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Superplasticity of AlMgSi alloys

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Commercial AlMgSi alloy sheets produced by thermomechanical treatment are found to be superplastic between 500 and 570 °C at strain rates of 10^{-5}–10^{-3} s^{-1}. The strain rate sensitivity, *m*, is about 0.4. It was found that the highly alloyed sample contains pre-existing cavities in higher volume fraction than the alloy of lower concentration. An exponential growth of cavity volume fraction was found during superplastic deformation which is characteristic of plasticity controlled cavitation. The growth rate of the cavity volume fraction can be decreased by applying back pressure.

1. Introduction

In the last decade great efforts have been made to produce superplastic materials from commercial aluminium alloys. Success was achieved for AlZnMgCu, AlCuMg and AlLiMg type alloys [1–4]. Some experiments on the superplasticity of the most common AlMgSi type 6XXX series alloys were also performed [5–7], but the details are not yet clear. The advantages of the AlMgSi alloys are their medium strength, fairly good corrosion resistance and weldability.

The present work focused on the determination of a suitable composition and thermomechanical treatment resulting in superplastic behaviour in these alloys. The relationship between microstructure, formability and cavitation of sheets with different compositions was studied.

2. Experimental procedure

Commercial AlMgSi alloys containing different amount of magnesium, silicon, copper and chromium were prepared under laboratory conditions (Table I). After semicontinuous casting, different thermomechanical treatments were applied to obtain fine-grained structure. Fig. 1 schematically shows one of the thermomechanical sequences applied. In this case the usual industrial technology for rolled products was interrupted after hot rolling by a solution and overageing treatment.

The superplastic behaviour of the alloys was studied by impression creep tests [8] between 500 and 570 °C at strain rates of 10^{-3}–10^{-6} s^{-1}. The biaxial formability was studied by bulging. Free bulging of circular sheets of diameter 50 and 100 mm was used to produce samples with different degrees of deformation. The deformation was characterized by the thickness strain, $\ln(h_0/h)$, calculated from the initial thickness, h_0, and the sheet thickness, *h*, measured at different sites on the deformed sheet. The formability limit was determined by bulging to cracking. The empirical parameter for characterizing the maximum deformation was the minimum radius of curvature, R_{min}.

The microstructure of sheets was characterized by transmission electron microscopy (TEM). The grain size, *d*, grain aspect ratio and volume fraction of cavities, V_c, were measured using optical metallography (OM). The cavity volume fraction was determined on mechanically polished surfaces by the griding method using ×200 magnification and a 1024 point grid.

3. Results and discussion

As a result of thermomechanical treatment, a complex precipitation structure was obtained (Fig. 2). Coarse particles were formed in the early stages of technology and during overageing. The finer particles were assumed to precipitate during hot working. After the recrystallization heat treatment, a few larger particles and many small precipitates, less than 100 nm in size, could be seen. The grain size measured in short transverse (ST) and long transverse (LT) directions, as well as the grain aspect ratio (GAR) are summarized in Table II.

The equivalent stress–equivalent strain rate relations of alloy type 6066 can be seen in Fig. 3. The strain rate sensitivity determined by the straight part of the curves was found to be $m = 0.4$, and practically independent of the composition (Fig. 4). The superplastic strain rate range, however, differs slightly in the alloys with minimum and maximum alloying content. The alloys with higher alloying concentrations were found to be superplastic at higher strain rates than the lower alloyed samples, according to the finer grain structure which is in close correlation with the precipitation structure.

For comparison, an alloy of practically the same composition as sample 6061/1, produced by the usual industrial route, was also investigated. No superplasticity was found in this case, the value of *m* was stated to be 0.16 and this alloy could be deformed only at five times higher stresses than that of the alloys discussed above.

To determine the correlation between superplastic formability and grain structure, some samples were bulged to cracking at 560 °C. The minimum radius of curvature was chosen as an empirical parameter of the superplastic formability limit, taking into account that the higher the maximum deformation, the larger is the volume of the cylindrical vessel which can be filled by the deformed sheet. Fig. 5 shows the dependence of minimum radius of curvature on the average grain size and grain aspect ratio. In the case of alloy 6066, i.e. of the highest alloying concentration, a smaller grain size and lower grain aspect ratio was found (Table II) and these result in lower minimum radius and better formability.

