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Deformation and fracture in directionally solidified Co–CoAl eutectic

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The effect of growth defects known as lamellar terminations on the yielding and fracture behaviour of Co–CoAl eutectic single crystals was studied using tensile tests and finite-element modelling. The yield strength and strain to fracture were found to decrease with increasing termination density. Observations of deformed surfaces and serial sectioning experiments on fractured tensile specimens revealed that crack initiation during the fracture process was enhanced by the presence of lamellar terminations. The fracture surfaces were found to have a staircase-type appearance, which indicated that the final fracture process was discontinuous with a step-wise propagation from one CoAl lamella to adjacent CoAl lamellae. A computer simulation was conducted to determine the stress distributions about lamellar terminations in model microstructures, since the experimental results suggested that the lamellar terminations behaved as stress concentrations in the microstructure. The finite-element calculation confirmed that lamellar terminations can influence the yielding process; the stress at which the first slip system was activated was found to decrease with increasing termination density.

1. Introduction

An understanding of the deformation and fracture behaviour of composites as a function of any defects that may exist in their microstructures is necessary to optimize their usefulness as structural materials. Recently, Wall *et al.* [1] demonstrated that the compressive yield strength of a Co–CoAl eutectic alloy decreased as the number of growth defects known as lamellar terminations increased in the microstructure of this *in situ* composite. From single-surface slip trace observations, Wall *et al.* argued that the lamellar terminations acted as stress concentrations in the microstructure because enhanced slip was found to take place in the vicinity of the terminations. The ability for slip to spread throughout the specimen was facilitated, therefore, as the termination density increased with a resultant decrease in the yield strength.

In the present paper, the earlier study of Wall *et al.* [1] has been extended by examining the effect of lamellar terminations on the yielding and fracture behaviour of single-crystal Co–CoAl eutectic tested in tension. This work was initiated because it is impossible to grow eutectic structures (with one exception) without the presence of these growth defects [2]. This type of defect may also form in the processing of layered composites. Thus, a complete understanding of the mechanical behaviour of eutectic (and possibly composite) materials requires an understanding of how the lamellar terminations affect the yielding and fracture behaviour within the eutectic microstructure. In addition to the experimental portion of the work, an analysis to determine the stress required to initiate yielding in the vicinity of a termination was performed using a computer program based on the finite-element method. This work was carried out so that the effect of the terminations on the yield process in the eutectic structure could be modelled and compared to the experimental results.

2. Experimental procedure

Co–CoAl eutectic alloys of 9.5 wt % Al were prepared from electrolytic Co (99.95%) and Al (99.999%) by arc-melting in an argon atmosphere. The Co phase is actually an f.c.c. stabilized solid solution containing 6.9 wt % Al and the CoAl phase is an off-stoichiometric B2 structure. The arc-melted ingots were inserted into 12.7 mm diameter 99.98% alumina crucibles and melted in an induction furnace using graphite as the susceptor. The ingots were withdrawn under a flowing argon atmosphere through a water-cooled copper chill block at 3 cm h^{-1}. This processing treatment resulted in a directionally solidified and aligned lamellar structure.

Single-crystal tension specimens were prepared by cutting out sections of single crystals from the ingots using an electrical-discharge machine. Sufficient lengths of single crystal could not be obtained from the ingots to produce an entire single-crystal test specimen. The specimen geometry that was adopted utilized a single-crystal gauge section welded at each end to a polycrystalline specimen (also eutectic

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Co–CoAl) using an electron beam unit. The single-crystal gauge section was cut so that the lamellar interfaces were aligned approximately parallel to the tensile axis. The polycrystalline sections were then machined to form the threaded grip sections of the tensile specimen. The final dimensions of the gauge section were 2.5 mm × 2.5 mm × 10.2 mm. Details of the specimen preparation can be found elsewhere [3]. After the specimens were prepared, they were heat-treated in order to reduce the number of Co and CoAl precipitates that formed during solidification, in the CoAl and Co phases, respectively. The heat treatment was carried out at a temperature of 1295 °C for 4 h after placing the specimens in argon-filled quartz tubes, and was completed by water-quenching the specimens to room temperature.

Two opposite longitudinal sides of each sample were polished with 0.5 μm alumina to allow observations of the deformation structure to be made after testing. Strain gauges were mounted on the other two sides after polishing with 320 grit SiC to monitor the strain and to verify that no bending effects were induced during testing. Tensile tests were conducted at room temperature using an initial strain rate of $0.94 \times 10^{-4}\,\mathrm{s}^{-1}$. A dual strip-chart recorder was used to obtain the output of the strain gauges, while the load was monitored on the strip chart of the testing machine.

The lamellar termination density and interlamellar spacing were determined for each specimen. Before describing the procedure utilized to make these measurements, a brief description of what is a lamellar termination will follow. Lamellar terminations form during growth and examples of such terminations are shown in Fig. 1. Lamellar terminations can also occur within a fault known as a mismatch surface [2]. These growth defects are believed to be caused by fluctuations in solidification parameters such as the thermal gradient and solidification rate, and details of their formation can be found elsewhere [2]. The presence of a variation in lamellar termination density within an ingot or between ingots can be attributed to the fact that, in addition to the lamellar microstructure, the Co–CoAl eutectic system can also exhibit a rod microstructure in which Co-rich rods are embedded in a CoAl matrix [4]. In fact, both morphologies have been observed to coexist in transverse sections [4]. Why such a transition in microstructure occurs in Co–CoAl is a complicated topic and will not be discussed further. It is sufficient to note that a transitional microstructure between the lamellar and rod morphologies is apparently responsible for the increase in lamellar terminations in Fig. 1b compared to the more defect-free lamellar microstructure in Fig. 1a.

