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Micro-yielding in a precipitation hardening Cu 1.81 wt % Be 0.28 wt % Co alloy

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The microstrain characteristics of a polycrystalline Cu 1.81 wt % Be 0.28 wt % Co precipitation hardening alloy have been determined for various precipitate conditions. The friction stress derived from measurements of closed hysteresis loops was found to remain constant ($\sim$ 3 MN m^{-2}) for all the conditions investigated. In contrast, the microscopic yield stress (MYS) remained constant (18 to 24 MN m^{-2}) for most ageing conditions, but increased significantly (to 48 to 64 MN m^{-2}) for conditions associated with a high G.P. zone or γ' precipitate density.

1. Introduction

In this paper, the microstrain characteristics of a polycrystalline precipitation hardening Cu 1.81 wt % Be 0.28 wt % Co alloy are described. This work is an extension of a previous investigation by Bonfield [1], but with the microstrain characteristics studied for a wider range of precipitate morphologies. The solution treated and solution treated, 50 % cold-rolled conditions have been examined as a function of ageing time at temperatures of 175, 315 and 425°C and the microstrain characteristics related to the microstructures observed in a recent, detailed transmission electron microscopy investigation [2-4].

2. Experimental procedure

2.1. Materials

The material investigated was a commercial copper–beryllium–cobalt alloy (Telcon 250) which had a composition of 1.81 wt % Be 0.28 wt % Co. The ageing of the solution treated (800°C for 1 h and water quenched) and solution treated, 50 % cold-rolled starting conditions were studied at temperatures of 175, 315 and 425°C for times up to 1040 h. Tensile specimens of rectangular cross-section were prepared and electropolished prior to testing [5].

2.2. Microstrain procedure

The microplastic behaviour was determined with both a Tuckerman optical strain gauge and a capacitance gauge [5]. The load-unload technique previously described [6, 7] was used to determine the friction stress (σ_F), the microscopic yield stress (MYS), defined as the stress required to produce a plastic strain of 2×10^{-6} and the stress for "gross microyielding" (σ_m) (the stress associated with a transition in the rate of plastic strain hardening) [1]. A step loading technique was employed with the optical gauge, whereas a dynamic load-unload cycle was used with the capacitance gauge (at a strain rate of 3×10^{-4} sec^{-1}).

The MYS and σ_m were measured directly from the experimental stress–microstrain curve. The friction stress, σ_F, was calculated from the closed hysteresis loops by two methods:

(1) From a plot of the maximum forward plastic strain, ϵ_p versus the loop area, W, with the friction stress calculated from [8]:

$$\sigma_F = \frac{W}{2\epsilon_p} \cdot \qquad (1)$$

The value of ϵ_p ideally should be calculated from the deviation of the stress-strain loop from the elastic line, but this deviation was difficult to determine and ϵ_p was estimated from the width of the hysteresis loop.

(2) From a plot of the loop area, W, versus the maximum applied stress, σ_a, with σ_F calculated by extrapolating the plot to zero loop area, as when $W = 0$

$$\sigma_a = \sigma_E = 2\sigma_F \qquad (2)$$

where σ_E is the elastic limit.

