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Effect of Powerful Current Pulses on the Structure and Mechanical Properties of the Aluminum Alloy Al-6%Mg-0.6%Mn

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Changes in the microstructure and mechanical properties of commercial aluminum alloy Al-6%Mg-0.6%Mn after recrystallization have been studied. This alloy was recrystallized by two methods: annealing in air at temperatures of 250 to 450 °C for 20 min in an electrical resistance furnace; and passing an electrical current pulse by discharging a bank of capacitors (with a duration of about 100 µs). It is shown that electrical pulsed treatment produced a fine-grained structure in the Al-6%Mg-0.6%Mn alloy with a grain size (2-3 µm) smaller than the one annealed in the furnace and improved the mechanical properties of this material.

Keywords flow stress, grain size, mechanical properties, microcrystalline structure, microhardness, powerful electrical pulsed treatment, recrystallization, superplastic properties

1. Introduction

Rendering a microcrystalline state to an alloy structure improves the mechanical properties. The smaller the grain size in the alloy, the higher the level of strength achieved (Ref 1). One factor that appreciably affects the size of recrystallized grains is the heating rate to the annealing temperature. An increase in the heating rate results in a finer structure (Ref 2, 3). Powerful electrical pulsed treatment (PEPT) provides high heating rates and is an efficient method for refining the microstructures of metals and alloys.

This study considers the specific features of the formation of a microcrystalline structure, and changes in the microhardness and mechanical properties of the alloy Al-6%Mg-0.6%Mn, which was subjected to PEPT. This alloy is not a thermally strengthened material, and, for this reason, it is not subjected to a special heat treatment in the final stage of processing. As such, the microstructure formed by recrystallization annealing is retained in the final products.

2. Experimental

As a material for the investigation, a hot-pressed rod of commercial Al-6%Mg-0.6%Mn with a standard chemical composition was chosen. Initially, this alloy had a non-recrystallized structure with extended grains. The rod was compressed at 420 °C to 70%, rolled at 400 °C, and, finally, rolled at room temperature to logarithmic degrees of deformation (e) equal to 0.3, 0.8, and 1.6 (where $e = \ln[h_o/h]$, and h_o and h are the initial and final thicknesses of the strip, respectively). As a result of this treatment, a recrystallized structure with different grain sizes was observed along with non-recrystallized regions.

The microstructure of the recrystallized alloy was studied using specimens 4 × 10 × 1 mm in size. The recrystallization of the alloy microstructure was performed in one of two ways: annealing in air at temperatures from 225 to 600 °C for 20 min in an electrical resistance furnace; or by using a PEPT. In the latter case, specimens were heated by passing a current pulse of about 100 µs duration through the sample. The current pulse was generated by discharging a bank of capacitors.

For the PEPT, the ends of the specimens were clamped in massive brass bits through which the electrical current was passed through a zone of the sample that was 4 mm in length. After the pulse-induced heating, the specimen was cooled in air for about 1 ms due to the intense heat removal at the clamped ends of the specimen. The change in the temperature of the specimen was determined by (Ref 4):

$$\frac{j^2}{\sigma_e} = \rho c \frac{\partial T}{\partial t} \quad \text{(Eq 1)}$$

where ρ, c, and σ_e are the density, heat capacity, and electroconductivity of the aluminum alloy, respectively, and j is the current density.

Integrating Eq 1 yields:

$$S(T_k) = K_j, \text{ where } K_j = \int_0^{t_k} j^2\, dt \text{ and } S(T_k) = \int_0^{T_k} \rho c \sigma dT$$

where t_k is the time of PEPT and T_k is the temperature attained in the specimen. The parameter K_j was determined using the experimental current oscillogram recorded with the help of a Rogowski loop. Given the temperature dependences of the density, heat capacity, and electrical conductivity for this material,

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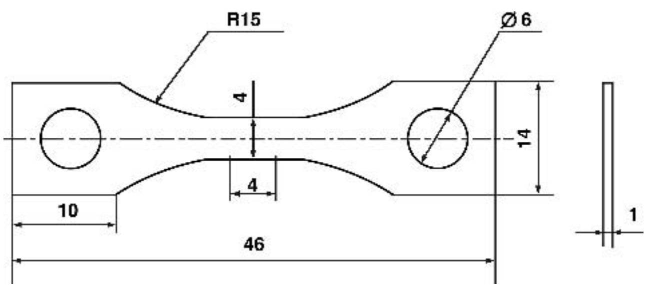

Fig. 1 Specimen geometry and dimensions

the average temperature for the electrical pulsed treatment was calculated.

