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Influence of Scandium Additions and Various Alloy Sheet Thickness on the Superplastic Properties of Al-Mg and Al-Mg-Mn Alloys

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The commercial 5083 (Al-Mg-Mn) alloy is one of the aluminium alloys designed for superplastic forming. This article describes the influence of Sc and Mn additions, and of various thickness of final sheet, on the superplastic behaviour of Al-Mg based alloys. A series of Al-Mg alloys with 0.1 to 0.4 wt.%Sc and 0.5 to 0.6 wt.%Mn were produced by ingot casting and conventionally processed by hot and cold rolling to form sheets with a thickness in the range from 0.6 to 2.4 mm. The investigations included determinations of the true stress, true strain characteristics, the maximum elongation to failure, the strain rate sensitivity index and the microstructure of the alloys as a function of the alloy chemistry and of the dimensions of the rolled sheet. The superplastic properties were investigated using uniaxial tensile testing with constant and variable strain rates from $5x10^{-4}$ to $1x10^{-2}s^{-1}$ and at a temperature 550°C.

Keywords: *AA5083 Al alloy, scandium, thermomechanical processing, superplasticity.*

1. Introduction

Superplasticity is the ability of polycrystalline materials to exhibit a high tensile elongation, which enables the fabrication of complex-shaped products under special forming conditions. The requirements for achieving superplasticity in materials are well known [1,2]. From among the numerous materials that exhibit superplastic properties, aluminium alloys are of particular commercial interest [3-5]. Recently, industrial superplastic forming (SPF) operations have begun to require a superplastic aluminium material that is capable of exhibiting a high strain rate ($>1x10^{-2}s^{-1}$) and a low temperature (<400°C) superplasticity [6,7]. Furthermore, it has been reported that it is possible to achieve good superplastic formability for the above-mentioned working conditions by making an additional reduction in the grain size of the material [6]. This can be achieved by using a thermomechanical treatment that involves a large reduction during cold rolling [8], by adding small amounts of Cu, Cr, Zr or Sc to the base alloy [8-12] or by new forming processes, such as equal channel angular pressing (ECAP), high-pressure torsion, accumulative roll bonding and friction stir processing [6, 13, 14-19]. For the present, the disadvantage of these attractive forming processes is the impossibility of producing bulk material in the form of a sheet.

The commercial 5083 (Al-Mg-Mn) alloy is one of the conventional aluminium alloys for superplastic forming, and its superplastic characteristics have been extensively investigated [3,9,20-27]. Generally, with this alloy, produced on a commercial scale by hot and cold rolling, the maximum tensile elongations were achieved in the range 400-670% [3,20]. It is now well established that small quantities of scandium added to the Al-Mg [10,11,28-32] and Al-Mg-Mn-type [12,33-35] alloys lead to an increase in the superplasticity. Elongations of over 1000% were reported for rolled sheet of Al-4%Mg-0.5%Sc and Al-6%Mg-0.3%Sc alloys [28,29]. The minor scandium addition to commercial or a slightly modified 5083 alloy subjected to a large rolling reduction or ECA pressing results in superplasticity with a tensile ductility in the range of 1000-2300% [8,33].

The SPF of aluminium alloys depends, besides the testing conditions, first of all on the chemical composition and the processing parameters. The objective of the current paper is therefore to investigate the influence of various scandium and manganese additions on the superplastic properties of an Al-Mg based alloy. Values were obtained for the flow stresses, the strain rate sensitivity, the maximum elongation and the microstructure as a function of the alloy chemistry and of the sheet thickness. The investigated alloys were produced by conventional hot and cold rolling, because the superplastic forming industry is based almost exclusively on the utilization of rolled sheet [32]. The experiments were uniaxial tensile tests at constant and variable, slow and intermediate strain rates at a temperature of 550°C.