3. Results

3.1. Microstrain behaviour

Typical microstrain measurements are shown in

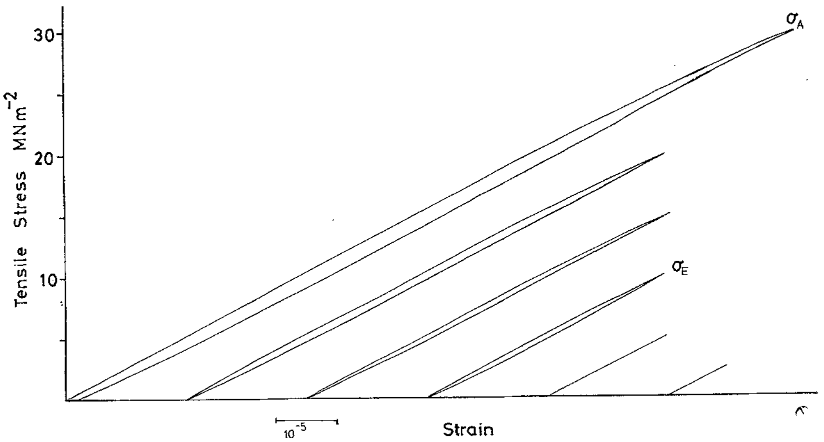

Figure 1 Typical stress-strain behaviour observed in the microstrain region

Fig. 1. For small stress levels (< 4 MN m^{-2}), elastic deformation was observed with a linear load-unload curve. As the specimen was cycled to higher stress amplitudes, a stress σ_E (the elastic limit) was reached at which the first closed hysteresis loop was produced. On increasing the stress level above σ_E, the area of the closed hysteresis loop increased progressively, although the area of a loop was constant for any given stress amplitude. Finally, a stress σ_A (the anelastic limit) was reached at which an open loop was produced. In the present investigation σ_A corresponds to the MYS i.e. the stress required to produce a plastic strain of 2×10^{-6}.

3.2. The friction stress

A calculation of the friction stress for various ageing conditions was made from a series of closed hysteresis loops, with $\sigma < \sigma_A$, as shown in Fig. 2 for four ageing conditions.

It can be seen that these results fall into two groups, as for the solution treated and 2 h at 425°C conditions (group 1) the maximum forward strain obtained in a closed loop was $\sim 8 \times 10^{-6}$, whereas for the 2 h at 175°C and 24 h at 315°C conditions (group 2) the maximum forward strain was $\sim 20 \times 10^{-6}$. For the latter conditions, the W-ϵ_p graphs clearly show a linear initial slope (which extrapolates to the origin), followed by a second slope of increased gradient. Equally, for the group 1 conditions, although the maximum forward strain was limited, it does appear that the W-ϵ_p graph consists of a small initial linear slope, followed by a second region of increased slope. For all four conditions, the initial linear slope was similar and the transition in slope occurred at a stress level significantly below the MYS (see Section 3.3). This general result was also obtained for the seventeen other conditions listed in Table I, which, as shown in

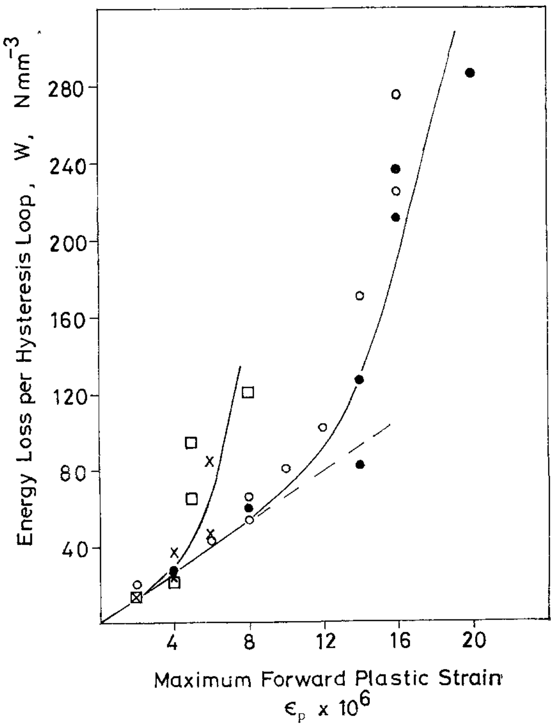

Figure 2 The variation of the energy loss per hysteresis loop with the maximum strain amplitude. Key: × – solution treated condition; ○ – solution treated condition aged 2 h at 175°C; □ – solution treated condition aged 2 h at 425°C; ● – solution treated 50% cold-rolled condition aged 24 h at 315°C.