Prior to metallographic examination, the specimens were aged at 140 °C for 4 h to observe the grain structure. The specimens were examined in an optical microscope. The grain size was estimated as the average between the longitudinal and transverse sizes of the grains d_x and d_y, that is, $(d_x + d_y)/2$. The measurements were performed using an EPIQUANT-2 (Carl Zeiss, Jena GmbH, Jena, Germany) semiautomatic structure analyzer by the random-intercepts method (Ref 5), which is based on the determination of the average length of the line segment intersecting a grain. That is, $d = l/n$, where n is the number of grains intersected by a line of length l. In every case, 300 grains were measured. This resulted in an error of <5% with a confidence probability equal to 0.9 (Ref 5).

Microhardness was measured using the Vickers method with a load of 50*g*. The fine structure was studied using a transmission electron microscope (JEM-2000EX) (JOEL Ltd., Tokyo, Japan). Tensile tests were performed on plane specimens (Fig. 1). The configuration ensured the maximum heating of the central zone (with a gage length of 4 mm), which was completely recrystallized. Tensile testing was carried out for a range of deformation temperatures (i.e., 20-375 °C) at strain rates between 8×10^{-4} and 2×10^{-2} s^{-1}.

3. Results and Discussion

The changes in the microhardness of the Al-6%Mg-0.6%Mn alloy depended on the annealing temperature, as shown in Fig. 2(a). It can be seen that the microhardness decreases sharply in the temperature range of 225 to 300 °C for all degrees of deformation. A further increase in the temperature (>300 °C) resulted in no noticeable changes in the microhardness, which reached its minimum value of 0.9 GPa.

Upon heating in an electrical resistance furnace, primary recrystallization and grain growth occurred in the Al-6%Mg-0.6%Mn alloy. Values for the relationship of grain size to annealing temperature are shown in Fig. 2(b).

In specimens that were subjected to rolling at deformations of 0.8 and 1.6, the growth of individual grains occurred in a temperature range of 225 to 300 °C. In the case of a deformation of 0.3, the growth of individual grains occurred in the temperature range of 225 to 350 °C. The minimum size of the recrystallized grain for a deformation of 0.3 was 8 μm. For a deformation of 0.8, the grain size was 4 μm. For a deformation of 1.6, the grain size was 2.5 μm. A further increase in the temperature up to 400 °C decreased the grain size (Fig. 3a, b). The effect on grain size for this increase in the annealing temperature was determined by the ratio of the acceleration in grain growth to the nucleation of the recrystallization centers (Ref 2, 3).

