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Effect of texture and grain size on the mechanical properties of warm-worked cadmium, zinc and zinc-0·35% aluminium alloy

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Abstract. Changes in the grain size and crystallographic texture during warm working and their influence on the room temperature mechanical properties are investigated on Cd, Zn and a Zn-Al alloy. The yield strength increase in the early stages of working in extruded cadmium is accounted for based on the development of a basal texture while in rolled zinc and zinc alloy, the properties are affected more by the grain size. Cadmium exhibits ductile fracture at all extrusion ratios whereas the fracture mode in zinc and the alloy changes from cleavage at small rolling strains to ductile at higher deformation strains.

Keywords. Grain size; texture; warm working; yield stress; fracture.

1. Introduction

It is now generally recognized that mechanical processing of materials in the warm working temperature range (0·4–0·6 T_m, where T_m is the absolute temperature of melting) results in improved mechanical strength without much loss of ductility (Yegneswaran *et al* 1978). This can be attributed to one or more of the following, namely, grain refinement, development of a stable substructure and development of crystallographic texture. In view of the limited number of available slip systems, strong textures often develop in c.p.h. metals and alloys during deformation processing. Textured materials exhibit anisotropy and both texture strengthening and texture weakening are possible depending on the type of texture present which in turn is determined by the details of processing (Hsu *et al* 1977).

The aim of the present investigation is to study the structural changes that occur during warm working of cadmium, zinc and zinc-0·35% aluminium and their influence on the resulting mechanical properties. These materials are selected since they can easily be worked at room temperature which is in the warm-working range. The Zn-Al alloy is chosen because aluminium refines the grain size and in addition could lower the stacking fault energy of zinc which influences the development of textures. The deformation process selected is extrusion for cadmium and rolling for zinc and the zinc alloy.

2. Experimental

Cadmium metal of 99·95% purity was melted and cast into billets. They were extruded at room temperature in a 250 ton vertical hydraulic press. Five extrusion ratios in the range 6–130 were employed.

Analar grade zinc (99·95 %) was used in the present work and high purity aluminium (99·98 %) was used to prepare the zinc-0·35 % aluminium alloy. The as-cast slabs of the metal and the alloy were hot-forged at 573 K and subsequently flat-rolled to 4 mm thickness. The material was then annealed. With the annealed strip as the starting material, different amounts of reduction were given by rolling at room temperature. The deformation produced by sheet rolling is represented as the true thickness strain because no significant lateral spread was observed.

Tensile tests were carried out at room temperature on rod samples of extruded cadmium and rolled sheets of zinc and Zn-Al alloy. Tukon microhardness measurements were done on the transverse section of the extruded samples. On the rolled sheets, measurements were done on the rolling plane. The grain size in the various samples was determined by standard metallographic techniques. The fracture surfaces of the tested specimens were observed in a scanning electron microscope (Cambridge Stereoscan 150).

The crystallographic texture developed during processing was examined by measuring the x-ray line integrated intensities from planes parallel to the exposed surface (rolling plane in the case of sheets, longitudinal as well as transverse sections in the case of rods). Philips x-ray diffractometer with Cu K-α radiation was used for this purpose. For comparison, random samples were prepared from well-annealed powders of cadmium and zinc and the line intensities were recorded under identical conditions.

3. Results and discussion

The extruded structure in cadmium showed completely recrystallized equiaxed grains at all strains. Little or no twinning was observed at any strain. Figure 1 shows the variation of the average grain diameter measured on the transverse section with true strain. The grain size shows a continuous increase with deformation—from 14 μm at a thickness strain of $\varepsilon = 1{\cdot}83$ to about 40 μm at $\varepsilon = 4{\cdot}15$. This may be attributed to the lower recrystallization temperatures at higher deformations and also to more heat generated during extrusion.

The variation of the yield stress (0·2 % strain offset flow stress) and the UTS at room temperature of the warm extruded cadmium with extrusion strain is recorded in figure 2. Both the quantities increase with true strain, reach a peak value and decrease thereafter with further deformation. The peak strength is reached at an ε value of about 2·25.

