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SUPERPLASTICITY OF THE 5083 ALUMINIUM ALLOY WITH THE ADDITION OF SCANDIUM

SUPERPLASTIČNOST ALUMINIJEVE ZLITINE 5083 Z DODATKOM SKANDIJA

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This paper deals with the superplastic properties of an Al-4Mg-0.6Mn alloy (AA5083) with the mass fraction of scandium 0.3 %. The investigated alloy was produced by ingot casting and thermomechanically treated with hot and cold rolling into sheet with a thickness of 1.4 mm. The superplastic properties of the alloy were investigated with tensile tests at strain rates in the range 3×10^{-4} s^{-1} to 1×10^{-2} s^{-1} and at temperatures from 470 °C to 570 °C. The true-stress, true-strain characteristics, the elongation to failure, the strain-rate sensitivity index and the microstructure of the alloy were determined. The elongation to failure increased with the test temperature and was over 1400 % at an initial strain rate of 7.5×10^{-4} s^{-1} and a temperature of 550 °C.

Key words: 5083 aluminium alloy, scandium, superplasticity

Članek obravnava superplastične lastnosti zlitine Al-4Mg-0.6Mn (AA5083) z dodatkom masnega deleža skandija 0,3 %. Zlitina je bila izdelana pri laboratorijskih pogojih z ulivanjem v jekleno kokilo in termomehansko obdelana z vročim in hladnim valjanjem v pločevino z debelino 1,4 mm. Superplastične lastnosti zlitine so bile preiskane z nateznim preizkusom pri preoblikovalnih hitrostih 3×10^{-4} s^{-1} do 1×10^{-2} s^{-1} in temperaturah od 470 °C do 570 °C. Določene so bile odvisnosti dejanska napetost-dejanska deformacija, razteznosti, indeksi občutljivosti za preoblikovalno hitrost in mikrostruktura preizkusne zlitine. Največja razteznost več kot 1400 % je bila dosežena pri začetni preoblikovalni hitrosti $7,5 \times 10^{-4}$ s^{-1} in temperaturi 550 °C.

Ključne besede: aluminijeva zlitina 5083, skandij, superplastičnost

1 INTRODUCTION

Superplasticity is the ability of polycrystalline materials to exhibit high tensile elongations prior to failure under special forming conditions. These elongations are up to 1000 % and sometimes higher. Superplastic sheet metals enable the fabrication of complex-shaped products with a single working operation using relatively inexpensive tools. From among the numerous materials with superplastic properties, aluminium alloys like AA2004 (Al-Cu-Zr), AA7075, AA7475 (Al-Zn-Mg-Cu) and AA5083 (Al-Mg-Mn) are of commercial interest.[1–3] The requirements for the superplastic behaviour of alloys are well known.[4,5] In general, the following conditions need to be satisfied to achieve superplasticity: (1) a very small grain size (<10 μm); (2) a deformation temperature above $0.5T_m$; (3) a strain-rate interval in the tensile test within the range 1×10^{-5} s^{-1} to 1×10^{-1} s^{-1}; and (5) a low flow stress (<10 N mm^{-2}) during the superplastic forming (SPF).

The strain rates at which superplasticity normally occurs in aluminium alloys (<1×10^{-3} s^{-1}) are often too slow for industrial applications. In recent years, there have been numerous attempts to produce aluminium-based materials that would exhibit a high-strain-rate (>1×10^{-2} s^{-1}) superplasticity combined with a low-temperature (<400 °C) superplasticity.[6–8] This can generally be achieved by further refining the grain size using a complex thermomechanical treatment that involves large reductions during cold rolling, by new processes such as equal-angular channel pressing[7, 9] or by adding small amounts of Cu, Cr, Zr or Sc to the base alloy.[10–12]

AA5083 is one of the principal aluminium alloys used for SPF and its superplastic characteristics have been extensively investigated.[3,6,13–15] Generally, with this alloy, maximum elongations to failure of about 400 % and, rarely, up to 600 %[3] were achieved at slow or intermediate strain rates of 1×10^{-4} s^{-1} to 5×10^{-3} s^{-1}. It is now well established that small quantities of scandium added to the Al-Mg-[16,17] and Al-Mg-Mn-[18,19] type alloys lead to an increase in the superplasticity. Elongations without failure of 1020 % and 1130 % were reported for Al-4Mg-0.5Sc[16] and for Al-6Mg-0.3Sc[17], whereas an elongation of 680 % has been achieved for a conventionally manufactured Al-Mg-Mn alloy with mass fractions 0.25 % Sc and 0.12 % Zr at 1.67×10^{-3} s^{-1} and at 490 °C.[19]

The present paper describes the effect of a 0.33 % addition of scandium on the superplastic behaviour of a standard 5083 alloy. The examined alloy sheet was prepared by a simple thermomechanical treatment similar to conventional industrial processing. The aim of the investigation was to determine the superplastic properties of the sheet, which are characterised by the flow stresses, the elongations to failure, the strain-rate sensitivity indexes and the microstructure.

