INDUCTION AND REMOVAL OF THERMAL EMF DURING STATIC AND ALTERNATING TWISTING

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Polycrystalline copper wires and tubes were plastically deformed in unidirectional and alternating twisting, and the induced thermal emf was determined. As the relative shear increases during unidirectional twisting, the thermal emf increases, passing through three stages analogous to the stages of hardening. A change in the sense of the deformation in any of the stages is accompanied by a corresponding removal of the thermal emf and the subsequent restoration of this emf to the value corresponding to the unidirectional twisting. Five stages were found in the increase of the thermal emf. The effects of the grain size and the deformation rate on the magnitude of the induced thermal emf were determined.

INTRODUCTION

Since the thermal emf induced by plastic deformation is highly sensitive to structural changes, it can be used to study various aspects of plastic deformation. For example, the thermal emf induced by plastic deformation correlates with the part of the absorbed energy expended on the work of deformation [1, 2]. A stable relation is observed between the differential thermal emf and the degree of deformation; the magnitude and sign of the induced thermal emf are related to the slip and twinning mechanisms [3], the dislocation density, etc.

We are concerned here with the use of the thermal-emf method to study characteristic details of the deformation mechanism such as the incomplete reversibility of macroscopic shear in the case of alternating twisting [4], the accumulation of macroscopic shear and its dissipation [5], the selectivity of the slip system [6], etc.

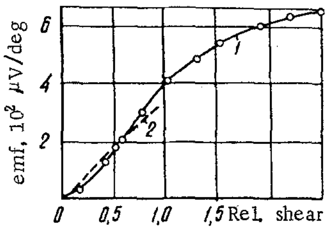

Fig. 1

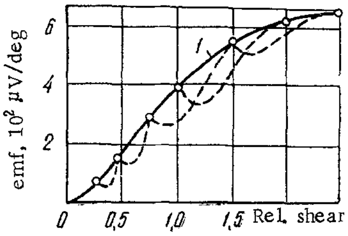

Fig. 2

Fig. 1. Change in the induced thermal emf with increasing shear during static twisting of the wires (curve 1) and tubes (curve 2).

Fig. 2. Removal of the thermal emf after a change in the direction of the twisting during various stages of deformation. 1) Overall curve corresponding to static twisting in the different directions; dashed curves) removal and restoration of thermal emf after a change in the twisting direction.

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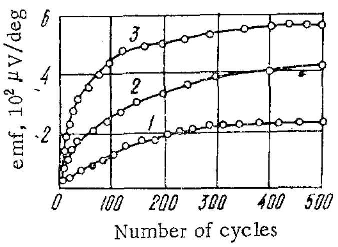

Fig. 3

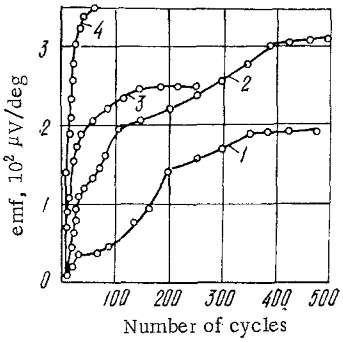

Fig. 4

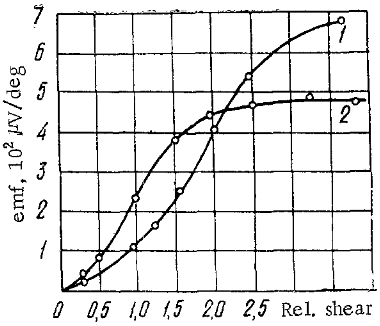

Fig. 5

Fig. 3. Induced thermal emf as a function of the number of cycles of alternating twisting of fine-grain copper. Broken lines 1-3 correspond to deformations at amplitudes of 0.00518, 0.0104, and 0.0153.

Fig. 4. The same as in Fig. 3 but for a coarse-grain copper. Curves 1-4) Deformation at amplitudes of 0.00318, 0.0088, 0.0291, and 0.0910, respectively.

Fig. 5. Effect of grain size on the dependence of the induced thermal emf on the degree of deformation during static twisting. 1) Sample having a grain size of 0.1 mm; 2) 0.001 mm.

EXPERIMENTAL METHOD

The V-shaped samples having arms 150-170 mm long were prepared from polycrystalline copper wire (0.50-0.75 mm in diameter) and tubes (inside diameter of 3.0 mm and outside diameter of 4.5 mm). The samples were annealed at 600-650°C; then one of the arms was subjected to unidirectional or alternating twisting on a special deformation apparatus; the induced thermal emf was measured (within $1 \cdot 10^{-4}$ μV/deg). The deformation amplitude was varied. The frequency was 0.95 Hz. Four series of experiments were carried out.

Series A. Wire and tubular samples were deformed to destruction by unidirectional twisting, and the induced thermal emf was measured at relative-shear intervals of 0.25. We also varied the grain size (from 0.1 to 0.001 mm) and the deformation rate (from a relative shear of 0.25 to 0.75 per minute).

Series B. The wire samples were deformed by unidirectional twisting to relative shear values of 0.25, 0.50, 0.75, 1.00, 1.50, and 1.85, and the final values of the induced thermal emf were measured. Then the sign of the twisting was changed in each case, and the sample was deformed to destruction, with the thermal emf varied at relative-shear intervals of 0.02-0.20.

