Effects of Temperature and Strain Rate on Elongation at Elevated Temperature in Al–4.5Mg Alloy

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The effects of temperature and strain rate on elongation of Al–4.5Mg alloy were investigated at 10^{-4} – 10^{-2} s⁻¹ and at 573–773 K. The elongation depended on the temperature and strain rate even in the solute-drag creep region; as a result, a large elongation of 352% was attained at 653 K and at 10^{-3} s⁻¹. Necking developed due to a decrease in plastic stability arising from apparent strain softening behavior at 10^{-2} s⁻¹ at 653 K or the low strain rate sensitivity at 10^{-3} s⁻¹ at 573 K. Also, significant cavitation was caused due to grain boundary sliding at 10^{-4} s⁻¹ at 653 K and at 10^{-3} s⁻¹ at 773 K. The development of necking and cavitation is responsible for the temperature and strain rate dependence of elongation.

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1. Introduction

Large elongations above 300% have been obtained at elevated temperatures in coarse-grained Al-high Mg alloys.^{1–4)} The Al-high Mg alloys exhibit a low value of the stress exponent of 3 or a large value of the strain rate sensitivity of 0.33 for dislocation creep because of viscous dislocation glide.^{1–11)} Taleff *et al.*¹¹⁾ noted that the large elongation for the Al-high Mg alloys is attributed to the high plastic stability arising from the large strain rate sensitivity of about 0.3. In this case, large elongation can be attained under wide conditions of temperature and strain rate, compared to the conditions where a large elongation is attained by superplastic flow. Furthermore, a fine-grained microstructure is not required to attain large elongation for solute-drag creep.

However, even in the solute-drag creep region, elongation depends on the temperature and strain rate and large elongation is not attained under all temperature and strain rate conditions.^{3,11)} This trend is the same as that in superplastic flow where the strain rate sensitivity is greater than 0.3.¹²⁾ These facts suggest that elongation is not determined only by the value of the strain rate sensitivity.

In general, commercial Al–Mg alloys contain impurities of Fe, Si and so on. Recently, Hosokawa *et al.*⁴⁾ investigated the effects of Si content on mechanical properties in the solute-drag creep region for Al–4.5Mg alloy, and they revealed that cavities were formed at the impurity particles. Hence, it is suggested that elongation in the solute-drag creep region is affected by cavitation. Hart¹³⁾ analyzed the plastic stability and they showed that the plastic stability is determined not only by the strain rate sensitivity, but also by the strain hardening coefficient. Sato *et al.*¹⁴⁾ analyzed the plastic instability in superplastic deformation through analysis of the neck shape change. It is suggested from their theories that the temperature and strain rate dependence of elongation in the solute-drag creep region is related to strain hardening behavior. In the present paper, the elongation of Al–4.5Mg alloy

is investigated at 573–773 K and at 10^{-4} – 10^{-2} s⁻¹. Furthermore, the temperature and strain rate dependence of elongation is investigated from the viewpoint of cavitation and strain hardening behavior.

2. Experimental Procedure

An Al–4.5Mg alloy was used. The chemical compositions in mass per cent were Mg 4.49, Fe 0.05 and Ti 0.01. The alloy was homogenized at 803 K for 10 hours, and then it was reheated to 753 K, hot-rolled to a thickness of 6 mm, and cold-rolled to 1 mm. The rolled sheet was annealed at 723 K for 25 s by an immersion molten salt-bath.

Tensile specimens with a gage length of 10 mm and a gage width of 5 mm were prepared with the tensile axes parallel to the rolling direction. Elongation-to-failure tests were conducted at 573–773 K and at 10^{-4} – 10^{-2} s⁻¹. In addition, strain-rate-change tests were carried out at 573–773 K to investigate the strain rate sensitivity. The temperature variation during the tensile tests was not more than 1 K. The specimens were pulled at a series of discrete constant true strain rates ranging from 7×10^{-6} to 7×10^{-2} s⁻¹. The strain rate was changed from a lower to a higher value when a steady flow stress was judged to have been attained. For both types of tests, the specimens were held in the furnace for 1.8×10^3 s before pulling. Grain growth occurred during heating for pulling. Average grain size of the specimen was increased from 62 μ m to 63 μ m, 65 μ m and 339 μ m during annealing for 1.8 ks at 573 K, 653 K and 773 K, respectively. Optical microstructures in Fig. 1 show the variation in grain sizes.