The relationship between cavitation and degree of deformation was investigated by bulging at optimum superplastic conditions. Fig. 6 shows the results of metallographic investigations obtained on alloys 6066/1 and 6066 before and after superplastic deformation (SPD). The sheet made of alloy 6066 contains a relatively high number of pre-existing cavities,

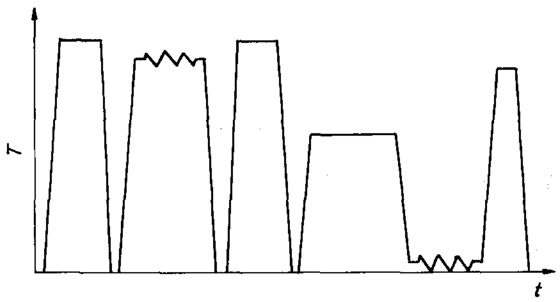

Figure 1 Schematic representation of the thermomechanical treatment.

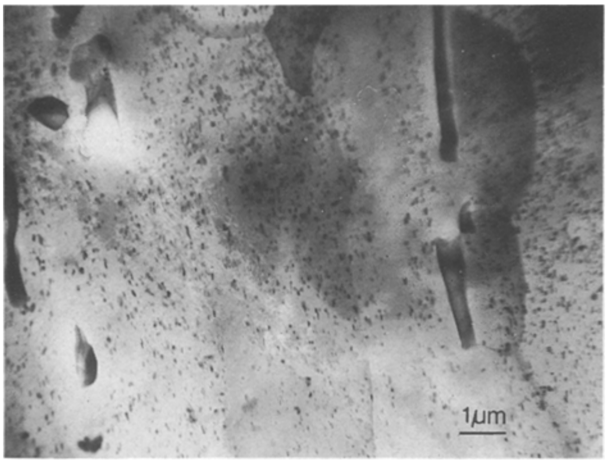

Figure 2 Transmission electron micrograph of sample 6066 taken before superplastic deformation.

TABLE I Composition of the alloys mass %

Alloy	Mg	Si	Cu	Cr	Fe	Mn
6061/1	1.0	0.6	0.25	0.25	0.5	0.2
6061/2	1.2	0.8	0.4	0.25	0.2	0.2
6061/3	1.2	0.8	0.4	0.4	0.2	0.2
6066	1.4	1.0	1.0	0.4	0.5	0.6

TABLE II Grain size measured in long (LT) and short (ST) transverse direction and grain aspect ratio (GAR = d_{LT}/d_{ST}) of the alloys

Alloy	d_{LT} (μm)	d_{ST} (μm)	GAR
6061/1	37	18	2.1
6061/2	25	13	1.9
6061/3	26	12	2.2
6066	18	10	1.8

