Deformation of duplex crystals and two-phase bicrystals of alpha-beta brass

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A two-phase transition zone of alpha-beta brass forms as a result of the melting of beta brass on alpha brass single crystal substrates. Specialized heat-treatments can convert this transition zone into a duplex crystal region of alpha-beta brass, or eliminate this region resulting in a sharp boundary between alpha and beta crystals. Specimens prepared by these treatments were deformed in uniaxial tension to study the initiation of plastic deformation and its propagation across the phase boundary. Although the phase boundary initially poses a resistance to the approaching slip, its effectiveness as a barrier depends on the crystallographic relationships between alpha and beta crystals. No void formation was observed at the boundaries.

1. Introduction

Mechanical behaviour of two-phase materials depends on the properties of the constituent phases and on the role of the phase boundaries. Grain boundaries and phase boundaries have been observed to act as barriers for slip propagation [1, 2]. The influence of the grain boundaries on the deformation of the single-phase materials has been explored by the use of bicrystals [3-5]. Such a work is part of the recent review on grain boundaries by Hirth [6].

The role of phase boundaries in the deformation behaviour of two-phase materials can be studied with duplex crystals and two-phase bicrystals. A duplex crystal has been defined by Smith [7] as "an oriented crystallographic unit consisting of two phases with a definite relationship to each other." A two-phase bicrystal can be defined as a macroscopic unit consisting of a single crystal of one phase joined to a single crystal of another phase.

Duplex crystals and two-phase bicrystals of alpha-beta brass were used in this study to investigate the resistance posed by the phase boundary to the progress of plastic deformation.

2. Experimental procedure

Randomly-oriented single crystals of alpha brass (70% copper-30% zinc) were grown by the Bridgman technique. To remove the micro-segregation, the crystals were homogenized at 800° for 16 h as suggested by Maddin [8]. Beta brass was melted on the substrates of these alpha brass single crystals in open-ended quartz tubes. During the solidification of beta brass, a large axial temperature gradient was created by putting one end of the alpha brass single crystal on a heat sink, as in Greninger's work [9].

In order to obtain duplex crystals and two-phase bicrystals, special heat-treatments, such as moving through a temperature gradient and localized cyclic annealing, were used. Details of these heat-treatments have been described elsewhere [10]. In duplex crystals, these heat-treatments helped to minimize the transition zone of alpha-beta, to coarsen the alpha and beta segments in the transition zone, and to crystallographically orient alpha and beta segments with respect to each other. Extensive grain growth of the beta phase took place during these treatments. In most of the duplex specimens obtained during this work single grains of beta were in contact with the duplex regions, and the beta grains were always continuous with all the beta segments of the duplex regions. All the alpha segments of the duplex regions were continuous

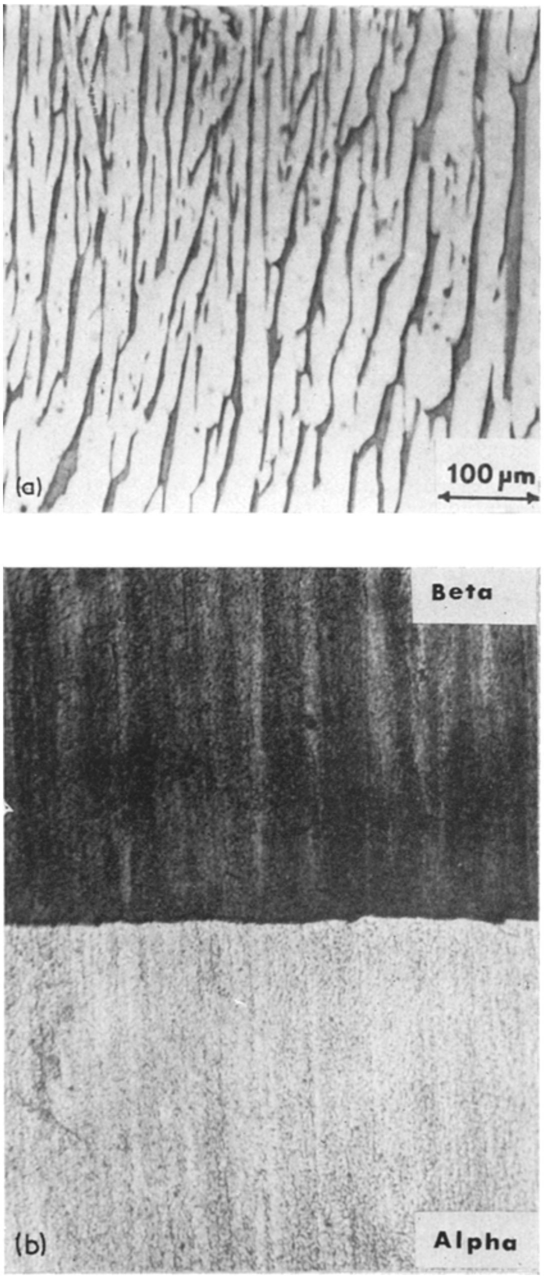

Figure 1 (a) Microstructure of an alpha-beta brass duplex crystal. (b) Sharp alpha-beta phase boundary in a two-phase bicrystal (ferric chloride etch). (Courtesy *J. Crystal Growth.*)