It is obvious that the yield strength variation with extrusion strain cannot be accounted for on the basis of grain size variation. Whereas the grain size continuously increased with strain, the yield stress exhibited a peak. Therefore, a Hall-Petch type grain boundary strengthening relationship is not obeyed in extruded cadmium. The yield stress-extrusion strain relationship in cadmium can however be understood in terms of the strong basal texture developed during extrusion. Figure 3 is a plot of the x-ray line intensity ratio $I_{0002}/I_{10\bar{1}1}$ with the transverse section exposed to the x-ray beam. It also shows the intensity of the $(10\bar{1}1)$ reflection in the extruded rod normalized with respect to the random sample. Both variations are a pointer to the development of a strong [0001] fibre axis at a true extrusion ratio of about 2·25. At large deformations, the ratio (I/I_0) $(10\bar{1}1)$ reaches unity indicating random texture. Since the basal planes are perpendicular to the extrusion direction, the texture is unfavourable for slip and

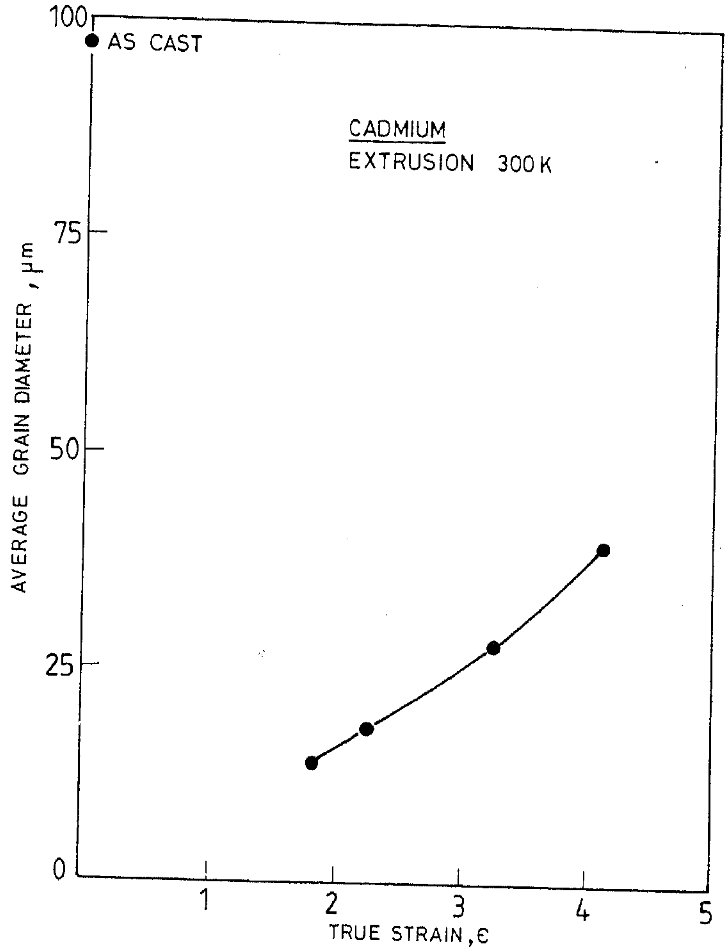

Figure 1. Variation of average grain diameter with true strain.

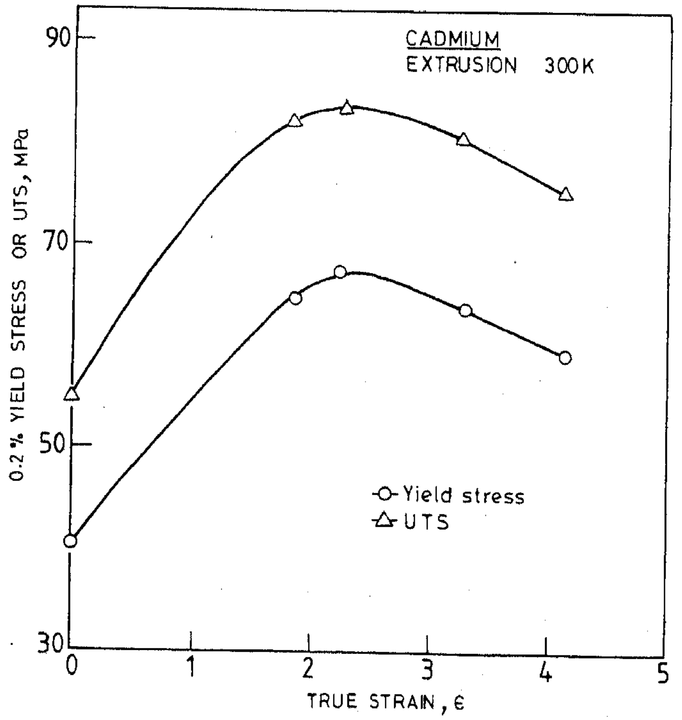

Figure 2. Variation of yield strength and UTS at 300 K with true strain.