2. Experimental

A series of Al-Mg alloys with different amounts of Sc, nominally in the range from 0.1 to 0.4wt.% and Mn with 0.5 and 0.6wt.%, were prepared by induction melting, using Al99.9, Mg99.8, Al-2.1Sc, Al-80Mn, and Al-5Ti-1B. The alloys were cast into a steel mould to form ingots with dimensions of 175x80x27mm^3. The marks, nominal and the real compositions of the alloys are listed in Table 1.

Table 1. Mark, nominal and real compositions of the investigated alloys (in wt.%)

Mark	Alloy	Si	Fe	Mn	Mg	Ti	Sc	Al
A	Al-Sc0.4	0.005	0.008	0.001	0.010	0.022	0.352	Bal
B	Al-5Mg	0.009	0.036	0.005	5.120	0.016	0.000	Bal
C	Al-5Mg-0.1Sc	0.012	0.017	0.005	5.060	0.016	0.164	Bal
D	Al-5Mg-0.2Sc	0.008	0.022	0.003	4.970	0.014	0.240	Bal
E	Al-5Mg-0.3Sc	0.011	0.016	0.004	6.050	0.017	0.308	Bal
F	Al-5Mg-0,4Sc	0.008	0.014	0.002	5.960	0.017	0.378	Bal
G	Al-4.5Mg-0.6Mn-0.3Sc	0.006	0.015	0.640	4.054	0.019	0.329	Bal
H	Al-4.5Mg-0.5Mn-0.4Sc	0.006	0.002	0.466	4.550	0.021	0.435	Bal

The ingots were homogenized in the air for 4 hours at 440°C and for 4 hours at 460°C. The scalped ingots were further prepared in three different ways: (1) hot rolling to a thickness of 8.8 mm, annealing for 4 hours at 475°C, cold rolling to a final sheet thickness of 1.4 mm with a reduction of 84% (alloys A, B, C, D, F, G); (2) hot rolling to a thickness of 11.8, 8.8, 6.7, and 4 mm, annealing for 4 hours at 475°C, cold rolling to a final sheet thickness of 1.9, 1.4, 1.0, and 0.6 mm with a reduction of 84% (alloy F); (3) hot rolling to a thickness of 15 and 11.8 mm, annealing for 4 hours at 475°C, cold rolling to final sheet thicknesses of 2.4 mm and 1.9 mm with a reduction of 84 % (alloy H). The samples for tensile tests with a 10 mm gauge length and a 5.4 mm gauge width were machined from cold-rolled sheet along the rolling direction and annealed for 2 hours at 500°C prior to testing. The uniaxial tests were carried out using a Zwick Z250 machine with a 0.5 KN load cell. The machine was equipped with a three-zone split-furnace. The testing procedure and the evaluation of the results were controlled by the TestXpert II software system. The measurements included a determination of the true stress, true strain characteristics, the maximum elongations and the strain rate sensitivity. The tensile tests were conducted at a constant strain rate (CSR) and at an initial strain rate (constant cross-head speed, CCHS) ranging from 5x10^{-4} to 1x10^{-2}s^{-1}; the forming temperature was 550°C. The strain rate sensitivity indexes were determined with the multi-strain-rate jump test. The microstructure was examined with light microscopy.

3. Results and Discussion

Fig. 1 presents the grain structure of some as-cast and homogenized alloys. The average grain size of the alloys prior to rolling varied from ~ 200µm (alloys A and B) to ~ 35µm (alloy G). 0.4 wt. % Sc did not decrease the grain size of the Al-Sc alloy (A) in comparison to the Al-Mg alloy (B).