with the alpha single crystals. Further heat-treatment of these duplex regions can produce two-phase bicrystals.

Tensile specimens of rectangular cross-section were obtained by careful machining. Typical gaugelengths of these specimens were about 35 to 38 mm. The specimens were then mechanically and chemically polished, and steel nuts were silver soldered to their ends. After light etching, the specimens were tested in uniaxial tension in an Instron testing machine. The rate of displacement of the cross-head was 0.05 cm min^{-1}. The slip distribution near the interface was studied by optical and electron microscopy.

3. Results and discussion

Micrographs of a typical duplex crystal region and that of the phase boundary in a typical two-phase bicrystal are shown in Fig. 1. The axis of loading relative to these regions is also shown in this figure. Observations of the slip propagation in such specimens during uniaxial tension can be classified as (1) the deformation behaviour of alpha, (2) slip accommodation near the phase boundaries, and (3) the deformation behaviour of the entire specimen. These observations are presented in the following sub-sections.

3.1. Deformation behaviour of alpha

In all the duplex crystal specimens, the plastic deformation always started as single slip in the alpha single crystal region at a point away from the duplex region as shown in Fig. 2a. With increasing strain, slip progressed towards the duplex region. The travel of the front of the plastic deformation towards the duplex region is illustrated in Fig. 2b, c and d. Typical slip distributions in the alpha single crystal region after 11% total strain at 4.8, 6.4 and 12.8 mm *away from* the duplex region are shown in Fig. 3a, b and c respectively. These figures show that different slip planes become active as the deformation progresses towards the duplex region. Away from the interface, in alpha, slip is observed mainly as single slip. Slip lines cluster in the regions deformed in single slip, giving rise to deep and heavy slip markings. Similar features were also observed in the bicrystal specimens.

3.2. Slip accommodation near the phase boundaries

In the duplex crystals, initial deformation of the duplex region occurs only in the alpha segments due to the continuation of slip from the alpha single crystal regions as shown in Fig. 4. Slip traces observed in these alpha segments are parallel to the primary slip traces in the alpha single crystal. This implies that the alpha

