JOURNAL OF MATERIALS SCIENCE 19 (1984) 3185–3190

Elevated temperature deformation behaviour of alpha–beta brass bicrystals

Part 1 *Ordered beta*

A. KHEZRI-YAZDAN,* K. N. SUBRAMANIAN
Department of Metallurgy, Mechanics and Materials Science, Michigan State University, East Lansing, MI 48824-1226, USA

Elevated temperature deformation behaviour of alpha–beta brass was investigated by using a model system at temperatures just below the order–disorder transformation temperature (T_c) of beta. Although the deformation mode at these temperatues is very similar to that at room temperature, grain boundary sliding in beta becomes an important mode of deformation at low strain rates.

1. Introduction

Various basic investigations to understand the deformation behaviour of two-phase materials have been carried out in recent years with fundamental units such as two-phase bicrystals of alpha–beta brass [1–17]. These studies have dealt with specimens having their inter-phase boundary either parallel or perpendicular to the tensile axis so as to impose constant strain or constant stress in both phases. Most of these investigations have been carried out at room temperature although a very few tests have been at other test temperatures [12–14]. Inter-phase sliding in such bicrystals is also reported in literature [15–17].

Beta brass exhibits an order–disorder transformation at 454° C (T_c). In the ordered state it has a caesium chloride structure and its plastic deformation, which depends on multiplication and motion of superlattice dislocations, will be difficult. In the disordered state it has a body-centred cubic structure, and its deformation will be relatively easy. Alpha brass has a face-centred cubic structure and it does not exhibit any phase transformation in the solid state.

The main purpose of the present investigation is to study the deformation behaviour of alpha–beta brass bicrystals at temperatures just below and above the ordering temperature of beta, so as to understand the role of the order–disorder transformation on the elevated temperature deformation behaviour of this two-phase alloy. This paper is the first of a series of three papers, and will be devoted entirely to deformation studies in the temperature range below the transformation temperature, where beta will exist in the ordered state.

2. Experimental procedures

Growth of two-phase bicrystals of alpha–beta brass, and details of preparation of tensile specimens are described elsewhere [1, 2]. The specimens prepared by such procedures consist of a single crystal of alpha connected to a single large grain of beta to form the inter-phase boundary, although the beta region may have a few very large grains. In such specimens the inter-phase boundary will be normal to the length of the specimen and will experience tensile stress during testing. For the present investigations, tensile tests were carried out at 371 and 427° C (700 and 800° F), just below the order–disorder transformation temperature of beta. Test temperatures were obtained by using a split tube furnace having a constant temperature zone of about 4 inch. The specimens were heated in an argon atmosphere to prevent oxidation and discoloration. A glass tube with insulating seals at both ends was used to keep the argon atmosphere around the specimen.

*Present address: Islamic AZAD University, YAZD, Iran.

Furthermore, to keep the temperature of the specimen uniform, a copper sheet covered the interior surface of the furnace. The furnace temperature was controlled by a thermocouple which was kept very close to the heating element so that it could sense the temperature fluctuations very easily. The temperature of the specimen was monitored by four thermocouples which were in contact with the specimen. The setting of the controller for achieving a required temperature of the specimen was usually achieved with dummy specimens having several thermocouples silver-soldered to them. To reduce the heating of the rest of the system, and especially the load cell, water cooling was employed.

The tests were performed using an Instron testing machine with cross-head speeds of 0.02, 0.1, and 0.5 cm min^{-1}. The strain-rate and stresses experienced by individual phases were also calculated for each specimen. The specimens usually reached the required test temperatures in about 45 min. A very small crack was left open in the split tube furnace so that the deformation behaviour of the specimen could be studied using oblique lighting. During the heating of the specimen, care was taken to adjust the Instron crosshead position so that the specimen did not experience any stress. Similarly, at the end of the test, the load was released so that the specimen would not experience any further stress due to contraction during cooling.

The deformed samples were handled very carefully and were viewed with an optical microscope to study the deformation of alpha, beta and regions near the phase boundary. Furthermore, during the course of this investigation, retesting of any samples tested earlier was avoided since part of the damage in such specimens would anneal out on heating again. So once a sample was strained and the test stopped at some stage, it was never tested again regardless of the amount of deformation introduced in the sample.