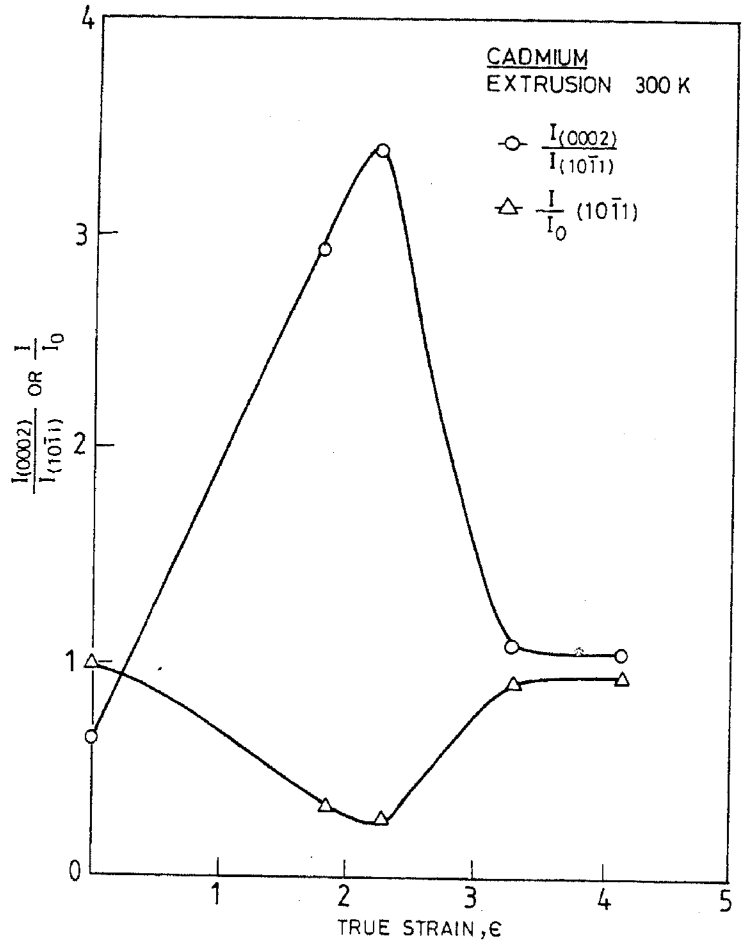

Figure 3. Variation of $(I_{(0002)}/I_{(10\bar{1}1)})$ or (I/I_0) $(10\bar{1}1)$ with true strain.

texture hardening is observed upto $\varepsilon = 2{\cdot}25$. The decrease in yield strength beyond this strain can be associated with a corresponding decrease in the intensity of basal texture as well as an increase in grain size. Similar texture hardening has been reported on cadmium and zinc by Bly *et al* (1973).

The variation of grain size with true thickness strain in rolled zinc and zinc alloy is shown in figure 4. The measurements were made in the rolling plane. In the early stages of deformation, extensive mechanical twinning has occurred and at large deformations, twins have decreased and the grain size becomes very small. The grain size has been measured without including twin boundaries. In both materials, the grain size continuously decreased with increasing strain. The normalized x-ray line intensity from (0002) planes and the ratio of intensities from (0002) and $(10\bar{1}1)$ planes in the sheet are plotted against true thickness strain in figure 5. Zinc shows a basal texture i.e., (0001) parallel to the rolling plane, in the initial stages of deformation. However, the texture is weak and above about $\varepsilon = 0{\cdot}3$, the intensities are close to that of a random sample. The alloy also has no significant texture especially in the initial stages of deformation.