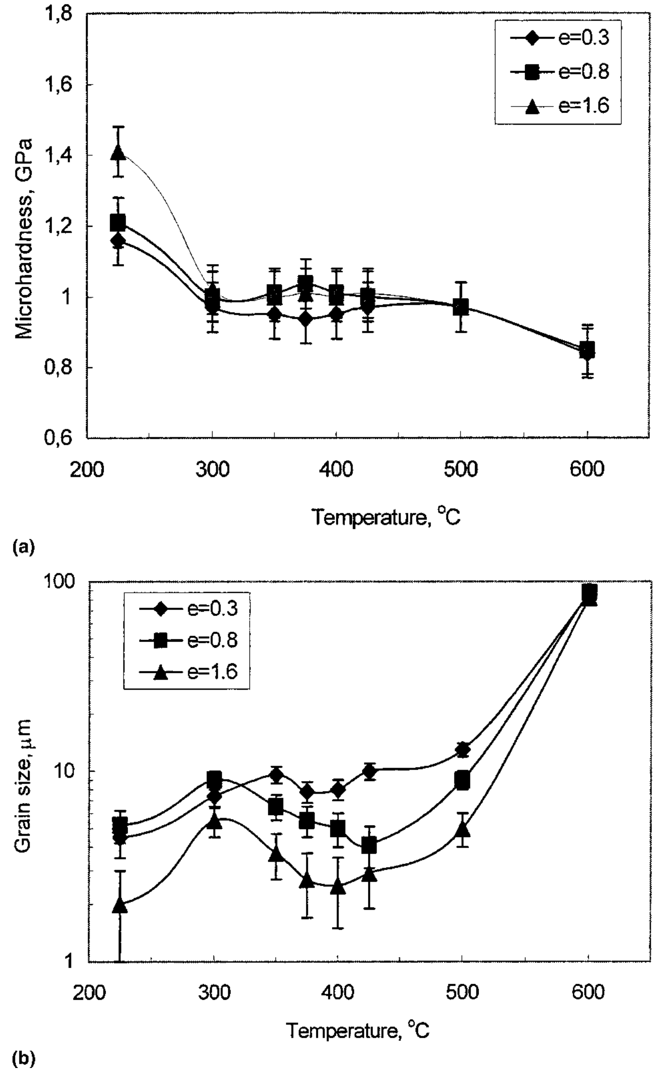

Fig. 2 (a) Microhardness and (b) grain size depending on the temperature of annealing in a furnace

This alloy contains 0.6% Mn, which acts to retard recrystallization, and affects grain migration and, to a lesser degree, the nucleation of the recrystallization centers. At temperatures of >400 °C, grain growth accelerates, with higher annealing temperatures leading to larger recrystallized grains. At an annealing temperature of 600 °C, the grain size reaches 80 μm (Fig. 2b).

Variations in the grain size and microhardness due to PEPTs are shown in Fig. 4(a) and (b), depending on the conditional temperature of this treatment. The specimen microhardness for deformations of 0.3 and 0.8 GPa on PEPT does not change until the energy corresponds to a calculated temperature of about 500 °C. The microhardness decreases in the range of calculated PEPT temperatures between 500 and 700 °C, which is a wider range than that found during furnace annealing. With a further increase in the induced energy, the specimen microhardness reaches a minimum equal to 1.1 GPa, which is still higher than the value obtained at the maximum temperatures for resistance furnace annealing (Fig. 4a).

For PEPT samples, primary recrystallization begins at induced energies of $K_j \sim (0.06\text{-}0.07) \times 10^5$ A^2s/mm^4, which correspond to a range of calculated temperatures (250-350 °C).