3. Results and discussion

3.1. Deformation studies at 371° C

Specimens deformed at 371° C with a crosshead speed of 0.02 cm min^{-1} had relatively high yield stresses. In all specimens, the initial deformation took place by single slip in alpha at regions away from the boundary. As deformation progressed, these slip lines in alpha became deeper and approached the alpha–beta phase boundary. This left a triangular shaped undeformed portion in alpha in the region near the phase boundary, as shown in Fig. 1. Upon further straining, slip in alpha interacted with the phase boundary and resulted in deformation in the beta phase. Arrows represent the direction of the tensile axis, and "A" and "B" are used to point out alpha and beta phases in all figures.

Grain boundary sliding and slight deformation within the grains were observed in beta regions. Grain boundary sliding was observed in boundaries that had an orientation close to 45° to the tensile axis. Small cracks developed at the grain boundaries in beta due to non-uniform deformation of grains (caused by different orientations), as shown in Fig. 2. These specimens usually failed by grain boundary fracture in beta.

The initial deformation of specimens strained at 371° C with a crosshead speed of 0.1 cm min^{-1} occurred in alpha by single slip. On further straining, slip from alpha interacted with the phase boundary. The phase boundary resisted progression

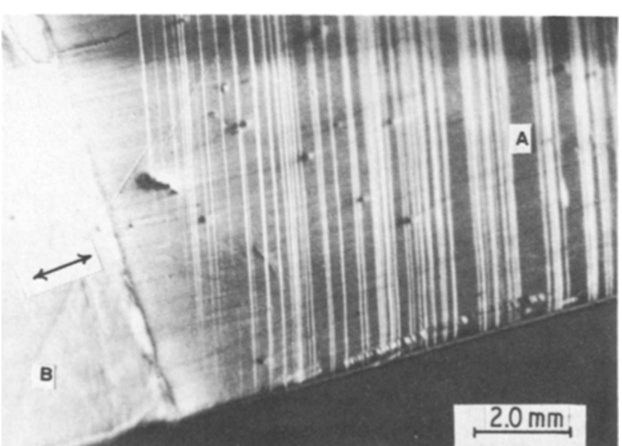

Figure 1 Interaction of slip in alpha with the alpha–beta phase boundary in a specimen tested at 371° C with a crosshead speed of 0.02 cm min^{-1}. Yield stress of alpha 34.3 MN m^{-2}. Critical resolved shear stress of alpha 16.2 MN m^{-2}. Total strain 3.4%.

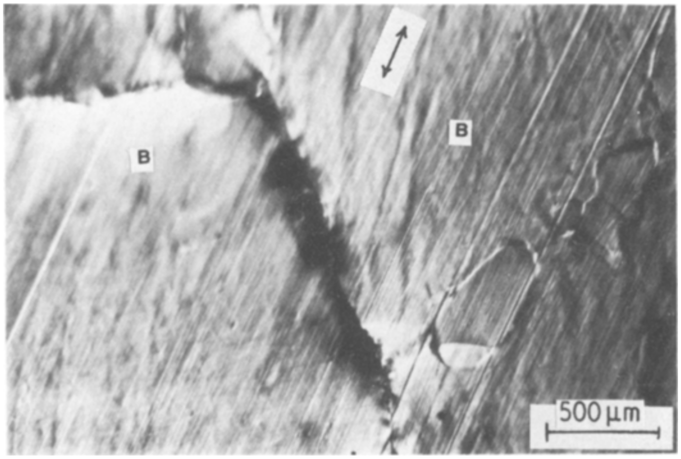

Figure 2 Small cracks developed in beta at the grain boundaries in a specimen tested at 371° C with a crosshead speed of 0.10 cm min^{-1}. Yield stress of alpha 31.9 MN m^{-2}. Critical resolved shear stress of alpha 14.7 MN m^{-2}. Total strain 10.2%.

of slip from the alpha phase to beta regions. Multiple slip in the alpha phase in regions near the boundary can be seen in Fig. 3. After extensive deformation, severe reduction in cross-sectional area of alpha occurred near the phase boundary. Beta deformed by grain boundary sliding and some of the beta grains near the phase boundary also deformed by slip. Stress–strain curves exhibited serrations that could be associated with grain boundary sliding in beta. The early stages of these curves are similar to the Stage I of the resolved shear stress against resolved shear strain plot for alpha brass single crystals.