2 EXPERIMENTAL

The Al-4Mg-0.6Mn-0.3Sc alloy was prepared by induction melting using Al99.9, Mg99.8, the master alloys Al-2.1Sc, Al-80Mn and Al-5Ti-1B. The melt was cast into a steel mould with dimensions of (175 × 80 × 27) mm. The chemical composition of the alloy is shown in **Table 1**.

Table 1: The chemical composition of the investigated alloy (in mass fractions *w*/%)

Tabela 1: Kemična sestava preiskovane zlitine (v masnih deležih w/%)

Si	Fe	Mn	Mg	Ti	B	Sc	Al
0.0064	0.0151	0.6400	4.054	0.0189	0.0024	0.329	Bal.

The ingots in the as-cast condition were homogenized for 4 h at 440 °C and for 4 h at 460 °C, and then air cooled. The scalped ingots with a thickness of 25 mm were hot rolled at 400 °C to a thickness of 8.8 mm, annealed for 4 h at 475 °C, and then subsequently cold rolled to a final sheet thickness of 1.4 mm with a reduction of 84 %. The samples for the tensile tests were machined from cold-rolled sheet along the rolling direction with a gauge section of 10 mm of length and 5.4 mm of width. The samples were annealed for 2 h at 500 °C to obtain a recrystallized microstructure. The average size of the recrystallized grains in the rolling direction was about 14 μm, and in the traverse section the size was about 8 μm.

The tensile tests of the investigated alloy were conducted on a Zwick Z250 testing machine with a 500 N load cell. The machine was equipped with a three-zone electrical resistance furnace. The testing chamber with a controlled temperature was over 300 mm in length. The testing procedure was conducted with the TestXpert II software system.

The measurements included determinations of the flow stresses, the maximum elongations to failure and the strain-rate sensitivity index *m.* The testing temperatures and strain rates ranged from 470 °C to 570 °C and from 3×10^{-4} s^{-1} to 1×10^{-2} s^{-1}. The tensile tests were conducted at constant strain rates (CSRs) and at constant cross-head speeds (CCHSs). The strain-rate sensitivity indexes were determined with the multi-strain-rate jump test. The microstructures of the tested samples were examined with light microscopy.

3 RESULTS AND DISCUSSION

The superplastic properties of the material were characterised by the flow behaviour during the tensile test. The flow stresses and the shapes of the flow curves are dependent on the temperature and the initial strain rate during the CCHS test. **Figure 1** shows a series of true- stress, true-strain curves for the investigated alloy at various temperatures in the range from 470 °C to 550 °C at an initial strain rate of 1×10^{-3} s^{-1}. The stress exhibits a sharp peak after loading, followed by a softening at lower temperatures (<490 °C), and then by a continuous hardening to failure at higher temperatures. The stresses were lower than 12 Nmm^{-2} for all the tested conditions and no steady state occurred. A similar course of stress-strain curves was observed for various initial strain rates at a temperature of 550 °C (**Figure 2**). After a rapid increase of the stresses to approximately 5 % strain, the tests performed at faster initial strain rates show no, or very little, increase of the flow stresses, whereas there is an indication of material hardening at lower initial strain rates (<1×10^{-3} s^{-1}).