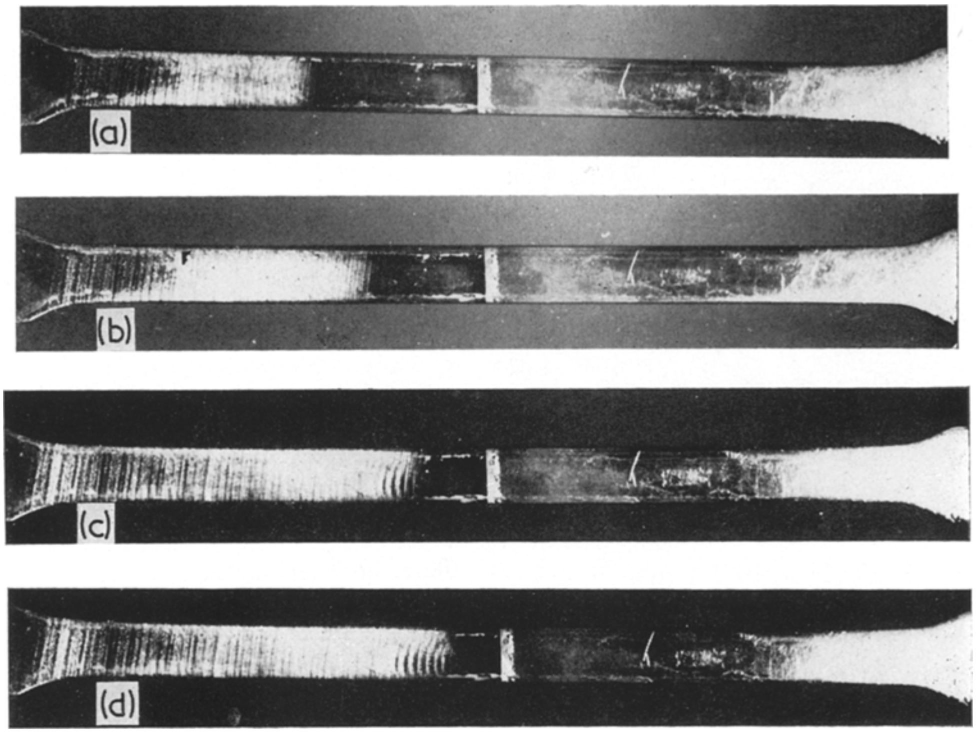

Figure 2 Slip distribution in the alpha single crystal region at various strains, (a) 2.3 %, (b) 4.5 %, (c) 5.5 % (d) 6.3 % total strain (× 3.5).

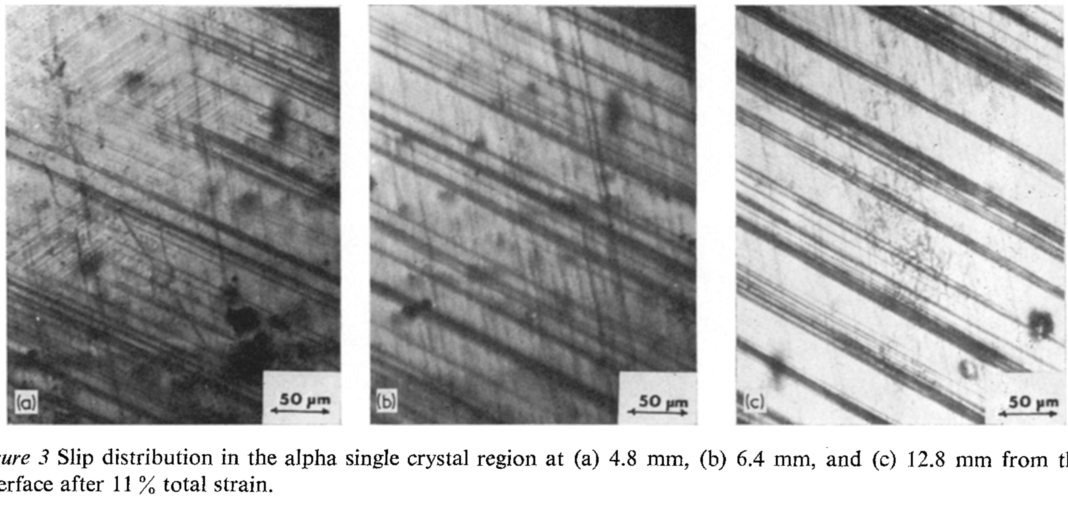

Figure 3 Slip distribution in the alpha single crystal region at (a) 4.8 mm, (b) 6.4 mm, and (c) 12.8 mm from the interface after 11 % total strain.

segments have the same orientation as the alpha single crystal. With increasing strain, the slip line density in each alpha segment increased, secondary and cross-slip systems became active near every individual alpha-beta phase boundary. Fig. 5a shows such features as seen under an optical microscope. At the same time, there is no slip in beta segments. On further deformation,

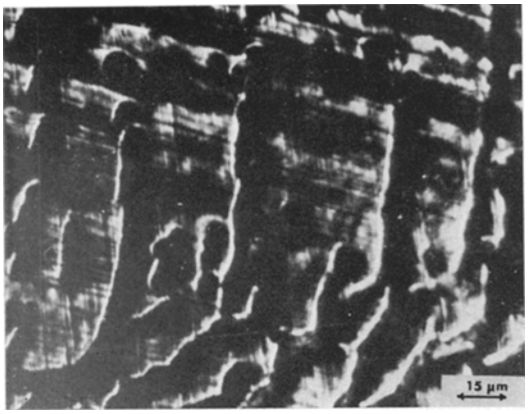

Figure 4 Initial deformation of the duplex region showing slip in the alpha segments.

fine slip is observed in beta segments as seen in Fig. 5b. The regions where slip lines appear to continue through the phase boundary are indicated by the letter A. Regions marked B and C show multiple slip and cross-slip respectively, in the alpha segments. In the duplex region, which consists of Widmanstätten plates, the active slip plane and slip direction in alpha are parallel to the slip plane and slip direction in beta respectively. At very large strains, slip in beta segments becomes coarse and at various places slip lines are observed to continue from alpha segments on a one-to-one basis. This feature is clear in the electron micrograph shown in Fig. 6.

