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Elevated temperature deformation behaviour of alpha–beta brass bicrystals

Part 2 *Disordered beta*

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Elevated temperature deformation behaviour of alpha–beta brass was investigated by using a model system at temperatures just above the order–disorder transformation temperature (T_c) of beta. At low strain-rates, the entire deformation was accompanied by slip in beta and at high strain-rates both alpha and beta deformed by single slip. This mode of deformation is quite different from that observed at temperatures below T_c.

1. Introduction
This paper is the second in a series of three papers dealing with elevated temperature deformation behaviour of alpha–beta brass with a model system, and will be devoted to studies in the temperature range just above the transformation temperature (T_c), where beta exists in the disordered state. The first paper in the series was devoted to deformation studies in the temperature range just below T_c [1]. The previous paper refers to the various basic studies carried out with two-phase bicrystals of alpha–beta brass.

2. Experimental procedures
Growth of two-phase bicrystals of alpha–beta brass, preparation of tensile specimens, and details of the experimental procedure used for elevated temperature tensile testing have already been described [1–3]. For the present investigations, tensile tests were carried out at 482 and 538° C (900 and 1000° F), just above the order–disorder transformation temperature of beta.

3. Results and discussion
In figures presented in this paper, the arrows are along the tensile axis, and "A" and "B" represent the alpha and beta phases respectively.

3.1. Deformation studies at 482° C
Specimens deformed at 482° and strained at a cross-head speed of 0.02 cm min^{-1} deformed initially by single slip in the beta grains. As a result the beta regions of the deformed samples had a rumpled appearance. Grain boundary sliding in the beta phase was not a dominant factor, and there was no indication of work-hardening in the stress–strain curves. Cracks opened up at some of the grain boundaries in beta. Alpha did not deform plastically at all, even though beta deformed in regions away from the phase boundary, as shown in Fig. 1.

Observations made on specimens deformed at 482° C and strained with a crosshead speed of 0.1 cm min^{-1} indicated that the entire deformation took place in beta. Slip lines formed in beta during deformation were clearly visible to the naked eye; these slip lines interacted with the phase boundary during further straining. Severe deformation resulted in reduction of cross-sectional area in the beta phase. This behaviour is illustrated in Fig. 2.

These observations are quite different from those made at room temperature [3, 4]. At room temperature tests alpha behaves in a more ductile manner and accommodates almost all of the defor-

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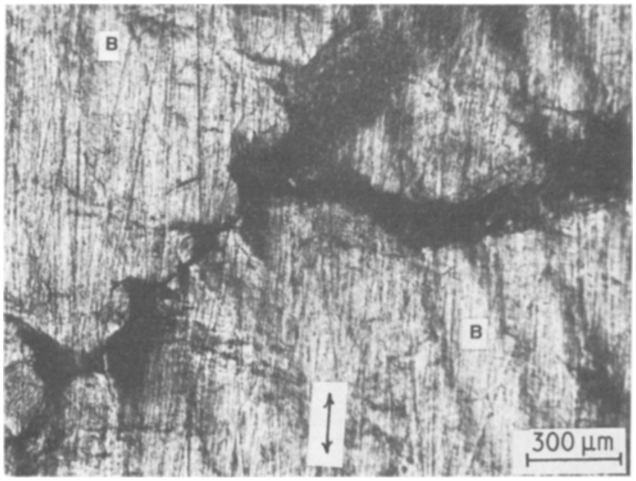


Figure 1 Severe deformation and grain boundary cracking in the beta phase away from the phase boundary in a specimen deformed at 482° C with a crosshead speed of $0.02\,cm\,min^{-1}$. Yield stress of beta $9.5\,MN\,m^{-2}$. Critical resolved shear stress of beta $4.7\,MN\,m^{-2}$.

mation. Interaction of slip in alpha with the phase boundary initiates slip in beta at low strain-rates. At high strain-rates, deformation does not progress through the boundary in room temperature tests [4]. However, in specimens tested at 482° C, the initial deformation occurs by slip in beta regions. The entire deformation at 482° C (at a crosshead speed of $0.10\,cm\,min^{-1}$) is accommodated by slip in the beta region. Although slip in beta interacts with the phase boundary, it does not activate deformation in the alpha region. Furthermore, the absence of any work-hardening in beta prevents the deformation of alpha.