The reason for the strain hardening of this alloy at higher temperatures and lower strain rates is the dynamic grain growth during the pulling of the samples.[17,18] Generally, the shapes of the true-stress, true-strain curves

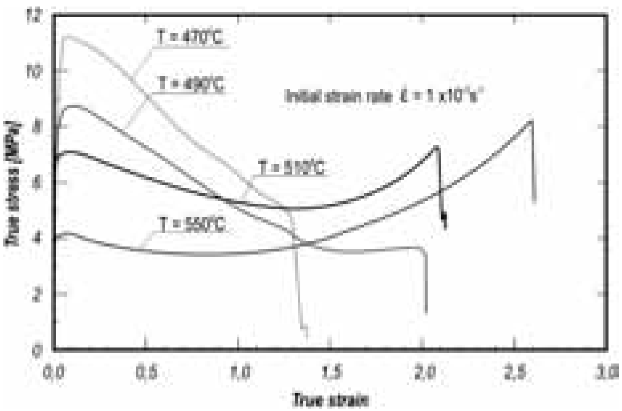

Figure 1: True-stress, true-strain curves for various tested temperatures at an initial strain rate of 1×10^{-3} s^{-1} (CCHS test)

Slika 1: Odvisnosti dejanska napetost – dejanska deformacija pri različnih preizkusnih temperaturah in začetni preoblikovalni hitrosti 1×10^{-3} s^{-1} (CCHS preizkus)

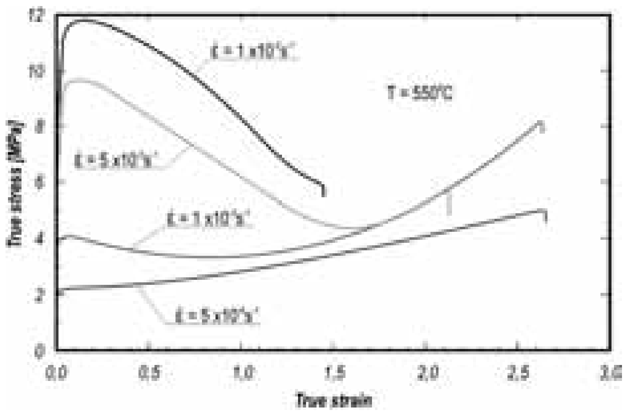

Figure 2: True-stress, true-strain curves for various initial strain rates at 550 °C

Slika 2: Odvisnosti dejanska napetost – dejanska deformacija pri različnih preoblikovalnih hitrostih in temperaturi 550 °C

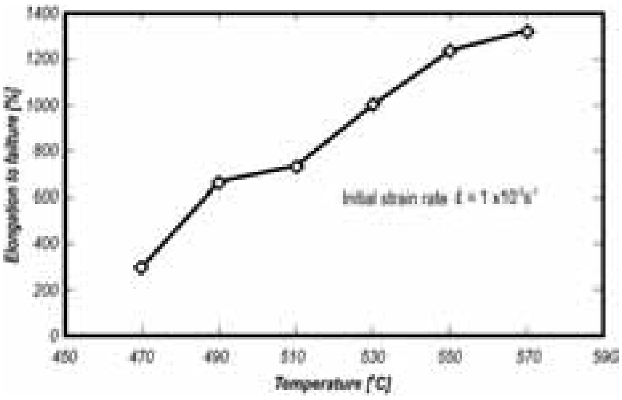

Figure 3: Elongation to failure as a function of the tested temperature at an initial strain rate of 1 x 10^{-3} s^{-1}

Slika 3: Razteznost pri različnih preizkusnih temperaturah in začetni preoblikovalni hitrosti 1 x 10^{-3} s^{-1}

of the investigated Al-4Mg-0.6Mn-0.3Sc alloy are comparable with the curves of alloys with similar compositions, like Al-Mg-Mn,[3,14,15] Al-Mg-Sc[17,18] and Al-Mg-Mn-Sc.[6]

