edited by G. C. Kuczynski, Proceedings of the 5th International Conference on Sintering and Related Phenomena, Notre Dame, Indiana, 1979, (Plenum Press, New York, 1980) pp. 321–32.
2. J. P. LeCOMPTE, J. JARRIGE, J. MEXMAIN, R. J. BROOK and F. L. RILEY, *J. Mater. Sci.* **16** (1981) 3093.
3. M. F. ASHBY, *Surface Sci.* **1** (1972) 526.
4. W. H. GOURDIN, C. J. ECHER, C. F. CLINE and L. E. TANNER, in "Proceedings of the 7th International Conference on High Energy Rate Fabrication", edited by F. Z. Blazynski, University of Leeds, 14–18 September (1981).
5. J. J. HREN, J. I. GOLDSTEIN and D. C. JOY, (Eds), "Introduction to Analytical Electron Microsopy" (Plenum Press, New York, 1979).
6. D. R. CLARKE, N. J. ZALUZEC and R. W. CARPENTER, *J. Amer. Ceram. Soc.* **64** (1981) 601, 608.

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The effect of the second-phase volume fraction on the grain size stability and flow stress during superplastic flow of binary alloys

Recently, Arieli [1] considered the effect of the second-phase volume fraction on the flow stress during superplastic flow of binary alloys and he showed, for five different superplastic binary alloy systems, that at constant temperature and strain rate the flow stress increases with the deviation of the second-phase volume fraction from that required for maximum grain-size stability. This deviation was characterized by a parameter $Z = (X'_\beta/X_\beta)$ where X'_β is the volume fraction determined from the phase diagram and X_β is the volume fraction of the second-phase required to stabilize the matrix grain size according to an analysis by Hellman and Hillert [2]:

$$X_\beta = \frac{4}{9\beta'}\frac{d_\beta}{d_\alpha}. \qquad (1)$$

In this relation, β' is a correction factor close to unity and d_β and d_α are the second phase and matrix grain-size, respectively.

In his analysis Arieli referred, among other binary systems, to Cu–Zn alloys with different compositions and he concluded that there is an excellent correlation between flow stress, σ_f and Z, as shown in Fig. 1 (which corresponds to Fig. 2 of his paper). For all his calculations, the data were taken from the paper by Suery and Baudelet [3].

The aim of this paper is to re-analyse the data obtained in the case of superplastic α/β brasses on the basis of the parameter Z, to discuss the calculations done by Arieli and finally to demonstrate that his conclusion is wrong at least for the Cu–Zn system.

All the data which were used for the determination of the constitutive equation for α/β brasses in the superplastic range [3] are given in Table I. They were obtained from tensile tests at constant strain rate on four α/β brasses with different phase proportions. The stress was calculated at a strain equal to 0.4, after the attainment of an approximately equiaxed structure, the α and β grain sizes being determined at this strain from metallographic observations. In the table values of the parameter Z are also given, this parameter being calculated by considering as matrix the phase with volume fraction higher than 0.5.

So for an α-phase volume fraction α smaller than 0.5, Z is given by:

$$Z = \frac{9}{4}\beta'\alpha\frac{d_\beta}{d_\alpha}, \qquad (2)$$

and for α greater than 0.5, by:

$$Z = \frac{9}{4}\beta'(1-\alpha)\frac{d_\alpha}{d_\beta}.$$

The correction factor β' is taken equal to 1.

The calculation shows that the parameter Z always lies between 0.95 and 1.20 with no systematic difference between all the alloys tested. This means that in this system, the experimental second-phase volume fraction is always close to that required for maximum grain-size stability with no significant deviation from it. No correlation can then be found between the flow

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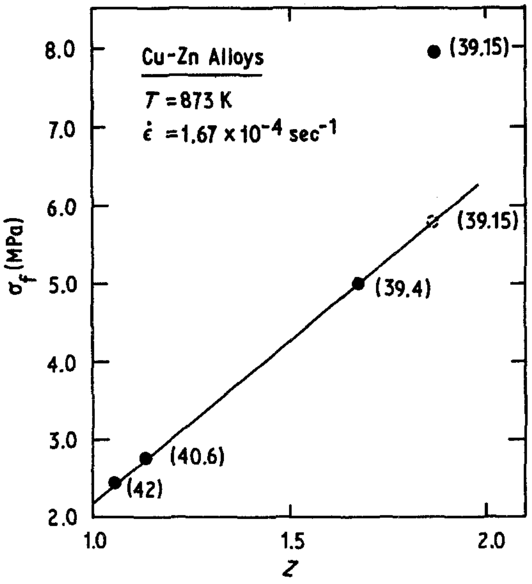

Figure 1 Variation of the flow stress with parameter Z for Cu–Zn alloys. The numbers in parentheses are the nominal percentage of Zn in the alloys. The open symbol shows the corrected σ_f for the Zn = 39.15 wt% alloy. From Arieli [1].

stress at constant temperature and strain rate and the parameter Z. This conclusion disagrees completely with that reached by Arieli and it is of some interest to analyse how the calculations were done in order to find a parameter Z which increases from about 1.05 for the alloy with $\alpha = 0.24$ to about 1.87 for the alloy with $\alpha = 0.71$.

The problem is concerned with the determination of d_α and d_β in order to obtain X_β (Equation 1). As indicated by Arieli himself [4], d_α values were measured from Fig. 1 of Suery and Baudelet [3] and d_β values were taken from Fig. 3 using $\sigma^2/\dot{\epsilon}$ data determined from Fig. 2. This procedure involves several problems.

(a) Fig. 1 corresponds to specimens with different α-phase volume fractions annealed for 45 min at 600° C. This time was found necessary to achieve temperature homogenization of the specimen before a tensile test. The determined value of d_α corresponds then to the initial grain size before deformation and not to the current grain size.