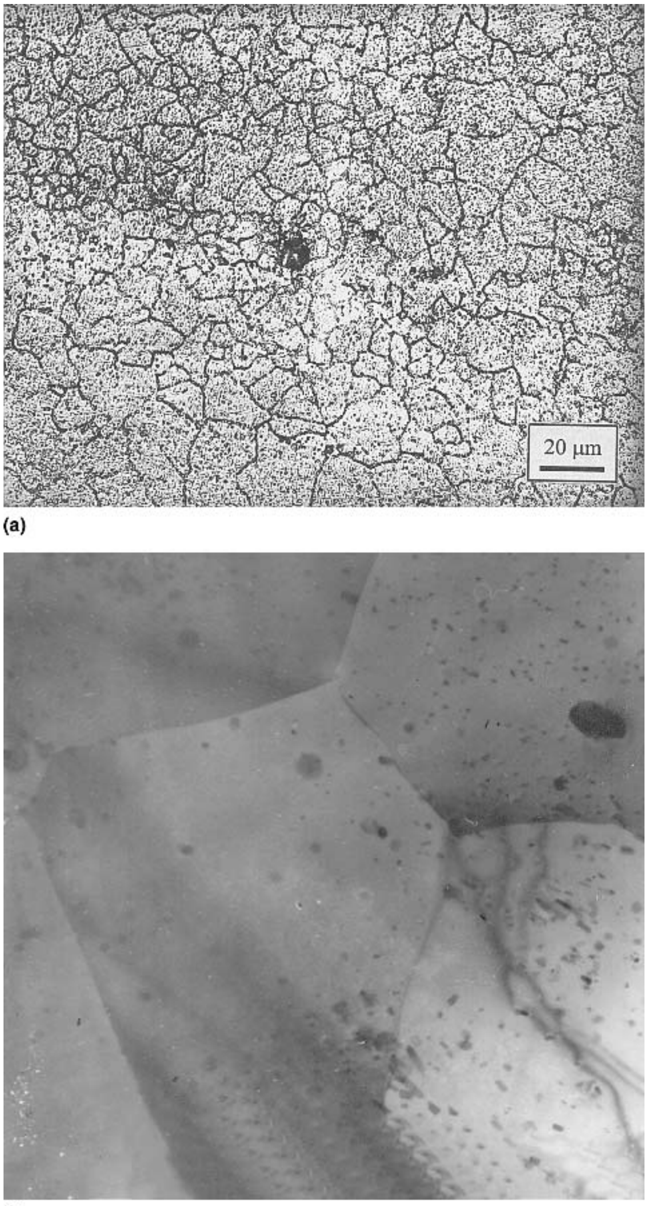

Fig. 3 Microstructure of the Al-6%Mg-0.6%Mn alloy annealed at 400 °C

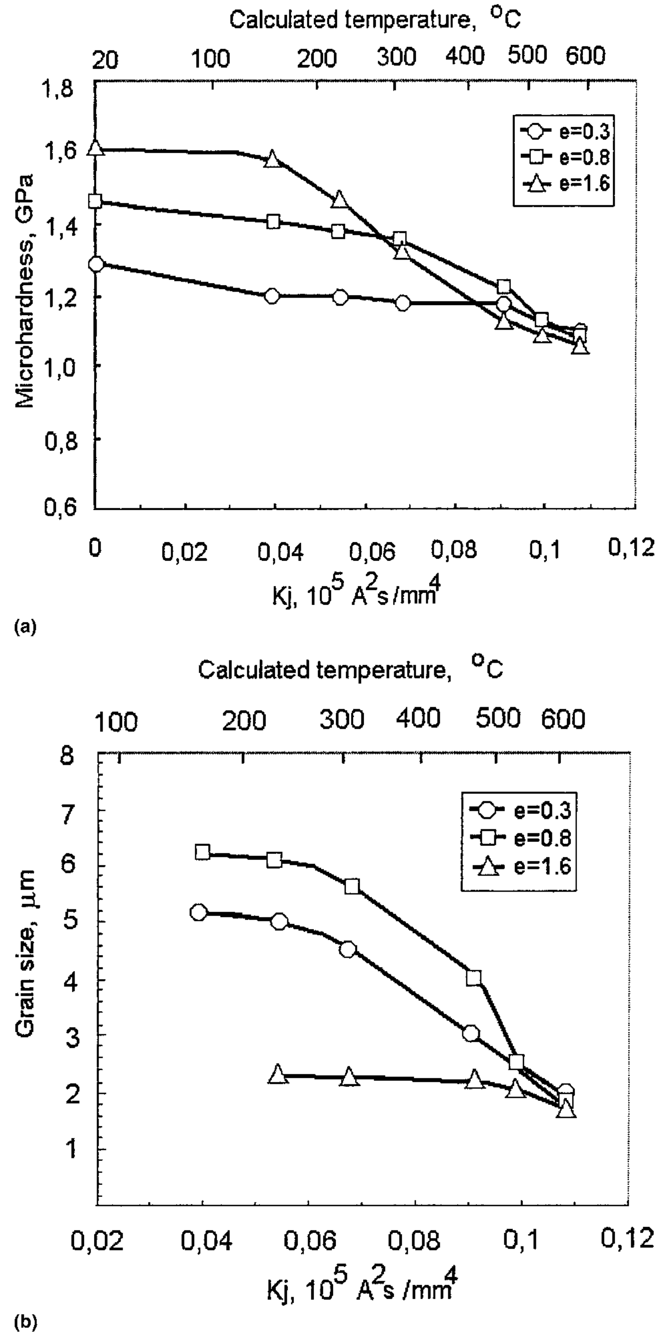

Fig. 4 (a) Microhardness and (b) grain size as a function of PEPT input energy

The formation of a recrystallized structure in the material occurs at K_j ~ (0.08-0.09) × 10^5 A^2s/mm^4. A further increase in energy results in only a slight increase in grain size (Fig. 4b). Grain growth is practically suppressed due to the pulsed heating and rapid cooling of the specimens.