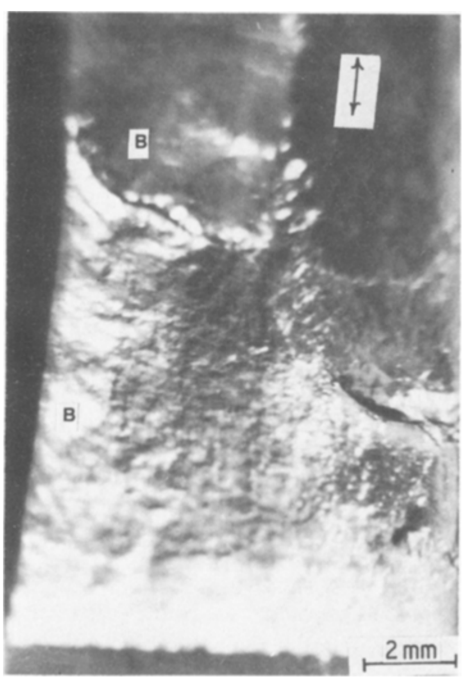
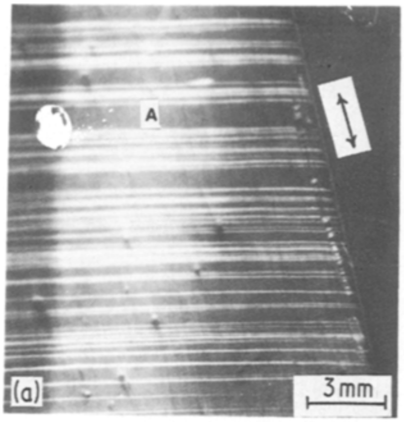


Figure 2 Severe deformation in the beta region near the phase boundary in a specimen tested at 482° C with a crosshead speed of $0.10\,cm\,min^{-1}$. Yield stress of beta $16.9\,MN\,m^{-2}$. Critical resolved shear stress of beta $8.33\,MN\,m^{-2}$. Total strain 12.56%.

Specimens tested at 482° C and pulled at a cross-head speed of $0.50\,cm\,min^{-1}$ initially deformed in alpha by single slip as illustrated in Fig. 3a. Slip lines in alpha became deeper and wider on further straining. The imposing strain-rate was still low enough, even at a crosshead speed of $0.50\,cm\,min^{-1}$, to promote climbing of dislocations by thermally activated processes. As a result of a dynamic recovery process, the stress level remained low and new slip systems were not activated in the alpha phase. However, beta deformed uniformly by coarse slip. This feature can be observed in Fig. 3b. It was found that a crosshead speed of $0.50\,cm\,min^{-1}$ resulted in uniform deformation in both the phases. The slip traces present in both the phases in regions near the phase boundary can be observed in Fig. 4. This deformation behaviour would imply that at 482° C, a crosshead speed of $0.50\,cm\,min^{-1}$ was suitable for imposing a uniform deformation in both the phases and that the phase boundary had very little or no effect on the deformation behaviour of these bicrystals; whereas, the phase boundary played a more significant role in room temperature tests of similar specimens [3, 5].

3.2. Deformation studies at 538° C

Specimens strained at 538° C with a crosshead speed of $0.1\,cm\,min^{-1}$ deformed entirely in the



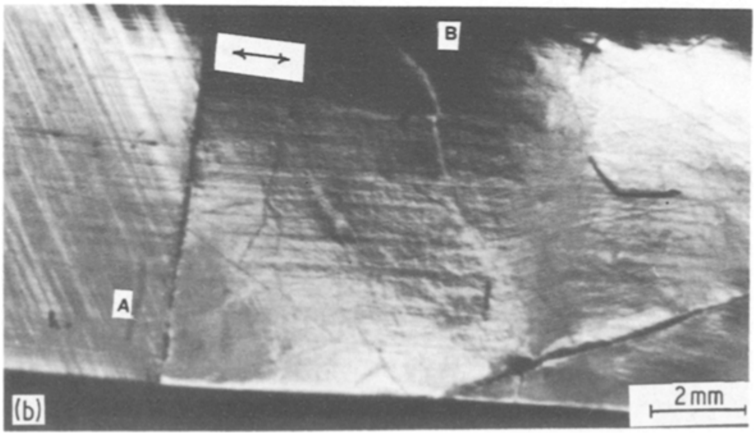


Figure 3 (a) Deformation of alpha by single slip away from the phase boundary in a specimen tested at 482° C with a crosshead speed of 0.50 cm min^{-1}. Yield stress of alpha 39.9 MN m^{-2}. Critical resolved shear stress of alpha 19.4 MN m^{-2}. (b) Deformation of both phases near the phase boundary in a specimen tested at 482° C with a crosshead speed of 0.50 cm min^{-1}. Yield stress of alpha 32.6 MN m^{-2}. Critical resolved shear stress of alpha 14.9 MN m^{-2}. Total strain 3%.

