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Indentation studies on two-phase bicrystals of alpha–beta brass with various phase boundary geometries

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Indentation studies were carried out on a two-phase model system of alpha–beta brass so as to understand the role of phase boundary on the propagation of deformation. Unlike in the case of uniaxial loading, the phase boundary acts as a very effective barrier for slip propagation, irrespective of its geometry.

1. Introduction

Recent studies using a model system of alpha–beta brass have indicated that the role of phase boundary on room temperature deformation depends on the strain rate and local stress state [1, 2]. In these investigations, the phase boundary was normal to the tensile axis.

The model system of two-phase bicrystals of alpha–beta brass can be produced with different inter-phase boundary geometries [1–3]. The oriented duplex interface has alpha and beta phases in definite crystallographic registry;

$$\{1\,1\,1\}_\alpha \parallel \{1\,1\,0\}_\beta$$

$$\langle 1\,1\,0\rangle_\alpha \parallel \langle 1\,1\,1\rangle_\beta$$

In the equiaxed duplex interface, alpha and beta regions do not have any definite relative crystallographic relationships; they are oriented in a random fashion. Flat (and sharp) inter-phase boundary between the two phases can also be obtained. Most of the bicrystals with sharp phase boundary will not have definite relative crystallographic orientation relationships between the phases. Room temperature tensile deformation studies on specimens with the above phase boundary geometries have shown the equiaxed (unoriented) duplex interface structure to be the most effective barrier to the progress of slip from alpha to beta [1, 2, 4]. The behaviour of flat (and sharp) interface is in between the above two extremes. Strain rate sensitivity of the specimens with the above phase boundary geometries has already been reported [1, 2]. Higher strain rates tend to produce fine slip in alpha, which in turn make initiation of deformation across the boundary more difficult. Cross-slip and wider slip bands have been observed in alpha regions at low strain rates. Most of the deformation studies [5–21] with two-phase bicrystals of alpha–beta brass have been with uniaxial tensile loading, and few investigations have been concerned with phase-boundary sliding [16–18].

Indentation studies were carried out during the present investigations so as to understand the effect of different stress state (as compared to uniaxial tension) and stress concentration near the phase boundary, on the effectiveness of the boundary as a barrier for slip propagation.

2. Experimental procedures

Methods to produce two-phase bicrystals of alpha–beta brass with various phase boundary geometries have been described elsewhere [1–3]. Indentation tests were performed to create a localized region of high stress concentration near the alpha–beta phase boundary. The tests were performed in an Instron testing machine

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using a 20° included angle conical steel indenter. The tests were performed on samples that had been machined and metallurgically polished to have square cross-sections approximately 4 mm × 4 mm; alpha and beta regions were about 25 mm long on either side of the interface.

The load applied to the indenter, the distance of the indentation in the alpha phase from the phase boundary, and the rate of load application to the indenter were all varied. Loads of 250 and 400 N were applied at crosshead speeds (CHS) of 0.005, 0.05, 0.5 and 5.0 cm min^{-1}. Approximate distances of the indentations in the alpha phase from the boundary used were 1.5, 1.0 and 0.5 mm.

Indentation tests were performed on specimens having duplex boundary regions and as well as on specimens with flat phase boundaries. Tested samples were studied by optical and scanning electron microscopy.

3. Results and discussion

Indentation tests were carried out on specimens having three interfacial geometries; oriented duplex, equiaxed duplex and flat (sharp). In all of the micrographs presented, the alpha single crystal portion of the specimens is shown at the left and is designated by "A"; the beta phase appears to the right and is designated by "B".

3.1. Oriented duplex boundary

The effect of the rate of indentation is shown in the micrographs presented in Fig. 1. In this series the indentation load was 250 N and the indentation distance was 1.5 mm from the boundary in the alpha region. The rate of load application for indentation was varied by using the CHS from 0.005 to 5.0 cm min^{-1}. At lower strain rates, for 250 N load and a distance of 1.5 mm, the deformation produced by the stress concentration consists of fine slip lines. Such slip lines interact less with the boundary structure than slip lines produced by higher rates of load application. The high loading rates produced much coarser slip lines which propagated further from the indentation into the oriented duplex boundary structure. However, the oriented duplex interface structure seems to be an effective barrier to slip under these tests conditions, and no interaction of slip with the oriented beta phase on the structure has been observed.

A test series was carried out using a 250 N load, and a constant, low CHS of 0.005 cm min^{-1}. The distance of indentation from the boundary for the indentation were 0.5 and 1.5 mm. At this load and low rate of load application, as would be expected, the indentation closer to the boundary (0.5 mm) produced more slip interaction with the nearby portions of the oriented duplex interface structure as shown in Figs. 2a and b. The indentation which was closer to the boundary, however, failed to produce any slip interaction into the duplex region or with the beta phase at this load and rate. Indentations using 250 N and higher CHS also failed to produce any propagation of slip into the duplex region of the interface, when the indentations were made at 0.5 and 1.5 mm away from the boundary. The slip patterns shown in Figs. 3a and b indicate that for an indentation distance of 0.5 mm, heavy slip with a higher slip line density is produced at the interface, than in the specimen indented at 1.5 mm distance from the interface. Although in both cases the propagation of slip to the interface was more effective at this rate of loading than at a lower rate, no propagation of slip into the duplex region was observed. Indentation with a 250 N load with a very high CHS of 5.0 cm min^{-1} was also carried out at 0.5 and 1.5 mm distances away from the interface. As expected, the highest stress concentration near the interface for this load was achieved using the 0.5 mm indentation distance. Once again, as shown in Figs. 4a and b the oriented duplex interface structure acted as an effective barrier to slip propagation at this load value of 250 N.