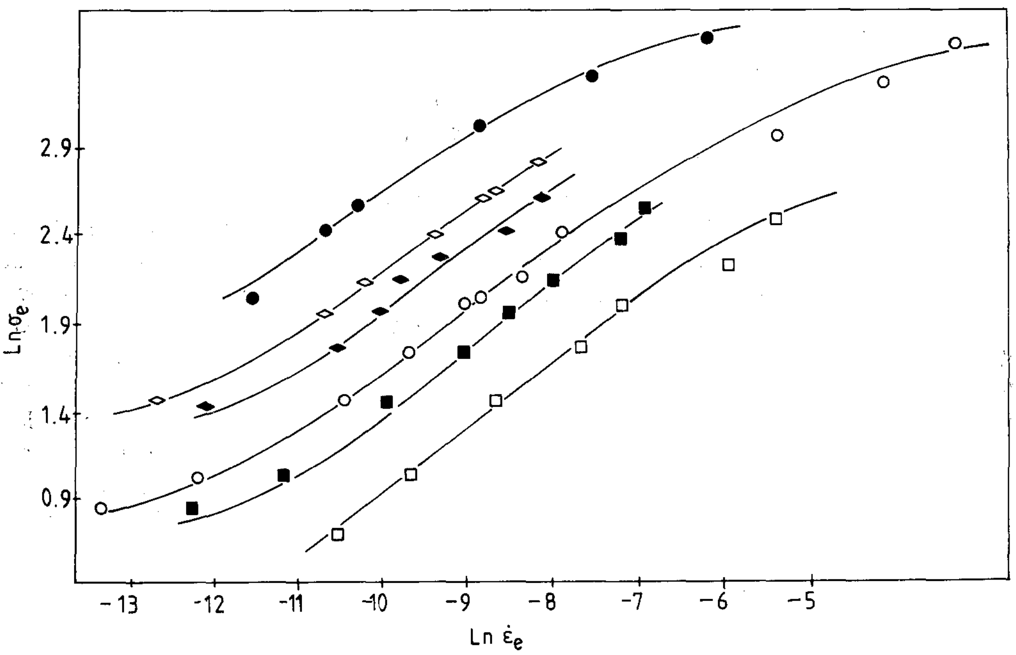

Figure 3 The equivalent stress–equivalent strain rate relationship measured at different temperatures by impression creep testing for alloy type 6066. (●) 486 °C, (◇) 500 °C, (◆) 512 °C, (○) 530 °C, (■) 545 °C, (□) 567 °C.

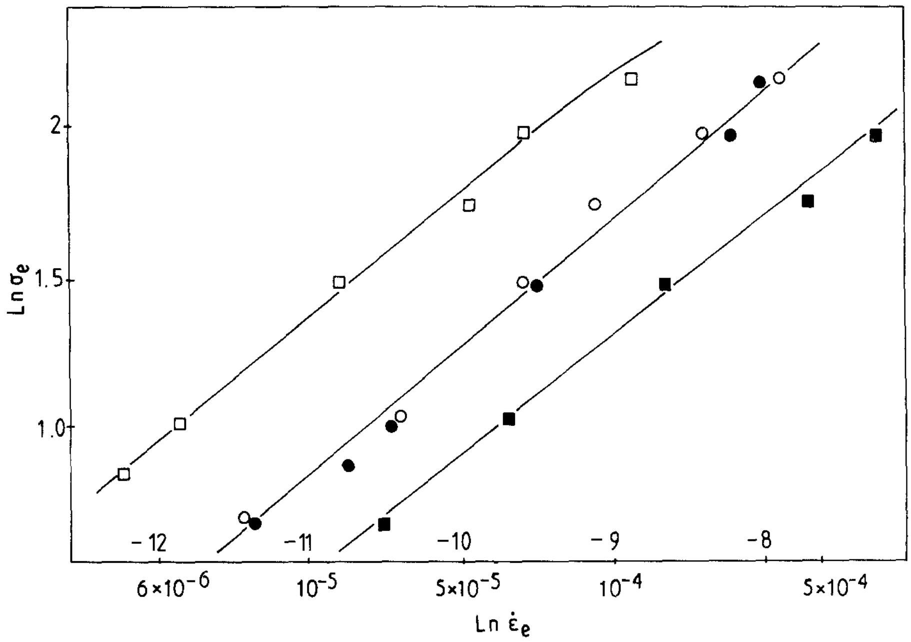

Figure 4 $\ln\sigma_e$–$\ln\dot{\varepsilon}_e$ plot of the alloys for the determination of the rate sensitivity, *m*. $T = 567\,^{\circ}C$, (□) 6061/1, (●) 6061/2, (○) 6061/3, (■) 6066.

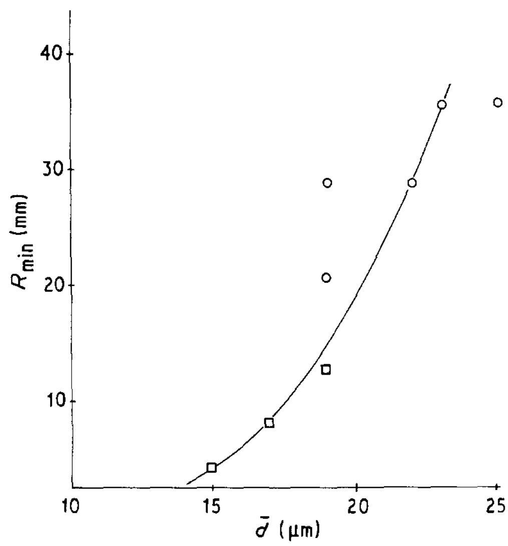

Figure 5 The minimum radius as a function of the average grain size. (○) 6061, (□) 6066.

while in alloy 6061/1, which contains alloying elements in lower concentrations, the volume fraction of pre-existing cavities is much lower. The difference can be explained by the precipitation structure. The pre-existing cavities are formed around coarse particles and their density must be lower in the more dilute alloy 6061.