The deformation behaviour of alpha in a bicrystal of alpha–beta brass, and the interaction of slip with the phase boundary at 371° C, were similar to those observed in specimens deformed at room temperature [2, 3]. In all these cases alpha brass deformed first. Deformation of beta, however, was accommodated by grain boundary sliding as well as by slip in individual grains. Grain boundary sliding in beta has never been observed in room temperature tests [2, 3]. Fracture took place in beta regions at the grain boundaries due to non-uniform deformation.

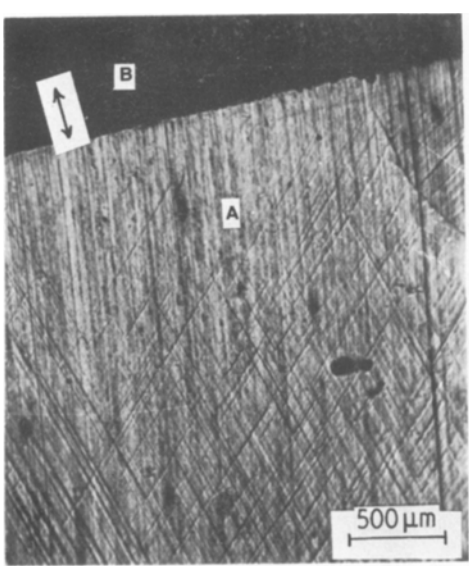

Figure 3 Multiple slip in alpha near the phase boundary in a specimen tested at 371° C with a crosshead speed of 0.10 cm min^{-1}. Yield stress of alpha 31.9 MN m^{-2}. Critical resolve shear stress of alpha 14.7 MN m^{-2}. Total strain 5.6%.

3.2. Deformation studies at 427° C

Specimens tested at 427° C and strained with a crosshead speed of 0.02 cm min^{-1} initially deformed in the beta phase by grain boundary sliding. During later stages of deformation, beta grains with a favourable orientation deformed by slip, as can be seen in Fig. 4. If the deformation of a favourably-oriented boundary is not stopped by the change in its orientation relative to the tensile axis in some regions, or by the interaction with other unfavourably-oriented boundaries, the entire deformation could have been accommodated by grain boundary sliding alone. In such cases the deformation of beta grains by slip is unnecessary. However, in the specimens tested during the course of this investigation, the grain boundaries in beta often intersected each other. Consequently, there was resistance to the progression of grain boundary sliding. So, beta grains deformed by slip due to shear stresses imposed by uneven deformation between beta grains. This behaviour is illustrated in Fig. 4b. In particular, grains having smaller width and sharper edges in the vicinity of larger grains deformed more than the others. Similar observations have been made with respect