For a comparison of the effect of varying the load, tests were performed using a 400 N load at a low indentation rate of 0.005 cm min^{-1} and a distance to the interface of 1.5 mm. The results of this test are presented in Fig. 5. The 400 N load was more effective, at this distance of indentation and loading rate, in producing a much higher slip line density at the interface structure, than 250 N load. This can be seen by comparing Fig. 5 with Fig. 1a. Extensive cross-slip observed in the slip line pattern produced by the 400 N load, attests to the fact that the oriented duplex interface geometry is an effective barrier to slip propagation in indentation loading.

3.2. Equiaxed duplex boundary

In order to investigate the effects of the type of interface structure on the progress of slip into an interface region, tests were performed on samples having an equiaxed duplex interface geometry. For comparison purposes, indentation tests were conducted using a load of 250 N, a CHS of 0.05 cm min^{-1}, and at a distance of 1.5 mm from the interface. The result of this test is shown in Fig. 6. This may be compared to results obtained with specimens having an oriented duplex interface geometry, which were

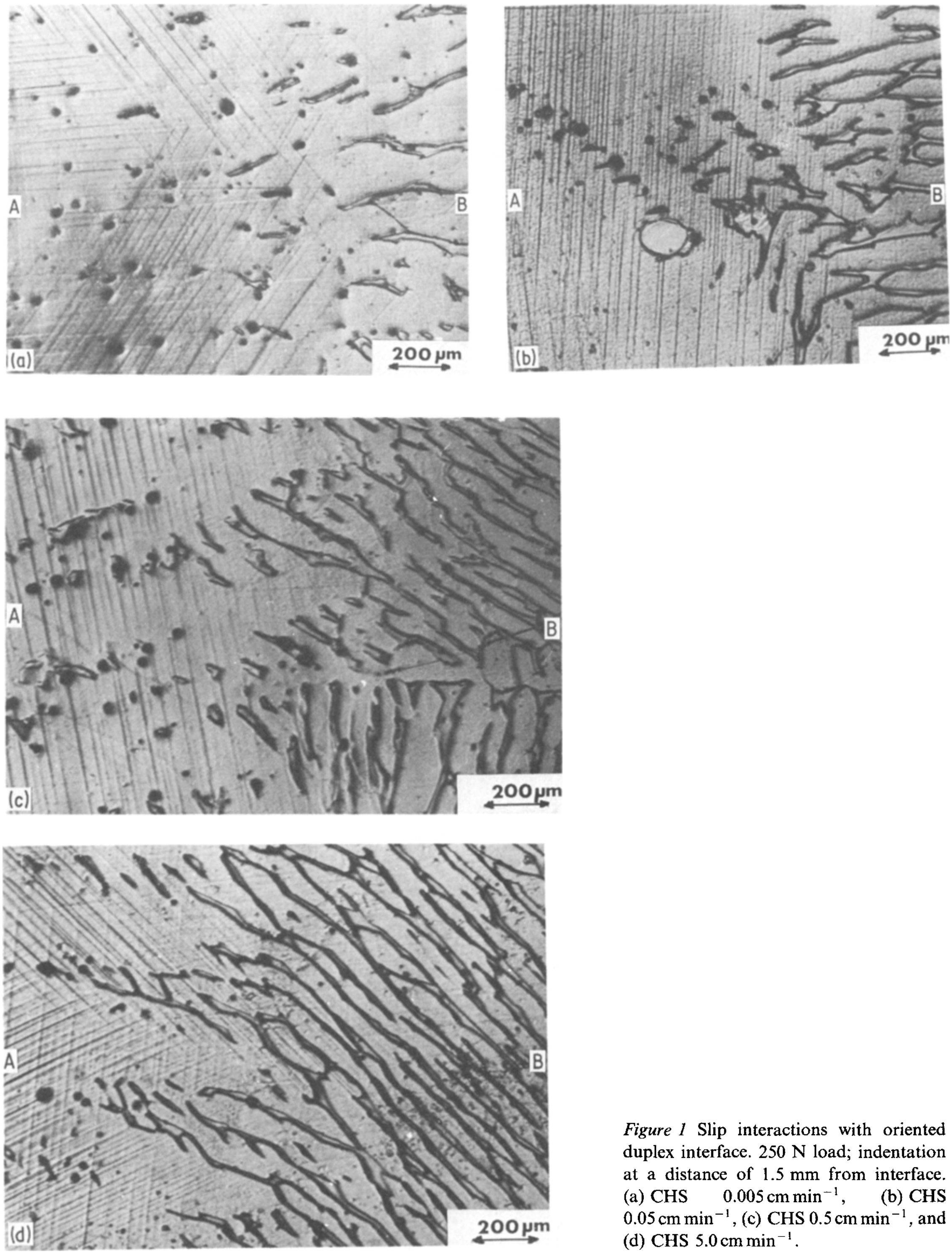


Figure 1 Slip interactions with oriented duplex interface. 250 N load; indentation at a distance of 1.5 mm from interface. (a) CHS 0.005 cm min^{-1}, (b) CHS 0.05 cm min^{-1}, (c) CHS 0.5 cm min^{-1}, and (d) CHS 5.0 cm min^{-1}.

