Determination of the strain-rate sensitivity and the activation energy of deformation in the superplastic aluminium alloy Al-Mg-Mn-Sc

Določevanje indeksa občutljivosti na preoblikovalno hitrost in aktivacijske energije za deformacijo superplastične aluminijeve zlitine Al-Mg-Mn-Sc

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Abstract: This paper deals with determining the strain-rate sensitivity *m* and the activation energy for the superplastic deformation *Q* of a cold rolled aluminium Al-Mg-Mn-Sc alloy. The experiments were carried out under uniaxial tension over the temperature range 390 °C to 550 °C and at a constant strain rate or constant cross-head speed between $1 \cdot 10^{-4}$ s^{-1} and $2 \cdot 10^{-2}$ s^{-1}. The *m*-values were determined on the basis of the true stress, true strain curves and also using the jump-test method. The *m*-values varied from 0.35 to 0.70, which depended upon the forming conditions. The activation energy for the deformation was determined by the flow curves at various temperatures and at an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1}.

Izvleček: Članek obravnava določanje indeksa občutljivosti na preoblikovalno hitrost *m* in aktivacijsko energijo za superplastično preoblikovanje aluminijeve zlitine Al-Mg-Mn-Sc. Preizkusi so bili narejeni z nateznim preizkusom pri temperaturah od 390 °C do 550 °C pri konstantnih preoblikovalnih hitrostih med $1 \cdot 10^{-4}$ s^{-1} in $2 \cdot 10^{-2}$ s^{-1} in konstantnih hitrostih raztezanja. Vrednosti *m* so bile določene na osnovi krivulj dejanska napetost – dejanska deformacija in tudi s skokovitim spreminjanjem preoblikovalne hitrosti. Vrednosti *m* so bile v mejah 0,35 do 0,70, kar je bilo odvisno od preoblikovalnih

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razmer. Aktivacijska energija za deformacijo je bila določena s krivuljami tečenja pri različnih temperaturah in konstantni začetni preoblikovalni hitrosti 7,5 · 10^{-4} s^{-1}.

Key words: strain-rate sensitivity, activation energy, superplasticity, Al-Mg-Mn-Sc alloy
Ključne besede: indeks občutljivosti na preoblikovalno hitrost, aktivacijska energija, superplastičnost, zlitina Al-Mg-Mn-Sc

Introduction

Superplasticity is the ability of certain polycrystalline materials to achieve large elongations in a tensile test without necking prior to failure. These elongations are up to 1000 %, and in some cases even more. The superplastic forming (SPF) of aluminium-alloy sheets has been commercially established for more than 30 years, and the mechanisms of SPF and the requirements for achieving the superplasticity of materials are now well known.[1, 2] In general, three important conditions are needed to attain the SPF of the material: (i) the grain size should be very fine and stabile, typically less than 10 µm; (ii) the flow stresses must be low compared with those of conventional materials; and, (iii) the strain-rate sensitivity values *m* must lie in the range of 0.4 to 0.8.[3]

The strain-rate sensitivity index *m* is considered to be the most important parameter that characterises superplastic deformation.[2] The characteristic equation that describes superplastic behaviour is usually written as $\sigma = K.\dot{\varepsilon}^m$, [1–6] where σ is the flow stress, *K* is a material constant, $\dot{\varepsilon}$ is the strain rate and *m* is the strain-rate sensitivity index of the flow stress. The *m*-value is a function of the forming parameters, such as the strain rate and the temperature, and is also connected with the microstructural characteristics.[7]

There are a number of reports where the various experimental methods for determining the value of *m* are described.[2–6] The most convenient method is a uniaxial tensile test at a particular constant temperature and at different strain rates. The simplest method is reflected in the relation ship between the flow stress (σ) and the strain rate ($\dot{\varepsilon}$). The *m*-value is then defined as the slope of the curve lg σ vs. lg $\dot{\varepsilon}$. The jump test is also quite often used.[2] Different variations of this method are distinguished by the way the results are handled.