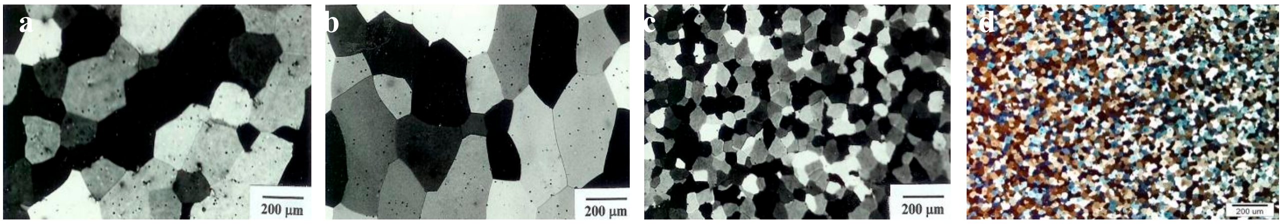


Fig. 1: Grain structure of as-cast and homogenized alloys: (a) Al-5Mg (alloy B); (b) Al-0.4Sc (A); (c) Al-5Mg-0.2Sc (D); (d) Al-4.5Mg-0.6Mn-0.3Sc (G)

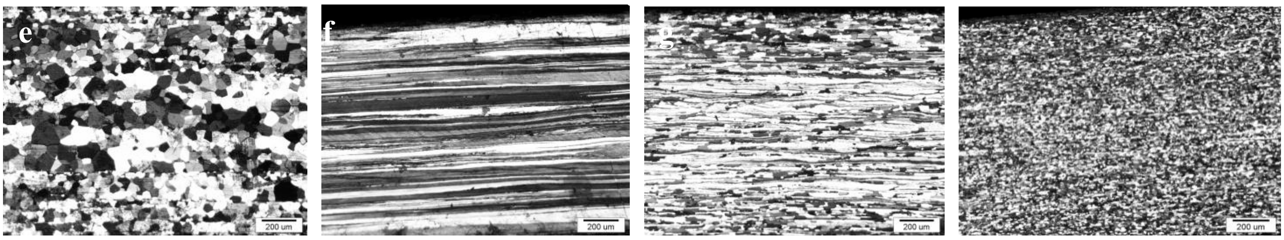


Fig. 2: Grain structure of cold rolled and annealed alloys: (e) Al-5Mg (alloy B); (f) Al-0.4Sc (A); (g) Al-5Mg-0.2Sc (D); (h) Al-4.5Mg-0.6Mn-0.3Sc (G)

The grain size can be further refined with a thermomechanical treatment of the alloys. The microstructure of the cold-rolled and subsequently annealed sheet for 2 hours at 500°C is shown in Fig. 2. The complete recrystallization occurred only in alloys B. The fibre grains in alloy A show that no recrystallization occurred during the annealing. The microstructures of the other Al-Mg-Sc-type alloys were partially recrystallized. The average size of the uniaxial grains of these alloys decreased with the increased Sc addition. The smallest grains of approximately 10µm occurred in the Al-4.5Mg-0.6Mn-0.3Sc alloy.

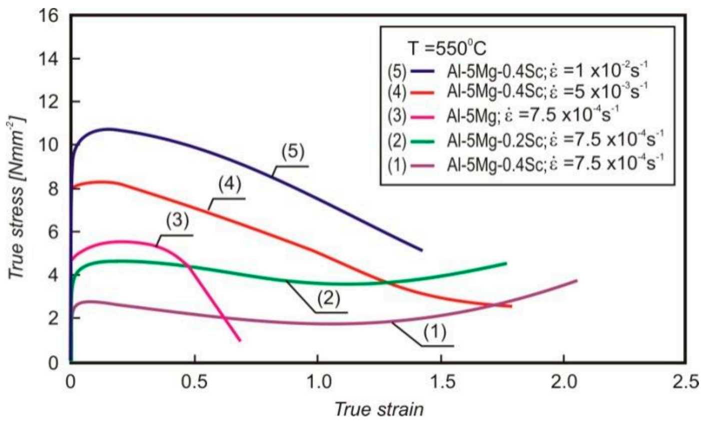


Fig. 3: Influence of scandium addition and initial strain rate on the true stress, true strain curves of Al-Mg and Al-Mg-Sc alloys at 550°C