Comparing the dependence of grain size and microhardness on the energy input (Fig. 4a, b), it can be concluded that, unlike the case with furnace annealing in which a change in the grain structure and a decrease in the microhardness occur concurrently, PEPT leads to an appreciable decrease in the microhardness only after the microstructure has been recrystallized.

Figure 5 shows the microstructure of the Al-6%Mg-0.6%Mn alloy after the PEPT with an input energy of K_j = 0.95 × 10^5 A^2s/mm^4. In this case, the alloy microstructure is fine grained and homogeneous. However, transmission electron microscope investigation of thin foils revealed that while an overwhelming number of grains were absolutely dislocation-free, as in the case of furnace annealing (Fig. 3b), some grains contained dislocations and subboundaries (Fig. 5b). The number of these grains was small, and they were randomly distributed (Fig. 5c). Their sizes were close to those of the recrystallized grains, indicating that PEPT does not lead to the complete recrystallization of the microstructure. This results because of the extremely short duration of this treatment. Regions of the microstructure that were not recrystallized were retained. The size of these regions was small and corresponded to a size equal to that of single grains. Seemingly, the high temperature and high heating rate of the PEPT caused a very high rate of nucleation of the recrystallization centers. The distances between the recrystallization centers are so small that only one to two grains can be located in the remaining non-