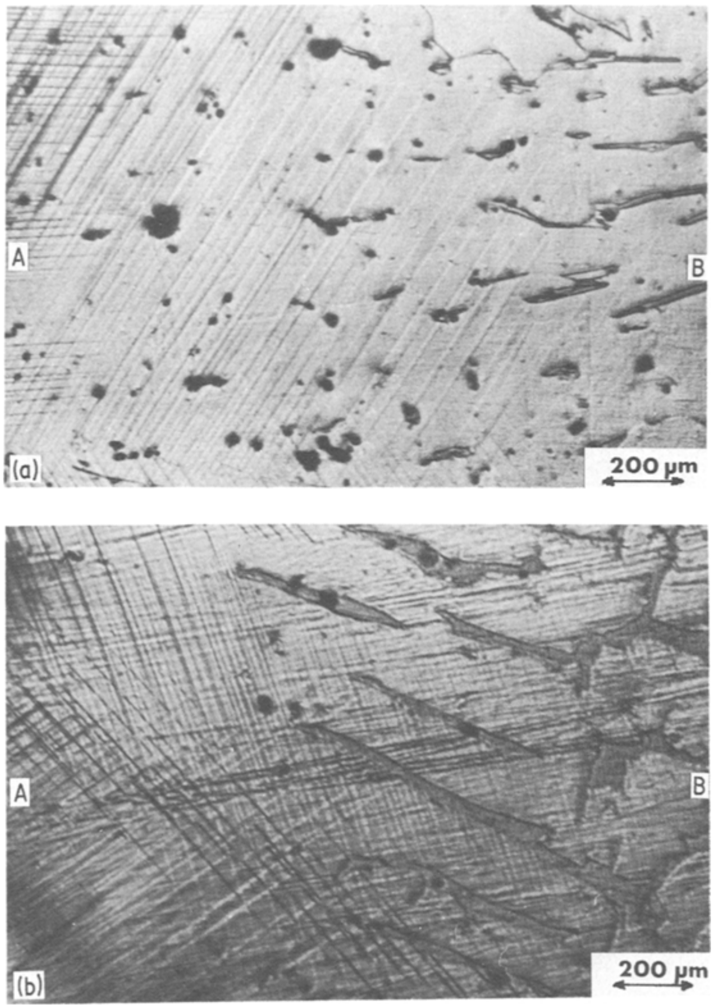


Figure 2 Slip interactions with oriented duplex interface. 250 N load; CHS $0.005\,cm\,min^{-1}$; indentation at (a) 1.5 mm, and (b) 0.5 mm.

tested under similar conditions, shown in Fig. 1b.

To investigate the effect of stress concentration on the equiaxed interface geometry, series of tests were conducted using a 400 N load, a close distance of indentation to the boundary of 0.5 mm, and various rates of indentation ranging from 0.005 to $5.0\,cm\,min^{-1}$. As anticipated from the results of the previous test series, for this load and distance of indentation to the interface, the higher rates of load application were more effective in generating a higher slip line density near the interface region. The effect of the various loading rates is shown in Figs. 7a to d; the slip line density in the interface region increases with increasing rates of load application. As found in the tests using the oriented duplex interface samples, a higher load coupled with a close distance of indentation to the interface, along with a high rate of load application produces more slip interactions with the interface structure. However, the equiaxed duplex interface geometry is not as effective a barrier to block the progress of slip as the oriented duplex interface geometry. This loading and distance of indentation to the boundary, even at a low CHS of $0.005\,cm\,min^{-1}$, produced considerable slip interaction with the portions of the equiaxed duplex interface regions near the alpha single crystal. This is shown in Fig. 7a, where extensive cross-slip is observed in the alpha phase. At higher loading rates, and particularly at the $5.0\,cm\,min^{-1}$ CHS, slip lines were observed to interact and progress through the beta phase regions present in the interface structure near the alpha single crystal. This most extreme stress concentration condition, however, was not effective in propagating slip through the interface