Since the lamellar termination density can vary somewhat throughout each specimen, the following procedure was adopted to make that measurement. The microstructures at the two ends (prior to welding) of each single-crystal specimen and at the centre of the specimen (after fracture) were characterized with respect to the interlamellar spacing and the transverse lamellar termination density. Measurements of the interlamellar spacing were made by placing a line segment perpendicular to the lamellar interfaces and counting how many pairs of lamellae intercepted the line segment. The transverse lamellar termination density was determined by counting the total number of terminations in the Co and CoAl phases on four random areas of each transverse section. These measurements were then converted into a transverse lamellar termination density, i.e. the number of terminations per unit area. The average values of these two measurements for the seven specimens tested are listed in Table I.

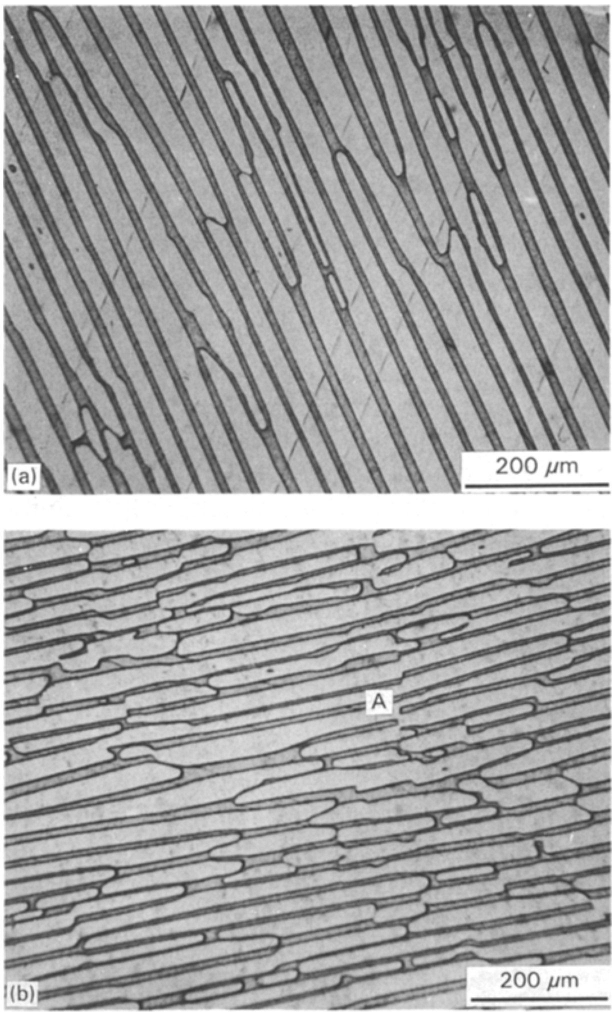


Figure 1 (a, b) Optical micrographs of transverse sections in directionally solidified Co–CoAl. Extensive lamellar terminations in the Co (light) phase are present in both micrographs and several examples of lamellar terminations in the CoAl phase (e.g. A) are present in (b). A higher termination density is present in (b) compared to (a).

3. Results

Two representative engineering stress–strain curves are shown in Fig. 2. The stress–strain curves of all specimens initially show a linear region which quickly enters a non-linear region, indicating that yielding began in the early stages of loading. Two distinct stress–strain curves were observed and an example of each is shown in Fig. 2. The slope of several curves decreased once yielding began until a constant stress was attained before fracture took place. For the re-

TABLE I Mechanical properties and microstructural analysis of Co–CoAl eutectic specimens

Specimen	Measured interlamellar spacing (μm)	Transverse termination density ($\times 10^6 m^{-2}$)	Yield strength (MPa)	Critical resolved shear stress (MPa)	Ultimate tensile strength (MPa)	Fracture strain (%)
1	36.3 ± 3.3[a]	196 ± 81[a]	496	238	[b]	[b]
2	34.8 ± 4.4	157 ± 60	490	238	593	1.9
3	36.7 ± 4.2	163 ± 120	593	288	703	1.9
4	32.8 ± 1.9	236 ± 103	421	204	[b]	[b]
5	33.0 ± 2.0	183 ± 81	524	254	676	1.75
6	31.0 ± 4.0	332 ± 114	421	204	600	1.1
7	30.0 ± 3.0	354 ± 76	379	171	[b]	[b]

[a] Standard deviation.
[b] Failed in the weld section.

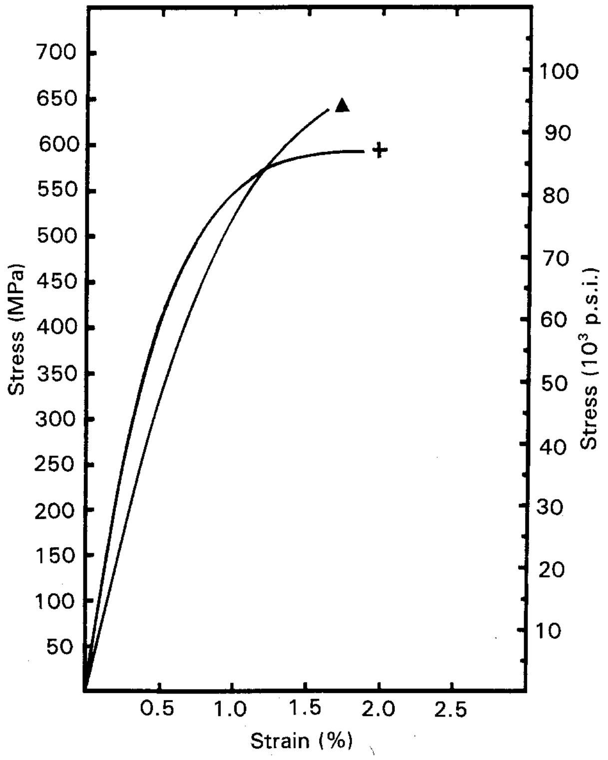


Figure 2 Two representative engineering stress–strain curves for Co–CoAl eutectic single crystals deformed in tension at room temperature: (▲) specimen 5 and (+) specimen 12.

maining specimens, a positive slope was maintained until fracture occurred. In addition, several of the specimens failed in the weld section and the stress–strain behaviour of these specimens beyond yielding will not be discussed; the yield strengths are valid for these specimens since they failed at strains of 1% or greater. The yield strengths at a 0.2% offset, the ultimate tensile strengths and the fracture strains (for those specimens which did not fail in the weld section) are given in Table I.