TABLE I Microstrain characteristics of Cu 1.81 wt % Be 0.28 wt % Co

Starting condition	Ageing temperature (°C)	Ageing time (h)	Precipitate	W-ϵ_p group	MYS (MN m^{-2})	σ_m (MN m^{-2})	Hardness VPN
S.T.	—	—	—	1	20	170	94
S.T.	175	2	GPz	2	56	240	115
S.T.	175	24	GPz/γ'	2	48	240	160
S.T.	175	100	GPz/γ'	2	54	360	200
S.T.	175	1040	γ'	1 to 2	36	480	375
S.T.	315	2	GPz/γ'	1	20	600	365
S.T.	315	24	GPz/γ'	1	24	600	415
S.T.	315	100	γ', γI	1	24	600	390
S.T.	425	2	γ', γI	1	22	460	285
S.T.	425	24	γI	1	23	440	240
S.T.	425	720	γ	1	25	240	185
S.T. 50% C.W.	—	—	—	1	25	360	252
S.T. 50% C.W.	175	2	—	1	25	480	260
S.T. 50% C.W.	175	24	—	1	23	520	280
S.T. 50% C.W.	175	100	—	1	24	520	300
S.T. 50% C.W.	315	2	GPz/γ'	1	18	1000	435
S.T. 50% C.W.	315	18	γ'	2	60	1040	420
S.T. 50% C.W.	315	24	γ'	2	64	1040	415
S.T. 50% C.W.	315	100	γ'	2	46	960	390
S.T. 50% C.W.	425	2	γ'	1	23	480	310
S.T. 50% C.W.	425	24	γ'	1	24	560	250
S.T. 50% C.W.	425	720	γ	1	24	390	187

S.T., Solution treated.
S.T. 50% C.W., Solution treated, 50% cold worked.
GPz, G.P. zones.
γ', Intermediate precipitate formed by continuous precipitation.
γI, Intermediate precipitate formed by discontinuous precipitation.
γ, Equilibrium precipitate.

the table, gave a W-ϵ_p relationship similar to those of either the group 1 or the group 2 conditions.

The initial linear portion of the W-ϵ_p graph was extrapolated through the origin and a value of σ_F was calculated from the slope with Equation 1. The W versus σ relationship also exhibited an initial linear slope (Fig. 3) but again deviated from this linear relationship at higher stress amplitudes. Good agreement was found between the friction stress values obtained with Equations 1 and 2. The friction stress values obtained for all the twenty-one conditions investigated fell within the range 2.8 ± 0.8 MN m^{-2}.

3.3. The microscopic yield stress

MYS values of the solution treated and solution treated, 50% cold-rolled material, aged at various temperatures and times, are shown in Table I. The values are the median of three to five tests, with a variation of $\pm$ 2 MN m^{-2}. In addition, the hardness and the stress for gross microyielding, σ_m, are tabulated. σ_m was taken as the transition in the stress-plastic strain curve, above which relatively large plastic strains ($\sim 10 \times 10^{-6}$) were produced by small additional stress increments ($\sim$ 5 MN m^{-2}). For the conditions investigated, σ_m occurred at plastic strains of 20 to 40 $\times$ 10^{-6}.

4. Discussion

It is significant that the plot of W versus ϵ_p has two regions, with an initial linear slope followed by a second slope of increased gradient. From Equation 1, the linear slope extrapolated through the origin, gives a value of the friction stress (σ_F) which, following the analysis of Lukas and Klesnil [8], may be considered as the lowest value of the short range "effective" stress, σ^*. The results indicate that σ_F for Cu 1.81 wt % Be 0.28 wt % Co is approximately constant for the solution treated, the solution treated, 50% cold-rolled and all the ageing conditions in-