The above observation suggests that the stress at which deformation continued across an alpha-beta boundary is greater than that for primary slip, for cross-slip and secondary slip in single crystal alpha. Owing to the microscopic nature of the alpha-beta segments, however, the stress required for the slip continuation across the boundary could not be measured in experimental studies utilizing duplex crystals. This difficulty can be overcome by using a two-phase bicrystal.

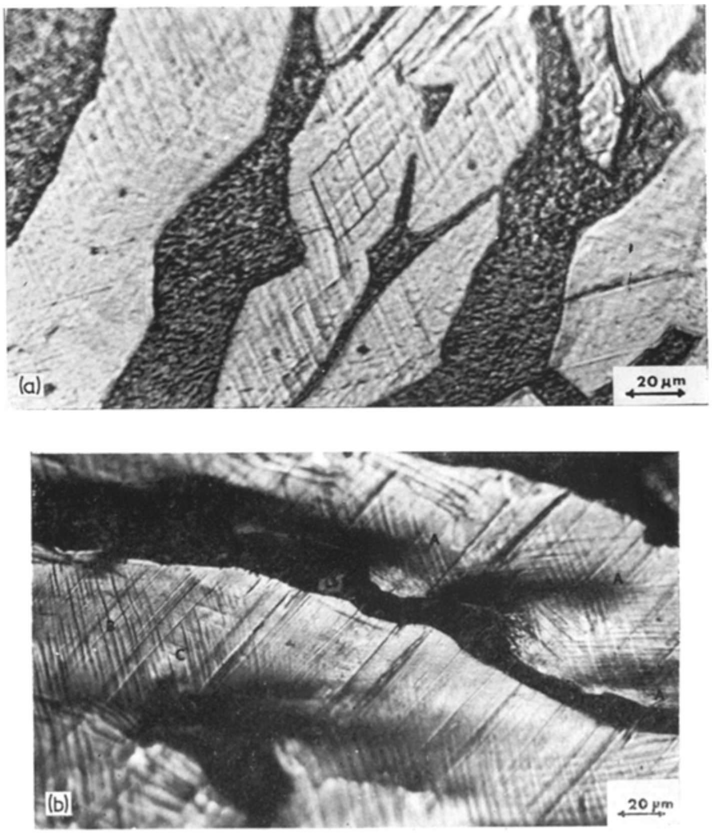

Figure 5 (a) Initiation of secondary slip and cross-slip in alpha segments before slip lines reach the alpha-beta interface. (b) Slip propagation through the alpha-beta phase boundary in the duplex region.

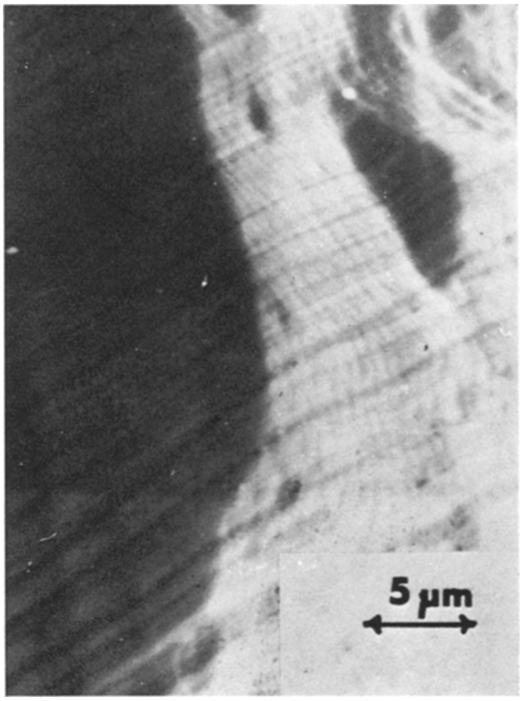

Figure 6 Electron micrograph showing slip propagation through the alpha-beta phase boundary. Light and dark regions are alpha and beta respectively. (Two-stage plastic-carbon replica).