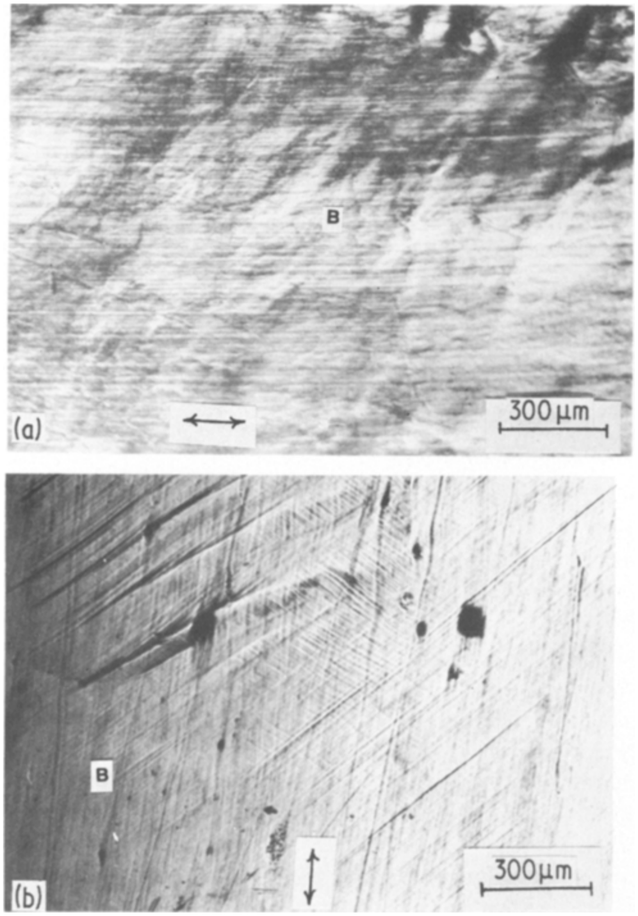

Figure 4 (a) Rumpled appearance in beta deformed at 427° C with a crosshead speed of 0.02 cm min^{-1}. Yield stress of beta 22.0 MN m^{-2}. Critical resolved shear stress of beta 10.8 MN m^{-2}. Total strain 4.9%. (b) Deformation of beta in a most favourably oriented grain by coarse slip, when grain boundary sliding is unable to accommodate the entire deformation, in a specimen tested at 427° C with a crosshead speed of 0.50 cm min^{-1}. Yield stress of alpha 33.3 MN m^{-2}. Critical resolved shear stress of alpha 13.2 MN m^{-2}. Total strain 12.9%.

to non-uniformity in the deformation by Baro [18], and the observations presented here are in complete agreement with his work. In all specimens, alpha did not deform plastically at all. The interaction of slip from beta region with the phase boundary did not result in any deformation in alpha phase.

Specimens tested at 427° C and strained at 0.10 cm min^{-1} initially deformed in alpha by single slip. Slip in alpha intersected with the phase boundary. In the region near the phase boundary beta acquired a rumpled appearance. Fig. 5 illustrates the interaction of slip from both alpha and beta regions with the phase boundary. In this

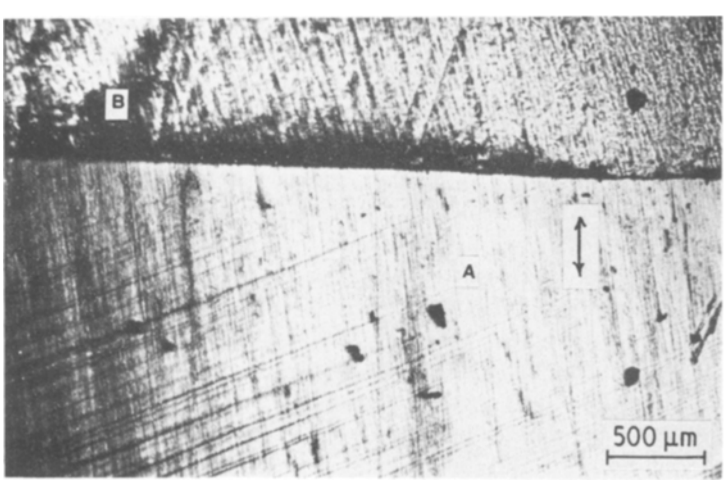

Figure 5 Independent slipping of alpha and beta in the region near the phase boundary in a specimen tested at 427° C with a crosshead speed of 0.10 cm min^{-1}. Yield stress of alpha 22.0 MN m^{-2}. Critical resolved shear stress of alpha 10.8 MN m^{-2}. Total strain 3%.

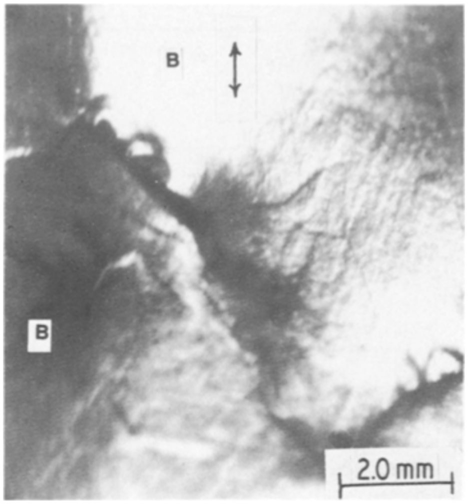

Figure 6 Grain boundary sliding leading to severe deformation of beta grains away from the phase boundary in a specimen tested at 427° C with a crosshead speed of 0.10 cm min^{-1}. Yield stress of alpha 36.5 MN m^{-2}. Critical resolved shear of alpha 16.2 MN m^{-2}. Total strain 3%.

specimen beta also deformed by grain boundary sliding. The deformation in the entire gauge length of the beta phase seemed uniform. The grain boundary sliding and slip in beta can be observed in Fig. 6. Stress–strain plots of these specimens did not exhibit any evidence of work hardening. The process of grain boundary sliding in beta caused large intermittent load drops during the early stages of deformation. As the deformation progressed, the amplitude of the load drops decreased and the fluctuations finally stopped. From this point on, the rest of the deformation occurred by slip in alpha and beta grains.