A knowledge of the activation energy enables the evolution of the deformation mechanism of SPF.[8] For aluminium SPF alloys this energy is usually within the range anticipated for grain-boundary diffusion in pure aluminium and interdiffusion in Al-Mg alloys.[9] The activation energy is usually obtained from an Arrhenius plot of ln $\dot{\varepsilon}$ vs. the reciprocal absolute temperature $1/T$ at a constant stress or from a plot of $\ln\sigma$ vs. $1/T$ at a constant strain rate.[2, 3]

The purpose of this paper is an experimental survey of two methods to determine the strain-rate sensitivity index and to determine the activation energy of the superplastic forming. The examined material was a slightly modified AA5083 (Al-Mg-Mn) alloy with the addition of scandium.

Experimental procedure

The strain-rate sensitivity index m and the activation energy Q of the SPF were determined for a Al-4.5Mg-0.46Mn-0.44Sc alloy. The alloy was produced by ingot casting and conventionally processed to a sheet with a thickness of 1.9 mm. The superplastic parameters m and Q were determined using a uniaxial tensile test. The samples for this test are shown in Figure 1.

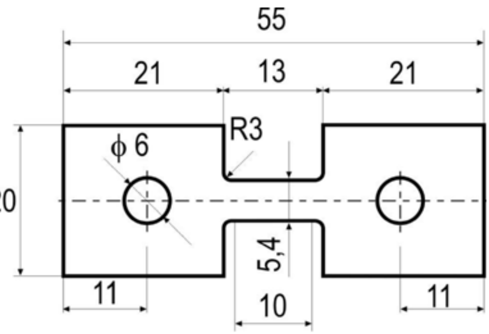

Figure 1. Sample for the tensile test

The tensile tests were carried out using a Zwick Z250 universal testing machine with 0.5 kN load cell. The machine was equipped with a three-zone electrical resistance furnace. A photograph of the tested equipment is shown in Figure 2. The testing procedure and the evolutions of the results were controlled by the TestXpert II software system.

The measurements included a determination of the flow stresses as a function of the true strain and of the strain rate at various strain rates and forming temperatures, which ranged from $1 \cdot 10^{-4}\ s^{-1}$ to $2 \cdot 10^{-2}\ s^{-1}$ and from 390 °C to 550 °C, respectively. The data from these experiments were used for a calculation of the strain-rate sensitivity indexes and the activation energy. The strain-rate sensitivity index m as a function of the strain rate was estimated from the stress-strain plots and from the multi-

Figure 2. The test equipment

strain-rate jump test. The tensile tests were conducted at a constant strain rate with a continuous change of cross-head speed and with a constant cross-head speed, where the initial strain rate decreased with the increased strain.

RESULTS AND DISSCUSION

Strain-rate sensitivity index *m*

The *m*-values are usually calculated from the logarithmic plot of the flow stress vs strain rate (method I). Figure 3 shows stress-strain rate plots at 550 °C covering the true strains from 0.7 to 1.4. The constant strain rates were in the range from $5 \cdot 10^{-4}\ s^{-1}$ to $1 \cdot 10^{-2}\ s^{-1}$. The curves exhibit the sigmoid shapes. The *m*-values at several strain rates and strains were calculated from the slopes of the plots; these values are presented in Figure 4. The highest *m*-values for all the strains were in the range of strain rates from $5 \cdot 10^{-4}\ s^{-1}$ to $1 \cdot 10^{-3}\ s^{-1}$.

