The metallography and deformation of the aligned Cd–Zn eutectic

Part 2 *Tension*

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The tensile deformation of the aligned Cd–Zn eutectic alloy has been investigated with particular attention paid to the influence of interlamellar spacing (λ). These tests were supplemented by optical and transmission electron metallography. At plastic strains of 10^{-6} the stress was independent of λ, at 10^{-5} the stress increased with decreasing λ and by 10^{-4} twinning had become the dominant deformation mode. Twinning stress was found to increase with decreasing cell or grain size, rather than being a function of λ. Electron microscopy demonstrated that individual twins were continuous through many lamellae of each phase. Differences between tension and compression tests are examined and possible reasons based on dislocation mechanics are discussed.

1. Introduction

Sahoo *et al.* [1] examined both tensile and compressive deformation of the Cd–Zn eutectic and observed that the deformation was controlled by slip in compression while twinning was dominant in tension. Using graphical techniques they concluded that in both cases the dependence of the 0.2% flow stress (σ) on growth rate could be expressed by the relationship:

$$\sigma = \sigma_0 + kR^n \tag{1}$$

where R is the solidification rate and σ_0, k, and n are empirically determined material parameters. The exponent n was found to have values of 0.25 and 0.20 for compression and tension, respectively. From this it was concluded that, within experimental scatter, the relationship between stress and λ followed a Hall–Petch type of equation, i.e. $\sigma \propto \lambda^{-0.5}$.

The $Mg–Mg_2Ni$ eutectic system has been observed to behave in a similar fashion to the Cd–Zn alloy [2]. In the compression tests the Mg-rich phase deformed by slip, while in the majority of tensile tests, deformation was twin-controlled. An added complexity in this material was that it solidified with one of two different crystallographic orientation relationships, one of which was not favourable for twinning. A model was developed which produced an equation of the form of Equation 1 with an exponent of 0.5 and this fitted well to the experimental data. On the other hand it was found that twin-controlled deformation could best be described with an exponent of 0.3. Thus, while there are strong qualitative similarities between the alloys, there is little agreement as to a functional dependence on λ. This apparent lack of consistency in determining an exponent may be due to the difficulty of accurately determining the parameters of Equation 1 when there are relatively large random deviations in the dependent variable, σ. Davidson [3] has applied nonlinear regression analysis to the results presented by Sahoo *et al.* [1] and obtained exponents of 0.44 ± 0.24 for compression and 0.27 ± 0.12 for tension. The 95% confidence limits given show that the exponent cannot be found with a great degree of precision. The other parameters show similar uncertainties. When the results for cellular specimens were omitted from the calculations then the exponent for the remaining compression samples rose to 0.7 ± 0.2. It is clear from this that the presentation

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of results in this quantitative form is not sufficiently sensitive to permit unambiguous comparison between materials or to allow acceptance of a Hall–Petch relationship as appropriate.

Twinning in other aligned eutectic alloys has been noted for Zn–Al [4], and for the Ni_3Nb phase in Ni or Ni/Al based alloys [5–8]. However in none of these was there investigation of twinning stress dependence on λ. An interesting feature of the twinning in the different systems is the widely varying role that lamellar structure can play in twin propagation. Twins in the Mg-rich phase are stopped by the interface with the non-deformable Mg_2Ni phase. Those in a lamella of Ni_3Nb may cause intensive slip in the adjacent phase to nucleate a twin in the next Ni_3Nb lamella, but the twin width is much less than the dimension of λ. A similar situation arises in Al–Zn except that the twin in the Zn-rich phase can grow much wider than the lamellar width and gives the impression at low magnifications of extending continuously across many lamellae. The Cd–Zn eutectic system differs from the others in being the only one in which both phases twin with parallel crystallography and similar twinning shears. However it remains a matter of conjecture whether the twinning dislocations travel through the interphase boundaries (accommodating the differences in Burger's vector and twinning shear with interface dislocations) or whether repeated nucleation in successive lamellae is required as in the other systems.

In a companion publication to this [9] the influence of λ on the compressive deformation of the Cd–Zn eutectic alloy was examined. It was concluded that pyramidal slip was only significant at the earliest detected stage of plastic flow and that basal slip predominated at plastic strain of 10^{-5} and greater. By conducting a similar series of tensile tests on this alloy it is possible to compare deformation characteristics during plastic flow prior to twinning and hence build up a picture of the influence of λ on the micro-mechanics of eutectic deformation.

