JOURNAL OF MATERIALS SCIENCE 19 (1984) 3196–3200

Elevated temperature deformation behaviour of alpha–beta brass bicrystals

Part 3 *Supporting studies*

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

The deformation behaviour of alpha and beta brass was investigated at temperatures just above and below the ordering temperature of beta. Deformation of beta, unlike alpha, was found to be highly sensitive to temperature and strain-rate. The predominant mode of deformation in beta at temperatures below T_c (the ordering temperature) was by grain boundary sliding and at temperatures above T_c it was by slip. Furthermore, beta did not exhibit any work-hardening at temperatures above T_c. The elevated temperature deformation behaviour of two-phase bicrystals of alpha–beta brass, with inter-phase boundary normal to the tensile axis, depended on the deformation of the individual phases.

1. Introduction

The elevated temperature deformation behaviour of alpha–beta brass has been studied recently using a model system to try to understand the role of the order–disorder transformation in the beta phase [1, 2]. This model system consisted of a single crystal of alpha joined to a large-grained polycrystal of beta, although the inter-phase boundary region usually consisted of a single large grain of beta in contact with the single crystal of alpha [3]. The deformation characteristics of such a model system will depend on the deformation of single crystal of alpha, individual grains of beta, grain boundaries in beta, and the inter-phase boundary. Elevated temperature deformation of this model system was found to be quite different from that at room temperature [4–6]. In order to understand this difference, single crystals of alpha and beta, polycrystals of beta, as well as two-phase alpha–beta brass (Muntz metal), were deformed at temperatures just above and below the order–disorder transformation temperature (T_c) of beta.

A review of the deformation behaviour of the model system used has already been presented in an earlier paper [1]. The present paper is the third in a series of three papers devoted to elevated temperature deformation behaviour of alpha–beta brass with a model system, and will be concerned with supporting studies to explain the results presented in the earlier papers [1, 2].

2. Experimental procedures

Single crystals of alpha and beta brass were grown by the Bridgeman method. These crystals were annealed at 800° C for 16 h to remove micro-segregation, as suggested by Maddin [7]. The tensile specimen preparation procedures used were similar to those of two-phase bicrystals of alpha–beta brass [1–2, 4–6]. The test methods used for elevated temperature studies were exactly the same as those used for two-phase bicrystals of alpha–beta brass [1]. Polycrystalline two-phase alpha–beta brass specimens were prepared from commercial 60 Cu–40 Zn alloy (Muntz metal).

3. Results and discussion

In order to understand the role of elevated temperature deformation behaviour of the individual phases on the overall deformation of two-phase bicrystals, single crystals of alpha and beta, as well as polycrystals of beta and alpha–beta brass, were strained at 371, 427, 482 and 538° C (700, 800,

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

 0022–2461/84 $03.00 + .12

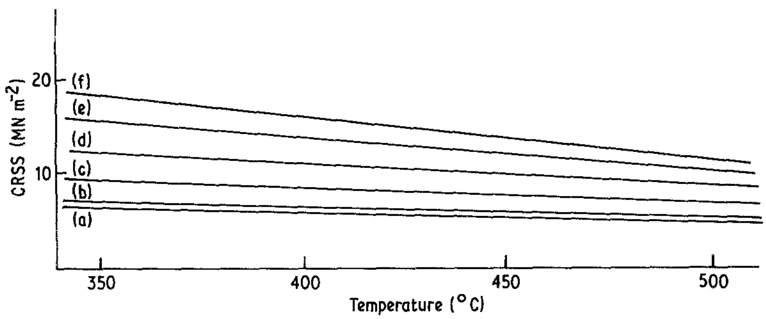

Figure 1 Critical resolved shear stress for alpha brass single crystals tested at temperatures ranging from 371 to 538° C. (a) Strain-rate 0.01 min^{-1}; (b) 0.02 min^{-1}; (c) 0.05 min^{-1}; (d) 0.10 min^{-1}; (e) 0.15 min^{-1}; and (f) 0.20 min^{-1}.