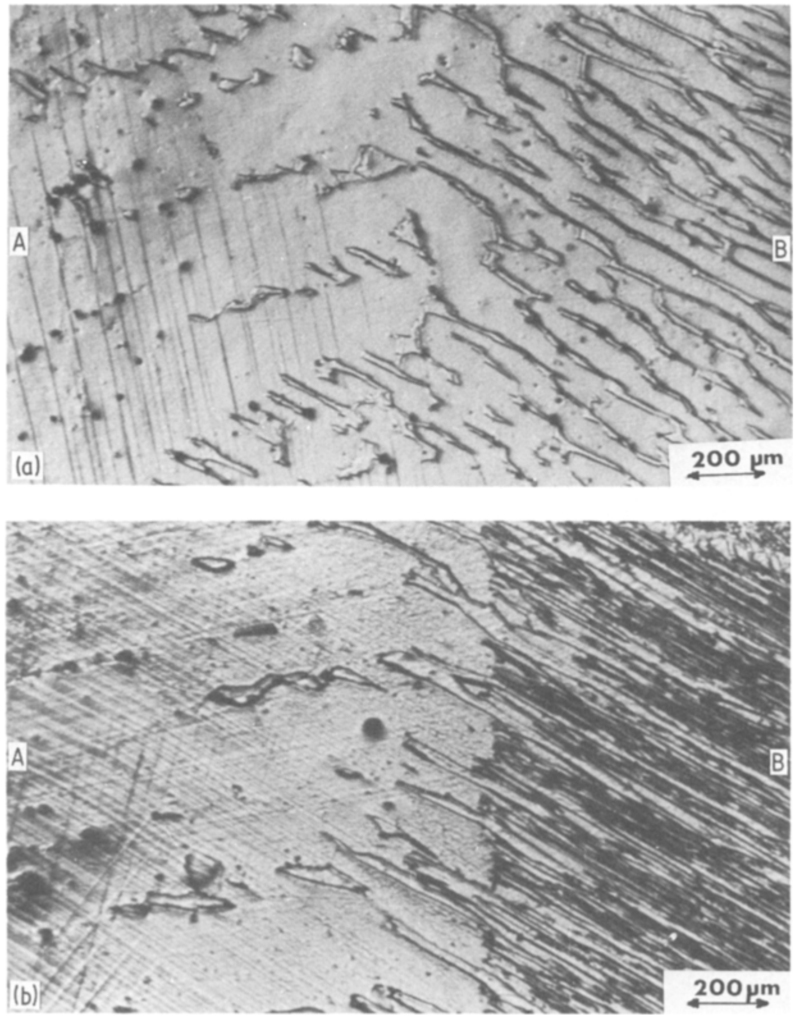


Figure 3 Slip interactions with a oriented duplex interface. 250 N load; CHS 0.5 cm min^{-1}; indentation at (a) 1.5 mm, and (b) 0.5mm.

structure into the beta phase present on the other side of the boundary.

The effect of varying the distance of indentation in the alpha phase from the interface is evident by comparing Figs. 8 and 7d. Both tests were conducted using 400 N load, and a CHS of 5.0 cm min^{-1}, but in one an indentation distance of 1.5 mm was used and in the other 0.5 mm was used. As shown by the comparison of these figures, when the indentation is made further away from the interface, the extent of slip interaction at the boundary is considerably less, and yet it is still capable of propagating slip partially through the interface structure. This effect is shown in Fig. 8, where the slip lines in the equiaxed alpha phase islands exist in regions further away from the alpha single crystal.

3.3. Flat boundary

The effect of stress concentration and slip interaction on flat bicrystal phase boundaries was also of interest in this study. The results of tests conducted using a 250 N load, indentation distances of 1.0 mm from the boundary, and crosshead speeds of 0.005 and 5.0 cm min^{-1}, are shown in Figs. 9a and b. Once again, as observed in other tests, the higher crosshead speed is more effective in generating more slip lines closer to the boundary than are low rates of loading. As may be seen in Fig. 9b where a high crosshead speed of 5.0 cm min^{-1} was used, the slip lines are both closer to the boundary and have a higher density compared to Fig. 9a.

Test conditions with a more severe stress concentration at the flat boundary were created by

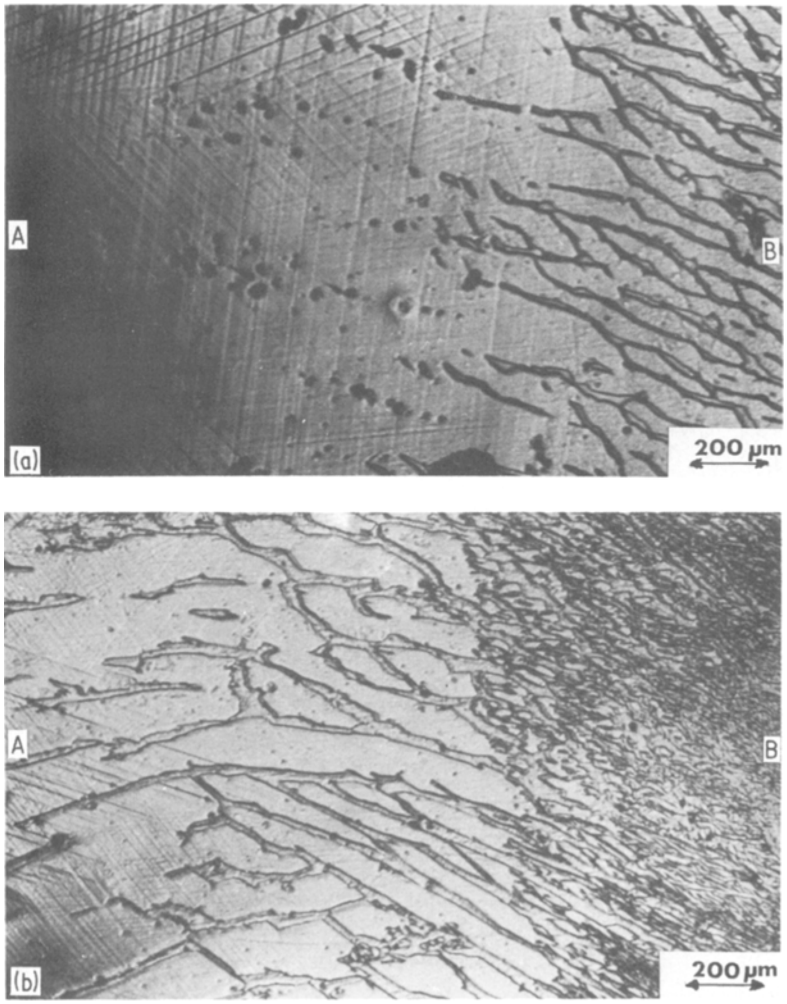


Figure 4 Slip interactions with oriented duplex interface. 250 N load; CHS $5.0\,cm\,min^{-1}$; indentation at (a) 1.5 mm, and (b) 0.5 mm.