The variation in the yield stress (0·2% strain offset flow stress) of warm rolled zinc and Zn-Al alloy at 300 K with rolling strain is shown in figure 6. In both materials, the yield stress is slightly higher in the transverse direction than in the longitudinal

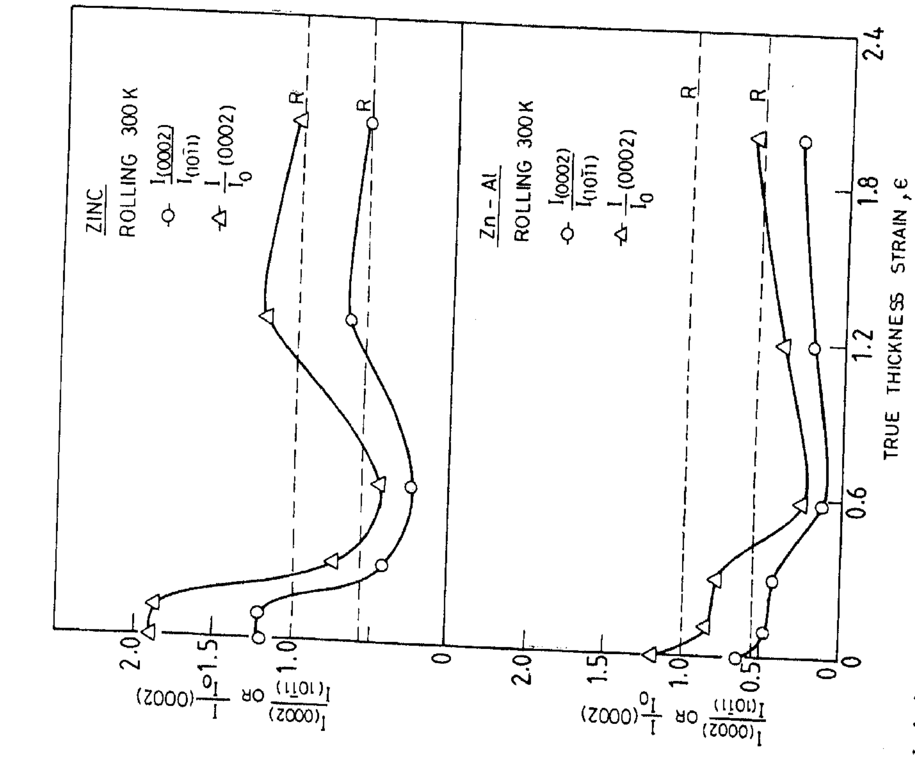

Figure 5. Variation of $(I_{(0002)}/I_{(10\bar{1}1)})$ or (I/I_0) (0002) with true thickness strain.

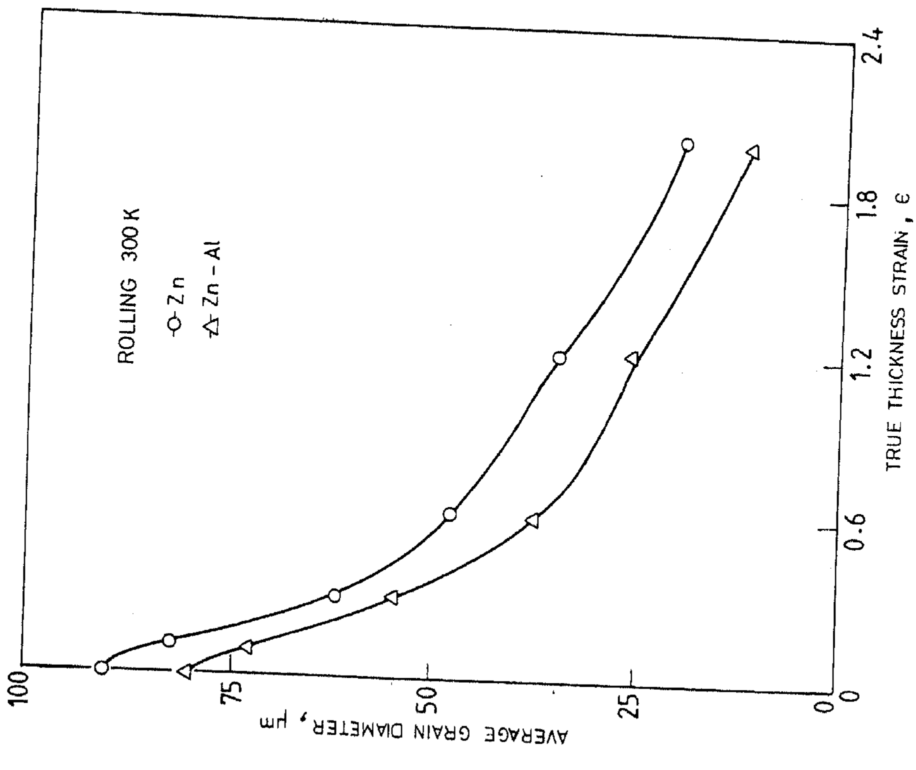

Figure 4. Variation of average grain diameter with true thickness strain.