The yield strengths cannot be compared directly since the lamellae in the specimens were not exactly parallel to the tensile axis. This misalignment occurred during the welding process and was not constant among the various specimens. In order to compensate for the misalignment, the critical resolved shear stress (CRSS) of each specimen was calculated using the following procedure. Yielding only in the f.c.c. Co phase was considered since it was possible to calculate the Schmid factors for the twelve potential {1 1 1} ⟨1 1 0⟩ slip systems. Similar calculations for the CoAl phase are more difficult since it has been shown that slip occurs on three unique slip planes and with two different slip directions depending upon crystallographic orientation [5]. Furthermore, yielding only in the Co phase was considered in the finite element modelling. The calculations were performed by determining the orientation of the lamellar interfaces with respect to the tensile axis and using the crystallographic data of Cline [4] to establish the orientation relationships between the desired planes and directions in the Co phase with respect to the lamellar interface. The maximum Schmid factor was determined for each specimen and the CRSS was calculated using the yield strength at a 0.2% offset. These results are also listed in Table I.

A slight variation in interlamellar spacing between the various specimens was observed (Table I) similar to the study of Wall *et al.* [1]. To determine whether the yield strength was a function of interlamellar spacing, a plot of these parameters is shown in Fig. 3. Although there is some scatter, the yield strength and CRSS appear to increase as the interlamellar spacing increases. This functional dependence is exactly opposite, however, to what has been observed in virtually all eutectic alloys [6]. Therefore, this result is thought to be fortuitous for if these yielding parameters are plotted versus the transverse termination density (Fig. 4), both are found to decrease with increasing termination density in agreement with previous work by Wall *et al.* [1]. This dependence is consistent with the idea that if the lamellar terminations act as sites of stress concentration, the yield strength should decrease as the number of these sites increases.

Although the data are limited, the fracture process also depends on the termination density; the fracture strain (for those specimens which did fail in the gauge section) is found to decrease with increasing termination density (Fig. 5). Furthermore, observations of the deformed surfaces indicated that fracture of the eutectic was controlled by crack initiation in the hard CoAl phase. Fig. 6 is an optical micrograph of a typical

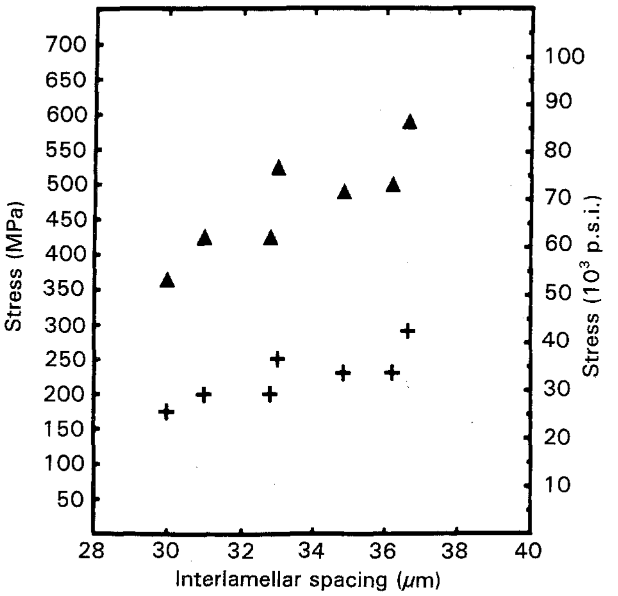


Figure 3 (▲) 0.2% offset yield strength and (+) critical resolved shear stress in tension versus interlamellar spacing.

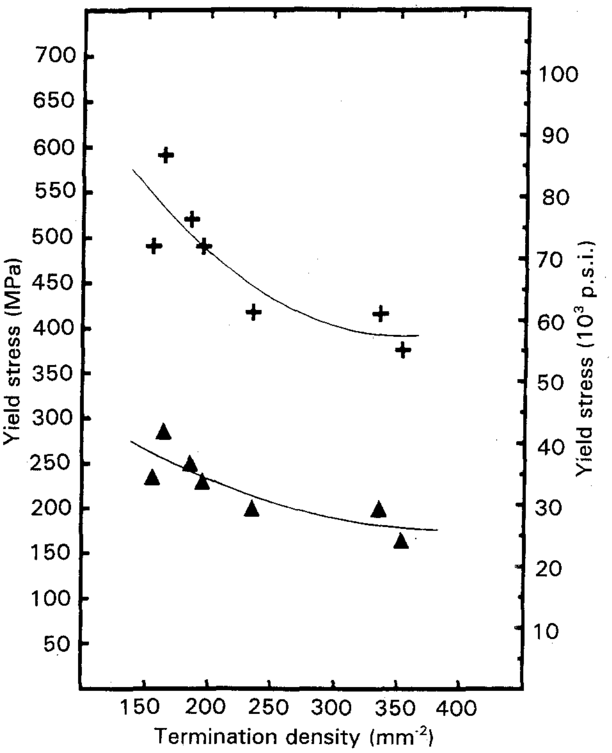


Figure 4 (+) 0.2% offset yield strength and (▲) critical resolved shear stress in tension versus transverse termination density.