At a cross-head speed of 0.5 cm min^{-1} and test temperature of 427° C, initial deformation took place in the alpha phase by single slip. Some multiple slip lines were observed in alpha. Multiple slipping resulted from the interaction of slip in alpha with the phase boundary. Beta grains near the phase boundary were deformed either due to the slip interaction in alpha with the phase boundary or on their own. The latter seemed to be more probable since no slip traces were found in contact with the phase boundary. These specimens fractured in the beta phase near the grain boundaries. The fracture progressed along those grain boundaries that were nearly perpendicular to the tensile axis.

Observations made on specimens deformed at 427° C with various strain-rates indicated that at a low strain-rate, deformation of alpha occurs by single slip after grain boundary sliding in beta. Grain boundary sliding has not been found to be significant at high strain-rates. Most of the specimens failed in the beta phase, as a result of build-up of stress concentration at grain boundaries in the beta.

3.3. Remarks on specimens deformed at temperatures below T_c (454° C) of beta brass

Deformation by grain boundary sliding in beta occurs in all of the specimens. However, grain boundary sliding is important only at high temperatures and low strain-rates. At low temperatures and high strain-rates, specimens failed in the beta phase along the grain boundaries. As the temperature was increased, more deformation was accommodated by either of the phases. The alpha phase deformed by single slip and the beta phase deformed by grain boundary sliding. These specimens exhibited a high strain-rate sensitivity and resulted in inter-crystalline fractures. At 371° C a crosshead speed of 0.02 cm min^{-1}, and at 427° C a crosshead speed of 0.1 cm min^{-1} were found to be suitable for imposing uniform deformation in both the phases. The quantitative data for some of these tests are given in Tables I and II. In these tables, actual strain-rates experienced by the individual phases in bicrystals of alpha–beta brass are also given along with the crosshead speed (CHS) of the Instron machine in the test. These calculations are carried out because the lengths of each phase present in the bicrystal specimens were not the same. $\dot{\epsilon}_\alpha$ is the strain-rate in the alpha phase and is calculated by dividing the crosshead speeds by

TABLE I Quantitative results for bicrystals deformed at 371° C

CHS (cm min^{-1})	Strain-rate (min^{-1})			Strain			$\dot{\epsilon}_\alpha/\dot{\epsilon}_\beta$	$\epsilon_\alpha/\epsilon_\beta$	PDF	Yield stress of PDF (MN m^{-2})
	$\dot{\epsilon}_\alpha$	$\dot{\epsilon}_\beta$	$\dot{\epsilon}_{Average}$	ϵ_α	ϵ_β	$\epsilon_{Average}$				
0.1	0.0399	0.0365	0.0178	0.154	0.0470	0.102	1.09	3.2	α	31.9
0.02	0.0074	0.0085	0.0039	0.0070	0.0080	0.008	0.87	0.875	β	34.3
0.02	0.0066	0.0100	0.0039	0.390	0.0260	0.034	0.66	1.5	α	34.3

TABLE II Quantitative results for bicrystals deformed at 427° C

CHS ($cm\,min^{-1}$)	Strain-rate (min^{-1})			Strain			$\dot{\epsilon}_\alpha/\dot{\epsilon}_\beta$	$\epsilon_\alpha/\epsilon_\beta$	PDF	Yield stress of PDF ($MN\,m^{-2}$)
	$\dot{\epsilon}_\alpha$	$\dot{\epsilon}_\beta$	$\dot{\epsilon}_{Average}$	ϵ_α	ϵ_β	$\epsilon_{Average}$				
0.5	0.174	0.176	0.087	0.219	0.039	0.129	0.99	5.6	α	33.3
0.5	0.161	0.191	0.087	0.285	0.027	0.167	0.84	10.5	α	30.2
0.1	0.041	0.059	0.024	–	0.018	–	0.69	–	α	25.1
0.1	0.036	0.032	0.017	0.036	0.024	0.03	1.13	1.5	α	36.5
0.1	0.035	0.065	0.023	0.035	0.035	0.03	0.54	1.0	α	29.5
0.02	0.008	0.011	0.005	0.099	0.200	0.141	0.73	0.49	α	27.8
0.02	0.006	0.007	0.004	–	0.100	0.280	0.86	–	β	22.0