900 and 1000° F) at various strain-rates. Studies with two-phase bicrystals of alpha–beta brass have shown that the inter-phase boundary, oriented normal to the tensile axis, does not play any role in the overall deformation at elevated temperatures [1, 2].

3.1. Deformation behaviour of alpha brass single crystals at elevated temperatures

Critical resolved shear stresses (CRSS) for alpha brass single crystals deformed at various temperatures with different crosshead speeds (CHS) were plotted as functions of strain-rates. From these plots, CRSS for strain-rates of 0.01, 0.02, 0.05, 0.10, 0.15 and 0.20 min^{-1} at various temperatures were obtained. Results of this analysis are presented in Fig. 1. CRSS of alpha brass decreases gradually with increase in test temperature.

3.2. Deformation behaviour of single, bi- and poly-crystals of beta brass at elevated temperatures

Using a procedure similar to that for alpha brass, CRSS of single crystals and yield stress (YS) of polycrystals of beta brass were obtained at various strain-rates and temperatures. Results of these analyses are presented in Figs. 2 and 3. CRSS and YS decrease drastically in the transformation temperature (T_c) range as a result of a change from order to disorder state in beta. Such a sudden drop in CRSS has been explained on the basis of decrease in short-range order [8]. Comparison of Figs. 2 and 3 with that of Fig. 1 indicates that CRSS (and YS) of beta is more strain-rate and temperature sensitive compared to that of alpha.

It was observed that at low strain-rates, the deformation of beta proceeded by creeping at temperatures above T_c. Coarse slip lines were seen on deformed samples of beta brass single crystals strained at low strain-rates and fine slip lines on specimens strained at high strain-rates. Often heavily deformed beta brass single crystals had a rumpled appearance. It is observed that grain boundaries in beta brass undergo grain boundary sliding at temperatures above 400° C [9]. Grain boundaries in beta brass are highly sensitive to the rate of deformation [10]. The deformation of beta brass is more or less accommodated in the grain boundaries by grain boundary sliding below T_c. Those grain boundaries, with an orientation close to 45° with the tensile axis, undergo continuous deformation [11]. Grain boundaries with orientations perpendicular or parallel to the tensile axis undergo very little grain boundary sliding. Both beta grains and grain boundaries resist deformation at high strain-rates.

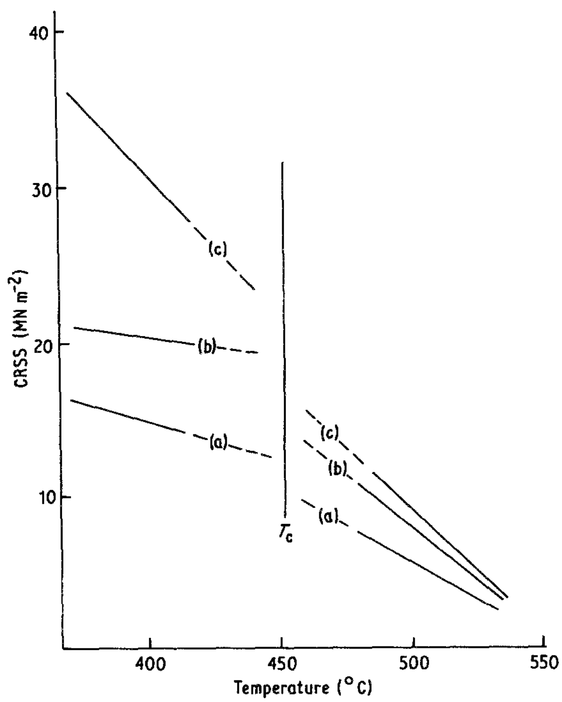

Figure 2 Yield stress for beta brass single crystals tested at elevated temperature and strained at various strain-rates. (a) Strain-rate 0.02 min^{-1}; (b) 0.10 min^{-1}; and (c) 0.20 min^{-1}.