The other method (method II) for determining the *m*-value is the multi-strain-rate jump test. The jump test was conducted by increasing and decreasing the strain rate by 20 % at every 100 % increment of elongation. The strain rate was constant during the single jumps, which was controlled by software for a continuously changing cross-head speed. The change of cross-head speed is shown in Figure 5 as an example of increasing the strain rate from $\dot{\varepsilon} = 2.5 \cdot 10^{-3}\ s^{-1}$ (downward strain rate) to $\dot{\varepsilon} = 3 \cdot 10^{-3}\ s^{-1}$ (upward strain rate) for a progressive elongation, and the corresponding simultaneous change of the

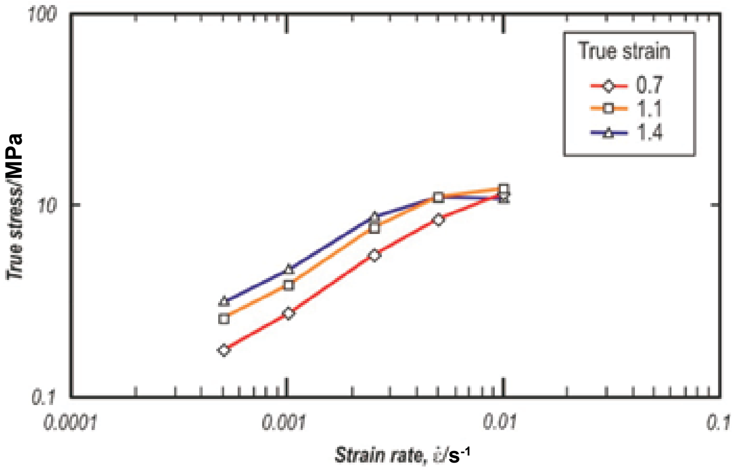

Figure 3. Stress-strain rate plots for various strains at a temperature of 550 °C

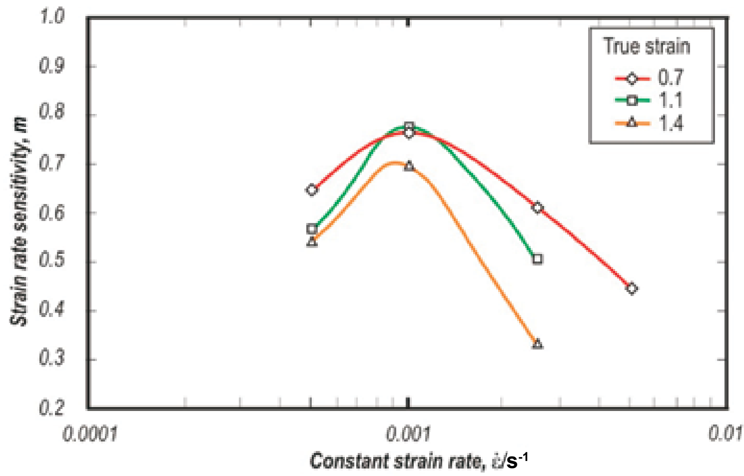

Figure 4. Strain-rate sensitivity index *m* as a function of constant strain rate for various strains at a temperature of 550 °C calculated from the stress-strain rate curves in Figure 3

force. The m-values for various strains or elongations, respectively, were calculated according to the equation:

$$m = \frac{\lg \frac{\sigma_2}{\sigma_1}}{\lg \frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1}} = \frac{\lg \frac{F_2(1+e)S_0}{F_1(1+e)S_0}}{\lg \frac{\upsilon_2(1+e)L_0}{\upsilon_1(1+e)L_0}} = \frac{\lg \frac{F_2}{F_1}}{\lg \frac{\upsilon_2}{\upsilon_1}} \qquad (1)$$

where σ_1 and σ_2 are the flow stresses, $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$ are the corresponding instantaneous strain rates, F_1, F_2 are the forces and v_1, v_2 are the cross-head speeds before and after the jump. By convention, the m-value is attributed to the downward strain rate $\dot{\varepsilon}_1$.[2]

The multi-strain jump test makes possible to examine the m values at various progressing strains or elongations