The growth of cavity volume fraction was analysed using the formula

$$c_v = c_{vo}\exp(-\beta\varepsilon) \quad (1)$$

where c_{vo} is the initial cavity volume fraction, and β characterizes the growth rate of the volume fraction. The curve $\ln c_v$–ε fitted to the data of several deformation experiments can be seen in Figs 7 and 8 for alloys 6061/1 and 6066, respectively. The growth parameter, β, was found to be 6.1 for alloy 6061/1 and 3.0 for alloy 6066. The cavitation process, in spite of the lower initial volume fraction, takes place more rapidly in alloy 6061 than in alloy 6066 according to the coarser grains and higher grain aspect ratio. In both the alloys 6061 and 6066 the observed exponential increase of cavity fraction as a function of degree of deformation is related to strain-controlled cavity growth [2].

In order to decrease the growth rate of cavities, a back pressure of 0.2 MPa was applied in the case of both alloys investigated. The effect of back pressure on the cavitation of alloy 6066 can be seen in Fig. 8. The growth rate parameter, β, could be reduced to 1.1 by applying back pressure. This low level of back pressure, however, was insufficient to increase significantly the superplastic formability of alloy 6066.

No effect of a back pressure of 0.2 MPa was observable in alloy 6061. This may be explained by the much higher inclination of this alloy to cavitation, according to the less favourable grain structure. A significant effect can only be expected at higher pressure levels.

4. Conclusions

According to impression creep investigations, commercial AlMgSi alloy sheets produced by thermomechanical treatment are superplastic between 500 and 570 °C at strain rates of 10^{-5}–$10^{-3}\,s^{-1}$. The strain rate sensitivity, *m*, is about 0.4. Higher superplastic formability can be achieved if the samples contain higher alloying concentrations and if they have a smaller grain size and lower grain aspect ratio.

The highly alloyed 6066 sample contains pre-existing cavities in a higher volume fraction than does alloy 6061. Exponential growth of the cavity volume fraction was found during superplastic deformation, which is characteristic of plasticity controlled cavitation.

The growth rate of cavity volume fraction can be decreased by applying back pressure. If the inclination