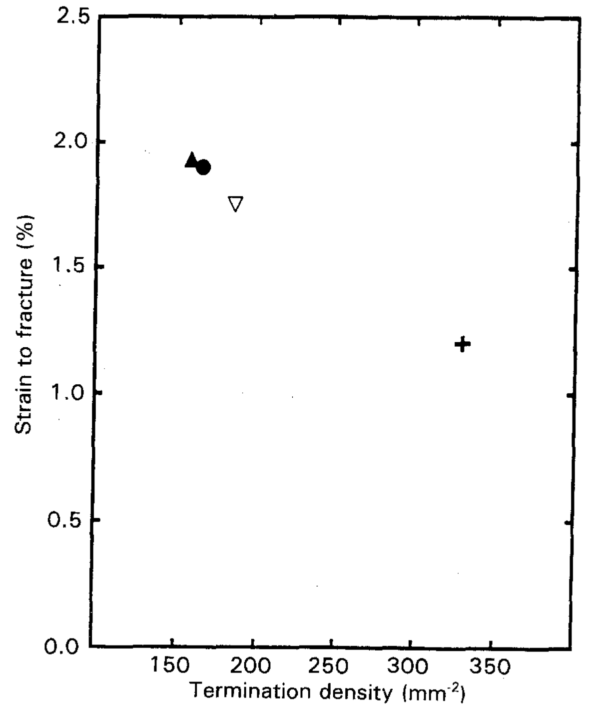


Figure 5 Fracture strain versus transverse termination density for specimens (▲) 2, (●) 3, (▽) 5 and (+) 6.

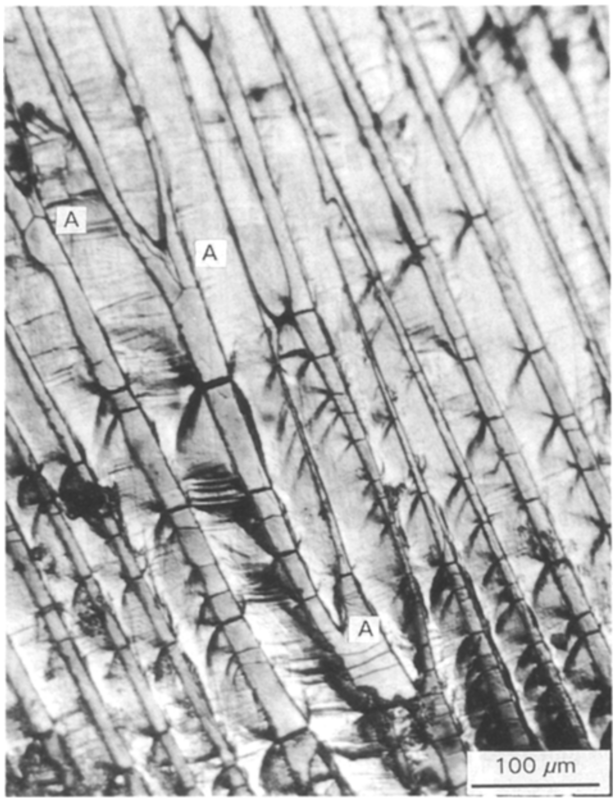


Figure 6 Optical micrograph of a deformed longitudinal surface showing cracks in the CoAl phase which have formed from impinging slip bands in the Co phase. Extensive crack formation (see regions marked A) took place in the vicinity of the lamellar terminations.

deformed surface, in which slip lines in the Co phase can be seen to impinge on the CoAl phase, apparently producing a number of cracks within the latter approximately perpendicular to the lamellar interface. There also appears to be a higher density of these cracks in the vicinity of the lamellar terminations (see Fig. 6) suggesting that crack initiation was facilitated by the presence of lamellar terminations within the microstructure. This was the predominant type of crack morphology observed in all the specimens, although occasionally cracks parallel to the lamellar interface either within the CoAl or along the interface were noted. These observations are in agreement with Cline [4] who also found that slip lines were present at the tips of cracks formed in the CoAl phase.

One half of each fractured specimen was subjected to transverse serial sectioning at intervals of approximately 50 μm starting from the fracture surface. Extensive crack formation was not observed except in the vicinity of the fracture surface. A representative micrograph is shown in Fig. 7 in which the cracks present are in the vicinity of lamellar terminations. This again suggests that terminations act as stress concentrators, promote extensive slip in their vicinity and ultimately cause fracture in the CoAl phase from slip band impingement.

The fracture surfaces were examined with an SEM, and a fracture morphology that can be best described as a "staircase" type of fracture was observed (Fig. 8). Examination of the fracture surfaces of the individual phases revealed that the Co phase has a dimpled fracture surface (Fig. 9a) while the CoAl phase has a cleavage-type fracture surface (Fig. 9b) in which river-line patterns can be seen. Based on these observations, a general model for fracture can be proposed (Fig. 10). As the stress is gradually increased on the eutectic, yielding initiates in the soft Co phase; the yield strength (in compression) for the individual Co phase with the same composition and orientation as the Co phase in the eutectic is only about 1/4 to 1/6 of the eutectic yield strength [1]. The initiation of the yield process leads to strain incompatibility between the two phases, and eventually high stress concentrations develop at regions where the slip bands (in the Co phase) impinge on the CoAl phase (see Fig. 6). When the stress concentration reaches a critical value, crack initiation takes place in the hard CoAl phase. This causes a redistribution of stresses which results in the formation of additional cracks at the ends of the slip bands. This process eventually leads to final fracture, as the crack grows in a discontinuous fashion from one CoAl lamella to an adjacent CoAl lamella via ductile fracture of the Co phase generating a staircase-type fracture. A similar fracture process has been observed in lamellar elastic–plastic eutectics such as Al–$CuAl_2$ [7, 8].