using a 400 N load, an indentation distance of 1 mm to the boundary, and low and high crosshead speeds of 0.005 and $5.0\,cm\,min^{-1}$. These test results are shown in Figs. 10a and b and may be compared to Figs. 9a and b where all conditions were the same except for the load. The higher 400 N load, even at a low crosshead speed of $0.005\,cm\,min^{-1}$, as shown in Fig. 10a, produces considerable cross-slip and as well as multiple slip near the flat boundary. This condition is more severe as shown in Fig. 10b for a high crosshead speed of $5.0\,cm\,min^{-1}$. These test results show that the flat bicrystal boundary is a very effective barrier to the progress of slip lines produced by indentation.

3.4. Indentation in the interface region

Identation tests were also conducted by placing the indentation directly in the equiaxed duplex interface region, which has been found to be the least effective type of interface geometry for blocking slip during indentation. Extensive cross-slip in the alpha phase regions of the structure was observed and is shown in Figs. 11a and b at points marked Y. Some fine slip was observed to propagate into the beta phase adjacent to the alpha phase island, or through the phase boundaries. This is shown in Fig. 11a at points marked Z. This fine slip which is more prominent near the alpha–beta interface becomes very fine and diffuse at short distances

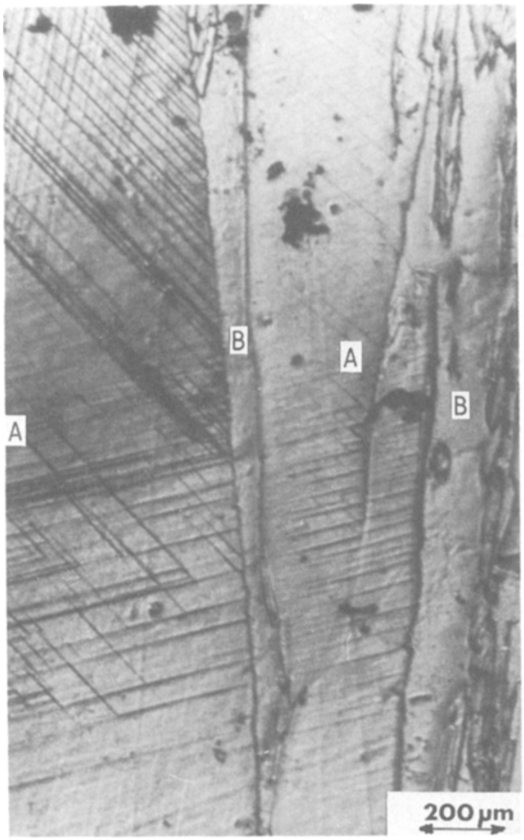


Figure 5 Slip interactions with oriented duplex interface. 400 N load; CHS $0.005\,cm\,min^{-1}$; indentation at 1.5 mm. Compare with Fig. 1a.

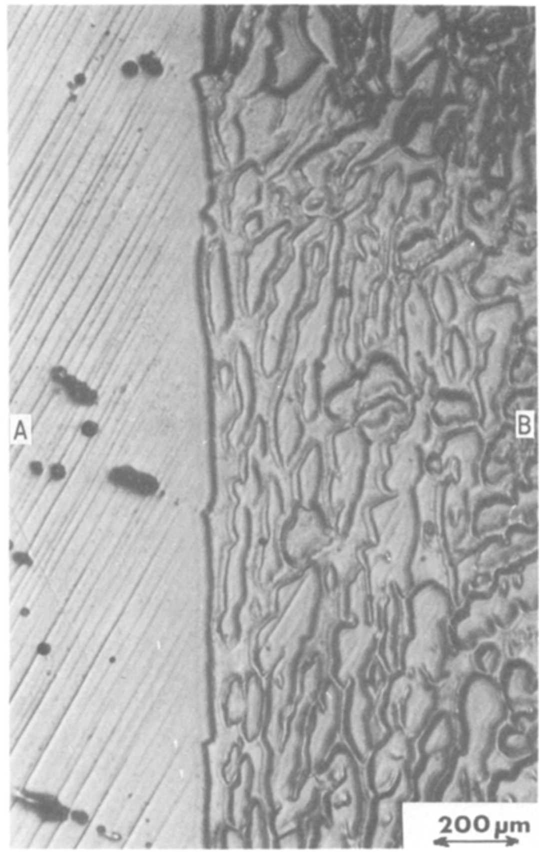


Figure 6 Slip interactions with equiaxed duplex interface. 250 N load; CHS $0.05\,cm\,min^{-1}$; indentation at 1.5 mm; compare with Fig. 1b.

away from the phase boundary in the beta phase. By indenting directly into the duplex interface, beta regions deformed slightly due to the very high local stress concentration. However, slip did not progress far enough in the beta regions to reach the beta grain in contact with the interface region.