To estimate necking, the local strain was investigated by measurement of the cross-sectional area of the deformed specimen. The local strain is given by

$$\epsilon_{\text{local}} = \ln(A_0/A) \quad (1)$$

where ϵ_{local} is the local strain, A_0 is the cross-sectional area of the specimen prior to the tensile test and A is the area of

Fig. 1 Microstructures of the annealed specimens; (a) 573 K, (b) 653 K and (c) 773 K, where the specimens are annealed for 1800 s.

the deformed specimen.

The volume fraction of cavities in the gage length of the deformed specimens was investigated by hydrostatic weighing in water with a corresponding gage head being used as a density standard. Also, cavities were observed by an optical microscope. The grain boundary sliding contribution was investigated by measurement of the transverse offset. The strain due to grain boundary sliding is given by¹⁵⁾

$$\varepsilon_{\text{GBS}} = \phi w / L \quad (2)$$

where ε_{GBS} is the strain due to grain boundary sliding, w is the average offset, L is the average linear intercept grain size and ϕ is a geometric constant which is equal to 1.5 for the transverse offset.¹⁵⁾ The grain boundary sliding contribution to total strain is given by

$$\xi = \varepsilon_{\text{GBS}} / \varepsilon_{\text{tot}} \quad (3)$$

where ε_{tot} is the total strain. The grain size was measured by optical microscope. The grain size was given by multiplication of the average linear intercept grain size by a constant ($= 1.74$). The specimens were polished and then electrolytically etched at 20 V for 90 s.

Fig. 2 The variation in elongation to failure as a function of strain rate at 573, 653 and 773 K.

3. Results

The variation in elongation to failure as a function of strain rate at 573, 653 and 773 K is shown in Fig. 2. The peak of elongation was attained at 10^{-3} s^{-1} under a constant temperature of 653 K. Also, the peak of elongation was attained at 653 K under a constant strain rate of 10^{-3} s^{-1} . As a result, a maximum elongation of 352% was attained at 10^{-3} s^{-1} and at 653 K in the strain rate and temperature range investigated. The elongation of the material clearly depended on the strain rate and temperature.

The stress vs. strain curves at 10^{-4} , 10^{-3} and 10^{-2} s^{-1} under a constant temperature of 653 K are shown in Fig. 3, where Fig. 3(a) shows the nominal stress vs nominal strain curves and Fig. 3(b) shows the true stress vs true strain curves. The true stress is calculated assuming that the elongation is uniform. A sharp peak stress was found at a small strain at 10^{-4} and 10^{-3} s^{-1} . Such a sharp peak stress is characteristic of viscous dislocation glide creep.¹⁶⁾ However, a sharp peak stress was not observed at 10^{-2} s^{-1} . It can be seen from Fig. 3(b) that the true flow stress was almost constant or slightly increased with increasing strain at 10^{-4} and 10^{-3} s^{-1} ; however, apparent strain softening behavior was found at 10^{-2} s^{-1} .

The stress vs. strain curves at 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} are shown in Fig. 4, where Fig. 4(a) shows the nominal stress vs. nominal strain curves and Fig. 4(b) shows the true stress vs. true strain curves. A sharp peak stress was found at a small strain at 653 and 773 K; however, it was not observed at 573 K. The true flow stress was almost constant or increased with increasing strain at all temperatures of 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} .