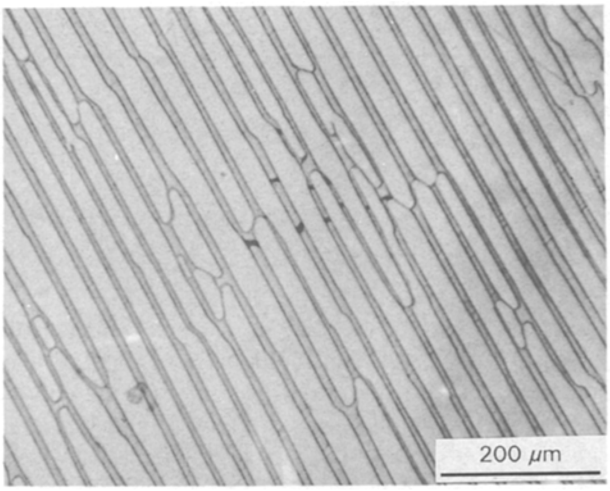


Figure 7 Optical micrograph of a transverse section close to the original fracture surface. The cracks which have formed are in the vicinity of lamellar terminations.

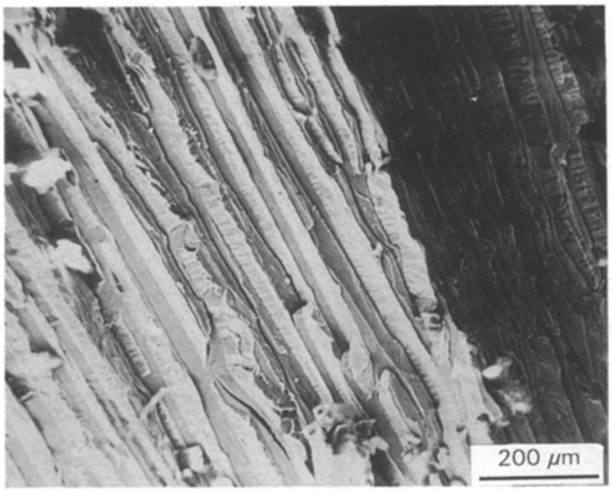


Figure 8 SEM micrograph illustrating the staircase-type fracture surface observed in the Co–CoAl eutectic.

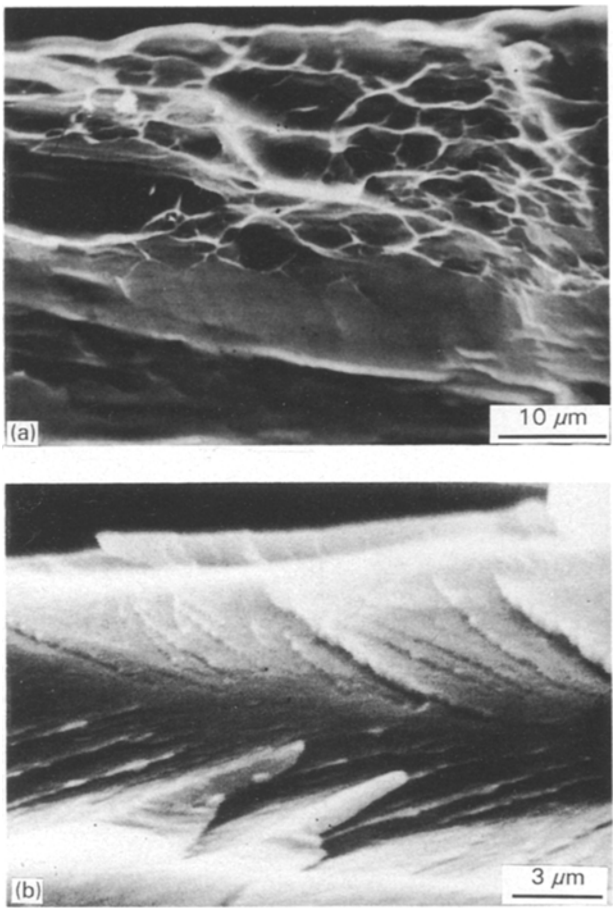
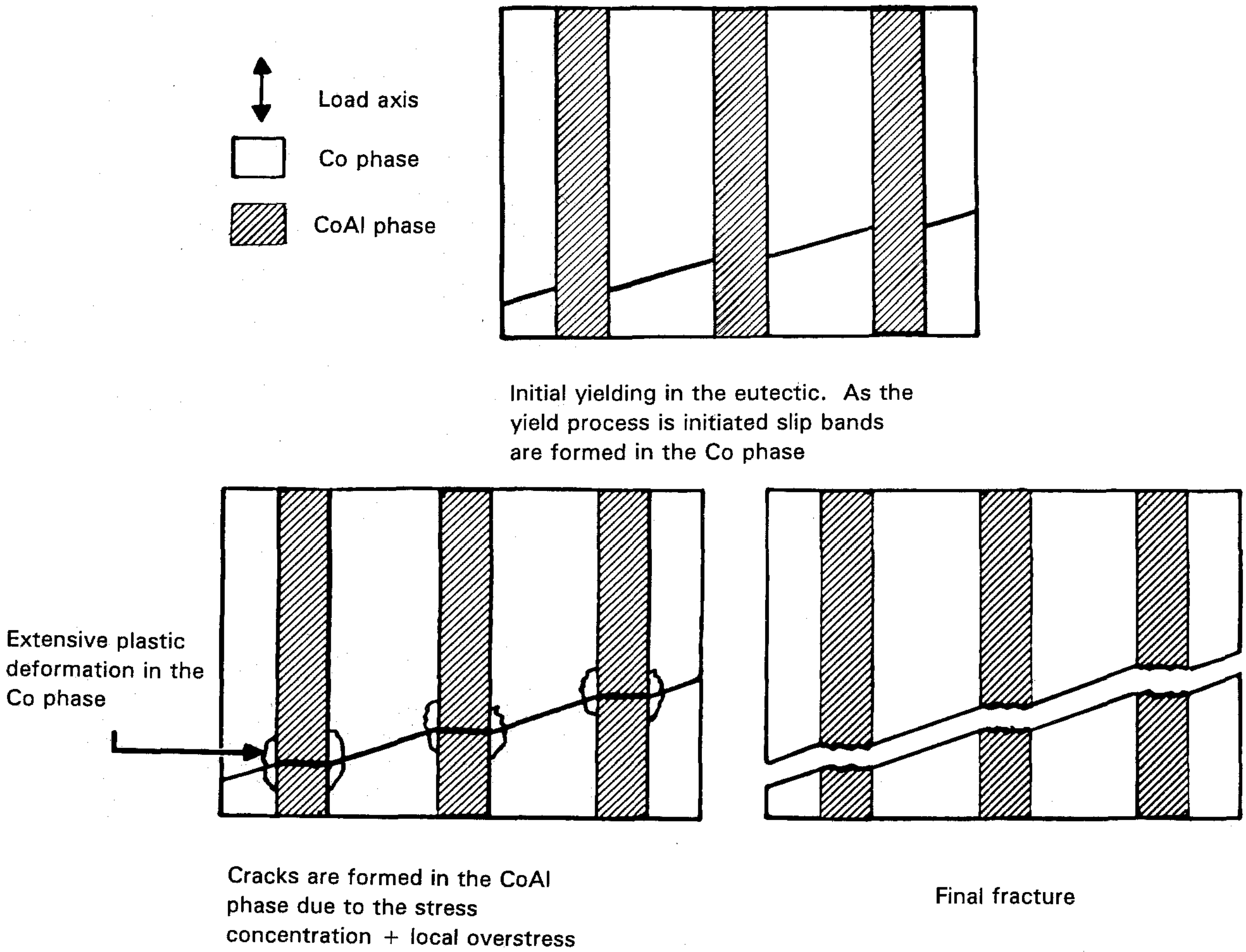