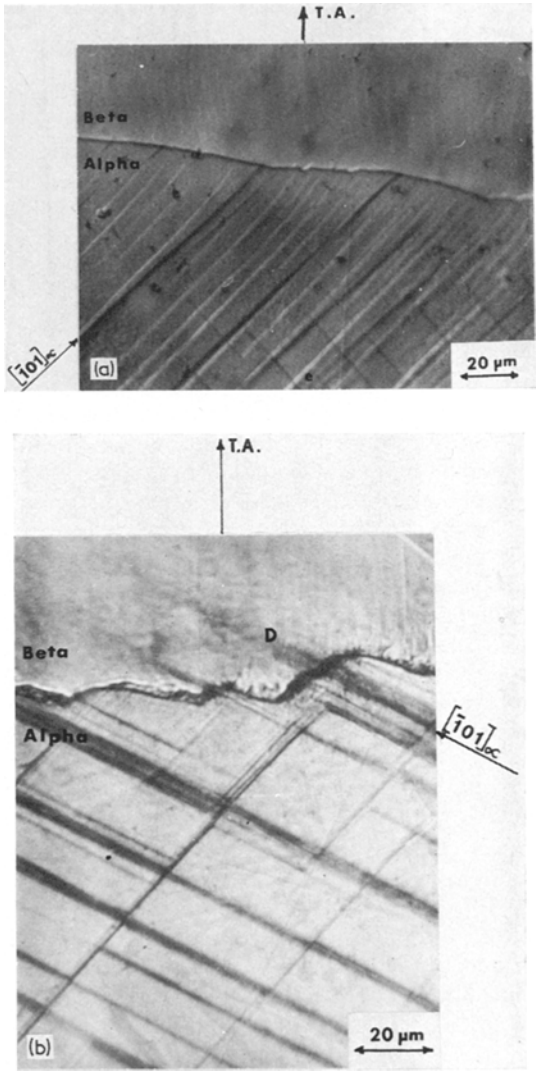

Figure 7 (a) Occurrence of secondary slip in alpha away from the alpha-beta phase boundary in a bicrystal satisfying specific crystallographic relationship as in duplex crystals. (b) Slip initiation in beta in the same bicrystal at a higher stress level. A diffuse slip band, D, is present in beta. It is parallel to the slip direction in alpha since the active slip plane in alpha is parallel to the active slip plane in beta.

Alpha and beta phases in the two-phase bicrystals may or may not, however, satisfy the specific crystallographic relationships as in duplex crystals. Features of the deformation of a bicrystal satisfying such relationships between alpha and beta can be seen in Fig. 7. Fig. 7a shows the occurrence of secondary slip and cross-slip in the alpha phase prior to any slip initiation in beta, as in the case of duplex crystals. Fig. 7b shows the slip initiation in beta in this specimen at a higher stress level. In such specimens, slip in beta was observed at a resolved shear stress of 2.4 kg mm^{-2}. In bicrystal specimens, that did not satisfy the specific crystallographic relationships, deformation did not progress across the boundary. However, as the resolved shear stress level reached about 4 kg mm^{-2}, the beta crystal deformed by itself in a region away from the phase boundary.

3.3. Deformation behaviour of the entire specimen

During deformation, slip in beta progresses to regions away from the boundary. Slip traces in beta can be detected by the naked eye at total strains of 70 to 90%. In all the specimens, at the time slip started in beta, the alpha single crystals were necking and twisting. Necking in alpha travelled back and forth similar to Lüders-band progression in the single crystals of alpha as observed by Brindley *et al.* [11]. During the necking of alpha, the applied stress remained constant. In beta, more and more slip occurred.

3.4. General comments

In the duplex crystals, alpha segments were in the form of Widmanstätten plates. X-ray analysis indicated that the close-packed planes and the close-packed directions in the two phases alpha and beta were parallel. Such relationships were also observed in some bicrystal specimens. In spite of this, there was an initial resistance for the progress of deformation across the boundary. This is indicated in Figs. 5a and 7a by the fact that slip was not observed in beta until secondary slip and cross-slip took place in alpha. This resistance exhibited by the phase boundary may be attributed to (i) the difference in shear moduli of alpha and beta, (ii) the difference in Burgers vectors of slip dislocations in the two phases, and (iii) the difference in the number of available slip systems. In the bicrystal specimens in which the specific crystallographic relationships were not satisfied, the phase boundary acted as a more effective barrier. However, in none of the specimens, was void formation found at the phase boundary to accommodate the deformation.

4. Conclusions

In all the specimens, the alpha-beta phase boundary poses a barrier to slip propagation. Stress caused by the interaction of single slip in alpha with the phase boundary is initially relaxed by activating other slip systems in the alpha phase. The effectiveness of this boundary as a barrier for slip propagation at higher stress levels depends on the relative crystallographic orientation of the two phases. Irrespective of whether the crystallographic relations are satisfied or not, void formation is not necessary at these phase boundaries to accommodate plastic deformation.

Acknowledgements

We are grateful to Drs R. Summitt and D. J. Montgomery for their encouragement. We are thankful to Dr S. M. Adams for very helpful discussions and Dr C. Nilsen for his help during the experimentation. Thanks are also due to Mr Hoffman, Director, Division of Enginering Research, Michigan State University, for the financial assistance provided to A. K. Hingwe.

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Received 22 July and accepted 15 August 1974.