Bull. Mater. Sci., Vol. 5, No. 5, December 1983, pp. 459-464. © Printed in India.

Changes in texture and grain size in hot rolled magnesium and effect on yield strength

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MS received 7 February 1983

Abstract. Variations in the grain size and basal texture in magnesium hot-rolled in the temperature range 570–770 K have been studied and compared with those observed in specimens hot-rolled at 570 K and annealed at different temperatures in the range 570–770 K. In specimens hot-rolled temperatures higher than 670 K, a rapid increase in grain size and a weakening in basal texture have been observed. The yield stress of the specimen is lower than that predicted by the Hall-Petch relation and this result is interpreted in terms of the reduced basal texture. The dependence of yield stress on grain size in magnesium hot-rolled at different temperatures lower than 670 K matches with that observed in specimens annealed at different temperatures.

Keywords. Texture; grain size; hot-rolling; Hall-Petch relation.

1. Introduction

In view of their limited ductility, magnesium alloys are generally hot-worked and the most common forming process is hot extrusion. However, magnesium and its alloys are also hot rolled; the changes in the microstructure and their influence on mechanical properties studied (Kelley and Hosford 1968; Sambasiva Rao and Prasad 1982). The two important microstructural features in the hot-rolled product that influence their mechanical properties are grain size and texture. To study the effect of grain size on the yield stress, Hauser *et al* (1956) and Wilson and Chapman (1963) produced grain size variations by using different annealing treatments on specimens hot-worked at a constant temperature. In such specimens, the associated textural variations were negligible. It is also possible to produce grain size variations in specimens by hot-rolling at different temperatures which has not been explored so far in magnesium materials. The aim of the present investigation is to study the changes in the grain size and texture in magnesium hot-rolled in the temperature range 570–770 K and examines their influence on the tensile yield strength.

2. Experimental

Magnesium (99.87% purity) was used in this investigation. The starting material for mechanical processing was a cast slab of 40 × 40 × 18 mm which was hot-forged at 720 K to a final thickness of 11 mm. The hot-forged slabs were reduced to 1.6 mm by flat-rolling at different temperatures in the range of 570–770 K. The hot-rolling schedule consisted of a reduction of 0.4 mm per pass followed by heating at the respective rolling temperature for 5 min. The strips rolled at 570 K were also given the following annealing treatments: (i) at 570 K for 30 min (ii) at 620 K for 1 hr (iii) at 670 K for 1 hr and (iv) at 770 K for 1 hr.

The average grain diameter in all the specimens was measured using the linear intercept method. The textures were measured using x-ray techniques, the details of which are explained elsewhere (Sambasiva Rao and Prasad 1982). Both the x-ray intensity of {0002} reflection as well as pole figures were obtained.

Sheet specimens of 15 mm gauge length and 4 mm gauge width with their tensile axes in the longitudinal direction were milled from the hot rolled sheets. Tensile testing was carried out on a tensometer at a nominal strain rate of $5 \times 10^{-4} \mathrm{sec}^{-1}$ and at liquid nitrogen temperature (77 K), room temperature (300 K) and in heated paraffin oil (420 K).

3. Results

The changes in grain size and basal texture intensity (I_{0002}) normalised with the random value (I_0) with rolling temperature are shown in figure 1. Hot rolling at

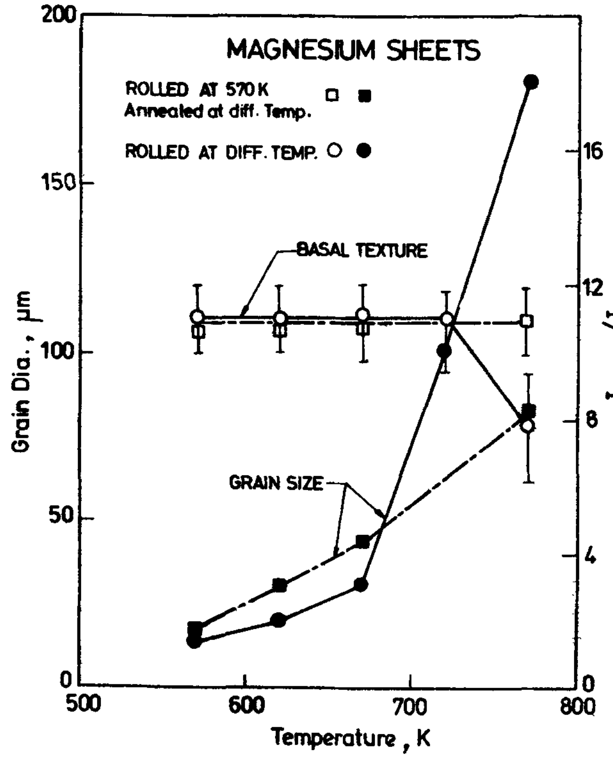

Figure 1. The variation of grain size and basal intensity with rolling temperature in magnesium rolled at different temperatures. Similar data as a function of annealing temperature obtained on magnesium rolled at 570 K and annealed at different temperatures are also shown.