the lengths of alpha. ϵ_α is the strain measured in the alpha phase after the test is completed. In these tables, the phase that deformed first (PDF) is also included, since the given yield stresses may belong either to the alpha or beta phase. Similarly, strain-rates ($\dot{\epsilon}_\beta$) and strain (ϵ_β) were also calculated for the beta phase. The average strain was calculated by using the total gauge length of the bicrystals. The tables also include the ratio of the strain accommodated in alpha and beta phases. These calculations, in terms of strain-rate and strains in each phase, become essential because the gauge lengths of the alpha and beta regions in these bicrystals were not the same. Qualitative observations made on specimens deformed at 427° C are presented in Table III.

4. Conclusions

Deformation studies on two-phase bicrystals of alpha–beta brass at temperatures just below T_c for the beta phase show that at low strain-rates beta deforms by grain boundary sliding, and the initial deformation occurs usually in alpha. At high strain-rates, grain boundary sliding in beta is minimal and most of the deformation is accommodated in the alpha phase.

References

1. A. K. HINGWE and K. N. SUBRAMANIAN, *J. Crystal Growth* **21** (1974) 287.
2. *Idem, J. Mater. Sci.* **10** (1975) 183.
3. C. F. NILSEN and K. N. SUBRAMANIAN, *ibid.* **19** (1984) 768.
4. T. TAKASUGI, O. IZUMI and N. FAT-HALLA, *ibid.* **13** (1978) 2013.
5. N. FAT-HALLA, T. TAKASUGI and O. IZUMI, *ibid.* **15** (1980) 3071.
6. T. TAKASUGI, N. FAT-HALLA and O. IZUMI, *Acta Metall.* **26** (1978) 1453.
7. N. FAT-HALLA, T. TAKASUGI and O. IZUMI, *J. Mater. Sci.* **13** (1978) 2462.
8. T. TAKASUGI, N. FAT-HALLA and O. IZUMI, "Strength of Metals and Alloys", Vol. 1, Fifth International Conference (Pergamon Press, Oxford and New York, 1982) p. 199.
9. T. TAKASUGI, O. IZUMI and N. FAT-HALLA, *J. Mater. Sci.* **15** (1980) 945.
10. H. KAWAZOE, T. TAKAYUKI and O. IZUMI, *Acta Metall.* **28** (1980) 1253.
11. A. EBERHARDT, M. SUERY and B. BAUDELET, *Scripta Metall.* **9** (1975) 1231.
12. N. FAT-HALLA, T. TAKASUGI and O. IZUMI, *J. Mater. Sci.* **14** (1979) 1651.
13. *Idem, Met. Trans.* **10A** (1979) 1341.
14. *Idem, Trans. J. Inst. Met.* **20** (1979) 493.
15. T. TAKASUGI and O. IZUMI, *Acta Metall.* **28** (1980) 465.
16. A. EBERHARDT and B. BAUDELET, *Phil. Mag.* **A41** (1980) 843.
17. H. SUZUKI, T. TAKASUGI and O. IZUMI, *Acta Metall.* **30** (1982) 1647.
18. G. BARO, *Z. Metallkde* **7** (1972) 384.

Received 3 October and accepted 3 November 1983

TABLE III Qualitative observations made on specimens deformed at 427°C

CHS ($cm\,min^{-1}$)	Deformation of alpha	Deformation of beta	Initial deformation	Region of failure
0.02	Single slip in alpha. Very little cross-slip	Coarse slip and rumpling	Alpha	–
0.1	Single slip approaching boundary. Uniform deformation	None	Alpha	–
0.1	Single slip	None	Alpha	In a grain boundary in beta
0.5	Single slip. Non-uniform deformation	Rumpled appearance	Alpha	Beta