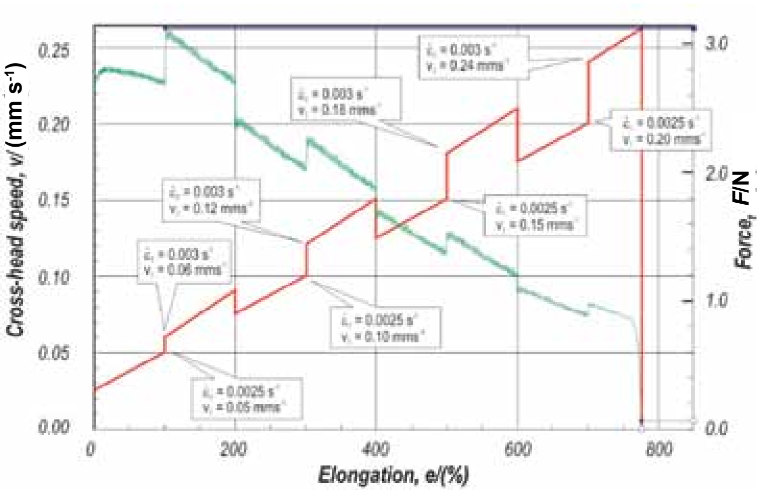

Figure 5. The change of cross-head speed (red line) and force (green line) during the multi-strain-rate jump test

Table 1. Cross-head speeds, forces and m-values for the investigated alloy during the jump test at a downward strain rate $\dot{\varepsilon} = 2.5 \cdot 10^{-3}$ s^{-1} and at 550 °C

ε	e/%	v_1/(mm s^{-1})	v_2/(mm s^{-1})	F_1/N	F_2/N	m
0.69	100	0.0501	0.0602	2.722	3.082	0.68
1.10	200	0.0752	0.0901	2.411	2.711	0.65
1.38	300	0.1000	0.1203	2.031	2.259	0.58
1.61	400	0.1248	0.1498	1.654	1.838	0.58
1.79	500	0.1502	0.1803	1.356	1.491	0.52
1.95	600	0.1755	0.2096	1.072	1.179	0.53
2.08	700	0.1990	0.2403	0.877	0.959	0.47

at a fixed strain rate during a single test. The experimental data of the cross-head speeds v_1 and v_2 with the corresponding forces F_1 and F_2 and the calculated m-values at a single strains during the jump test from Figure 5 are given in Table 1.

Indexes m, calculated from the jump test, are plotted as a function of strain rate for strains over the range from 0.7 (100 %) to 2.6 (1300 %) at temperature of 550 ºC in Figure 6. The index m is changed at all the strains with the strain rates; the data demonstrate the bell-shape curvature that is typical of superplastic materials. The m-values also change with the increased strain.

The highest m-values were achieved in the range of constant strain rates $3.5 \cdot 10^{-4}$ s^{-1} to $1 \cdot 10^{-3}$ s^{-1} (Figure 6). The maximum m-value was in accordance with the largest elongation of about 2000 % (Figure 7).

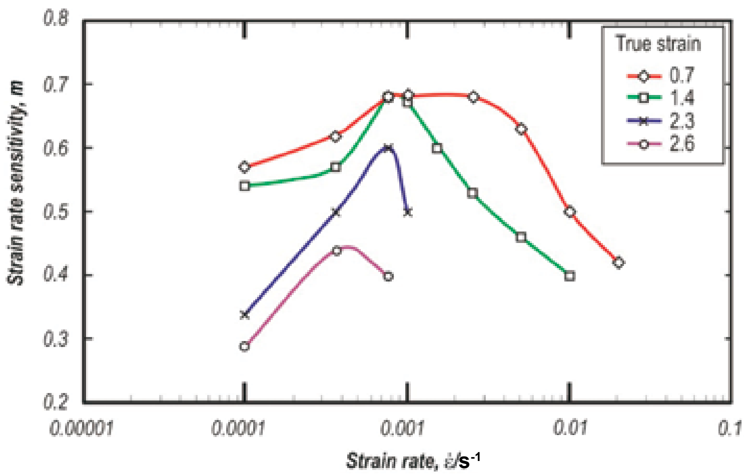

Figure 6. Strain-rate sensitivity index m as a function of the constant strain rate for various strains at 550 °C (jump test with a 20 % increase of the strain rate)