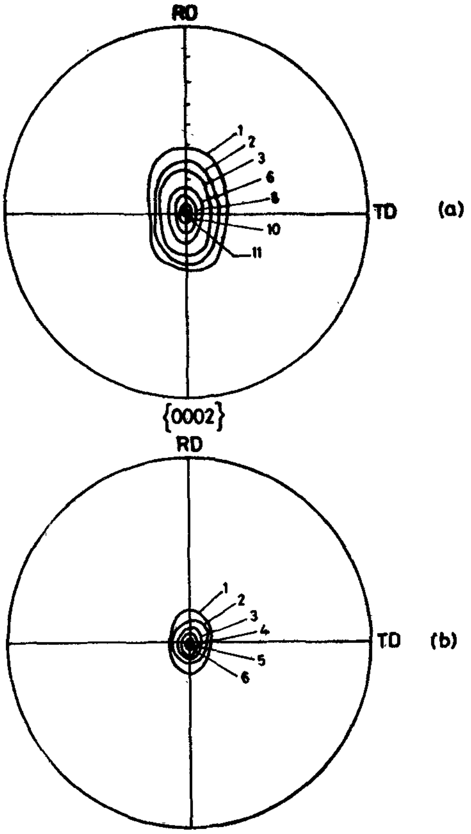

Figure 2. The basal pole figures obtained on magnesium hot rolled at (a) 570 K and (b) 770 K. (RD-rolling direction, TD-transverse direction, SN-sheet normal. The numbers against the contours indicate multiples of random intensity).

temperatures higher than 670 K gives rise to grain coarsening which occurs rapidly with further increase in temperature. The basal texture intensity remains unaltered up to about 700 K and becomes weaker at 770 K. The {0002} pole figures for magnesium rolled at 570 K and 770 K are given in figure 2a, b respectively. The peak intensity of the basal poles at the sheet normal is reduced from 11 times the random value at 570 K to about 6 times the random intensity at 770 K.

In figure 1, are included the grain size and texture variations as a function of annealing temperature obtained on specimens rolled at 570 K and annealed at different temperatures. The grain size increased with increase in annealing temperature but no abnormal coarsening beyond 670 K as in the case of specimens rolled at different temperatures was observed. The intensity of basal texture remained constant with annealing temperature confirming the earlier observations (Hauser *et al* 1956; Wilson and Chapman 1963).

The variation of 0.2% yield strength with grain size in longitudinal specimens of magnesium rolled at different temperatures is shown in figure 3. The data obtained at 77, 300 and 420 K are included in this figure. The data obey the Hall–Petch relation :

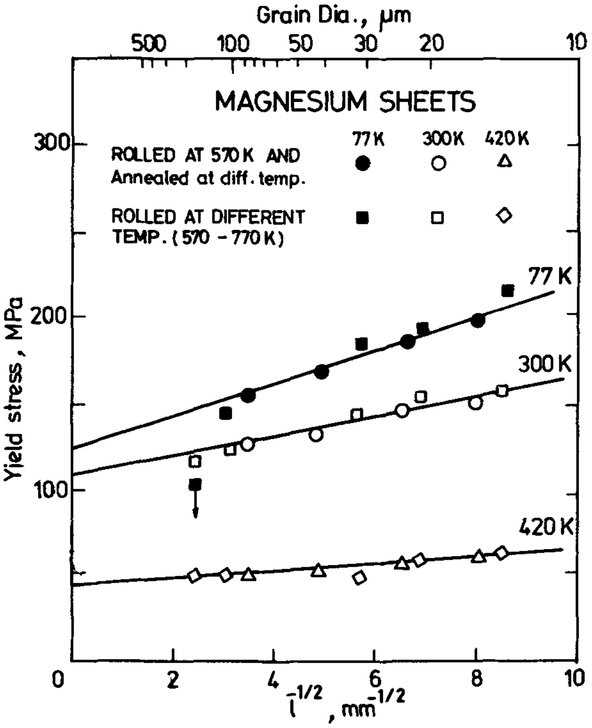

Figure 3. The variation of yield strength with inverse square root of grain diameter in longitudinal specimens of hot rolled magnesium tested at 77, 300 and 420 K. The data obtained on magnesium rolled at different temperatures as well as on magnesium annealed at different temperatures are represented.