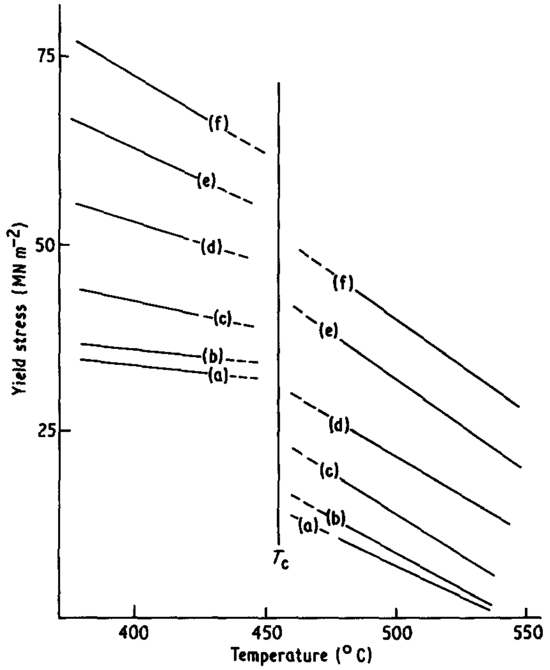

Figure 3 Yield stress for beta brass polycrystals tested at elevated temperatures and strained at various strain-rates. (a) Strain-rate $0.01\,min^{-1}$; (b) $0.02\,min^{-1}$; (c) $0.05\,min^{-1}$; (d) $0.10\,min^{-1}$; (e) $0.15\,min^{-1}$; and (f) $0.20\,min^{-1}$.

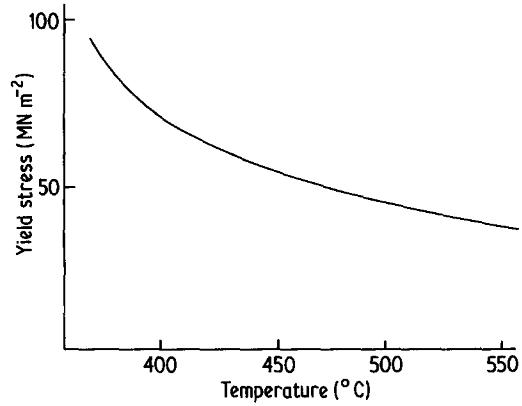

Figure 4 Yield stress for 60 Cu–40 Zn alpha–beta brass (Muntz metal) tested at elevated temperatures with a strain-rate of $0.04\,min^{-1}$.

Grain boundary deformation was observed in most cases when the test temperature was high and the strain-rate was low. Formation of cracks at grain boundaries in beta brass has been observed quite frequently [12].

3.3. Deformation behaviour of two-phase 60 Cu–40 Zn alloy (Muntz metal) at elevated temperatures

Tensile tests on 60 Cu–40 Zn alpha–beta brass polycrystals were carried out with various strain-rates at different temperatures. The yield stress of this alloy increased with increasing strain-rate and decreased with increasing test temperature. This agrees with results obtained for most two-phase polycrystalline materials [13]. Variation of yield stress of this alloy with temperature at a specific strain-rate is presented in Fig. 4. The yield stress of this alloy does not exhibit any abrupt change at the transformation temperature (T_c) of the beta phase. Surey and Baudelet report strain-rate sensitivity for this alloy even at 600° C [12].

Baro's investigations of alpha–beta brass at temperatures above T_c for beta indicate that moving dislocations also contribute to the total deformation, along with grain boundary sliding [13]. The two processes depend on one another and the deformation proceeds so that no stress concentrations result. The reorientation of hard alpha phase at elevated temperature has been compared to flotation of alpha in soft beta phase.