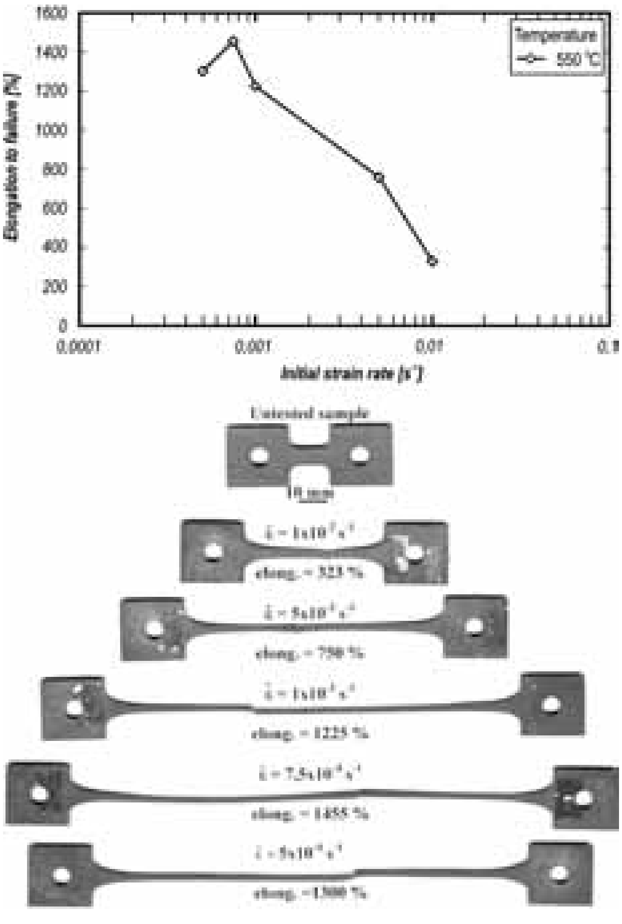

Figure 4: Elongation to failure as a function of initial strain rate and the samples after tensile testing at 550 °C

Slika 4: Razteznost pri različnih začetnih preoblikovalnih hitrostih in preizkušanci po nateznem preizkusu pri 550 °C

The elongations to failure were measured with a tensile test under constant cross-head speed (CCHS) at temperatures in the range from 470 °C to 570 °C and at initial strain rates from 5 × 10^{-4} s^{-1} to 1 × 10^{-2} s^{-1}. The elongation to failure depended strongly on the test temperatures (**Figure 3**) and on the strain rate (**Figure 4**).

An elongation of over 1000 % was achieved at initial strain rates up to 1 × 10^{-3} s^{-1} and 550 °C (maximum elongation of 1455 % at 7.5 × 10^{-4} s^{-1}). Since a 200 % elongation can be considered as an initial indicator of superplasticity,[8,20] elongations at higher strain rates up to 1 × 10^{-2} s^{-1} at 550 °C and lower temperatures in the range from 470 °C to 510 °C are still in the superplastic regime.

The strain-rate sensitivity index *m* is one of the most important parameters that characterize the superplastic behaviour of a material. In this work the *m* values as a function of the strain rate at a temperature of 550 °C were estimated with the multi-strain-rate jump test. These tests were conducted by increasing and decreasing the strain rate by 20 % for every 100 % increment of elongation. The indexes *m* are plotted as a function of the strain rate for strains in the range from 1.1 (200 %) to 2.1 (700 %) in **Figure 5**. The index *m* changes at all strains with the strain rate. The *m* plots show peaks that occur within a narrow range of strain rates from 3 × 10^{-4} s^{-1} to 5 × 10^{-4} s^{-1}. A maximum value of $m = 0.67$ was obtained in this range at a true strain of 1.1 and $m = 0.46$ at $\varepsilon = 2.1$ and at strain rate 5 × 10^{-4} s^{-1}. The peaks of the *m*-plots are shifted to a lower strain rate at higher strains.

The microstructure of the alloy was examined with regard to the crystal grains after pulling the samples at an initial strain rate of 7.5 × 10^{-4} s^{-1} and a temperature of 550 °C to various elongations in the range from 200 % to 1200 % (**Figure 6**). The initial microstructure consisted of recrystallized grains grown during the two hours of annealing prior to the tensile test. The static and dynamic grain growth in the grip and in the gauge sections of the samples as a function of annealing or of pulling time during the tensile test are shown in **Figure 7**. The

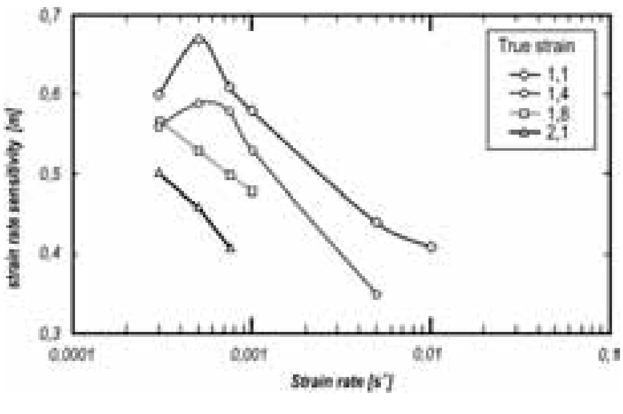

Figure 5: Strain-rate sensitivity index *m* as a function of the strain rate for various strains at 550 °C

Slika 5: Indeks občutljivosti za preoblikovalno hitrost *m* pri različnih preoblikovalnih hitrostih in temperaturi 550 °C