$$\sigma_y = \sigma_0 + kl^{-1/2} \tag{1}$$

where σ_y is the yield strength, l is the average grain diameter, σ_0 and k are Hall-Petch constants representing the intercept and slope of the Hall-Petch line. It is to be noted that the 77 K datum for the specimen rolled at 770 K (grain dia.180 μm) is very much below the Hall-Petch line. This tendency is reduced for results at 300 K and 420 K. In figure 3 are also shown the data for the specimens hot rolled at 570 K and annealed at different temperatures. The data for both sets of specimens match well at grain sizes finer than about 100 μm. The Hall-Petch constants σ_0 as well as k are temperature-dependent.

4. Discussion

It has been shown in a number of materials that softening mechanisms involving recovery and recrystallization occur dynamically during hot working (Jonas *et al* 1969). Although detailed studies have not been made on the hot-working mechanisms in magnesium, the available data on steels, aluminium and copper clearly show (Tegart 1968) that the process of dynamic recrystallization occurs during hot working. It was also shown that the temperature and strain rate of deformation influences the dynamically recrystallized grain size which becomes larger at high temperatures and slow strain rates. The present data (figure 1) on magnesium rolled at different temperatures are in accordance with this and suggest a near exponential increase in the grain diameter with rolling temperature. On the other hand, the grain growth as a result of static recrystallization at different temperatures following hot rolling at 570 K, is related to the annealing temperature in a near linear fashion (figure 1).

The hot rolling texture in magnesium sheets has been identified (Kelley and Hosford 1968; Sambasiva Rao and Prasad 1982) to consist of basal planes parallel to the rolling plane with $[11\bar{2}0]$ as the rolling direction. The theory of development of rolling textures is not well developed, and the most complete treatment of this subject so far has been that of Calnan and Clews (1951). According to them, the process of rolling can be described in simple terms as a compression perpendicular to the rolling plane and a tension in the rolling direction. In simple slip, the model predicts that the compression will rotate the active slip plane such that its normal moves towards the stress axis. As easy slip in magnesium occurs on basal planes, the rolling process will orient the basal planes such that they are parallel to the sheet surface. This is responsible for the strong basal textures observed in the material (figure 2a). At temperatures higher than 700 K, the occurrence of prismatic slip also becomes easy due to the very low critical resolved shear stress (Flynn *et al* 1961) and because of this the basal texture is weakened considerably (figure 2b). On the other hand, if the material is hot-rolled at a lower temperature (570 K) and subsequently annealed at a higher temperature (770 K), no such possibility of the occurrence of enhanced prismatic slip exists and hence the texture remains unaltered (figure 1).

The yield stress-grain size data presented in figure 3 are as expected (Armstrong 1968) for HCP metals with c/a ratio greater than or equal to the ideal value; both the constants σ_0 as well as k are temperature-dependent. The influence of strong basal texture on the grain boundary strengthening has been analysed recently (Sambasiva Rao and Prasad 1982) in terms of the basic deformation processes *viz.*, slip and twinning. It has been shown that strong basal texture results in enhanced σ_0 value and lowered k value in the Hall-Petch relation.

The data in figure 3 show that a large drop in the yield stress of the specimen rolled at 770 K and tested at 77 K lies much below the Hall-Petch line. This could have been caused by (i) lack of sufficient grain boundary constraint when the grain size is large (Armstrong 1961), and/or (ii) weaker basal texture in the specimen. In order to have the effect of the grain constraint felt on the yield stress, Armstrong (1961) showed that there should be at least 15-20 grains present in the cross-section of the specimen. Otherwise there is a tendency for the yield stress to drop below the value predicted by the Hall-Petch relation (1). In specimens rolled at 770 K, the above explanation cannot account for the deviation since there are at least 250 grains in the specimen cross-section. Further, the near disappearence of this drop at elevated test temperatures also cannot be explained. Thus, the weaker basal texture is the only reason for this drop in the yield stress. At higher test temperatures, the occurrence of prismatic slip assists the plastic deformation process and reduces the influence of basal texture.

5. Conclusions

(i) Hot rolling of magnesium at temperatures higher than 670 K causes abnormal increase in the grain size with an associated reduction in the basal texture. (ii) At 77 K the yield strength of magnesium hot rolled at temperatures higher than 670 K is lower than that predicted by the Hall-Petch relation, which is interpreted in terms of reduced basal texture. (iii) The dependence of yield stress on grain size in magnesium hot rolled at different rolling temperatures (lower than 670 K) matches with that observed in specimens rolled at a constant rolling temperature and annealed at different temperatures.

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