SHORTENING BEHAVIOR OF TWISTED COPPER WIRES

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INTRODUCTION

Since the pioneering experiments of Swift (1), the lengthening behavior of metals during free-end torsion has been the subject of several experimental (2-7) and theoretical (7-10) investigations. From fixed end tests, Montheillet et al. (11,12) concluded that the axial stress that develops is related to the deformation texture that is induced. Similar investigations, i.e., which correlate the axial effects observed with the developed anisotropy of the material, have recently been completed for the case of free end testing (13).

In this paper, experimental results are presented regarding the length changes displayed by twisted pure copper wires. The experiments were conducted at room temperature. Large amounts of torsional deformation (up to 600%) were applied. It is of particular interest that permanent *shortening* was observed in the "as-received" samples. The shortening behavior was replaced by lengthening when the samples were twisted after annealing above the recrystallization temperature.

Texture measurements combined with several deformation texture simulations have revealed that it is the $\langle 111 \rangle$, $\langle 100 \rangle$ and $\langle 112 \rangle$ initial fibre textures that are responsible for the length change phenomena.

EXPERIMENTAL

The material was 99.99% OFHC copper wire. The as-received samples had previously been wire drawn. The specimens were about 100 mm long and 2 mm in diameter. Selected samples were heat treated in a vacuum for 1 hour at 150, 200, 250, 300 and 550°C. The annealed and as-received samples were twisted at room temperature; the rate of shear for these tests was 0.002 s^{-1} .

The tests were conducted on a computer controlled free end torsion apparatus designed and constructed in our institute. The free end conditions were modified slightly by applying a tensile stress of 1.6 MPa, which was employed to prevent the wires from buckling and to achieve large shear deformations (14,15). Using the von Mises flow criterion as a first approximation it can be shown that the presence of the applied stress only leads to negligible deviations from true free end testing conditions (16).

The textures were examined by measuring pole figures and calculating ODFs on a Siemens texture goniometer at McGill University. Only the initial textures were measured as, after

twisting, a radial texture gradient develops which renders the wires unsuitable for X-ray investigation.

RESULTS

Figure 1 shows the measured length changes as a function of the accumulated shear. The axial strain was calculated as $\Delta l/l_0$, where Δl is the measured length change and l_0 is the initial length of the specimen. In Fig. 2, the yield stress at 0.2% plastic strain is shown as a function of the prior annealing temperature. This figure indicates that recrystallization takes place at about 225°C. On the basis of the results shown in Figs. 1 and 2, it can be concluded that shortening takes place in the unrecrystallized and lengthening in the recrystallized samples.

Figure 1

Length changes during the free end twisting of copper wires. The wires were annealed prior to twisting at the temperatures shown.

Figure 2

Effect of annealing temperature on the yield strength in shear.

The stress-strain curves were calculated using the Nadai formula (17); the changes in the dimensions of the samples during deformation were taken into account leading to the results displayed in Fig. 3. The high flow stresses and low rates of work hardening associated with the unrecrystallized samples are a consequence of the previous drawing operation. In these materials, there is an increase in the rate of work hardening beyond a shear strain of 2. This is a point to which we will return below. The recrystallized samples display the well known II, III and IV stages of work hardening (15).

The textures present in the wires after annealing and prior to deformation display strong fibre components. The intensities of the different components are summarized in Table 1.

The unrecrystallized textures are very sharp. Two fibres can be seen: the $\langle 111 \rangle$ and the $\langle 100 \rangle$ ($\langle hkl \rangle$ parallel to the wire

Figure 3

Stress-strain curves of the pure copper wires during large strain, free-end torsion. The temperature of prior annealing is indicated on each curve.

Table 1
ODF intensities along the fibre lines
as a function of annealing temperature.

Temp. (°C) Fibre	Room T unrecrystallized	100	200	250 recrystallized	300 recrystallized
<111>	17	15	15	<1	<1
<100>	7	7	9	6	2
<112>	<1	<1	<1	5	8

axis), the <111> being 2-2.4 times more intense than the <100>. In the recrystallized samples the <111> component is absent. The texture consist of the <100> and <112> fibres, with proportions depend on the annealing temperature.

It can be concluded from Table 1 that recrystallization leads to a dramatic change in the texture, which indicates that the length change behavior is strongly texture dependent.