The superplastic behaviour of the material is characterized by the true stress' dependence on the true strain, by the strain rate sensitivity, and the elongation to failure. Fig. 3 shows the stress-strain curves for a series of Al-Mg-Sc and Al-Mg alloys at a temperature of 550°C and at various initial strain rates. In all cases, there is an immediate strain hardening, which decreases with the increasing Sc addition (curves 1–3). The stress maximum is followed by softening, which is most pronounced for the Al-Mg alloy without Sc (alloy B). The slightly increased hardening of the Al-Mg-Sc alloys at higher strains and lower strain rates (curves 1 and 2) is probably the consequence of the dynamic grain growth during the longer pulling. The hardening characteristics are changed with the test conditions. After a rapid jump of the stresses on loading at higher strain rates ($\geq 5x10^{-3}s^{-1}$), a continuous decrease in the flow stress takes place with strain until the failure occurs (curves 4 and 5).

The elongation to failure is often used as an appropriate measure for the superplastic behaviour of a material because, in addition to the working and test conditions, it depends on the alloy chemistry and on the thickness of the tested sheet. Fig. 4 shows the maximum elongations of the Al-Mg alloys with different additions of Sc and Mn for a fixed initial strain rate of $7.5x10^{-4}s^{-1}$ and 550°C; the sheet thickness was 1.4 mm. The elongation increased with the increasing Sc addition and achieved the highest value for a combined addition of Sc and Mn. The increased elongation is in accordance with the decrease in the grain size and its stability caused by Sc.

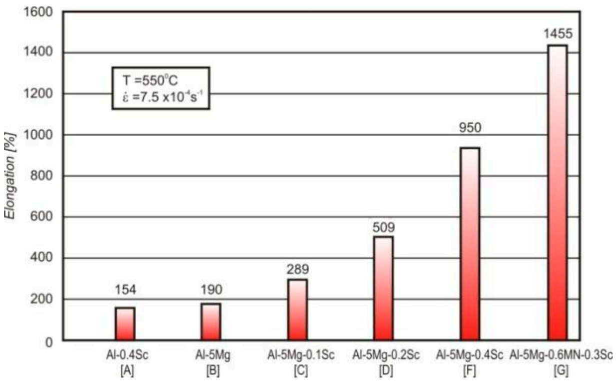


Fig. 4: Elongation to failure of Al-Mg alloys with various additions of Sc and Mn at initial strain rate of $7,5x10^{-4}s^{-1}$ and 550°C

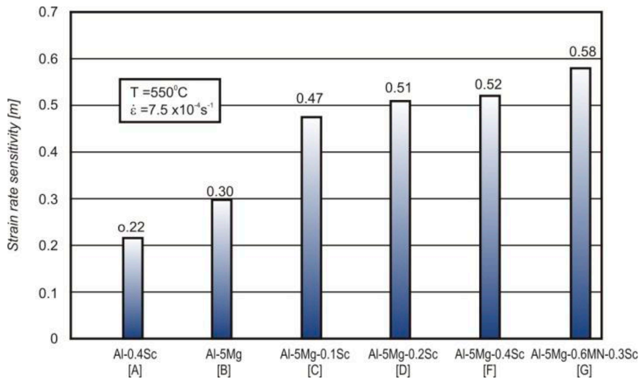
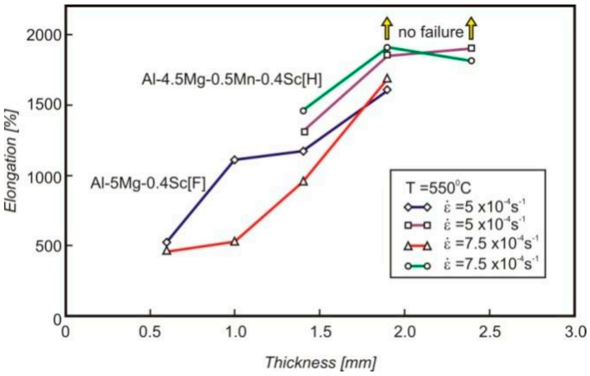