The variation in stress as a function of strain rate was investigated by strain-rate-change tests. The results are shown in Fig. 5. From Fig. 5, the strain rate sensitivity at 653 and 773 K was about 0.3 in the strain rate range of 7×10^{-6} to

Fig. 3 The stress vs. strain curves at 10^{-4} , 10^{-3} and 10^{-2} s^{-1} under a constant temperature of 653 K, where Fig. 3(a) shows the nominal stress vs. nominal strain curves and Fig. 3(b) shows the true stress vs. true strain curves.

$7 \times 10^{-2} \text{ s}^{-1}$. On the other hand, the strain rate sensitivity at 573 K was about 0.3 in the strain rate range $< 10^{-4} \text{ s}^{-1}$; however, it was less than 0.3 in the strain rate range $\geq 10^{-4} \text{ s}^{-1}$. The strain rate range $\geq 10^{-4} \text{ s}^{-1}$ at 573 K is probably in the power-law breakdown region.

The variation in local strain as a function of normalized distance from the center at 10^{-4} , 10^{-3} and 10^{-2} s^{-1} under a constant temperature of 653 K is shown in Fig. 6(a), where the specimen is deformed to 260% at 10^{-4} and 10^{-3} s^{-1} and it is deformed to 230% at 10^{-2} s^{-1} . In these figures L is a distance from center of gauge and L_{total} is a half gage length after deformation. Inspection of Fig. 6(a) revealed that necking was significantly developed at 10^{-2} s^{-1} , compared to that at 10^{-4} and 10^{-3} s^{-1} . Therefore, the fact that the elongation at 10^{-2} s^{-1} was lower than that at 10^{-3} s^{-1} is likely to be attributed to significant development of necking at 10^{-2} s^{-1} . Many studies^{13,14,17-21)} have shown that the plastic stability increases with increasing strain hardening coefficient as well as increasing strain rate sensitivity. As shown in Fig. 3, at 10^{-2} s^{-1} under a constant temperature of 653 K apparent strain softening behavior was found even at an initial strain stage where deformation should be uniform. This indicates that the plastic stability at 10^{-2} s^{-1} is not high because of apparent strain softening, despite a high strain rate sensitivity of about 0.3, resulting in significant development of necking. Poschmann *et al.*²²⁾ have also shown the flow softening of Al-5Mg alloy at 673 K and 1.16 s^{-1} . They suggested that the

Fig. 4 The stress vs. strain curves at 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} , where Fig. 4(a) shows the nominal stress vs. nominal strain curves and Fig. 4(b) shows the true stress vs. true strain curves.

stress decrease may be associated with changes in the solute-dislocation interaction as the strain increases, enhancing the capability of the dislocations to rearrange and to form low energy configurations.

The variation in local strain as a function of distance from the center at 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} is shown in Fig. 6(b), where the specimen is deformed to 200%. Necking was significantly developed at 573 K, compared to that at 653 and 773 K. As shown in Fig. 2, the elongation at 573 was lower than that at 653 K. This fact is likely to be attributed to significant development of necking at 573 K. The strain hardening behavior was found at 573 K as well as at 653 and 773 K (Fig. 3). However, the strain rate sensitivity at 573 K under a constant strain rate of 10^{-3} s^{-1} was less than 0.3, as shown in Fig. 5. Therefore, it is likely that significant development of necking at 573 K is because of the lower strain rate sensitivity.

The variation in volume fraction of cavities as a function of strain at 10^{-4} , 10^{-3} and 10^{-2} s^{-1} under a constant temperature of 653 K is shown in Fig. 7(a). It should be noted that the cavity volume fraction at 10^{-4} s^{-1} was much larger than those at 10^{-3} and 10^{-2} s^{-1} .