2. Experimental details

Samples of the Cd–Zn eutectic for tensile testing were taken from the same directionally solidified ingots that provided the specimens for compressive testing [9]. Rods 30 mm long were sectioned longitudinally with a low-speed diamond saw. Each piece was then ground and polished to provide a flat bar, 2.3 mm thick, from which specimens similar to those described by Davidson *et al.* [10] were produced by spark machining at the lowest possible discharge energy. Finally they were electropolished, removing a layer at least 5 times the depth to which deformation artifacts could be observed under the optical microscope.

High sensitivity strain measurements were carried out during tensile testing by means of two etched foil resistance gauges attached to each sample. When quenched specimens were tested the strain gauges were not used since this would have increased the delay between quenching and testing to an unacceptable value.

Heat treatment and metallographic preparation were described in part 1 of this publication [9] and specimen nomenclature follows the same system as was used there.

3. Results

3.1. Mechanical testing

Typical stress–strain curves are shown in Fig. 1. Twinning occurred at all growth rates with very little prior plastic deformation (10^{-4} or less) and was evidenced by abrupt load decrements accompanied by audible clicking from the sample. In most cases the load drops were initially sporadic and very small with a significant increase in load between each twinning event. Major twinning began with continual twinning giving large load decrements at a constant or slowly increasing average stress.

Generally the tensile deformation curves showed an increase in the stress level with decreasing interlamellar spacing although this dependence did not extend to the three most rapidly grown alloys. The alloys with larger interlamellar spacings also exhibited much smaller stress drops during twinning.

The behaviour of the material beyond the limits of the strain gauges can be seen in Fig. 2 which contains nominal stress – crosshead displacement curves. Several points can be seen:

1. The frequency of twinning decreased as specimen strain increased, the effect being more pronounced in specimens with smaller λ; this observation is similar to the results of Sahoo *et al.* [1].

2. The rate of increase of average stress with strain, i.e. the nominal strain-hardening rate, was higher for specimens with smaller λ; and