Figure 9 SEM micrographs showing (a) the dimpled fracture surface observed in the Co phase and (b) the cleavage-type fracture appearance in the CoAl phase.

4. Discussion

A comparison of the yield strength determined in tension and compression (the latter data obtained from Wall *et al.* [1]) as a function of termination density is shown in Fig. 11. The tensile yield strengths are significantly lower than the compressive yield strengths, consistent with data observed in other eutectic systems such as Al–$CuAl_2$ [8]. Some of this difference is due to the fact that the lamellar interfaces were parallel to the direction of loading in the com-



Initial yielding in the eutectic. As the yield process is initiated slip bands are formed in the Co phase

Cracks are formed in the CoAl phase due to the stress concentration + local overstress

Final fracture

Figure 10 Schematic diagram of the longitudinal surface illustrating the formation of the fracture morphology observed in Fig. 8.

pression tests, while some misalignment was present in the tension specimens. However, a portion of the difference can be attributed to thermally induced residual stresses that arise on quenching the specimens from the heat-treatment temperature as a result of the difference in thermal expansion coefficients that exists between the two phases.

A calculation of the residual thermal stress is possible if the difference in thermal expansion coefficients is known. An estimate of the thermal expansion coefficient for CoAl is available from the work of Cline [4], who measured the lattice parameter of CoAl at room temperature and 910 °C; a value of $14 \times 10^{-6}\,{}^{\circ}\mathrm{C}^{-1}$ was calculated. The thermal expansion coefficient for f.c.c. Co varies from $12.3 \times 10^{-6}\,{}^{\circ}\mathrm{C}^{-1}$ at room temperature to $17.6 \times 10^{-6}\,{}^{\circ}\mathrm{C}^{-1}$ at about 930 °C. Although the specimens were quenched from 1295 °C, the difference in thermal expansion coefficients at about 900 °C was used, since data were available at that temperature and some relaxation of the stress would occur on quenching.

The equation derived by Laszlo [9] was used to calculate the residual stress in the Co phase:

$$\sigma_1^{\mathrm{R}} = \frac{V_2 M_1 M_2}{V_1 M_1 + V_2 M_2} \Delta\alpha \Delta T \qquad (1)$$

where the subscripts 1 and 2 refer to the Co and CoAl phases, respectively, V_i is the volume fraction for the phase i, $M_i = E_i/(1 - \nu_i)$ where E_i is Young's modulus and ν_i is Poisson's ratio for each phase, and $\Delta\alpha$ and ΔT are the differences in thermal expansion and temperature, respectively. Inserting values for the volume fractions of Co and CoAl [10] and Young's moduli and Poisson's ratio [11], a residual tensile stress of 387 MPa was calculated for the Co phase. Since the Co phase is in a state of tension at room temperature after quenching, the eutectic would be expected to yield at lower stresses in tension than in compression, consistent with the experimental data. If it is assumed that the yield process is controlled entirely by the soft Co phase and the constraints imposed by the hard CoAl phase are neglected, then the difference between the yield strengths in tension and compression would be expected to be about 774 MPa. The difference in yield strength between compression and tension was determined at constant termination density from Fig. 11, and an average value of about 450 MPa was obtained. The difference between the calculated and experimental values is most likely due to uncertainty in the value of the thermal expansion coefficient for CoAl and to some relaxation of the stresses on quenching.

It has been suggested that lamellar terminations act as stress concentrations within the microstructure. This result has been confirmed from an elastic–plastic analysis of yielding with anisotropic slip in an aligned two-phase microstructure utilizing a finite-element approach [3]. A brief summary of this analysis follows.

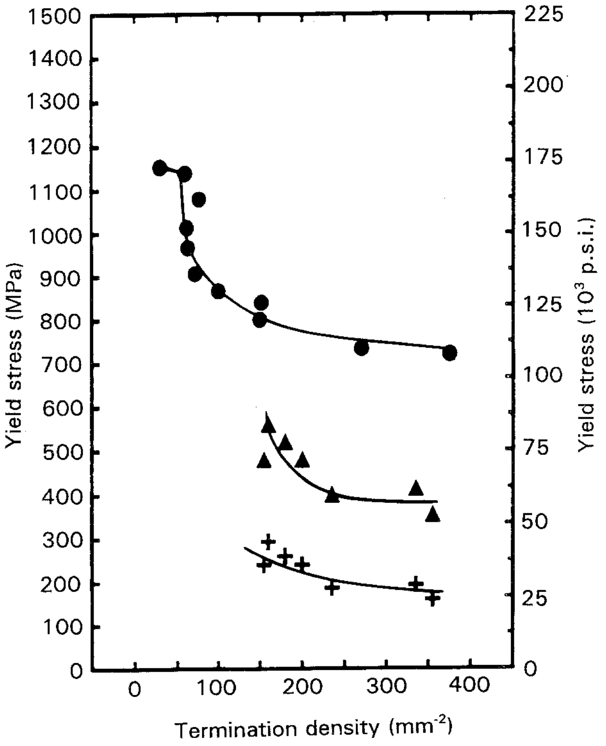


Figure 11 (●) Compressive and (▲) tensile 0.2% offset yield strengths and (+) critical resolved shear stress in tension versus transverse lamellar termination density.