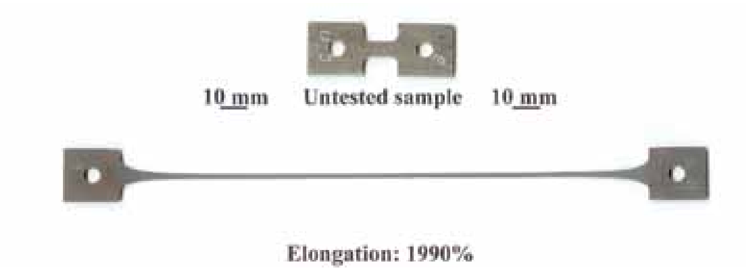

Figure 7. Untested and tested sample of Al-4.5%Mg-046%Mn-0.44Sc alloy at 550 °C and an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1}

Table 2. Indexes *m* of the investigated alloy at a true strain of 0.7, various strain rates and a forming temperature of 550°C for methods I and II

Strain rate, $\dot{\varepsilon}$	Method I	Method II
$1 \cdot 10^{-3}$ s^{-1}	$m = 0.77$	$m = 0.62$
$2.5 \cdot 10^{-3}$ s^{-1}	$m = 0.68$	$m = 0.68$

The *m*-values of the tested alloy are comparable to the reported data for alloys with a similar composition and forming conditions.[10, 11, 12] The *m* values that were obtained with method I varied somewhat from those of method II. However, these differences originated from a fault in the measurements of extreme low forces and cross-head speeds during the tensile tests.

Activation energy of superplastic deformation

An activation energy for the superplastic deformation *Q* was determined by assuming that the strain rate follows an Arrhenius type of dependence for the absolute temperature:[2, 3, 13, 14]

$$\dot{\varepsilon} \cdot \exp\frac{Q}{R \cdot T} = A \cdot \sigma^n \qquad (2)$$

where *A* is the material constant, *R* is the gas constant and $n = 1/m$ is the stress exponent. The activation energy *Q* under a constant strain rate $\dot{\varepsilon}$, can be calculated with an equation deduced from (2):

$$\ln \sigma = \frac{\ln \dot{\varepsilon} - \ln A}{n} + \frac{1}{T} \cdot \frac{Q}{R \cdot n} \qquad (3)$$

The slope of the line obtained with a linear regression method in the plot *ln* σ *vs.* $1/T$ is $Q/(R \cdot n)$.

An example of a determination of the activation energy for the investigated alloy is shown for the case of SPF at an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1} and at a true strain of $\varepsilon = 0.5$. Figure 8 shows the flow curves at an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1} for forming temperatures in the range from 390 °C to 550 °C.

The flow stresses during true strain of 0.5 and at various temperatures from Figure 8 were used for the plot ln σ *vs.* $1/T$ in Figure 9.

The slope of the line in Figure 9 is: $k = Q/(n \cdot R) = Q \cdot m/R = 8419.069$. Taking the average strain-rate sensitivity index $m = 0.46$ over 390–550 °C, the average activation energy for a given test condition is: $Q = k \cdot R/m = 8419.069 \cdot 8.3144/0.46 \approx 152$ kJ/mol. The obtained average activation energy for high-temperature superplastic forming of the investigated Al-Mg-Mn-Sc alloy is about 152 kJ/mol, which is close to the reported values of similar alloys.[7, 11, 15] The value of 152 kJ/mol is also close to the activation energies for Al lattice diffusion (142 kJ/mol)[8] and for magnesium diffusion in aluminium (136 kJ/mol) [8, 11, 16]. The value of 152 kJ/mol is much higher than the activation energies for the grain-boundary diffusion of these alloy types.[14] This suggests that a dislocation pile-up model and a dislocation glide model control the superplastic deformation mechanism.[11]

