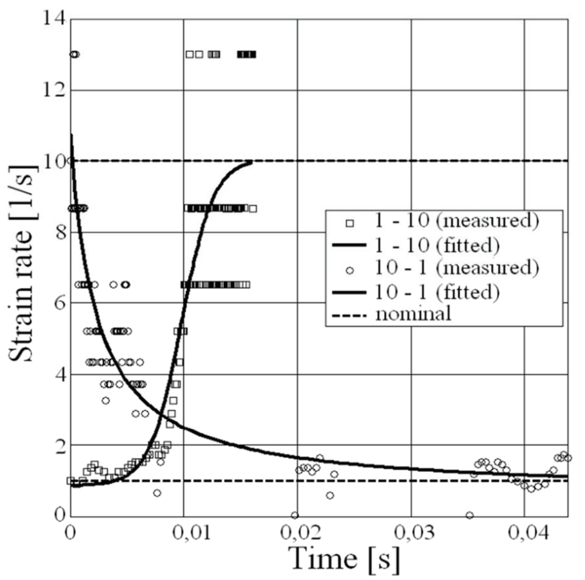
In the current investigation the maximum value of strain sensitivity index *m* was limited to 0,143. It is less than the minimum characteristic value of the same parameter of the superplastic material so the material under study does not exhibit the superplastic behaviour under the different deformation conditions within the temperature range of 300 – 510°C and the strain rate range of 0,1 – 50 s^{-1}. During the transient CSR, the change in the flow stress strongly depends on a strain rate history.



a) transient increase in $\dot{\varepsilon}$ from 1 to 10 s^{-1}

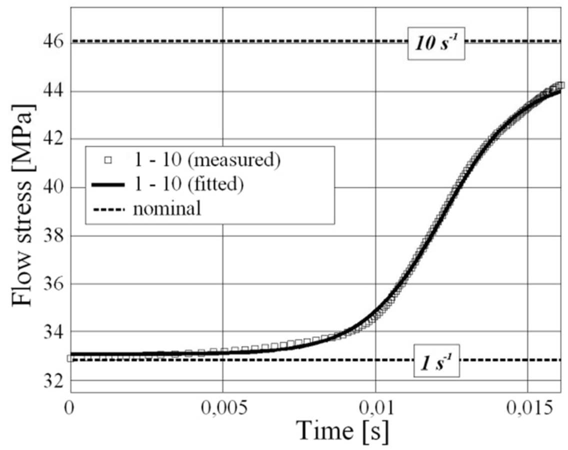


b) transient decrease in $\dot{\varepsilon}$ from 10 to 1 s^{-1}

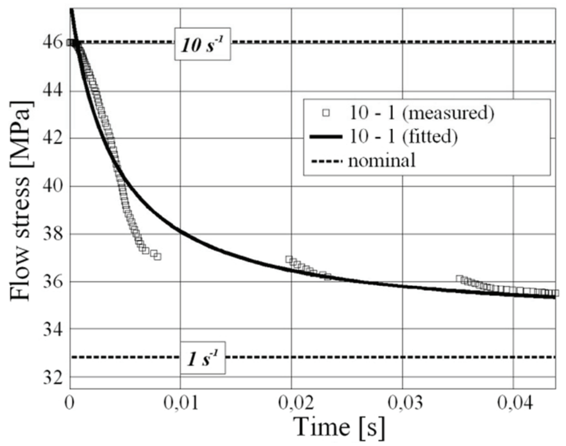


c) strain-rate histories (tests)

Fig. 3. Transient CSR at temperature of 430°C.



a) transient increase in $\dot{\varepsilon}$ from 1 to 10 s^{-1}



b) transient decrease in $\dot{\varepsilon}$ from 10 to 1 s^{-1}

***Fig. 4.** Flow stress σ_s vs. time during a transient CSR.*

The data presented in this paper provide a basis for the development of a phenomenological flow stress model for a wide range of aluminium alloys. It is also of great interest to investigate the evolution of a microstructure after transient increase and decrease in strain rate for better understanding the AD 31 - alloy's behaviour under constant and varying deformation conditions within the temperature range normally used during hot forging process.

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REFERENCES

Baxter, G.J., Furu, T., Zhu, Q., Whiteman, J.A., Sellars, C.M., 1999, The influence of transient strain-rate deformation conditions on the deformed microstructure of aluminium alloy Al-1% Mg., *Acta Materialica*, 47, 2367-2376.

Behrens, B.-A., Conrads, H., Petrov, P., 2008, Rheological behaviour of AW 6082 aluminium alloy at elevated temperatures within wide range of strain rates, *Steel research international*, 79, 261-264.

Enikeev, F.U., 1997, Strain rate sensitivity index m: definition, determination, narrowness, *Material Science Forum*, 243 – 245, 77-82.

Grinberg, I., Petrov, P., Gnevashev, D., Voronkov, V., 2010, Physical and mathematical modelling of the technology of thin-walled shells extrusion-type forging, *Technology of light alloys*, 2, 101 – 106 (in Russian).

Petrov, P., Behrens, B-A., Conrads, H., 2010, Effect of transient change in strain rate on plastic flow behaviour of Al-Zn-Mg-Cu alloy at elevated temperatures, *International Journal on Material Forming*, *Proc. Conf. Esaform 2010*, eds, Ceretti, E., Giardini, C., Brescia, 3, Supplement 1, 355-358.

Petrov, P.; Voronkov, V.; Potapenko, K., Ivanov, V., 2011, The Effect of transient change in strain rate on plastic flow behaviour of Al-Mg-Si alloy at elevated temperatures. *AIP Conference Proceedings 1353*, *Proc. Conf. Esaform 2011*, Part I, eds, Minary, G., Berlin, 374-379.

Testani, C., Ielpo, F.M., Alunni, E., 2000, AA2618 and AA7075 alloys superplastic transition in isothermal hot-deformation tests, *Materials and Design*, 21, 305-310.

BADANIA NAPRĘŻENIA UPLASTYCZNIAJĄCEGO STOPU Al-Mg-Si (AD31) PODCZAS NAGŁYCH ZMIAN PRĘDKOŚCI ODKSZTAŁCANIA W PODWYŻSZONYCH TEMPERATURACH

Streszczenie

W przemysłowych procesach kształtowania objętościowego np. wyciskaniu, występują nagłe zmiany prędkości odkształcania podczas formowania materiału. Dla dokładnego opisania płynięcia materiału w tego typu procesach, konieczne jest przeprowadzenie doświadczeń pozwalających określić wpływ takich znacznych zmian prędkości na plastyczne płynięcie materiału. W niniejszej pracy badano stop aluminium AD-31 należący do grupy stopów Al-Mg-Si w temperaturach 300 – 510^{o}C. W próbach osiowosymetrycznego spęczania próbek cylindrycznych, prędkość odkształcania była gwałtownie zwiększana bądź zmniejszana w stosunku do wartości wyjściowej, przy odkształceniu inżynierskim ~35 %. Wyniki badań doświadczalnych pozwoliły na wyznaczenie izotermicznych krzywych umocnienia badanego stopu. Na podstawie otrzymanych zależności wyznaczono indeks wrażliwości prędkości odkształcania w funkcji odkształcenia i temperatury.

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