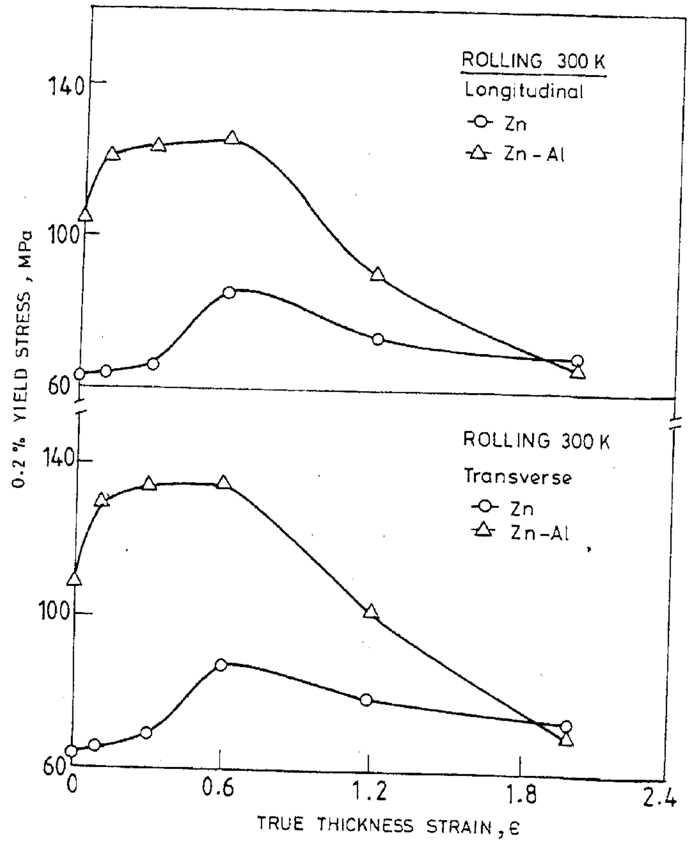

Figure 6. Variation of yield stress with true thickness strain.

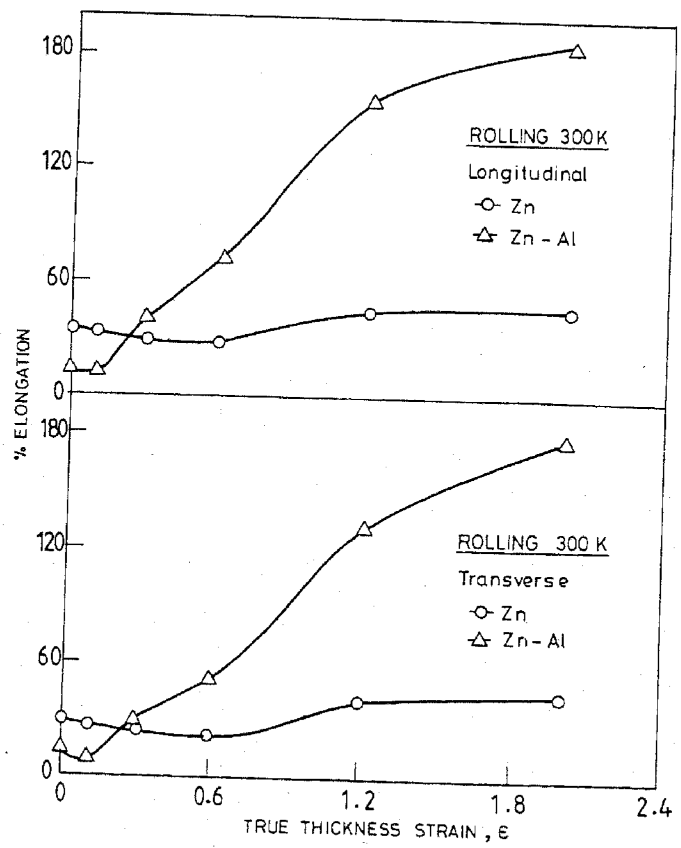

Figure 7. Variation of % elongation with true thickness strain.

direction. In either direction, the yield stress increases with true thickness strain initially and then decreases beyond a certain strain. UTS also shows a similar behaviour. The tensile elongation to fracture is shown in figure 7. In general, whenever there is an increase in yield stress, a decrease in elongation is recorded. Transverse samples show slightly lower elongations at all strains. At large thickness strains, the alloy exhibits high elongation to fracture. The fracture mode in Zn and Zn-Al varies with true thickness strains (figure 8). In the initial stages of deformation, the material exhibits cleavage fracture. With increasing strain, the fracture shows a mixed mode i.e., cleavage and ductile, while at higher deformations only ductile fracture is observed. By contrast, cadmium shows ductile fracture at all strains.