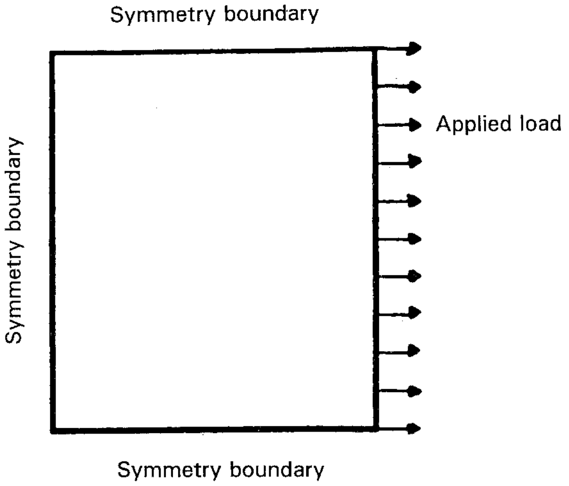


Figure 12 Boundary conditions utilized in the finite-element modelling.

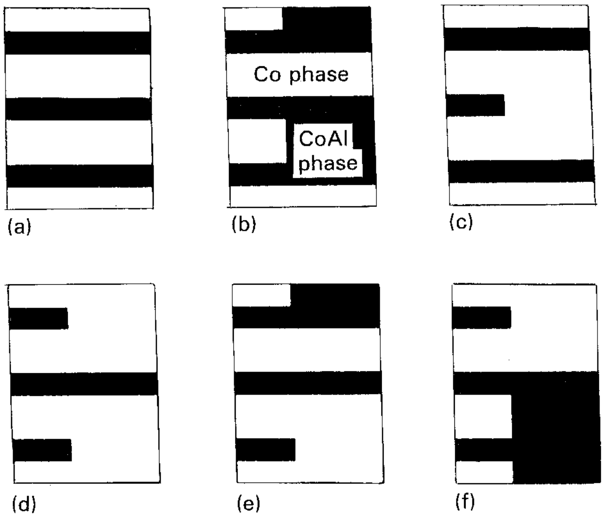


Figure 13 Description of the models used in the finite-element calculations. (a) No terminations; (b) one termination in every alternating Co phase; (c) one termination in every alternating CoAl phase; (d) two CoAl phase terminations alternating with one CoAl phase; (e) one Co phase termination alternating with two consecutive CoAl phase terminations; (f) three consecutive Co phases alternating with two consecutive CoAl phase terminations of a distance of one lamella.

A computer simulation was conducted to determine the stress distribution in the vicinity of a lamellar termination on a longitudinal surface. The finite-element code employed took into account the crystal structures of the individual phases and their anisotropy. The code was first developed by Wilson [12] and later modified by Gerdeen *et al.* [11] to incorporate anisotropic slip within an incremental plasticity framework for f.c.c. crystals, which is described by 24 piecewise, continuous yield functions, also known as the generalized Schmid's law for f.c.c. crystals.

Details of the development of the equations to calculate the strains and stresses and their inclusion into the finite element formulation are given by Gerdeen *et al.* [11]. Longitudinal lamellar terminations, i.e. lamellar terminations on the longitudinal surfaces, were modelled since a three-dimensional computer code would be required in order to model transverse terminations. A plane strain condition perpendicular to the plane of the model was assumed using the symmetry boundary conditions shown in Fig. 12. Six different models described in Fig. 13 were examined:

(a) no terminations,

(b) one termination in every alternating Co phase,

(c) one termination in every alternating CoAl phase,

(d) two consecutive CoAl phase terminations alternating with one CoAl phase,

(e) one Co phase termination alternating with two consecutive CoAl phase terminations separated by a distance of two lamellae, and

(f) three consecutive Co phase terminations alternating with two consecutive CoAl phase terminations at a distance of one lamella.

The intention in selecting this series was to begin with models composed only of a Co or a CoAl phase termination and then approximate the actual microstructures by using combinations of CoAl and Co phase terminations. The material property data required for the analysis are given by Gerdeen *et al.* [11].

The accuracy of the finite-element method depends on the number of elements that are used to discretize the structure. Therefore, an analysis was performed to select the proper number of elements for each simulation based on the supposition that as the number of elements is increased, the solution should converge. This criterion was applied by performing a series of simulations in which the number of elements was increased until the predicted stress differed for sequential simulations by less than 0.5%.

Calculations were then made of the stress required to activate slip on a single slip system, termed the first yield stress, in the softer Co phase. This approach was adopted since the yield strength of the Co phase is low compared to the CoAl phase. The relationship between the first yield stress and the longitudinal termination density for all six models is shown in Fig. 14. The longitudinal termination density was calculated assuming a characteristic width of six lamellae with an interlamellar spacing of 30 μm and a length of 68.6 μm; the latter was the minimum length required so that the results would not be affected by the boundary conditions. Fig. 14 shows that the first yield stress decreases with increasing longitudinal termination density. This relationship is consistent with the results observed experimentally for the transverse termination density (Fig. 4) and for the longitudinal termination density data shown in Fig. 15.