(b) Fig. 3 was drawn by taking the flow stress at $\epsilon = 0.4$ together with the value of d_β at this

TABLE I Thermomechanical and structural data obtained from tensile tests on Cu–Zn alloys with different compositions and used for the determination of the relation between the flow stress and the parameter Z

Alloys	T (° C)	α	$\dot{\epsilon}$ (min^{-1})	σ (MPa)	d_α (μm)	d_β (μm)	Z
Cu–42 Zn	600	0.235	2.08×10^{-3}	2.1	22.7	39.6	0.92
Cu–42 Zn	600	0.243	4.30×10^{-3}	2.4	19.1	34.3	0.98
Cu–42 Zn	600	0.227	8.28×10^{-3}	2.95	16	31.5	1.01
Cu–42 Zn	600	0.234	10^{-2}	3.2	15.9	30.6	1.01
Cu–42 Zn	600	0.251	2.11×10^{-2}	4	13.7	26.4	1.09
Cu–42 Zn	600	0.241	4.11×10^{-2}	4.85	11.9	23.5	1.07
Cu–42 Zn	550	0.356	10^{-2}	4.32	12.7	17	1.07
Cu–40.6 Zn	600	0.447	2.09×10^{-3}	2.25	23.2	25.65	1.11
Cu–40.6 Zn	600	0.444	4.21×10^{-3}	2.85	19.45	21.9	1.12
Cu–40.6 Zn	600	0.456	8.46×10^{-3}	3.65	16.4	18.5	1.16
Cu–40.6 Zn	600	0.468	10^{-2}	3.85	15.9	17.75	1.18
Cu–40.6 Zn	600	0.443	2.12×10^{-2}	4.6	14.4	15.5	1.07
Cu–40.6 Zn	600	0.472	4.16×10^{-2}	6.3	13.2	13.7	1.10
Cu–40.6 Zn	550	0.56	10^{-2}	5.45	12.4	11.3	1.09
Cu–40.6 Zn	650	0.36	10^{-2}	2.9	21.7	27	1.01
Cu–40.6 Zn	700	0.206	10^{-2}	2.43	26.8	54.4	0.94
Cu–39.4 Zn	600	0.621	2.11×10^{-3}	3.25	28	20.8	1.15
Cu–39.4 Zn	600	0.621	4.2×10^{-3}	3.95	24.10	17.8	1.15
Cu–39.4 Zn	600	0.633	8.55×10^{-3}	4.7	19.8	14.1	1.16
Cu–39.4 Zn	600	0.638	2.07×10^{-2}	6.35	17.35	12.1	1.17
Cu–39.4 Zn	600	0.623	4.2×10^{-2}	8	15.4	11.15	1.17
Cu–39.15 Zn	600	0.716	2.16×10^{-3}	3.85	23.7	14.6	1.04
Cu–39.15 Zn	600	0.699	4.18×10^{-3}	4.5	20.9	13.5	1.05
Cu–39.15 Zn	600	0.708	8.39×10^{-3}	5.5	18	11.5	1.03
Cu–39.15 Zn	600	0.718	10^{-2}	5.95	17.6	10.9	1.02
Cu–39.15 Zn	600	0.687	2.14×10^{-2}	7.55	14.8	9.4	1.11
Cu–39.15 Zn	680	0.539	10^{-2}	3.1	22.5	21.9	1.07

strain (when the structure has become equiaxed) whereas in Fig. 2 the stress corresponds to the maximum in the load–elongation curve when the structure is still elongated in the direction of the tensile axis. The values of d_β deduced from Fig. 3 using data of Fig. 2 do not then correspond to the experimental ones.

(c) Because of the lower value of the strain-rate sensitivity in the alloy with the largest α-phase volume fraction, the plot $\sigma^2/\dot{\epsilon}$ versus d_β was not given for this alloy and as a consequence Fig. 3 does not allow the calculation of d_β for this alloy as indicated by Arieli.

From these calculations it is not surprising to find different values of Z for the four alloys investigated, these values being obtained by considering inconsistent values of the α and β grain-sizes.

Another important problem arises on the significance of the flow stress. Arieli considered as the flow stress, the stress at the maximum of the load–elongation curve. This stress has no significance by itself, it depends on the initial structure of the alloy and can be very different for materials prepared under different conditions. The flow stress has to be associated with the structure of the material, at least with the grain size if the structure is equiaxed, and it is not the case for α/β brasses in the initial conditions.

Furthermore, Arieli makes a correction to the "flow stress" for the alloy with the lowest zinc concentration, in order to obtain a "new stress in line with the others". This correction in the form $\sigma^{2/2.5}$ firstly does not give this alignment in contradiction to what is shown in Fig. 1 and, secondly, has no physical significance. Perhaps it may be possible to correct the stress as $\sigma^{2.5/2}$ if it is assumed that for the same strain rate the stress should be larger than that experimentally found if the strain-rate sensitivity coefficient is 0.5 rather than 0.4.

All these problems concerning the calculations carried out by Arieli for the Cu–Zn alloys lead to the conclusion that there is no correlation between the flow stress and the parameter Z, this parameter being approximately constant for the alloys tested, whereas the flow stress increases as the α-phase volume fraction increases. This disagreement introduces a very serious doubt on the validity of the calculation for the other binary systems and then on the validity of the parameter Z in order to characterize the structure of two-phased superplastic materials.

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References

1. A. ARIELI, *J. Mater. Sci.* **16** (1981) 2760.
2. P. HELLMAN and M. HILLERT, *Scand. J. Metallurgy* **4** (1975) 211.
3. M. SUERY and B. BAUDELET, *Phil. Mag. A* **41** (1980) 41.
4. A. ARIELI, private communication (1982).

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