The plastic behaviour of ⟨1 0 0⟩ and ⟨1 1 1⟩ textured polycrystalline metals during simultaneous torsion and extension

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On the basis of computer-calculated yield functions, the work hardening of ⟨1 0 0⟩ textured Cu–0.64 at% Co–0.48 at% Si and ⟨1 1 1⟩ textured polycrystalline copper wires were studied by simultaneous torsion and extension and by pure extension. Representing the work hardening by resolved shear stress–resolved shear strain curves, the rate of hardening is significantly lower for torsion than for pure extension. This behaviour is explained by the operation of different slip systems activated in the two modes of deformation. In the ⟨1 0 0⟩ textured Cu–Co–Si wires, heterogeneous plastic deformation was observed beyond about 80% shear strain.

1. Introduction

It is generally accepted that the plastic flow of polycrystals needs at least five different slip systems to be activated in each grain. For grains of special shapes, however, less than five systems are sufficient for macroscopic plastic deformation [1]. In a given grain the amount of slip is different in the operating slip systems. In general, the plastic deformation of the whole specimen is determined by prescribed constraints. Assuming that the same constraints are valid in all the individual grains, the amount of slip in the slip systems can be calculated from the Taylor [2] or from the Bishop and Hill theories [3, 4]. From a geometrical point of view the rate of work hardening of polycrystalline samples depends strongly on how many slip systems must be activated to produce the desired deformation.

In previous papers the yield functions of different textured and non-textured polycrystalline materials have been calculated by a computer method [5, 6]. On the basis of those results, in the present paper the work hardening behaviour of ⟨1 0 0⟩ textured Cu–0.64 at % Co–0.48 at % Si (further denoted by Cu–Co–Si) and of ⟨1 1 1⟩ textured copper specimens are studied by simultaneous torsion and extension and by pure extension.

2. Experimental details

The samples investigated were 100 mm long wires of 1.5 and 2 mm diameter in the cases of Cu–Co–Si and copper, respectively. The Cu–Co–Si samples were solution heat treated for 1 h in a vacuum better than 10^{-2} Pa at 1000° C, which produced a coarse-grained polycrystalline structure with an average grain size of about 100 μm with strong ⟨1 0 0⟩ texture [5]. Torsion and extension measurements were made on the solution-treated samples, as well as on samples obtained after further ageing first at 450° C for 6 h and secondly at 510° C for 6 h. The latter heat treatments did not modify the texture. The precipitation structure of the Cu–Co–Si alloy will be studied in a subsequent paper.

In the case of the copper samples, the ⟨1 1 1⟩ texture was produced by annealing the samples first at 700° C for 1 h and secondly at 800° C for 3 h. The ⟨1 1 1⟩ texture was revealed by the X-ray back-reflection and twin-boundary lines methods described previously [5].

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The simple tension experiments were carried out using an Instron tensile test machine, while the torsion experiments were made by the method described previously [7, 8] at a strain rate of $2 \times 10^{-3}\,\text{sec}^{-1}$ at room temperature. The shear flow stress was calculated by Nádai's formula [9]. In the course of torsion measurements, the tensile stress applied was always less than 30% of the tensile yield stress. The following parameters were measured simultaneously: tensile stress, σ; torque, M: angles of elastic and plastic torsion; as well as plastic elongation. Plastic flow was reached by continuously increasing the torque while keeping the tensile stress constant.

3. Stress–strain relations

In previous papers [5, 6] the yield functions of $\langle 1\,0\,0\rangle$ and $\langle 1\,1\,1\rangle$ textured polycrystalline samples were studied for simultaneous torsion and extension. The essence of our method is the following. Assuming five operating slip systems in each grain and averaging first for the operating slip systems in each single grain, thereafter for all the grains in a specimen the computer calculation yields numerical values for τ_r^c/τ as a function of σ/τ, which will be denoted by $f(\sigma/\tau)$ [5, 6]. Here τ_r^c is the critical shear stress of the operating slip systems, σ the tensile and τ the shear stress belonging to yielding.