3. The stress drops were smaller and much more prolific in the more coarsely spaced alloys.

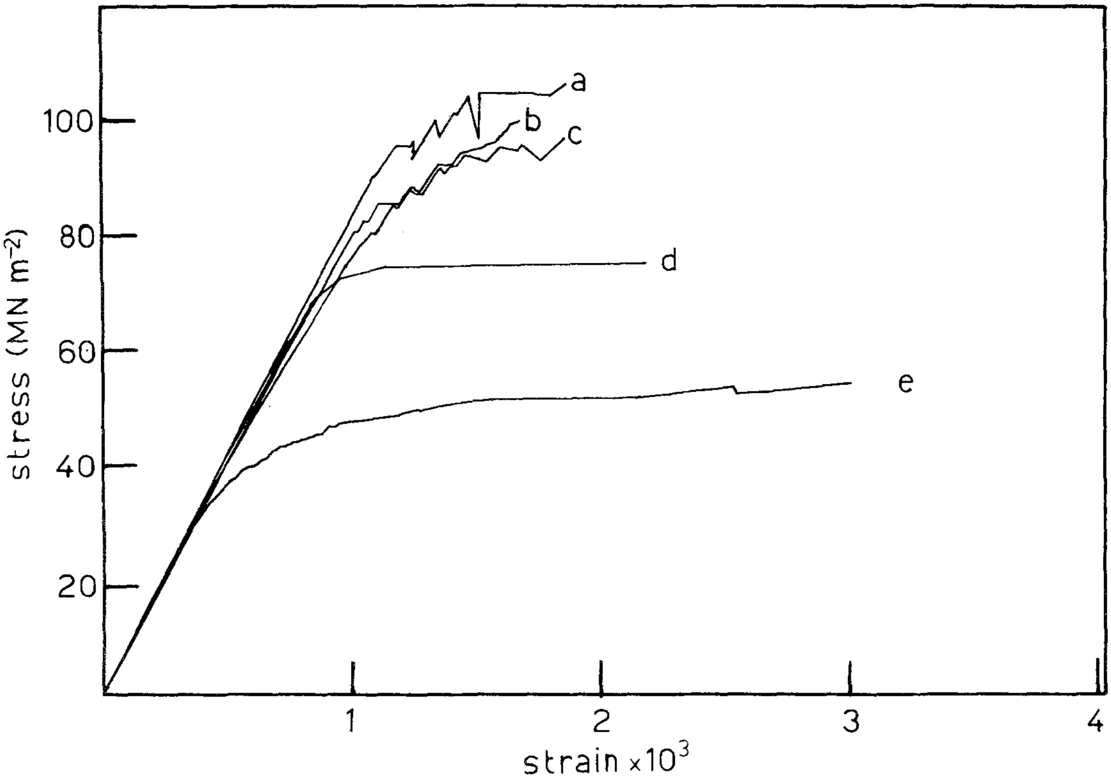

Figure 1 Typical tensile stress–strain curves for the Cd–Zn eutectic alloy obtained with strain gauges. Details of specimen growth rate are given in Table I. Curve a, specimen D3; curve b, specimen F1; curve c, specimen C1; curve d, specimen B2; curve e, specimen A3.

Full results derived from the mechanical testing are given in Table I. Those specimens without flow stress and modulus data were tested without strain gauges. Flow stresses at plastic strains of 10^{-3} and 10^{-4} were included, although the values were not considered to be very reliable. There were two reasons for this:

1. after the first twin occurred it was not possible to separate the components of offset strains due to continuous plastic flow from those due to twinning; and
2. the strain registered during a twinning event was strongly dependent on whether the twin occurred within the gauged section or not.

There are two choices for defining the twinning stress. One is to take the stress at which continual twinning began while the other is to use the stress at the first significant twinning event. The first procedure was selected since the second was rather more subjective and the values obtained would have been more readily influenced by structural imperfections.

Fig. 3 shows plots of stress against $\lambda^{-0.5}$ for yield stress, flow stress at 10^{-5} plastic strain and twinning stress. There are no clear functional relationships exhibited in the data. The yield stress is essentially independent of λ, the 10^{-5} flow stress increases with decreasing λ although there is too much scatter to reveal a more specific functional dependence, and the twinning stress increases with decreasing λ until, with spacings of $1.5\,\mu$m and less, it becomes independent of λ. Also included in the figure is the twinning stress for two specimens which were solution treated and water quenched. The quenched specimens showed a strength increase of around 40% over the untreated ones. Both quenched specimens exhibited less than 10 major load drops due to twinning before assuming a relatively smooth stress–strain curve.

3.2. Metallography

The optical microstructure of eutectic Cd–Zn alloys deformed in tension was similar to those reported previously [1]. Throughout the range of interlamellar spacings there was a close correspondence of twins on either side of a cell of grain boundary. In the case of the more finely spaced

TABLE I Results of tension tests on Cd–Zn eutectic alloys

Specimen	Growth rate (μm sec^{-1})	λ(μm)	E (GN m^{-2})	Stress (MN m^{-2})					Twinning		Remarks
				yield	10^{-5}	10^{-4}	10^{-3}	UTS	σ*	$\epsilon_{\mathrm{pl}}^{\dagger}$($\times 10^{-3}$)	
A1	0.5	5.1	81.8	14	28.5	36.3	47.9	50	39	0.3	
A2			–	–	–	–	–	67	43	–	
A3			91.5	6	21.4	37.7	51.9	> 59	42	1.5	Slight banding
B1	2.0	2.7	–	–	–	–	–	> 67	59	–	
B2			87.7	15	43.9	72.3	75.5	79	71	2.9	
B3			–	–	–	–	–	78	73	–	
B4			88.7	11	31.7	56.3	–	> 74	67	10.6	
C1	12	1.5	83.4	24	42.7	79.3	–	> 98	64	2.8	
C2			85.4	12	46.5	85.5	94.7	> 118	92	4.5	
C3			–	–	–	–	–	122	101	–	
C4			88.2	7.3	18.7	57.6	99.2	> 112	94	11.4	
C5			–	–	–	–	–	160	140	–	Quenched
D1	30	0.72	85.6	15.4	50.8	92.8	94.9	> 110	100	3.2	
D2			–	–	–	–	–	135	99	–	
D3			87.2	9	36.5	95.7	–	> 119	96	5	
E1	120	0.4	–	–	–	–	–	149	95	–	
E2			84	15	26.9	48.6	88.4	> 107	95	10.6	
E3			87.6	21	48.8	93	104	> 132	102	3.7	
F1	300	0.35	83.9	15	46.6	85.8	–	> 98	92	2.6	
F2			–	–	–	–	–	148	102	–	
F3			87	12	74.2	82.6	90.9	> 117	84	0.35	
F4			–	–	–	–	–	> 150	137	–	Quenched