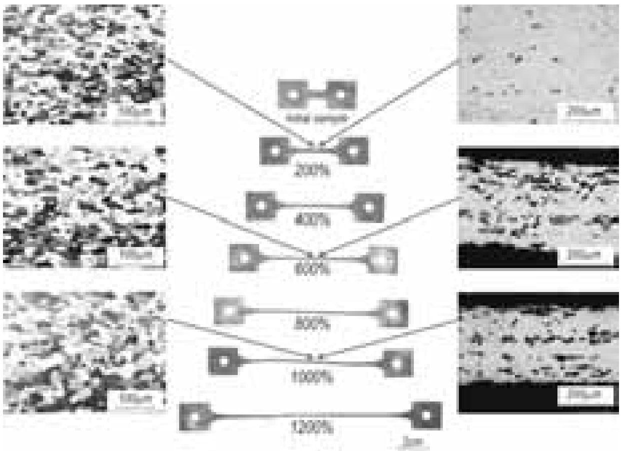

Figure 6: Samples after tensile testing at various elongations with microstructures and cavitations in the gauge length at 550 °C and 7.5 x 10^{-4} s^{-1}

Slika 6: Preizkušanci po nateznem preizkusu pri različnih raztezkih in posnetki mikrostruktur ter kavitacij v vzdolžnih prerezih merilnih dolžin pri 550 °C in 7,5 x 10^{-4} s^{-1}

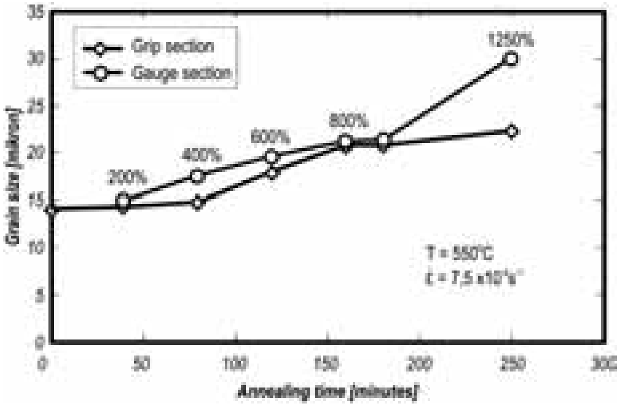

Figure 7: Static and dynamic grain growth in the longitudinal grip and gauge sections of the samples at an initial strain rate of 7.5 ×1 0^{-4} s^{-1} and at 550 °C

Slika 7: Statična in dinamična rast kristalnih zrn v vzdolžnih prerezih glav in merilnih dolžin preizkušancev pri začetni preoblikovalni hitrosti 7,5 × 10^{-4} s^{-1} in 550 °C

dynamic grain growth is, especially at longer pulling times (at elongations over 900 %), greater than the static one. The grains in the gauge section were slightly elongated with a grain aspect ratio of about 1.4, which remained nearly constant for all the elongations.

The cavitation that occurred during the superplastic forming in the gauge section was examined with the same samples and under the same testing conditions as shown in **Figure 6**. The fraction of cavitation increased with the increasing strain. However, the volume share of the cavitation did not exceed a value of 20 % at larger elongations up to 1200 %.

4 CONCLUSIONS

An Al-4Mg-0.6Mn-0.3Sc alloy sheet with a thickness of 1.4 mm produced with a simple thermomechanical treatment including hot and cold rolling, exhibited good superplastic properties, reflected in large elongations to failure, high strain-rate sensitivity indexes and low flow stresses. Elongations over 1000 % were achieved at initial strain rates up to 1 × 10^{-3} s^{-1} and temperatures higher than 530 °C (maximum elongation of 1455 % at 7.5 × 10^{-4} s^{-1} and 550 °C). The strain-rate sensitivity indexes varied with the strain rate and have the highest values within a narrow range of strain rates from 3 × 10^{-4} s^{-1} to 5 × 10^{-4} s^{-1}. The dynamic grain growth and the fraction of cavitation increase with the increasing strain. The Al-4.0Mg-0.6Mn-0.3Sc alloy sheet with a thickness of 1.4 mm, produced with a conventional rolling process, makes it possible to obtain a good, low-strain-rate superplasticity characterised by an elongation of over 1000 % at a temperature higher than 530 °C and a strain rate up to 1 × 10^{-3} s^{-1}.

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