The yield locus of $\langle 1\,0\,0\rangle$ and $\langle 1\,1\,1\rangle$ textures can be seen on Figs. 1 and 2. The computed yield functions obey the normality condition prescribed by the generalized flow law [6].

For the sake of comparison of the results obtained by simple extension and by simultaneous torsion–extension experiments, the stress–strain data were converted to resolved shear stress, τ_r, and resolved shear strain, γ_r in the following way.

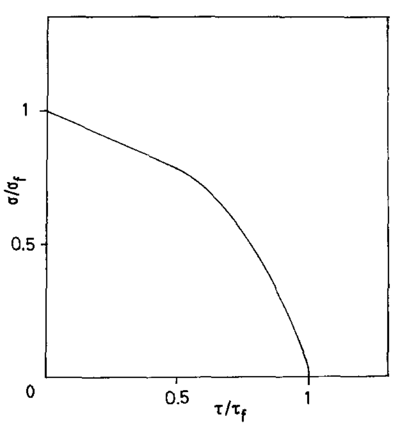

Figure 1 The yield function corresponding to the $\langle 1\,0\,0\rangle$ texture.

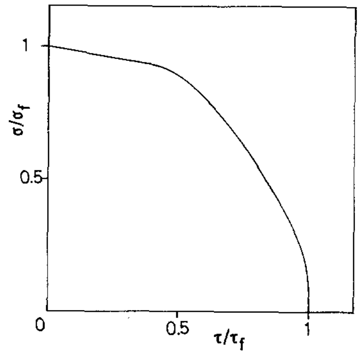

Figure 2 The yield function corresponding to the $\langle 1\,1\,1\rangle$ texture.

The resolved shear stress can be given simply by the computed $f(\sigma/\tau)$ function, as

$$\tau_r = \tau f(\sigma/\tau) \tag{1}$$

The average resolved shear strain can be expressed by the plastic work as

$$\tau_r \, d\gamma_r = \sigma \, d\varepsilon + \tau \, d\gamma$$

Hence the resolved shear strain can be obtained by numerical integration along the deformation path curve

$$\gamma_r = \int \left(\frac{\sigma}{\tau_r} d\varepsilon + \frac{\tau}{\tau_r} d\gamma \right) \tag{2}$$

The stress–strain curves for the $\langle 1\,0\,0\rangle$ textured Cu–Co–Si and $\langle 1\,1\,1\rangle$ textured copper obtained by using Equations 1 and 2 are shown in Figs. 3 and 4.

4. Plastic heterogeneity along the $\langle 1\,0\,0\rangle$ textured Cu–Co–Si wires

The torsional deformation along the Cu–Co–Si wires was uniform only up to about 80% torsional deformation. Up to this point the torque needed for plastic deformation increased continuously. At about 80% torsional strain a strongly deformed zone appeared somewhere along the specimen (Fig. 5.). In the course of further torsion, plastic deformation occurred only at one or the other end of this zone; other parts of the wire deformed only elastically. Later on, further similar zones appeared and plastic deformation continued only at the end of one of these zones. Depending on the amount of tensile

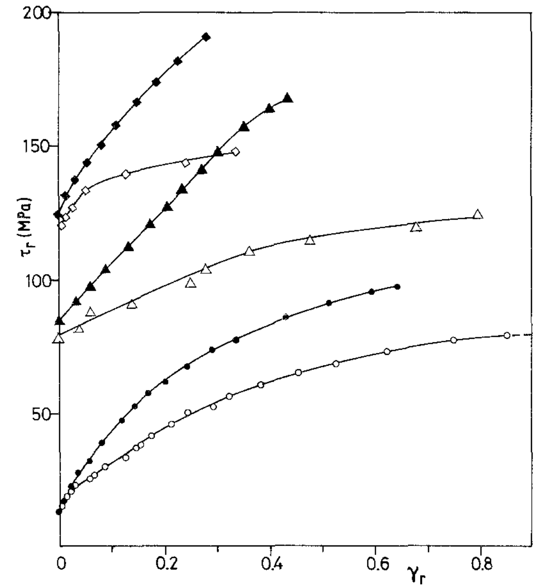

Figure 3 Stress–strain curves of ⟨1 0 0⟩ textured polycrystalline Cu–Co–Si alloy for extension (full symbols) and for simultaneous torsion and extension (open symbols). The heat treatments applied were: 1000° C, 1 h (●, ○); 1000° C, 1 h + 450° C, 6 h (▲, △); 1000° C, 1 h + 450° C, 6 h + 510° C, 6 h (♦, ◊).