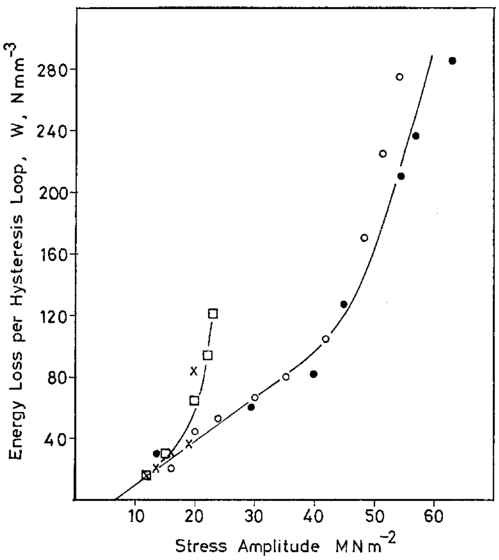

Figure 3 The variation of the energy loss per hysteresis loop with the applied stress amplitude. Key: × – solution treated condition; ○ – solution treated condition aged 2 h at 175°C; □ solution treated condition aged 2 h at 425°C; ● – solution treated 50% cold-rolled condition aged 24 h at 315°C.

vestigated. Therefore, it may be concluded that the friction stress (σ_F) of this alloy is independent of changes in both the dislocation and precipitate substructure. The structural changes produced during ageing include [2-4]:

(a) the depletion of beryllium from the matrix solid solution;

(b) the progressive increase and decrease in the number of continuous and discontinuous precipitate "obstacles";

(c) for the solution treated and 50% cold-rolled starting condition, the progressive decrease in dislocation "obstacles" due to recovery and recrystallization.

Hence, it appears that dislocation-"obstacle" interactions are not significant in the initial portion of the anelastic region and that energy is dissipated by the reversible motion of dislocations in local, "precipitate-free" regions of the matrix (in which the solid solution strengthening contribution of beryllium is small).

The second slope in the W-ϵ_p plot could be attributed to the inclusion of "open" loops (which appear "closed" at the experimental sensitivity). Alternatively, following the argument first advanced by Lawley and Meakin [9], the departure from linearity may be associated with a second friction stress due to short range stresses or a dynamic loss energy dissipative process. As the deviation in slope occurred at a stress level significantly below the MYS, the present results discount the former explanation, but further work is required to resolve this point.

In contrast, the MYS (or anelastic limit) may be related to the stress required to overcome the maximum amplitude of the internal stress field [10]. Hence the general variation of the MYS with ageing may be considered in terms of the long range stress field produced by the precipitate and dislocation substructure. The results shown in Table I embrace a "high" and "low" dislocation density solution treated condition, coherent GP zones, semi-coherent γ' precipitate, semi-coherent γI discontinuous precipitate and non-coherent equilibrium γ precipitate [2-4]. It is significant that the MYS values fall in only two groups, namely a "high" value (48 to 54 MN m^{-2}) associated with particular conditions which produce a maximum density of GP zones and/or semi-coherent γ' precipitate [2-4] and a "low" value (20 to 24 MN m^{-2}) associated with all the other conditions. This finding contrasts with the continuous variation with ageing of a macroscopic property, such as hardness, and indeed, of the stress for gross microyielding (σ_m) (Table I). It reinforces the suggestion [1] that the MYS represents, in general, the irreversible movement of dislocations in a limited number of regions of the alloy. Hence the MYS is controlled by the long range stress field in the "local" regions and, in contrast to macroscopic yielding, is not continuously varied by a change in the nature of the precipitate.

5. Conclusions

(1) The friction stress (σ_F) of Cu 1.81 wt % Be 0.28 wt % Co is independent of changes in the dislocation and precipitate substructure.

(2) The microscopic yield stress (MYS) of Cu 1.81 wt % Be 0.28 wt % Co is significantly increased only for particular high density GP zone or γ' precipitate conditions, while the stress for gross microyielding (σ_m) reflects the continuous variation with ageing exhibited by the macroscopic mechanical properties.

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