beta phase by coarse slip. Grain boundary sliding was not too important and most of the deformation was accompanied by beta grains. Alpha did not deform plastically at all. Necking took place in the beta region resulting in needle-point fracture, as can be seen in Fig. 5.

Specimens tested at 538° C with a crosshead speed of 0.2 cm min^{-1} resulted in deformation of beta. The deformed beta region appeared rumpled. Grain boundary deformation was not too significant, but the beta region present near the phase boundary deformed heavily. Necking took place in beta grains and led to a needle-point fracture. Although some cracks were observed at several points in beta, the deformation at a later stage was entirely accommodated within beta grains. There was no strain-hardening, due to thermally activated dynamic recovery in beta, and the deformation in beta continued until fracture. Alpha regions did not deform during this process.

Deformation studies of specimens tested at 538° C with a crosshead speed of 0.5 cm min^{-1} indicated that the beta phase was very soft compared with the alpha phase and as a result the entire plastic deformation took place in beta. There was very little grain boundary sliding. At a test temperature of 538° C, beta grains deformed with less strain-rate sensitivity as compared with the grain boundaries in beta. This non-uniformity resulted in cracks in beta phase.

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

Two-phase bicrystal specimens used in these studies consist of four entities that can undergo deformation. These are single crystal alpha, grains in beta, grain boundaries in beta, and the phase boundary between alpha and beta. Of these four, at temperatures above T_c, the beta grains accommodate most of the deformation. There is very little grain boundary deformation in beta at these temperatures. The deformation of these entities are highly strain-rate sensitive. There is no work-hardening of beta at these temperatures and, as a result, alpha did not deform unless the applied

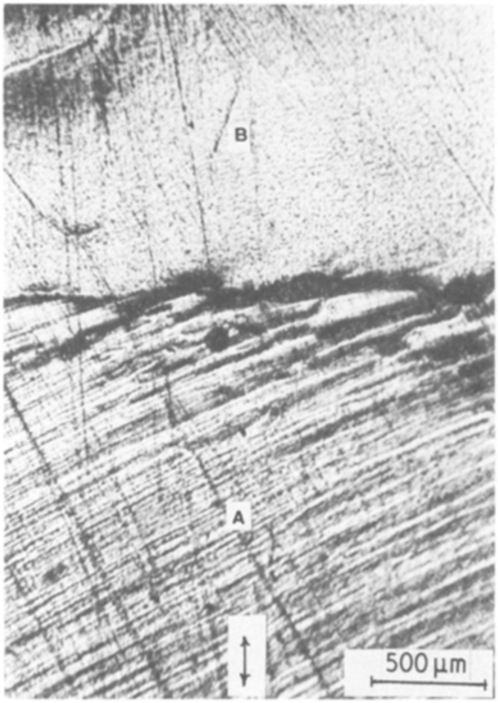


Figure 4 Interaction of single slip in alpha with the boundary. Deformation in alpha has progressed through the boundary into beta regions. Crosshead speed 0.5 cm min^{-1}.

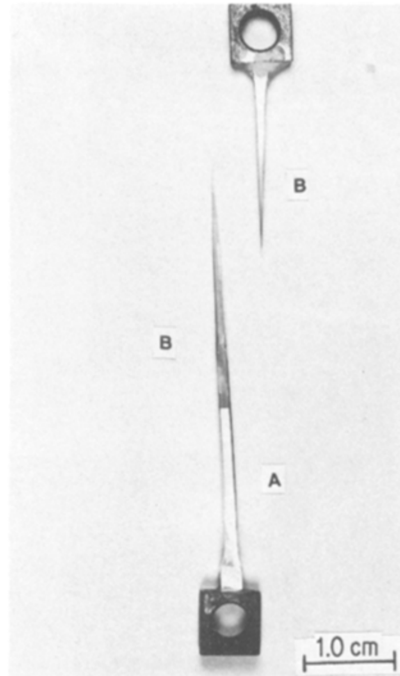


Figure 5 Needle-point fracture in the beta phase. No visible plastic deformation in alpha in a specimen tested at 538° C with a crosshead speed of 0.10 cm min^{-1}. Yield stress of beta 10.8 MN m^{-2}. Critical resolved shear stress of beta 5.1 MN m^{-2}. Total strain 150%.