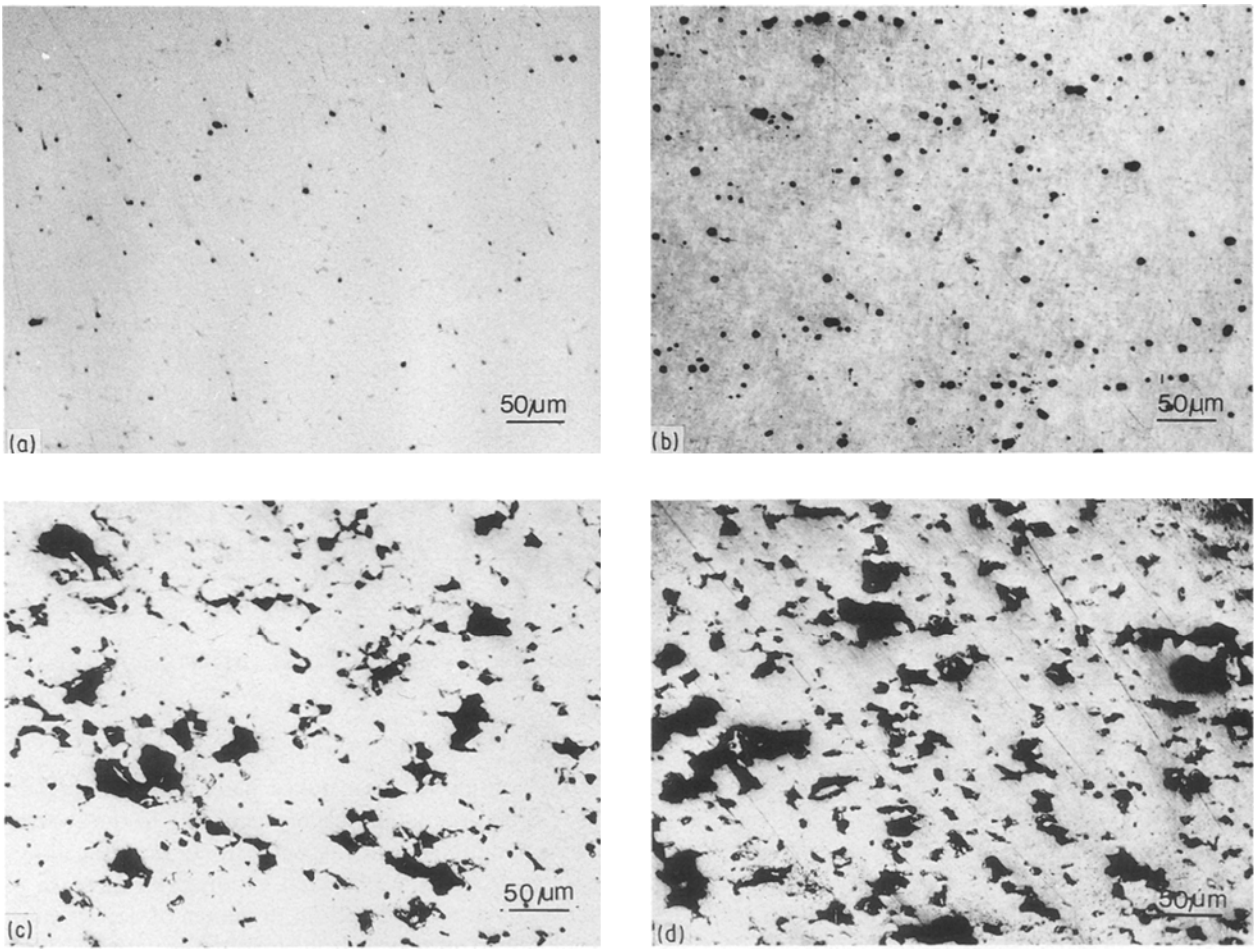

Figure 6 Cavities before SPD (a) 6061/3, (b) 6066; after SPD (c) 6061/3, ε = 0.36, (d) 6066, ε = 0.6.

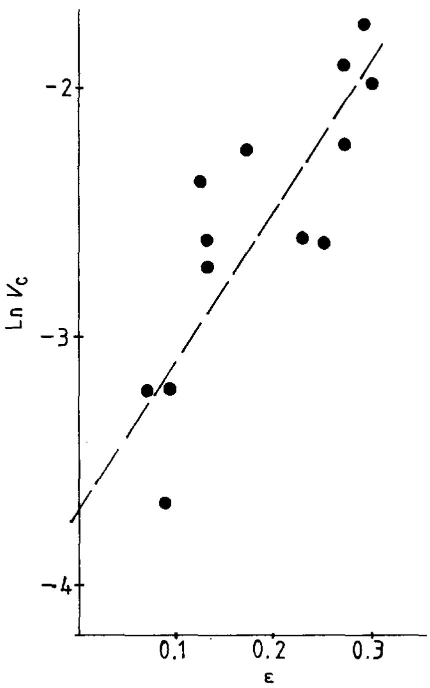

Figure 7 Cavity volume fraction as a function of thickness strain in alloy 6061 after different thermomechanical treatments.

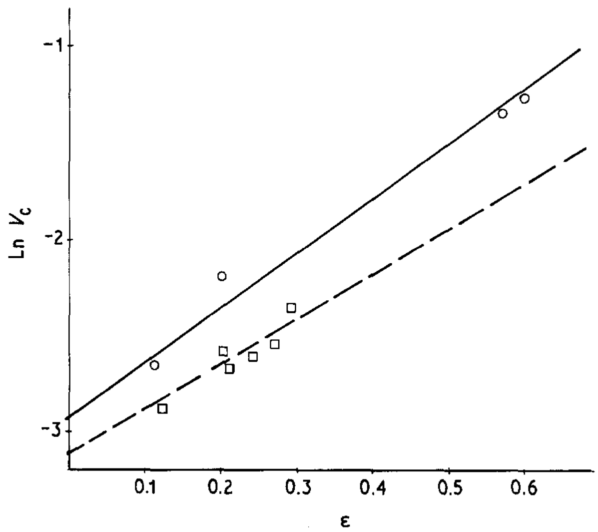

Figure 8 Cavity volume fraction as a function of strain in alloy 6066, (——) without back pressure and (— —) with 0.2 MPa back pressure.

to cavity formation and growth is sufficiently low, as it is in alloy 6066, even a back pressure of 0.2 MPa results in an observable reduction of growth rate of the cavity volume fraction.

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