Models (a), (c) and (d) indicate that as the total number of CoAl phase terminations increases from zero to two to four, respectively, the stress drops almost at a linear rate. Consideration of models (a), (b) and (c) shows that the drop in stress from no terminations (model (a)) to models (b) (three terminations in the Co phase) and (c) (two terminations in the CoAl phase) is almost the same. This indicates that, within the characteristic width used, the effect of two CoAl phase terminations on the first yield stress is approximately the same as that of three Co phase terminations. This same result can be derived from a physical argument. Because the harder CoAl phase is the load-carrying phase, its termination causes a transfer of load to the softer Co phase which has a relatively low load-carrying capacity. This leads to extensive deformation in the Co phase and initiation of yield in the vicinity of the termination. In contrast, at a Co phase termination, the local volume fraction of the CoAl phase is doubled (since the Co lamella width is twice that of the CoAl lamella) which increases the load-carrying capacity in that region. Thus, it can be argued that terminations in the CoAl phase are more detrimental to the yield stress than the terminations in the Co phase, and this is consistent with the data in Fig. 14. The elastic stress distributions about the Co and CoAl phase terminations were also determined [3, 11]. The data indicate that the stress in the vicinity of a termination is higher in the case of a CoAl phase termination compared to a Co phase termination.

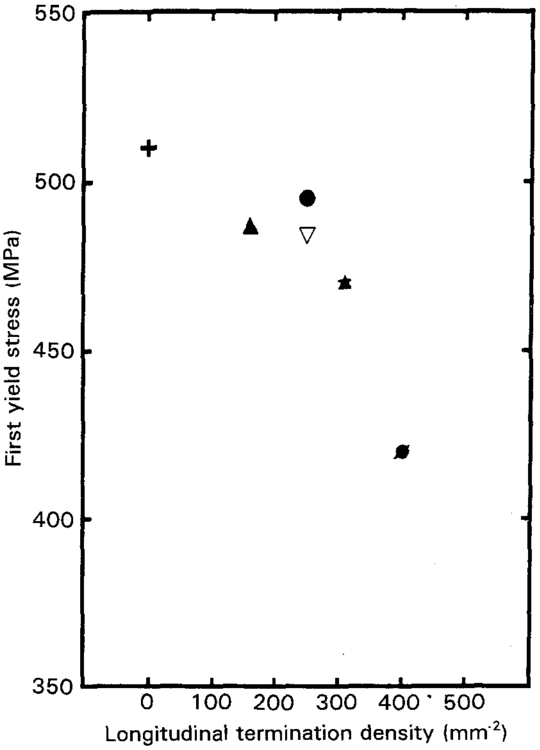


Figure 14 Calculated first yield stress versus longitudinal termination density. The number of Co and CoAl phase terminations used in the various models are indicated after each model identification, where S and H represent the symbols for the Co and CoAl phases, respectively: (+) A, (▽) B: 3S, (▲) C: 2H, (★) D: 4H, (●) E: 1S + 2H, (●) F: 3S + 2H.

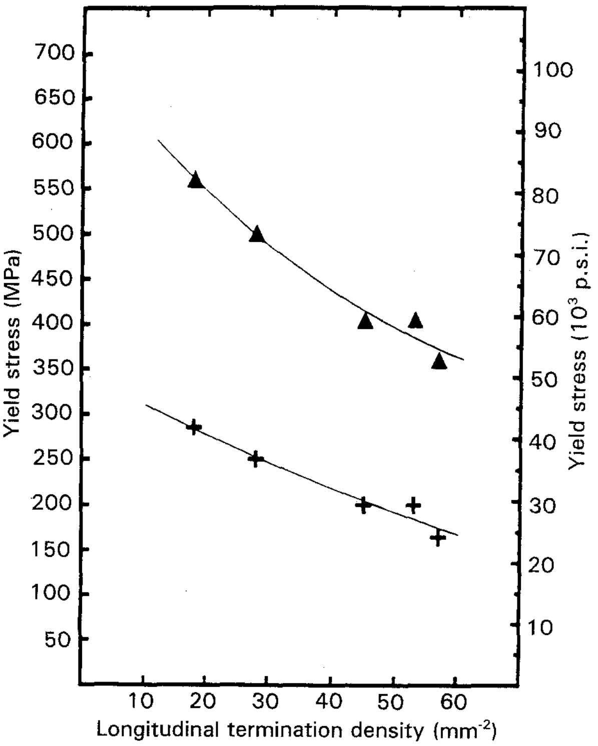


Figure 15 (▲) 0.2 % offset yield strength and (+) critical resolved shear stress in tension versus longitudinal termination density.

In addition to the first yield stress, progressive load increments above the first yield stress were used to identify additional slip systems that could be activated in the microstructures containing terminations. It was determined that more slip systems were activated at lower stress levels than observed in the ideal microstructure (model (a)). Also, the slip systems predicted were in good agreement with those observed experimentally through single-surface slip trace analysis [3, 11].

5. Summary

The yield strength and critical resolved shear stress were found to decrease as the density of transverse or longitudinal lamellar terminations increased. These results indicate that the lamellar terminations help to initiate the yield process by acting as stress concentrators in the microstructure. Finite-element modelling of yielding in an elastic–plastic two-phase aligned structure confirmed that the first yield stress (stress at which the first slip system was activated) was dependent on the longitudinal termination density. It was also concluded from the computer simulation results that a termination in the CoAl phase was more detrimental than a termination in the Co phase. This was explained by examining the redistribution of stresses about Co versus CoAl terminations.

The strain to fracture was also dependent on termination density. A model based on discontinuous crack growth in the CoAl phase and ductile fracture of the Co phase was proposed to explain the fracture process. Stress concentrations were built up at the Co–CoAl interfaces from slip bands operating in the soft Co phase. Eventually, a critical stress was achieved which resulted in crack initiation in the hard CoAl phase. As the number of terminations increased, the density of sites at which intense deformation and fracture initiation took place also increased, leading to lower fracture strains.

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