The variation in volume fraction of cavities as a function of strain at 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} is shown in Fig. 7(b). The cavity volume fraction at 773 K was much larger than those at 573 and 653 K. As shown in Fig. 2, the elongation at 10^{-4} s^{-1} was lower than that at 10^{-3} s^{-1} under a constant temperature of 653 K. Also,

Fig. 5 The variation in stress as a function of strain rate at 573, 653 and 773 K.

the elongation at 773 K was lower than that at 653 K under a constant strain rate of 10^{-3} s^{-1} . These results are likely to be related to significant development of cavitation.

4. Discussion

Taleff *et al.*³⁾ showed that the elongation of Al-high Mg alloys strongly depends on the parameter of $\dot{\epsilon}/D$ and ($\dot{\epsilon}$ is the strain rate and D is the diffusivity of Mg in Al), namely, large elongation is obtained in the solute-drag creep region; however, the elongation is reduced in the power-law breakdown region. On the other hand, the results in the present investigation demonstrated that the elongation depends on the temperature and strain rate even in the solute-drag creep region; namely, the peak of elongation was attained at 10^{-3} s^{-1} under a constant temperature of 653 K, and it was attained at 653 K under a constant strain rate of 10^{-3} s^{-1} . As a result, a maximum elongation of 352% was attained at 653 K and at 10^{-3} s^{-1} . Investigation of local necking and cavitation indicated that under a constant temperature of 653 K, the lower elongation at 10^{-4} s^{-1} is attributed to development of cavitation, and the lower elongation at 10^{-2} s^{-1} is attributed to development of necking. Under a constant strain rate of 10^{-3} s^{-1} , the lower elongation at 573 K is attributed to development of necking, and the lower elongation at 773 K is attributed to development of cavitation.

4.1 Local necking

The development of necking arose from a decrease in plastic stability due to apparent strain softening behavior or the lower strain rate sensitivity. The values of flow hardening parameter γ , ($= \partial \sigma / \partial \epsilon$) at a strain of 0.75 obtained from true stress-true strain curves shown in Fig. 2 and Fig. 3, and the strain rate sensitivity m , ($= \partial \log \sigma / \partial \log \dot{\epsilon}$) obtained from Fig. 4 were shown in Table 1, where σ is a true stress, ϵ is a true strain and $\dot{\epsilon}$ is a strain rate. In Table 1, the values

Fig. 6 The variation in local strain as a function of relative distance from the center at 10^{-4} , 10^{-3} and 10^{-2} s^{-1} under a constant temperature of 653 K (Fig. 6(a)), and at 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} (Fig. 6(b)), where L is a distance from center and L_{total} is a half gage length after deformation. In Fig. 6(a), the specimen is deformed to 260% at 10^{-4} and 10^{-3} s^{-1} and 230% at 10^{-2} s^{-1} . In Fig. 6(b), all specimens are deformed to 200%.

Table 1 Values of flow hardening parameter, strain rate sensitivity and plastic instability index at a strain of 0.75 for several deformation conditions.

	Temperature K	γ	m	I^*
$\dot{\epsilon} = 1 \times 10^{-3} / \text{s}$ $\epsilon = 0.75$	573	-0.11	0.2	-5.6
	653	-0.06	0.3	-3.5
	773	-0.02	0.3	-3.4
	Strain rate s^{-1}	γ	m	I
653 K $\epsilon = 0.75$	1×10^{-2}	-0.75	0.25	-7.0
	1×10^{-3}	-0.06	0.3	-3.5
	1×10^{-4}	-0.10	0.3	-3.4

* $I = (\gamma - 1)/m$, Ref. 14)

of plastic instability parameter, $I (= (\gamma - 1)/m)$ which was proposed by Sato *et al.*, were also shown. They explained that when $I < -2$, the neck becomes sharp. It is noted that I values at 573 K under a constant strain rate of 10^{-3} s^{-1} , and at 10^{-2} s^{-1} under 653 K were -5.6 and -7.0, respectively, which were much smaller than the others. These analysis results reveal that the development of sharp necking occurred at 573 K under a constant strain rate of 10^{-3} s^{-1} , and at 10^{-2} s^{-1} under a constant temperature of 653 K were clearly attributed to more extensive decrease in plastic stability.