*Stress at onset of continuous twinning.
†Plastic strain at first detected twinning event.

alloys the orientation changes across cells were so small that in some cases the twins appear continuous through successive cells. On the other hand when there were grain boundaries with large misorientations the high stresses at the tip of the twin were responsible for nucleating a different twinning system in the adjacent grain in a region close to the tip.

When tensile samples were examined after several per cent deformation it was seen that the twinned region extended up the shoulder towards the grips and the gauge section itself had almost totally converted to a twinned orientation.

Plastic deformation during a tensile test began in the finer alloys when a particular region began to spheroidize (Fig. 4), leading to increased deformation in that particular area. In the more coarsely spaced alloys spheroidization during deformation was not observed.

Fig. 5 shows a transmission electron micrograph of twins in a longitudinal section of eutectic alloy solidified at 120 μm sec^{-1} and subsequently deformed. Twins are seen to be continuous through adjacent lamellae of each phase and electron diffraction confirmed that both phases of the eutectic twinned by the usual $\{10\bar{1}2\}\langle 10\bar{1}1\rangle$ mode.

4. Discussion

4.1. Elastic modulus

The measured values of Young's modulus are independent of λ with a mean of 86.4 GN m^{-2} and 95% confidence limits at ± 5 GN m^{-2}. This is greater than either the result of Sahoo *et al.* [1] of 79 GN m^{-2} or the value of 54 GN m^{-2} obtained using an ultrasonic resonance method [1]. The cause of these differences is not known. From compliance values of cadmium and zinc [12] and from the theoretical volume fraction of 20% Zn, the ROM (Rule of Mixtures) calculation of composite modulus in $\langle 11\bar{2}0\rangle$ is 90 GN m^{-2}. Rotation of the compliance tensor of each phase to a tensile axis 5 degrees from parallel to (0 0 0 1) shows that the Young's modulus of cadmium will decrease by 0.6% while that of zinc will increase by the same amount. Thus any small deviation from the idealized orientation is unlikely to account for the difference between the predicted and measured moduli. Sahoo *et al.* [1] concluded that their