3.5. Comparison with uniaxial tensile loading

Indentation loading creates a highly localized complicated stress state, whereas the uniaxial loading of the model system used (with phase boundary normal to the tensile axis) produces the same stress due to applied load at all regions of the specimen. The duration of load application in indentation is extremely short as compared to tensile loading in which the test is continued until the desired amount of deformation is produced. In addition, the indentation loading of ductile material such as alpha brass causes highly localized plastic deformation. At slow rates of indentation loading, the entire deformation is accommodated locally and slip does not progress far enough to interact with the phase boundary. At high rates of indentation loading, due to strain rate sensisivity, deformation is less localized and slip progresses comparatively further and interacts with the interface. On the other hand, during uniaxial tensile loading of similar specimens at higher strain rates, fine slip occurs in alpha and it is usually less effective for propagation of slip across the interphase boundary [1, 2].

Such differences between indentation loading and uniaxial tensile loading are fully consistent with the observed phase boundary effects. In general, slip in alpha due to indentation loading is not able to cause slip to progress through the phase boundary, since localized stress concentration is relieved by highly localized slip. In uniaxial loading the boundary experiences stress

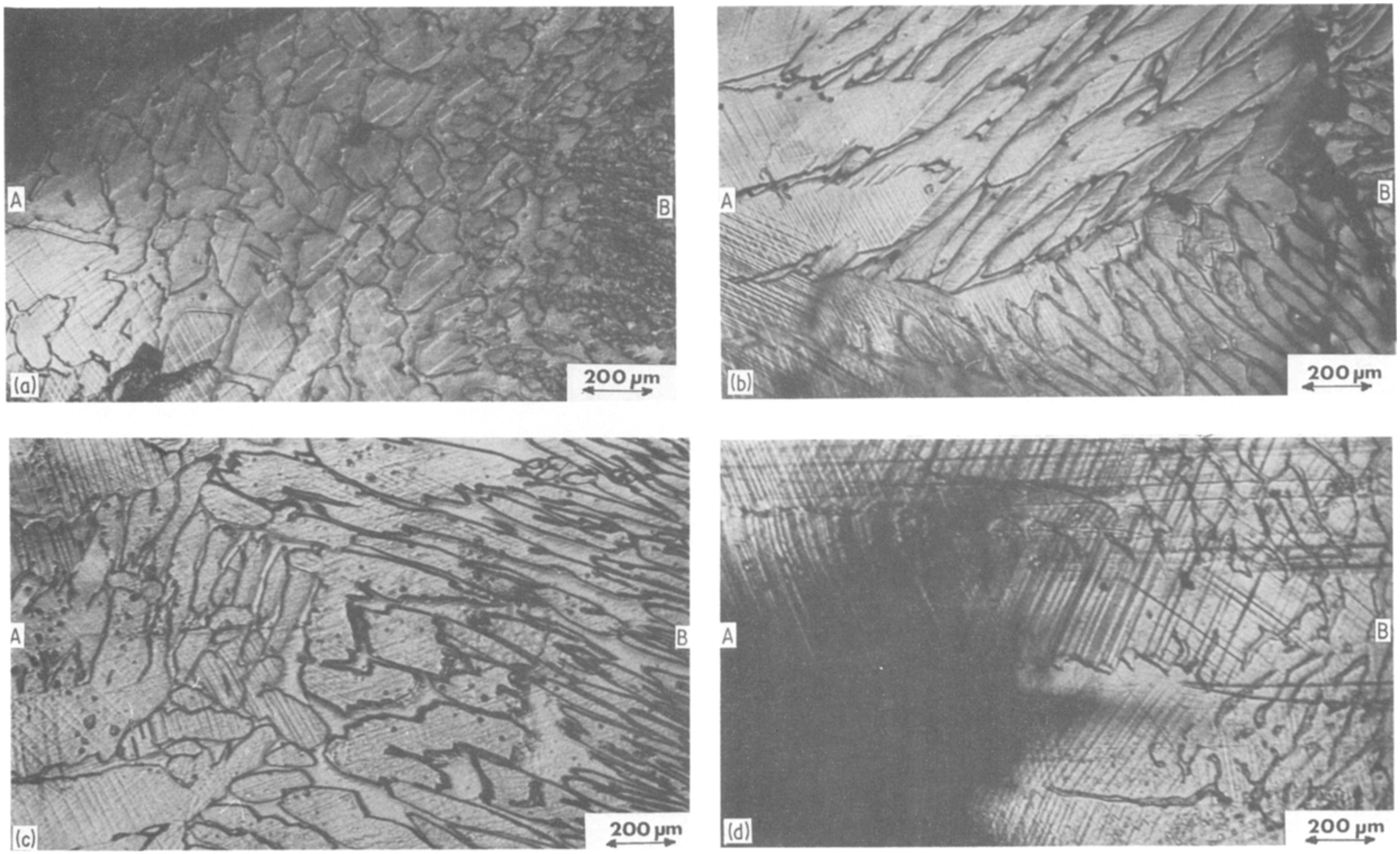


Figure 7 Slip interactions with equiaxed duplex interface. 400 N load; indentation at 0.5 mm from interface at various CHS. (a) CHS 0.005 cm min^{-1}, (b) CHS 0.05 cm min^{-1}, (c) CHS 0.5 cm min^{-1}, and (d) CHS 5.0 cm min^{-1}.