stress applied and on the precipitate structure of the samples, fracture took place in different ways. If the sample was in solid solution state and the tensile stress was small, the length of the strongly deformed zones increased continuously, finally extending to the whole specimen when the specimen failed (Fig. 5.). In the case of higher applied tensile stresses or if the sample contained precipitates, the fracture occurred before the zones were extended to the whole specimen. After the appearance of the first strongly deformed zone the torque needed for further plastic deformation remained constant (Fig. 6.). After fracture the torsional strain in the highly deformed zones can be determined from the angle of the threads on the surface of the wire. This was found to be about 230% in the zones independently of the microstructure and of the tensile stress applied. It can also be seen well in Fig. 5 that the diameter in the strongly deformed zones is somewhat smaller than in the other parts of the sample.

5. Discussion

The stress–strain curves shown in Figs. 3 and 4 for torsion and for pure extension start from about the same point but for further deformation there is a considerable difference in the work hardening rates. In the case of both ⟨1 0 0⟩ and ⟨1 1 1⟩ textures the work hardening rate during torsion is smaller than during extension.

The difference in the rate of work hardening can be explained as a consequence of the different loading. In the case of simple extension of ⟨1 0 0⟩ and ⟨1 1 1⟩ textured wires, there are eight and six such slip systems, respectively, in which the shear stresses are equal and the highest among the possible 12 slip systems. Therefore, in the case of simple extension, the ⟨1 0 0⟩ or ⟨1 1 1⟩ textured wires represent such polycrystals, in which every grain is ideally oriented for multiple slip, that is in which equal amounts of slip occur in several slip systems.

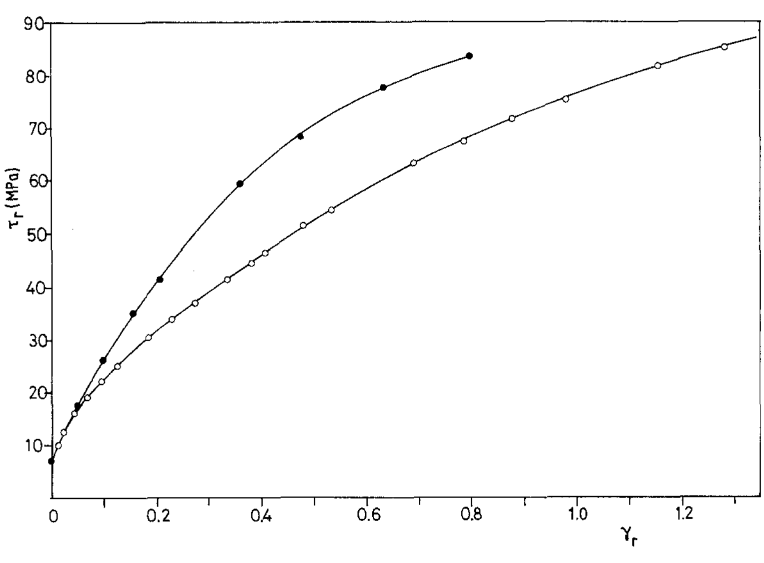

Figure 4 Stress–strain curves of ⟨1 1 1⟩ textured polycrystalline copper for extension (●) and for simultaneous torsion and extension (○).