3.4. Deformation behaviour of two-phase bicrystals of alpha–beta brass

Some of the major differences found in the deformation behaviour of bicrystals of alpha–beta at room temperature and at elevated temperatures are reviewed in Table I. A summary of the observations made on the deformation behaviour of two-phase alpha–beta brass bicrystals tested at elevated temperatures is presented in Table II.

At test temperatures just below T_c the alpha phase is softer than beta, even though beta deforms by a grain boundary sliding mechanism. However, at low test temperatures and strain-rates, some regions in alpha deform first. When alpha experiences strain-hardening, the stress level rises in the specimen and ultimately beta deforms either by the interaction of slip in the alpha phase with the phase boundary or deforms on its own.

Above T_c the beta phase is the softer phase. Once beta deforms, either beta fractures (low temperature, high strain-rates and presence of grain boundaries perpendicular to the tensile axis) or deforms by creeping (high temperature and low strain rates) until the end of the test. At temperatures above T_c beta exists in the b c c structure and it has been found that beta deforms more easily than the alpha phase, and it is difficult to produce

TABLE I Deformation behaviour of alpha–beta brass bicrystals at low and high temperatures (cross-head speed = 0.10 cm min^{-1})

	Room temperature	Elevated temperature
Sequence of deformation	Initially in α and finally in β	Initially in α and then in β below T_c. Initially in β and then in α above T_c
Role of phase boundary (normal to tensile axis)	Effective barrier for propagation of slip from α to β	Does not play any role
Slip behaviour	Single slip, multiple slip and cross-slip in α, and single slip in β	Single slip both in α and β
Overall deformation of two-phase bicrystals	Highly non-uniform	Relatively uniform at specific temperatures and specific strain-rates; otherwise non-uniform
Fracture behaviour	Fracture after extensive deformation in α	Grain boundary fracture in β below T_c and needle-point fracture in β above T_c

TABLE II Deformation behaviour of two-phase alpha–beta brass bicrystals at elevated temperatures – summary

Temperature (°C)	Strain-rate*	Sequence of deformation	Slip behaviour	Mode of deformation	Region of failure
371	Low	Grain boundary sliding in β and then slip in α	Single slip and multiple slip in α; grain boundary sliding and fine slip in β	Uniform	β
	Medium	Grain boundary sliding in β and then slip in α	Single slip, multiple slip and cross-slip in α; grain boundary sliding and single slip in β	Non-uniform	β
427	Low	Grain boundary sliding in β	Single slip in α; grain boundary sliding, fine slip and rumpling in β	Non-uniform	β
	Medium	Grain boundary sliding in β and then slip in α and β	Single slip in α; coarse slip and rumpling in β	Uniform	β
	High	Minimal grain boundary sliding in β and then slip in α and β	Single slip in α and coarse slip in β	Non-uniform	β
482	Low	Slip in β grains	No slip in α, single slip and rumpling in β	Non-uniform	β
	Medium	Slip in β grains and then minimal slip in α	Rumpling in β and single slip in α	Non-uniform	β
	High	Slip in β and then slip in α	No slip in α and extensive deformation in β	Uniform	β
538	Low	Slip in β grains	No slip in α and extensive deformation in β	Non-uniform	β
	High	Slip in β grains	No slip in α and extensive deformation in β	Non-uniform	β

*Strain-rates: low ~ 0.005 sec^{-1}; medium ~ 0.025 sec^{-1}; high ~ 0.10 sec^{-1}.

the stress level in the alpha phase (hard phase) required to deform it. It is only by using a high strain-rate that the deformation of the alpha phase becomes possible.

These observations are consistent with that of Baro, who reports that the alpha platelets (harder phase above T_c) reorient along their longer dimensions with the tensile axis during elevated temperature deformation, while the beta phase plays the role of a soft matrix, making the alignment of alpha platelets possible [13].