Discussion

Polycrystal model simulations were carried out to determine the role of the different initial texture components on the length change process during twisting. Two representative textures were selected: the as-received material for the unrecrystallized case and the 300°C annealing texture for the recrystallized case. From the measured ODFs, discrete orientation distributions were generated for the purpose of the length change simulations. 2704

orientations were considered for each texture. The ODF intensity value for each orientation was taken as a weighting factor in calculating the stress and strain contributions of each grain of the polycrystal.

The Sachs model, which was modified to allow for the rate sensitivity of slip (9), was employed to simulate the deformation process. The boundary conditions selected corresponded to the free end twisting of thin-walled tubes. This model was selected because it is rather difficult to simulate the free end torsion of solid polycrystalline bars. (Such a calculation requires that the condition of zero axial force be satisfied when a suitable integration is carried out over the cross section of the bar.) Nevertheless, the present results are still useful because of the similarity between the free end behaviors of a bar and a tube (1,9). The essential difference is that, in the bar, the rate of length change is decreased by the constraining effect of the core.

A relatively high slip rate sensitivity exponent of $m=0.1$ was employed in the simulations, as recent investigations show that the slip rate sensitivity is considerably higher than the macroscopically measured strain rate sensitivity (20). The length change curves obtained in this way are shown in Fig. 4.

Figure 4

Simulated axial strains for samples containing the experimental initial textures for the unrecrystallized (as-received) and recrystallized (300°C) samples.

As can be seen from Fig. 4, the opposite length change behaviors of the unrecrystallized and recrystallized samples are well reproduced by the present simulations. A significant difference, however, is the lengthening displayed by the as-received sample up to shear strain of about two in the simulations. The shortening observed experimentally at strains below $\gamma=2$ may, however, be attributable to anelastic and other effects associated with the strain path change imposed. It is possible that the wire drawing process leads to significant

internal stresses which can play a role during subsequent shearing. As wire drawing always results in lengthening, the internal stresses must be such as to hinder any further lengthening (Bauschinger effect). During subsequent shearing these internal stresses are likely to promote the occurrence of those dislocation slips which contribute to shortening of the wire. Such contributions are expected to gradually die out at large strains. This initial anomaly does not appear in the recrystallized samples, as the internal stresses disappear during recrystallization.

In order to clarify the roles of the different fibre components in the length change process, simulations were carried out to determine the effects of the $\langle 111 \rangle$, $\langle 100 \rangle$ and $\langle 112 \rangle$ fibres. For this purpose, discrete orientation distributions were generated, exhibiting a 5° gaussian spread around the wire axis. The rate sensitive Sachs model was again employed, with an m value of 0.1. The length changes and stress-strain curves obtained are displayed in Figs. 5a and 5b, respectively. When these curves are interpreted in conjunction with the fibre intensity data of Table 1, the following observations can be made. After annealing at up to 200°C , the $\langle 111 \rangle$ texture is about 2 to 2.5 times more intense than the $\langle 100 \rangle$; as a result, the shortening caused by the $\langle 111 \rangle$ fibre overwhelms the lengthening effect of the $\langle 100 \rangle$ texture at

Figure 5

Simulated axial strains (a) and stress-strain curves (b) predicted by the present model for the twisting of samples containing each of the three idealized drawn fibres. The shear stresses have been normalized by the CRSS for slip.

large strains ($\gamma > 2$). After annealing above the recrystallization temperature ($T > 225^\circ\text{C}$), the $\langle 111 \rangle$ texture is completely eliminated, and the strong $\langle 112 \rangle$ fibre, together with the weaker $\langle 100 \rangle$ and random background textures, lead to the observed lengthening behavior of the wires.

In the present simulations, hardening of the slip systems was neglected. Nevertheless, the simulated 'texture-hardening' or change in Taylor factor during straining (Fig. 5b) can be compared with the experimental stress-strain curves displayed in Fig 3. Significant changes in Taylor factor occur during the shearing of samples containing two of the fibres: the $\langle 100 \rangle$ and $\langle 111 \rangle$ components. The former displays general softening with strain (with an additional fluctuation), whereas the latter hardens continuously beyond strains of $\gamma=1$. When these results are weighted by the approximate volume fractions of the texture components contained in the present as-received wires, the apparent stage IV hardening displayed at strains beyond 2 by the unrecrystallized samples can be readily accounted for. Thus, the non-zero slopes displayed at high strains by the τ/γ curves of these materials are not necessarily indicative of the occurrence of true work hardening, i.e. of an increase of τ_0 with strain.

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