The present data on zinc show an increase in yield strength with deformation without much loss in ductility. This is in conformity with the observation made on different materials in earlier studies (Young and Sherby 1973; Naziri and Pearce 1969). However, in the present work, the yield stress decreased at higher strains and the elongation increased. Since a significant texture is not observed, the grain size effect on the mechanical properties is stronger in both zinc and the alloy. In figure 9, the yield strengths measured on warm-rolled Zn and Zn-Al are tested for the validity of the Hall-Petch equation $\sigma = \sigma_0 + K \cdot d^{-1/2}$ where σ is the yield strength, d is the grain diameter and σ_0 and K are constants. The relationship is found to hold only above a certain grain size. The decrease in flow stress and increase in elongation below the critical grain size

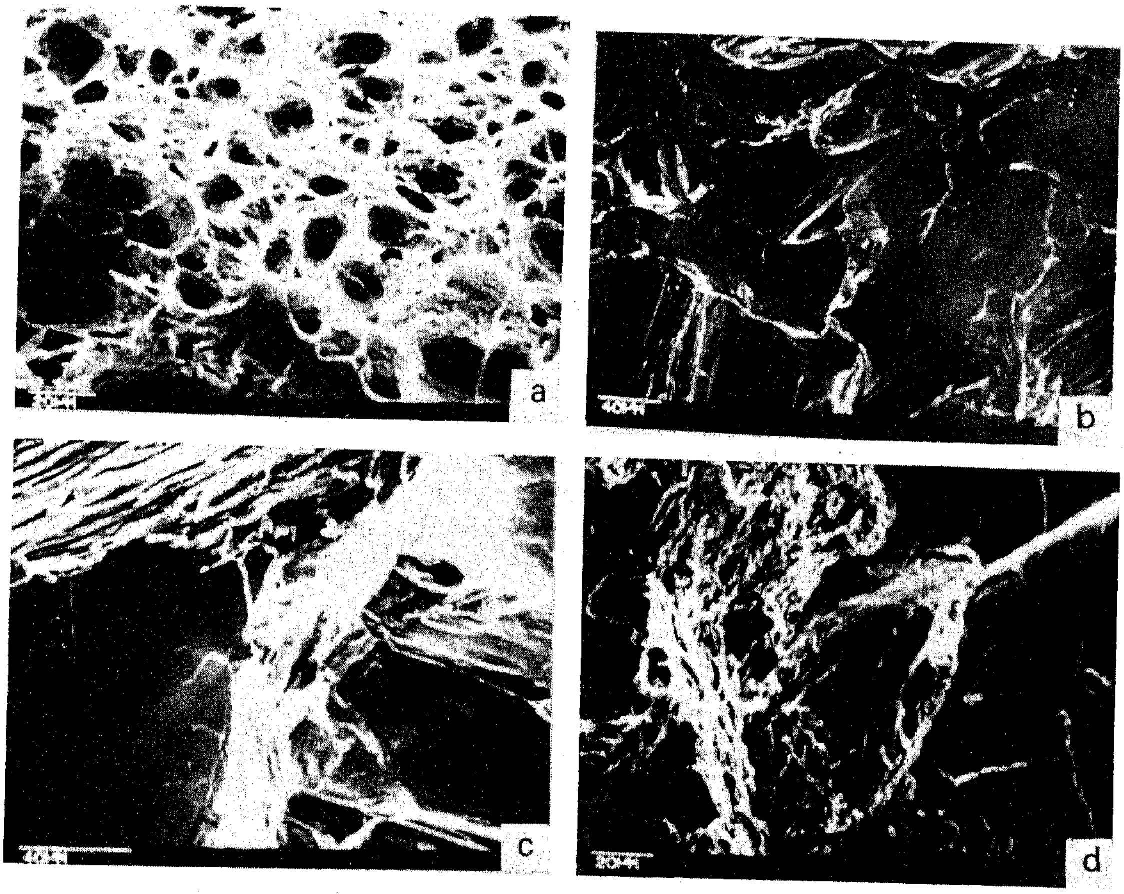

Figure 8. Scanning electron micrographs of fracture surfaces (**a**) Cd, $\varepsilon = 1{\cdot}83$ (ductile). (**b**) Zn-Al, $\varepsilon = 0$ (cleavage). (**c**) Zn-Al, $\varepsilon = 0{\cdot}1$ (mixed mode). (**d**) Zn-Al, $\varepsilon = 0{\cdot}3$ (mixed mode).