3.5. Factors that influence uniform deformation of both the phases present in a two-phase material

One of the main objectives of this work is to find conditions for obtaining uniform deformation in both the phases present in a two-phase material. The total number of available slip systems in each of the phases present in two-phase materials is different. As a result, temperature sensitivity, strain-rate sensitivity and phase transformation can be utilized to promote uniform deformation in both phases. There are many factors that control the deformation behaviour of a two-phase material. For instance, there is always a possibility that one phase may still be deforming in an elastic manner while the other is deforming plastically. Generally, at different test temperatures, one phase remains harder than the other. By imposing a proper crosshead speed (strain-rate) on a two-phase bicrystal, a uniform deformation could be achieved provided the strain-rate sensitivities of both the phases are different. The role of the phase boundary in the overall deformation behaviour of such two-phase bicrystals can also be a controlling factor. The deformed samples revealed in most cases that each phase had deformed on its own without the influence of the other phase. In rare occasions slip progressed through the phase boundary and produced deformation zones in the other phase. Deformation in either phase proceeded by single slip, and the phase boundary did not play an important role in the deformation behaviour of two-phase bicrystals of alpha–beta brass at elevated temperatures, when it was normal to the tensile axis. Below T_c, alpha is soft and the beta phase is hard. Above T_c beta becomes softer than alpha. In either case, the softer phase plays the role of a matrix. Crosshead speeds of 0.02 cm min^{-1} at 371° C, 0.1 cm min^{-1} at 427° C, and 0.5 cm min^{-1} at 482° C resulted in producing a uniform deformation in both phases for specimens with total length of about 2 in and each phase having nearly equal lengths.

4. Conclusions

1. The deformation behaviour of the beta phase is highly sensitive to strain-rate. This sensitivity is not affected by variations in temperature, while the deformation of the alpha phase is relatively insensitive to strain-rate and temperature.

2. Uniform deformation of two-phase bicrystals of alpha–beta brass with total lengths of 2.0 inch (length of α and $\beta \approx 1$ inch each) can be achieved by using low strain-rate (cross-head speed of 0.02 cm min^{-1}) at 371° C, moderate strain-rate (crosshead speed of 0.10 cm min^{-1}) at 427° C and high strain-rate (crosshead speed of 0.50 cm min^{-1}) at 482° C.

3. In room temperature tests, the deformation of two-phase bicrystals was dominated by the interaction of slip in the alpha phase with the phase boundary. At high temperatures, each phase deforms on its own and slip interaction with the phase boundary is not of any significance, provided it is normal to the tensile axis. Cross-slip in alpha was not often observed during the course of this work, although it was a very common feature in room temperature deformation.

4. The grain boundaries present in beta regions deform by grain boundary sliding at temperatures just below T_c, provided they are favourably oriented and the strain-rate is small or moderate.

References

1. A. K. YAZDAN and K. N. SUBRAMANIAN, *J. Mater. Sci.* 19 (1984) 3185.
2. *Idem, ibid.* 19 (1984) 3191.
3. A. K. HINGWE and K. N. SUBRAMANIAN, *J. Crystal Growth* 21 (1974) 287.
4. *Idem, J. Mater. Sci.* 10 (1975) 1983.
5. C. F. NILSEN and K. N. SUBRAMANIAN, *ibid.* 19 (1984) 768.
6. *Idem, Phys. Status Solidi* 79 (1983) 281.
7. R. MADDIN, *Trans AIME* 175 (1948) 86.
8. N. BROWN, "Mechanical Properties of Intermetallic Compounds" edited by J. H. Westbrook (John Wiley, New York, 1960) p. 177.
9. J. A. MARTIN, M. HERMAN and N. BROWN, *Trans. AIME* 209 (1957) 78.
10. H. OHMORI and K. WAKASA, *Jpn J. Sci.* 37 (1953) 1188.
11. M. CHUNKE, *ibid.* 25 (1950) 380.
12. M. SUREY and B. BAUDELET, *J. Mater. Sci.* 8 (1973) 363.
13. G. BARO, *Z. Metallkde* 7 (1972) 384.

Received 3 October and accepted 3 November 1983