stress level is high enough to initiate deformation in it. Such a condition exists at a crosshead speed of 0.50 cm min^{-1} in specimens tested at 482° C. This observation suggests that at higher temperatures, deformation at higher crosshead speeds should promote deformation in both the phases. However, this behaviour was not fully apparent in the tests carried out at 538° C. Deformation at crosshead speeds of 0.50 and 1.00 cm min^{-1} promoted grain boundary cracking in beta; neither the alpha nor the beta phase deformed by slip. Results indicated that 538° C was too high a temperature for creating uniform deformation in both phases.

Quantitative and qualitative data for tests carried out during this study are presented in Tables I to IV. These tabulations are made in a manner

TABLE I Quantitative results for bicrystals deformed at 482° 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	0.172	0.180	0.088	0.318	0.072	0.198	0.96	4.4	α	32.6
0.5	0.171	0.179	0.078	0.113	0.362	0.235	0.96	0.31	β	39.9
0.1	0.053	0.052	0.023	0.039	0.079	0.056	1.01	0.49	β	33.2
0.1	0.050	0.044	0.024	0.045	0.199	0.123	1.14	0.22	β	16.9
0.1	0.045	0.045	0.024	0.464	–	–	1.00	–	β	44.4
0.2	0.034	0.036	0.018	0.040	0.018	0.029	0.94	2.20	α	35.0
0.02	0.011	0.011	0.005	–	0.117	0.059	1.00	–	β	9.5
0.02*	0.007	0.008	0.003	–	0.343	0.160	0.88	–	β	22.6
0.1	0.032	0.038	0.176	–	–	–	0.85	–		

*Specimen reintroduced and strained at five times the initial strain-rate.
CHS = crosshead speed.
PDF = phase deformed first.

TABLE II Qualitative results for bicrystals deformed at 482° C

CHS ($cm\ min^{-1}$)	Deformation of alpha	Deformation of beta	Initial deformation	Region of failure
0.02	None	Rumpled appearance	Beta	Necked in beta
0.1	Single slip bands. Widely spaced	Single slip	Beta	–
0.1	Single and multiple slip. Non-uniform deformation	Rumpling. Uniform deformation	Beta	Non-uniform deformation. No failure
0.5	Single slip. Uniform deformation. Extensive deformation	Rumpling and slip in beta. Slip near boundary also	Alpha	Beta grain boundary

TABLE III Quantitative results for bicrystals deformed at 538° 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	0.161	0.187	0.087	0	0.075	0.035	0.86	0	β	27.2
0.5	0.161	0.179	0.085	0	0.136	0.065	0.90	0	β	28.4
0.2	0.068	0.129	0.045	0	1.084	0.376	0.53	0	β	13.3
0.1	0.046	0.049	0.023	0	0.280	0.136	0.94	0	β	5.5

TABLE IV Qualitative results for bicrystals deformed at 538° C

CHS ($cm\ min^{-1}$)	Deformation of alpha	Deformation of beta	Initial deformation	Region of failure
0.5	None	Extensive deformation	Beta	Needle point fracture in beta
0.1	None	Grain boundary sliding	Beta	At grain boundary in beta
1.0	None	Grain boundary deformation	Beta	Grain boundary cracking

similar to that used for specimens tested at temperatures below the ordering temperature for beta [1].

4. Conclusions

1. Deformation studies on two-phase bicrystals of alpha–beta brass at temperatures above T_c show that, at low strain-rates, beta deforms by slipping in beta grains and the alpha phase does not deform at all. At high strain-rates, both beta and alpha deform by single slip.

2. At temperatures above T_c, the individual grains in beta with b c c structure deform more easily than the grain boundaries in beta.

3. Deformation at temperatures above T_c occurs without any work-hardening. Thus, the alpha phase does not deform unless the initial yield stress is high enough to initiate slip in alpha. The plastic deformation of both phases normally occurs in the single slip mode under such conditions.

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