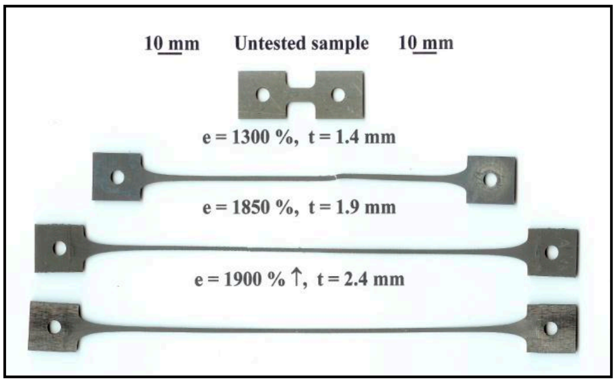
Fig. 5: Strain rate sensitivity index *m* of various investigated alloys. SPF conditions: $\dot{\varepsilon}= 7.5x10^{-4}s^{-1}$ $\varepsilon = 0.693$ (100%), sheet thickness d = 1.4 mm

The strain rate sensitivity index *m* of the Al-Mg alloys with various Sc and Mn contents was measured at a constant strain rate of $7.5x10^{-4}s^{-1}$ prior to the single jump at a strain level of 0.693 and a temperature of 550°C. Fig. 5 shows that *m*-value of the Al-Mg alloys increased in the range from 0.47 to 0.52 with the increasing Sc and has a maximum value for the Al-4.5Mg-0.6Mn-0.3 Sc alloy. The binary alloys Al-5Mg and Al-0.4Sc exhibited *m*-values of 0.22 and 0.3, respectively. Therefore, it is apparent that the superplasticity cannot be achieved in binary Al-Sc alloys that have a Sc content bellow 0.4wt. %. The variation of the *m*-value is similar to that of the elongation to failure: high elongations are associated with high *m*-values.

The deformation behaviour of the alloys was further investigated as a function of the sheet thickness at two initial strain rates and at a temperature of 550°C (Fig. 6a). The elongation to failure increased with the increasing thickness in the range from 0.6 to 2.4 mm. The sheets of the alloys F and H with thicknesses of ≥ 2 mm exhibited ductilities up to 1700% and 2000%, respectively. The appearance of some samples of Fig. 6a is demonstrated in Fig. 6b, where the tested samples have a very uniform deformation within the gauge length.

It is well known that elongations of 300-400% are the most often required for industrial superplastic forming [7,36]. The percentage of the cavitation of alloy H under these elongations is less than 5 % [35]. This suggests that it is possible to achieve such a ductility for the 5083 alloy with a scandium addition up to about 0.4 wt.%, processed by a simple hot and cold rolling to a sheet with a thickness in the range from 0.6 to 2.4 mm and superplastc forming of the sheet at lower temperatures (< 500°C) and higher strain rates (> $5x10^{-3}s^{-1}$).





6a 6b

Fig 6a and 6b **:** Maximum elongation as a function of the thickness of the samples at initial strain rates of $5x10^{-4}s^{-1}$ (at constant cross-head speed of 0.30 m/min) and $7.5x10^{-4}s^{-1}$ (at constant cross-head speed of 0.45 mm/min), and a temperature of 550°C for the Al-5Mg-0.4Sc [F] and Al-4.5Mg-0.5Mn-0.4Sc [H] alloys

4 Conclusions

The effects of the various Sc and Mn contents and the effect of the alloy sheet thickness on the superplastic properties of an Al-Mg alloy were investigated. The elongation to failure and the strain rate sensitivity index of the Al-Mg based alloy increased with the increasing level of Sc content in the range from 0.1 to 0.4 wt. % and achieved the highest values for a combined content of Sc and Mn. The addition of about 0.4 wt. % Sc to the Al-Mg and Al-Mg-Mn type alloys, fabricated by a simple manufacturing route to a sheet with a thickness from 0.6 to 2.4 mm, resulted in a good superplastic ductility. Samples with a gauge thickness of about 2 mm and optimum Sc (0.3-0.4wt.%) and Mn (0.5-0.6wt.%) contents exhibited up to 2000% elongation at an initial strain rate of $7.5x10^{-4}s^{-1}$ and 550°C.

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