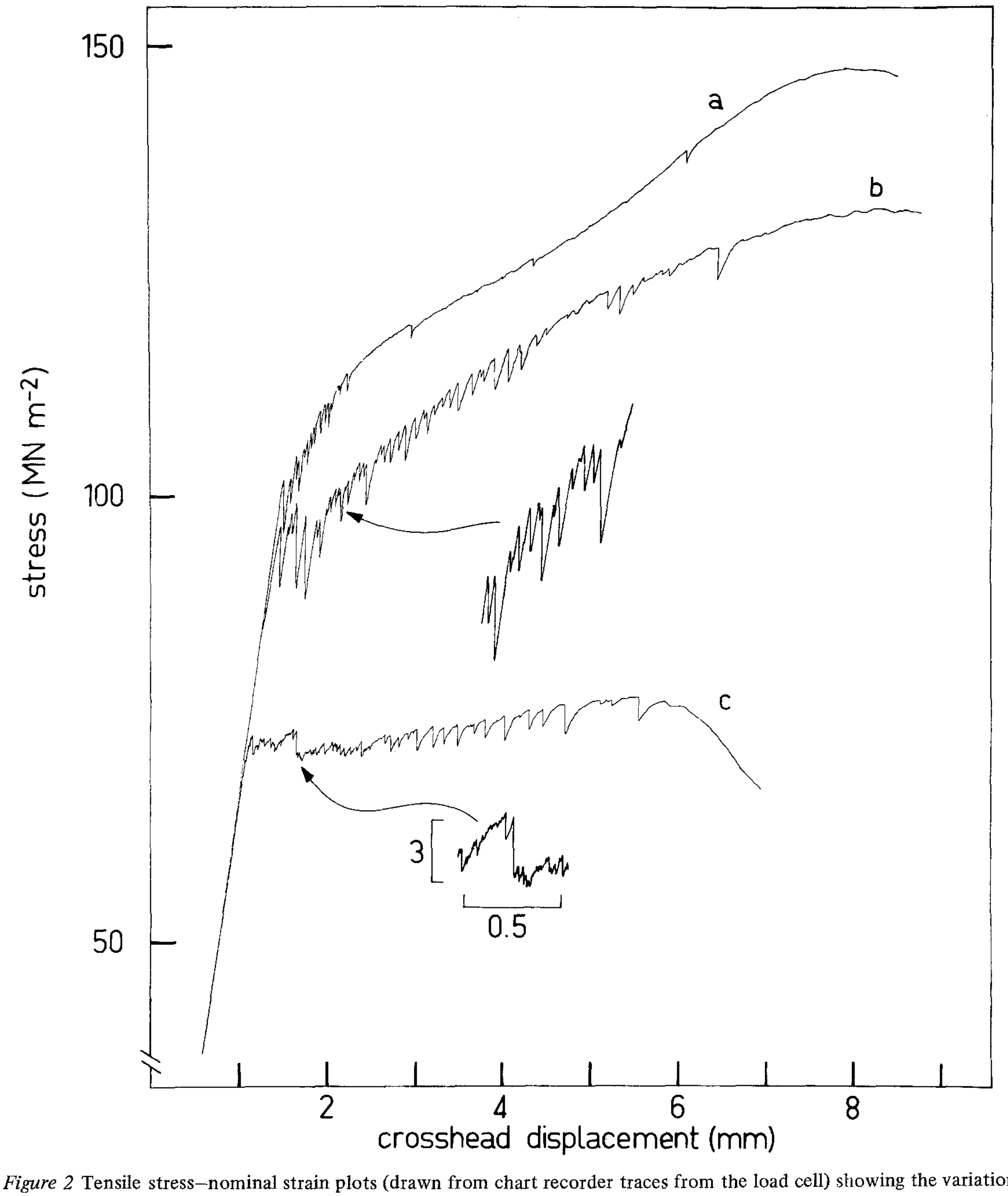

Figure 2 Tensile stress–nominal strain plots (drawn from chart recorder traces from the load cell) showing the variation of twinning behaviour with λ. Both insets are to the same scale. Gauge length was 12.5 mm. Curve a, specimen F2; curve b, specimen D2; curve c, specimen B3).

average composite modulus was lower than their calculated theoretical value because the Zn-rich phase contained a high enough density of crystal defects to lower its modulus by 30%. This is not supported by the present observations in electron microscopy.

4.2. Deformation behaviour

The twinning stress does not increase monotonically with decreasing λ but is relatively constant for the three most finely spaced alloys. Optical microscopy has shown that the grain/cell boundaries generally provide the major barriers to twin growth. Therefore the observed variation of twinning stress with solidification rate could be explained by the reasoning that twin growth was relatively easy, while the adjacent phase was crystallographically parallel but was hindered by a