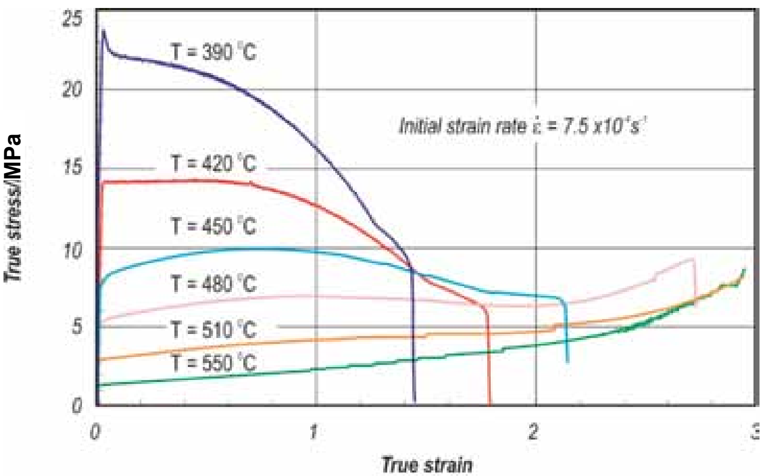

Figure 8. Flow curves for various tested temperatures at an initial strain rate of $7.5 \cdot 10^{-4}$ s^{-1}

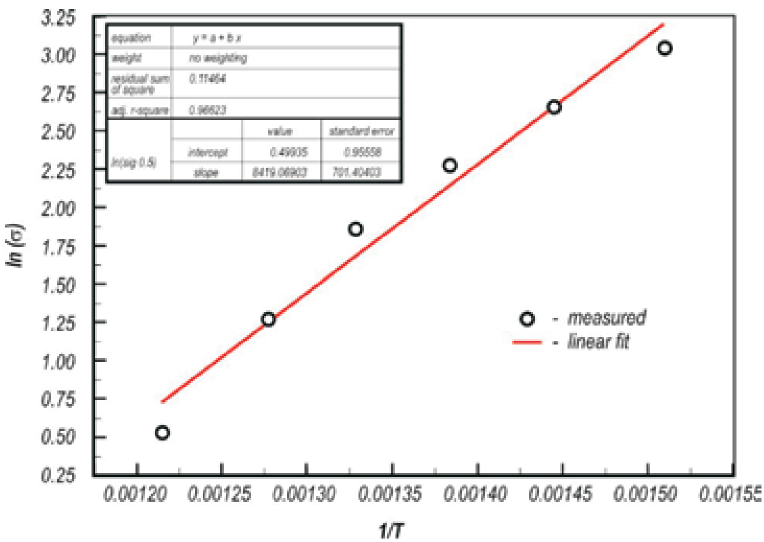

Figure 9. Measured and linear fitted values between $\ln\sigma$ and $1/T$

CONCLUSIONS

The strain-rate sensitivity *m* of cold-rolled Al-4.5Mg-0.46Mn-044Sc was determined on the basis of the true stress, true strain curves and by the method of the multi-strain-rate jump test. The *m*-values measured using these two different methods differed somewhat. The differences originated from the fault during the measurement of extremely low forces and cross-head speeds during the tensile tests. The *m* values varied from 0.35 to 0.70, which depended upon the forming conditions. The strain-rate jump test enables an examination of the *m*-values at various progressing strains or elongations at a fixed strain rate during a single test. The calculated activation energy for the superplastic forming was 152 kJ/mol, which is comparable to earlier reports for Al-Mg-Mn-Sc alloys with a similar composition.

Acknowledgement

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