Fig. 7 The variation in volume fraction of cavities as a function of strain at 10^{-4} , 10^{-3} and 10^{-2} s^{-1} under a constant temperature of 653 K (Fig. 7(a)), and at 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} (Fig. 7(b)).

Fig. 8 Cavities formed at grain boundaries in the specimen deformed to failure at 653 K and 10^{-3} s^{-1} .

4.2 Cavitation

The origin of cavity development at 773 K or at 10^{-4} s^{-1} is not clear. One of the possibilities is that cavity growth is accelerated due to higher temperature or longer time.²³⁾ Another is cavitation due to grain boundary sliding. Grain boundary sliding often occurs even in the dislocation creep region.²⁴⁾ Ayensu and Langdon²⁵⁾ showed that the overall level of cavitation increases with strain due to grain boundary sliding during creep. Watanabe and Davies²⁶⁾ noted that ledges produced by movement of lattice dislocation along the grain boundary can act as nucleation sites of grain boundary cavities. In the present investigation, cavities were formed at grain boundaries (Fig. 8). This trend is the same as that of superplastic flow whose dominant deformation process is grain boundary sliding.

The variation in grain boundary sliding contribution as a function of strain at 10^{-4} , 10^{-3} and 10^{-2} s^{-1} under a constant temperature of 653 K is shown in Fig. 9(a). It can be seen that grain boundary sliding occurred significantly at 10^{-4} s^{-1} , compared to that at 10^{-3} and 10^{-2} s^{-1} . Therefore, it is suggested that significant development of cavitation at 10^{-4} s^{-1} arises from active grain boundary sliding.

Fig. 9 The variation in grain boundary sliding contribution as a function of strain at 10^{-4} , 10^{-3} and 10^{-2} s^{-1} under a constant temperature of 653 K (Fig. 9(a)), and at 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} (Fig. 9(b)).

The variation in grain boundary sliding contribution as a function of strain at 573, 653 and 773 K under a constant strain rate of 10^{-3} s^{-1} is shown in Fig. 9(b). The grain boundary sliding contribution at 773 K was almost the same as that at 653 K, though the grain boundary sliding contribution at

573 K was much lower than those at 653 and 773 K, indicating that significant development of cavitation at 773 K is not attributed to large grain boundary sliding contribution.

It is noted that the grain size in the specimen annealed at 773 K was much larger than those annealed at 573 and 653 K as shown in Fig. 1. Wilkinson and Cáceres²⁷⁾ showed that the strain-enhanced grain growth rate during grain boundary sliding also increases with increasing grain size. They suggested that it results from the stress concentration caused by grain boundary sliding. Hence, the stress concentration caused by grain boundary sliding may increase with increasing grain size. Therefore, significant development of cavitation at 773 K at 10^{-3} s^{-1} may be related to the large grain size.

5. Conclusions

(1) The effects of temperature and strain rate on elongation of Al-4.5Mg alloy were investigated at 10^{-4} – 10^{-2} s^{-1} and at 573–773 K. The peak of elongation was attained at 10^{-3} s^{-1} under a constant temperature of 653 K, and it was attained at 653 K under a constant strain rate of 10^{-3} s^{-1} . As a result, a maximum elongation of 352% was attained at 10^{-3} s^{-1} and at 653 K.

(2) The lower elongation at 10^{-2} s^{-1} under a constant temperature of 653 K and the lower elongation at 573 K under a constant strain rate of 10^{-3} s^{-1} was attributed to development of necking. The development of necking arose from a decrease in plastic stability due to apparent strain softening behavior or the lower strain rate sensitivity.

(3) The lower elongation at 10^{-4} s^{-1} under a constant temperature of 653 K and the lower elongation at 773 K under a constant strain rate of 10^{-3} s^{-1} was due to significant cavitation. The significant cavitation is likely to be related to grain boundary sliding.

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