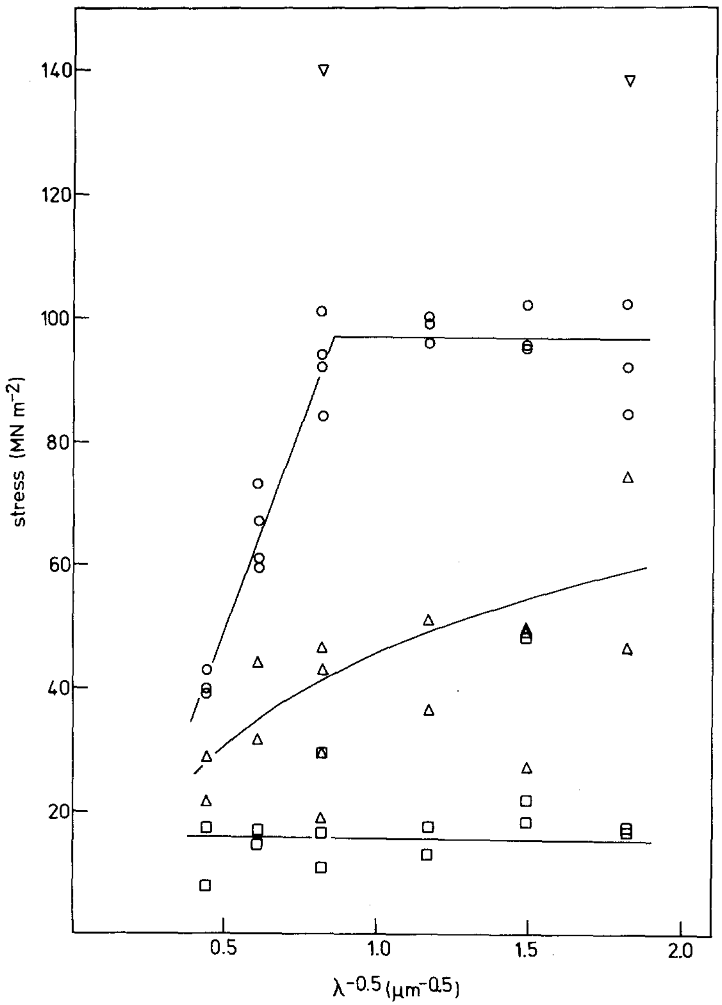

Figure 3 Plot of stress against $\lambda^{-0.5}$ showing the variation in the influence that λ may have over the tensile stress parameters. □ yield; △ 10^{-5}; ○ twinning; ▽ twinning (quenched alloys).

change in crystallographic orientation such as at a grain boundary or possibly a cell boundary. With a decrease in cell or grain size each twin would be smaller, and therefore, the stress at the twin tip would also be expected to be smaller. Thus material with a smaller cell or grain size would require a higher applied stress to force twinning in the adjacent cell or grain. Fig. 6 shows the twinning stress plotted as a function of the average cell size for each specimen solidification rate. Grain size was used only for non-cellular alloys. It is evident from Fig. 6 that there is strong support for the cell/grain size being the controlling factor in deformation by twinning. It is not possible to determine the relative contribution of high and low angle boundaries without a much more detailed analysis.

Work such as that by Bell and Cahn [13, 14] on twinning of high purity, single crystal zinc has shown the tensile twinning stress to be strongly dependent on the presence of suitable twin nuclei. By careful experimental technique aimed at eliminating twin nuclei they were able to achieve twinning stresses as high as $100\,\mathrm{MN\,m^{-2}}$ with substantial plastic flow preceding twinning. Similar twinning stresses were observed for the eutectic alloy. However, there was very little plastic flow prior to twinning (less than 10^{-4}). The low plastic strain suggests that twin nuclei may have been already present in the eutectic alloy specimens before testing, possibly having been introduced during spark machining. The similarity of twinning stress levels was most likely coincidental because the phases of the eutectic alloy would have had some degree of mutual solid solubility and the small difference in the c/a ratio (and hence differing twinning shears) would have given rise to some constraint.

Bell and Cahn suggested that a pile-up of pyramidal dislocations produced the local stress

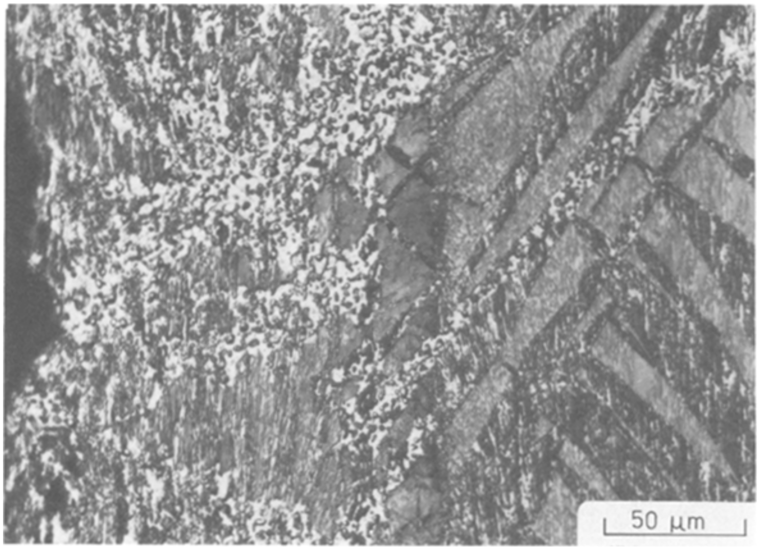

Figure 4 Optical micrograph showing severe deformation-induced coarsening in the neck region of specimen F2; longitudinal section, tensile axis vertical.