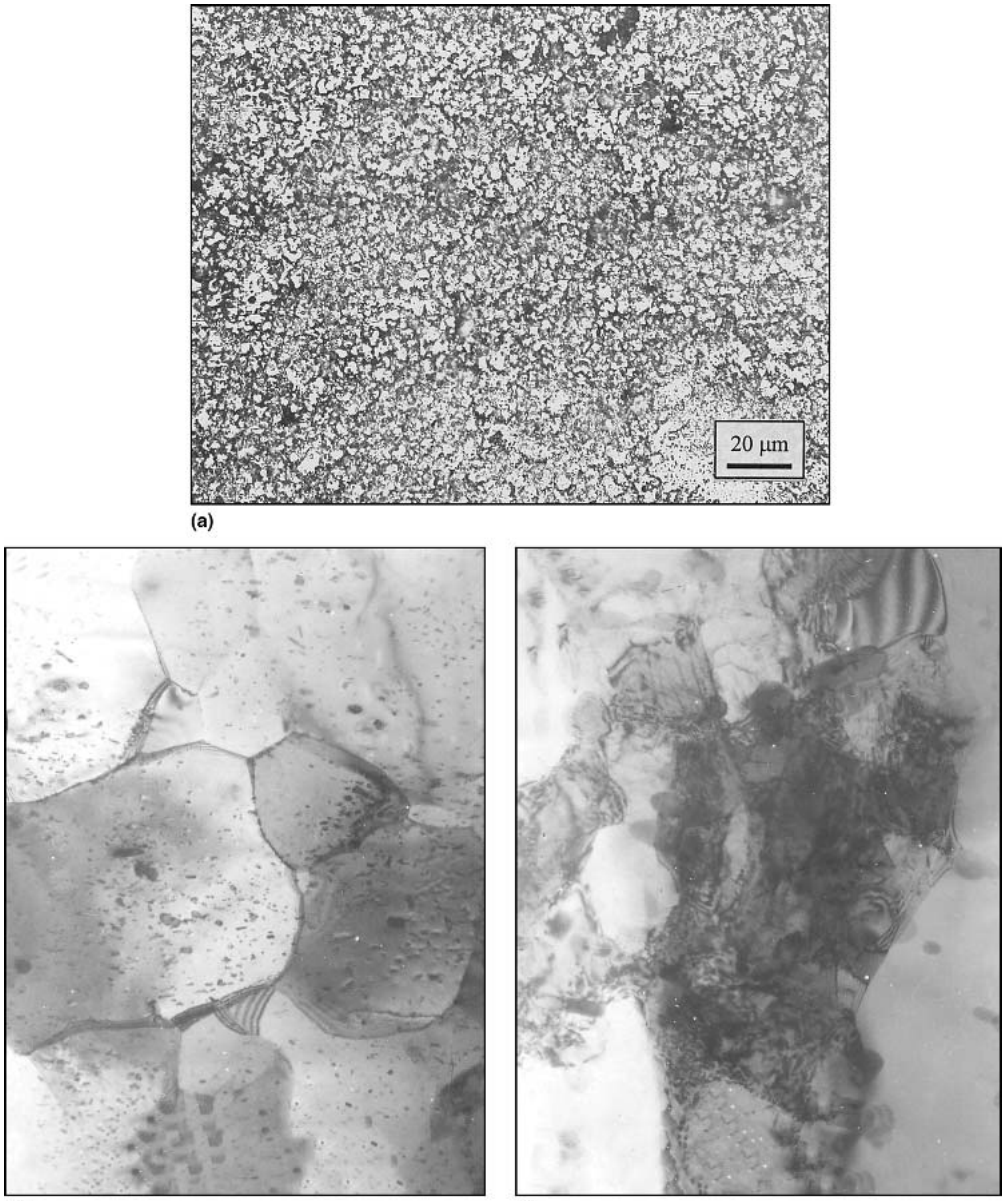

Fig. 5 Microstructure of the Al-6%Mg-0.6%Mn alloy subjected to PEPT

recrystallized regions. Similar differences in the evolution of the microstructure on furnace annealing and PEPT were observed in 99.9% Cu (Ref 6).

The dependence of microhardness and grain size on the induced energy from the PEPT allowed the determination of a preferable treatment regimen for the production of a fine-grained microstructure. Figure 6 shows the variation in flow stress, σ_{20}, with deformation temperature. In the range of 20 to 325 °C, the flow stress of the specimens subjected to PEPT with an input energy of K_j of ~0.95×10^5 A^2s/mm^4 (i.e., a calculated temperature of about 500 °C) was slightly higher than that of the specimens annealed in the furnace at 300 °C. The presence of a finer structure after PEPT ensures, according to the Hall-Petch equation (Ref 7, 8) $\sigma_T = \sigma_o + kd^{-1/2}$, a higher resistance to plastic deformation.

The tensile tests performed at 375 °C for the range of strain rates from 8×10^{-4} to 2×10^{-3} s^{-1} showed that specimens annealed in the furnace (with an average grain size of 9 μm) and those subjected to PEPT (with an average grain size of 3 μm) exhibit superplastic characteristics. That is, the relative elongation of the samples depends on the strain rate, and the strain-rate sensitivity coefficient *m* is greater than 0.3. At the same time, superplasticity at low strain rates was observed more clearly after PEPT. The decrease in grain size from 9 to 3 μm allowed an increase in the relative elongation from 122% to 182% at a strain rate of 8×10^{-4} s^{-1}. At the same time, the flow stress σ_{20} decreased from 26.9 to 15.5 MPa (Fig. 7a), and the strain rate sensitivity coefficient *m* increased from 0.3 to 0.5 (Fig. 7b). The increase in the strain rate to 2×10^{-2} s^{-1} suppressed the effect of the PEPT on the relative elongation, flow stress, and strain rate sensitivity.

4. Conclusions

- A microstructural examination of Al-6%Mg-0.6%Mn annealed in a furnace and subjected to PEPT showed that the