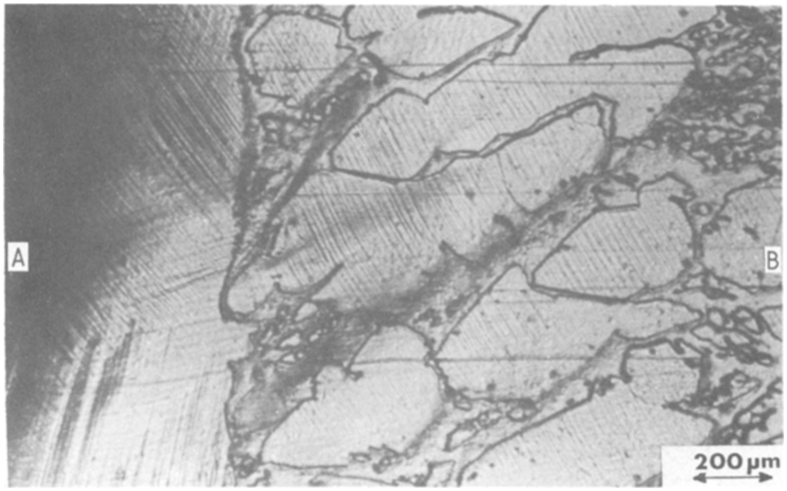


Figure 8 Slip interactions with equiaxed duplex interface. 400 N load; CHS 5.0 cm min^{-1} indentation at 1.5 mm from interface. Compare with Fig. 7d.

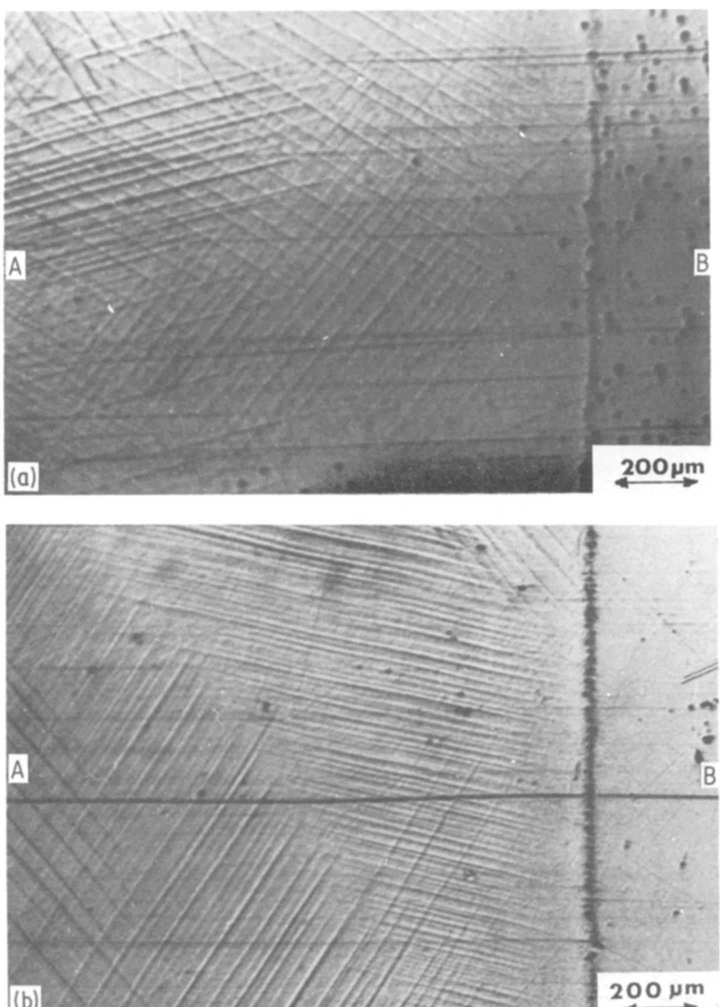


Figure 9 Slip interactions with bicrystal flat interface. 250 N load; indentation at 1.0 mm from interface at different rates of loading. (a) CHS 0.005 cm min^{-1}, and (b) CHS 5.0 cm min^{-1}.