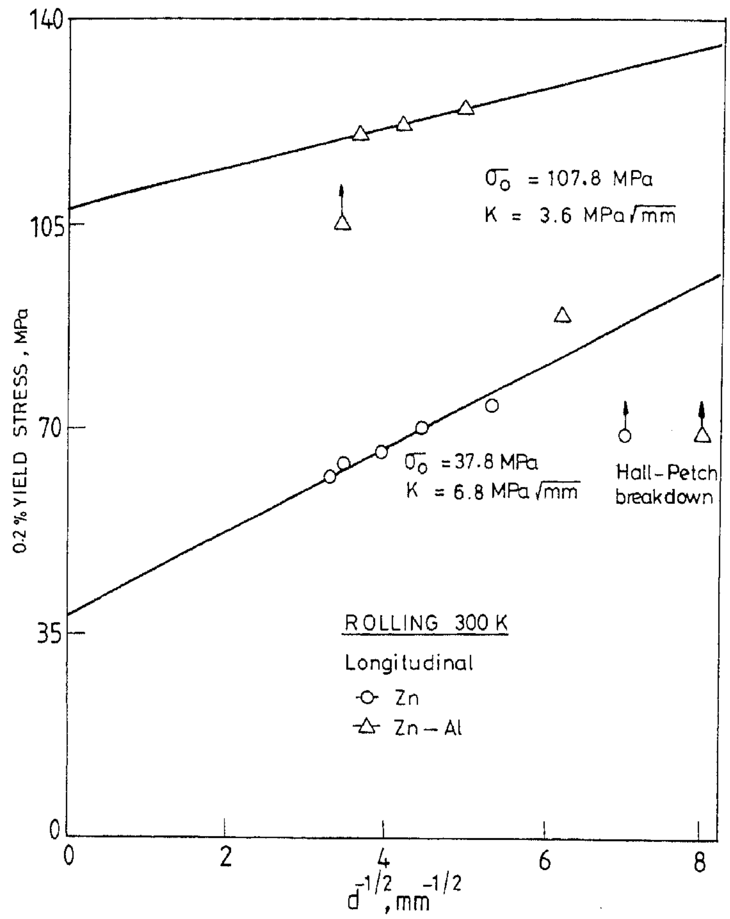

Figure 9. Yield strength-grain size relation.

must involve a change in dominant deformation mechanism and has been attributed in the literature to the onset of superplasticity (Ecob and Ralph 1983). The very small grain sizes produced at larger thickness strains are indeed conducive for superplastic behaviour. In fact, Zn-Al has shown a steep increase in elongation to fracture at higher warm working strains (figure 7). Similar behaviour has been noticed by Ecob and Ralph (1983) in a Zn-0·1 Al-0·05 Mg alloy. The scatter in the experimental results and the small range of grain size make the determination of the Hall-Petch constants difficult. However, the values estimated for zinc, $\sigma_0 = 37{\cdot}8$ MPa and $K = 6{\cdot}8$ MPa $\sqrt{\text{mm}}$, are in good agreement with those from an earlier work on zinc (Prasad *et al* 1974).

4. Conclusions

(i) Warm extrusion enhances the strength of cadmium with no significant loss in ductility. The increase in strength is due to strong unfavourable basal texture i.e., the fibre axis is [0001].

(ii) In zinc and Zn-0·35 Al alloy, the grain size decreased continuously with increase in true thickness strain in rolling. The grain size in the alloy is smaller than in the metal at all strains.

(iii) Only a weak texture is observed in zinc and Zn-Al and the grain size has a greater effect on the mechanical properties of these materials. The Hall-Petch equation is obeyed above a certain grain size. At finer grain sizes near-superplastic behaviour is observed.

(iv) Cadmium failed in a ductile manner at all extrusion strains. In zinc and zinc alloy, there is a continuous change in fracture mode with thickness strain. The materials failed by cleavage at small deformations, by mixed mode at intermediate deformations and by completely ductile mode at higher strains.

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