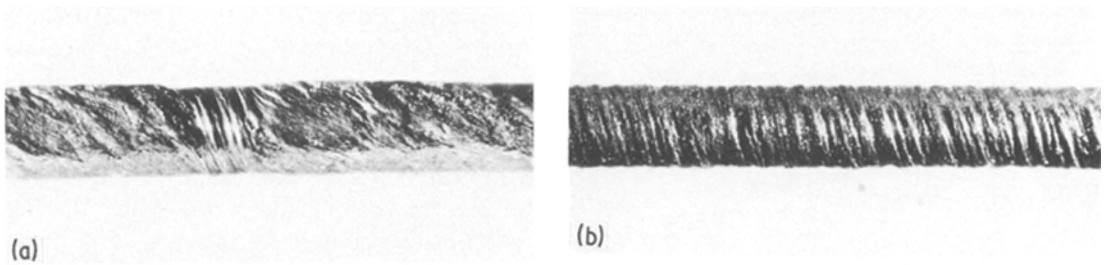

Figure 5 Heterogeneous plastic deformation of a ⟨1 0 0⟩ textured Cu–Co–Si alloy wire. (a) The appearance of the heterogeneity. (b) The surface of the specimen after the extension of the heterogeneity.

This means that in these wires a high-density forest dislocation structure develops during extension which leads to a strong hindering effect on the moving dislocations. This is the reason that the work hardening rate is high during extension.

In the course of simultaneous torsion and extension the amount of torsional shear strain is at least one order of magnitude higher than the tensile strain. This means that the dislocations move mainly in parallel planes (near to the plane of the torsional shear stress), so dislocation intersections occur less frequently than in the case of pure extension. This is the cause of the significantly lower work hardening rate in torsion than in extension.

A similar difference in the work hardening rate during pure extension and pure torsion of non-textured materials has also been observed [10].

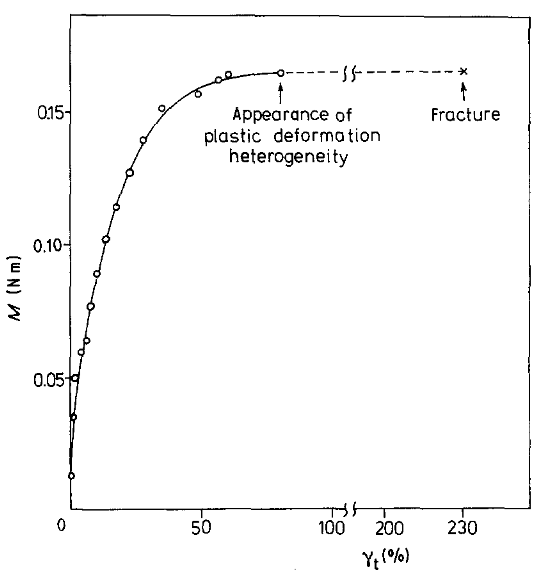

Figure 6 The torque *M* as a function of plastic torsional strain γ_t for a ⟨1 0 0⟩ textured solution-treated Cu–Co–Si sample.

The heterogeneous plastic deformation of the ⟨1 0 0⟩ textured wires can be explained by the evolution of a new texture during deformation. This is supported by the fact that heterogeneous plastic deformation always appeared at about 80% torsional shear strain, independent of the yield stress or the precipitate structure of the alloy. It is known that in copper the mean texture component for torsion is (1 0 0)[0 1 1] (where the (1 0 0) directions are parallel to the wire axis and the [0 1 1] vectors are parallel to the direction of shear). This texture component is developing during torsion up to about 80% shear strain and it remains unchanged upon further deformation [11]. In our Cu–Co–Si alloy samples there is a strong ⟨1 0 0⟩ initial texture which can easily be transformed during torsion into the ideal shear texture, (1 0 0)[0 1 1], by simple rotation of the grains around the wire axis.

As a consequence of the relatively large grain size, the formation of this ideal shear texture is not uniform along the whole specimen. The first strongly deforming zone (Fig. 5) appears at that site of the wire where this process is at the most advanced stage. This zone can be sheared up to about 230% strain. During this deformation process the external torque is constant, but because of the reduction of the cross-section the flow stress increases in the deforming zone, which means that there is still further work hardening.

6. Conclusion

The plastic deformation and work hardening of ⟨1 0 0⟩ and ⟨1 1 1⟩ textured wires depend strongly on the mode of deformation. This behaviour can be explained by the significant difference in the nature of the activated slip systems in the case of different deformation processes.

The development of a new texture during torsion can lead to heterogeneous deformation along the twisted bar.

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