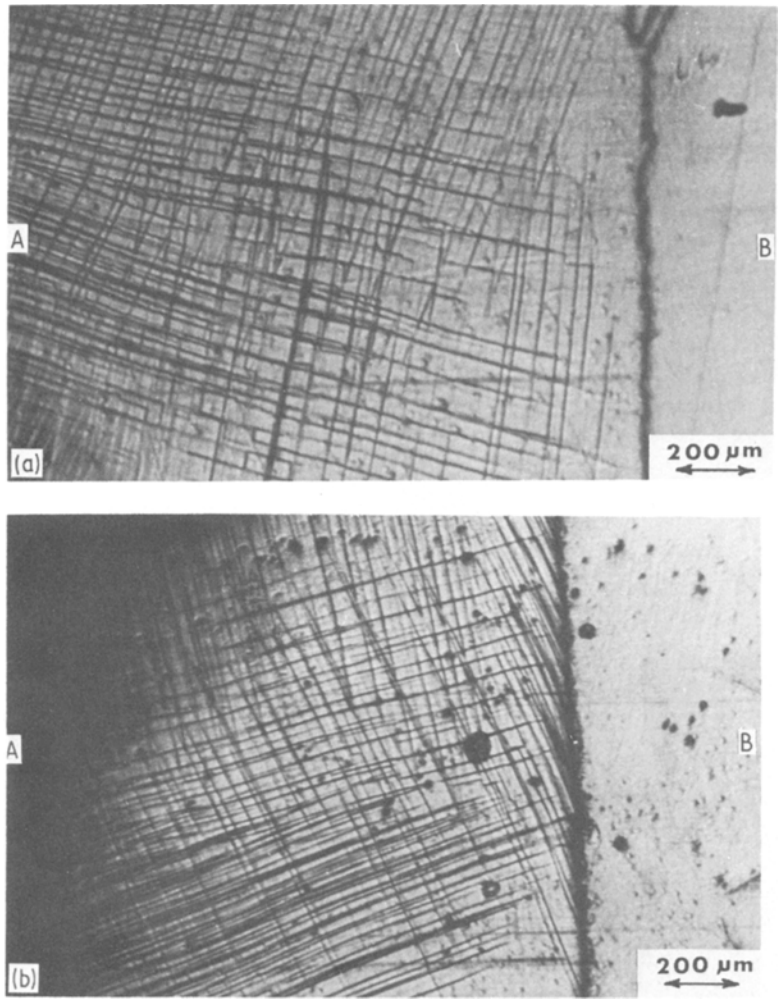


Figure 10 Slip interactions with flat interface bicrystal. 400 N load; indentation at 1.0 mm from interface at different rates of loading (a) CHS 0.005 cm min^{-1}, and (b) CHS 5.0 cm min^{-1}.

due to applied loading. The stress due to dislocation pile-up at the boundary acting in addition to the applied load aids in slip propagation across the boundary under such conditions.

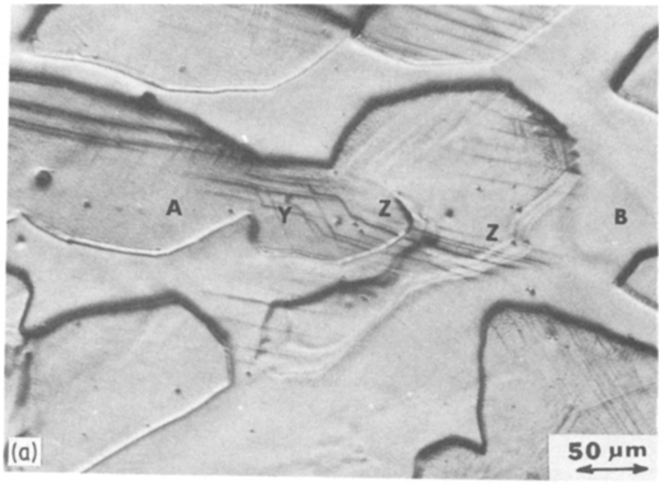
The equiaxed duplex interface consists of alpha and beta regions without any specific relative crystallographic registry. As a result, progress of slip from alpha to beta will be very difficult as has been observed under uniaxial tensile loading [1]. However, progress of slip through the alpha–beta interface has been observed only with equiaxed duplex interface, when large indentation loads are applied at close proximity to the interface. The complex stress state caused by indentation may be responsible for this behaviour.

4. Conclusions

1. It is not easy to propagate slip through the phase boundary by localized stresses caused by indentation, unless the indentation is placed right in the interface.
indentation is placed right in the interface.

2. Under indentation loading, equiaxed duplex phase boundary is not a very effective barrier for slip propagation. However, oriented duplex boundary effectively blocks slip during similar conditions. These results are just the opposite of what is observed under uniaxial loading of similar specimens.

3. Higher rates of indentation loading (unlike in uniaxial loading) results in slip distribution in alpha suitable for progress of slip across the phase boundary.



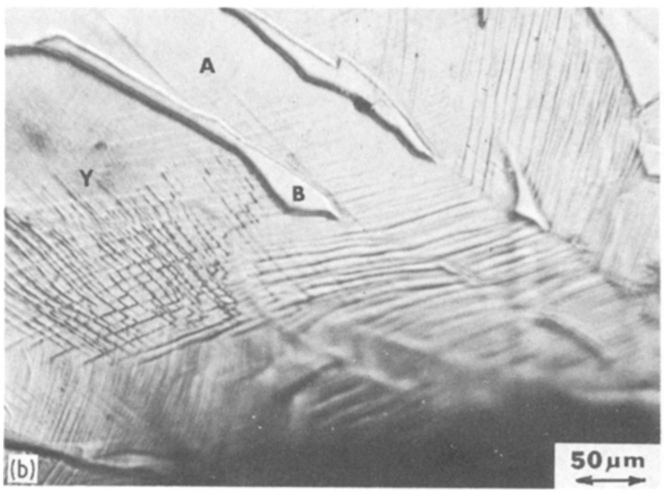


Figure 11 Slip interactions with equiaxed duplex interface; indentation in the duplex interface; CHS $0.05\,cm\,min^{-1}$. (a) Cross-slip and slip propagation through the boundaries. Slip in the beta phase regions at Z, and cross-slip in the alpha region at Y. (b) Extensive cross-slip in the alpha phase region at Y.

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