for twin nucleation. This could conceivably have occurred at very low strains at the interphase boundaries of the eutectic, however, it would have led to the dependence of twinning stress on interlamellar spacing. The observed insensitivity of twinning stress to λ at finer spacings, as well as the independence of yield stress from λ at all spacings imply that pile-ups against the interphase boundaries are not important. On the other hand the 10^{-5} flow stress increases with decreasing λ, indicating the possibility of significant pyramidal slip. At such low strains the detection of plastic flow is highly dependent on the testing technique employed and, as expected from the greater strain sensitivity of the tensile tests, the absolute values of yield stress are lower for tensile specimens than for those tested in compression [9]. In fact yield is only detected in compression at stresses similar to the twinning stresses in tension.

In order to explain the variation of compressive yield stress with λ it was suggested [9] that intersecting pyramidal slip may be important in the microstrain region. If this is to remain compatible with the tensile deformation results then there must be a deformation process occurring which is either peculiar to the tensile mode or so limited in extent that it is not detected by the slightly less sensitive compression tests. An instance

Figure 5 Transmission electron micrograph showing twin boundaries extending through both the cadmium and the Zn-rich phases; longitudinal section.

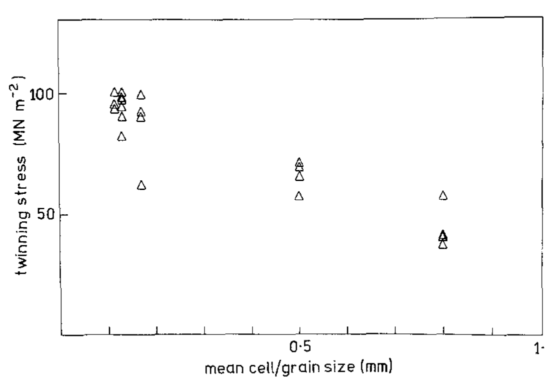

Figure 6 Plot illustrating the dependence of twinning stress on cell/grain size (measured as the mean linear intercept).

of the former could be deformation of existing twin nuceli, while the latter could perhaps be operation and exhaustion of basal sources operating at low stress. The evidence discussed above supports the probability of twin nuclei existing but there is no clear indication of how they would be expected to behave at low stress.

Thermally induced residual stresses can often account for differences between compression and tension tests of aligned composite materials. However, for the Cd–Zn eutectic, they are thought to play only a minor part in controlling deformation, since they would have been largely dissipated through recovery occurring while the samples were at room temperature.

There is no clear evidence on the question of whether twin growth across lamellae occurred mainly by transmission of twinning dislocations through the phase boundaries or else by repeated nucleation in adjacent lamellae. Close examination of the twin boundaries by optical microscopy (in the case of samples with larger λ) or by electron microscopy (for smaller λ) showed that the twin boundaries were often not collinear from one lamella to the next of the same phase. If this represents the state during deformation then it indicates that repeated nucleation is the likely mechanism. However the possibility of boundary relaxation after unloading cannot be ignored and a form conclusion cannot be drawn at this stage.

5. Conclusions

The average static Young's modulus value was $86 \pm 5\,\mathrm{GN\,m^{-2}}$ which agrees well with the value of $90\,\mathrm{GN\,m^{-2}}$ obtained from a ROM calculation using dynamic modulus data for single crystal cadmium and zinc.

After plastic strains of less than 10^{-4}, tensile deformation proceeds by twinning and there is generally almost complete transformation of the gauge section to the twin orientation. Individual twins extend across many lamellae and both the cadmium and the Zn-rich phases undergo the same twin reaction.

Initial plastic deformation can be explained either by expansion of existing twin nuclei or by basal glide at a stress which is independent of λ.

In all except the coarsest eutectic alloys each load decrement registered in tension correspond to a burst of twinning activity rather than growth of a single twin only.

The difficulty of propagating twins across grain and cell boundaries resulted in dependence of twinning stress on grain/cell size. The interlamellar spacing did not seem to be a determining factor.

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