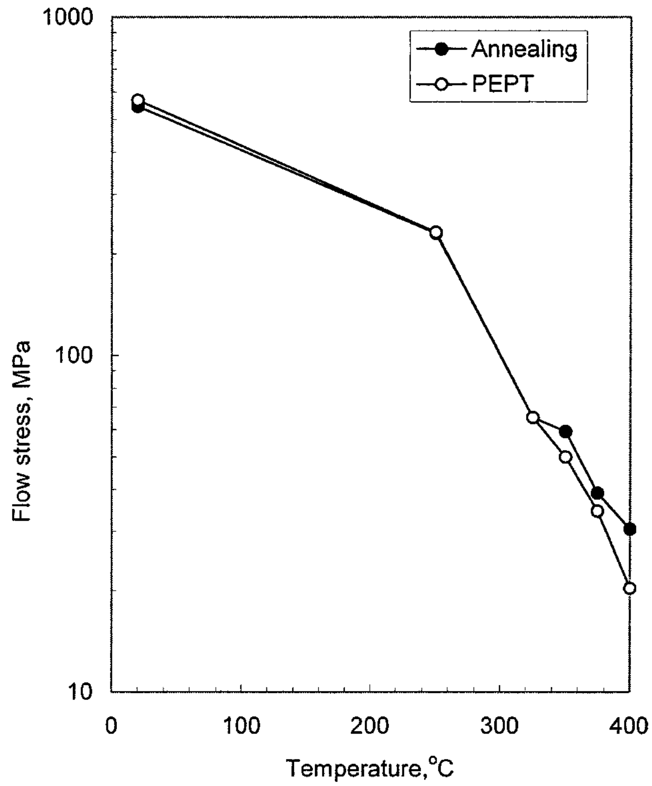

Fig. 6 Flow stress of the Al-6%Mg-0.6%Mn alloy as a function of test temperature ($e = 0.8$)

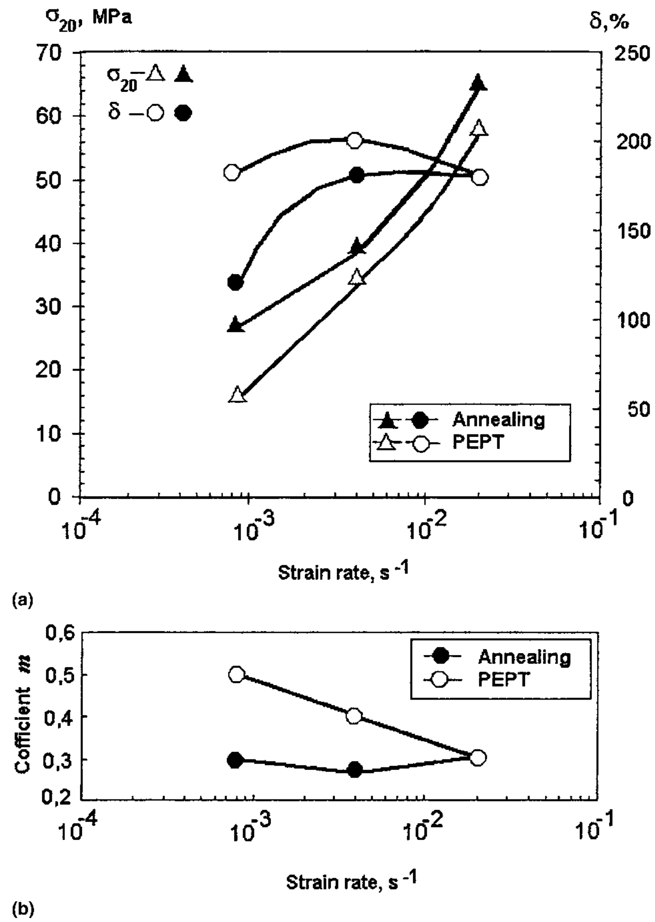

Fig. 7 (a) Flow stress σ_{20} and relative elongation δ; and (b) strain-rate sensitivity coefficient *m* of the Al-6%Mg-0.6%Mn alloy as a function of strain rate at 375 °C

PEPT shifted the start temperature for microstructural changes to higher temperatures.

- It was found that the PEPT produced a microstructure that was suitable for superplastic deformation (grain size equal to 3 μm), regardless of the degree of preliminary deformation. A specific feature of PEPT is the formation of a homogeneous fine-grained microstructure despite the fact that primary recrystallization is incomplete.
- The PEPT improved the operative characteristics (i.e., increased strength by 30%) and technological characteristics (i.e., decreased flow stress by 40% and increased plasticity by 60%) of the Al-6%Mg-0.6%Mn alloy compared with furnace-annealed samples.

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