Series C. Fine-grain wire samples (0.10 mm in diameter) were deformed by alternating twisting to destruction at relative-shear amplitudes of 0.0052, 0.0104, and 0.0153, and the induced thermal emf was measured after 5, 10, and 50 cycles.

Series D. The samples of this series were subjected to the same treatment as in series C, but these samples were coarse-grain samples (grain size of 0.5-0.6 mm); the deformation amplitudes were 0.0032, 0.0088, 0.0291, and 0.0910.

DISCUSSION OF RESULTS

In the experiments of series A we studied the relationship between the induced thermal emf and the shear; the results are shown in Fig. 1, where curve 1 corresponds to the deformation of wire samples, while dashed curve 2 corresponds to the deformation of the tubular samples. Since these tubular samples became unstable rapidly and were destroyed, we were not able to study the entire deformation process in their case.

Curve 1 shows that the thermal emf induced in unidirectional twisting increases with an increase in the strain hardening. This curve can be thought of as consisting of three stages, corresponding to the stages on the hardening curve for single crystals. A difference between the two curves is that the first hardening stage is not observed in our case. However, we can assume that only a single slip system is actively participating in the shear in the individual grains during the initial stage of the deformation of a polycrystalline material. The induced thermal emf reflects the distortions in this system.

The increase in the induced thermal emf in the first stage of curve 1 (at shear values from 0.25 to 1.00) is completely consistent with a dislocation nature of the hardening in the second stage. In this stage the increasing concentration of sessile dislocations and the increase in the dislocation accumulation near barriers markedly affect the state of the ionic and electronic substance, increasing the differences between the deformed and undeformed states of the metal.

In the third stage of curve 1 (at shear values above 1.0) the hardening proceeds more slowly than in the second stage, due to the discharge of local stresses as a result of transverse slip and dislocation annihilation. The concentration of dislocations and of dislocation accumulations increases much more slowly; the ultimate result is a retardation of the rate of increase in the induced thermal emf.

In the experiments of series B, we studied the removal of induced thermal emf as a function of the sense of the deformation during various deformation stages. The experimental results are shown in Fig. 2, where curve 1 corresponds to unidirectional twisting and to curve 1 in Fig. 1. The dashed curves show the change in the induced thermal emf due to the change in the sense of the deformation.

We see from Fig. 2 that a change in the sense of the deformation is accompanied by some removal of induced thermal emf; the extent of this removal depends on the magnitude of the preexisting deformation. Continuation of deformation with the same sense again raises the thermal emf, to the values corresponding to shear during unidirectional twisting.

A change in the deformation sense after a shear of 0.25 reduces the induced thermal emf by 38%. After a preliminary deformation to 0.50, on the other hand, the reduction is 11%. Deformations corresponding to relative shear values of 0.75, 1.00, 1.50, and 1.85 correspond to reductions of 9.0, 17.0, 6.1, and 7.6% in the induced thermal emf. It follows that the maximum relative decrease in the thermal emf occurs at the end of the first hardening stage (38%) and in the second stage (17%). This is true because during the first stage reverse displacement is not blocked, and a more complete "recovery" can occur, to a state equivalent to that existing before deformation.

The second maximum in the decrease in the thermal emf (17%) occurs at the transition to the third hardening stage, where, although the blocking of the reverse displacements or dislocation is very pronounced, the internal stress level allows a significant recovery toward the previous state as a result of the change in the sense of the deformation. Here dislocation annihilation should apparently play an important role. The relatively slight decrease in the third hardening stage (6.1-7.6%) implies considerable stabilization of distortions and an irreversibility of states due to mechanical effects.

In the experiments of series C we studied the induced thermal emf as a function of the number of cycles; the results are shown in Fig. 3, where curves 1-3 correspond to deformations at relative-shear amplitudes of 0.0052, 0.0104, and 0.0153. We see that during alternating twisting the induced thermal emf increases in stages with increasing number of cycles.

Although the general features of the curves in Fig. 3 are similar to those of the torsion-net deformation curves [7], they are broken lines each consisting of five segments. We can interpret this behavior by assuming that during alternating deformation at a low amplitude in each grain only a single slip system – that having the minimum critical cleavage stress – participates in back-and-forth rotation and translation in the initial stage; as this system becomes hardened, the induced thermal emf increases. When the next slip system comes into play, the hardening assumes a different behavior; etc. A similar selection of slip systems has been observed during alternating-twisting deformation of copper single crystals [6].

The results found in our study of coarse-grain copper are shown in Fig. 4, where curves 1-4 correspond to deformations of 0.0032, 0.0088, 0.0291, and 0.0910. We see from Fig. 4 that the deformation of coarse-grain copper is distinguished from that of fine-grain copper by a lag in the increase in the thermal emf after a new slip system comes into play (especially at amplitudes of 0.0032 and 0.0088). This behavior implies that, although the induced thermal emf correlates with the hardening, it is less sensitive than the stress to the development of defects in slip planes. It follows that each slip system which enters the shear formation is characterized by an easy-slip stage with a relatively weak initial accumulation of defects. Slip systems having a lower reticular density, including at least one of the ⟨110⟩ slip directions, presumably then take part in the deformation.

Figure 5 shows the effect of the grain size on the induced thermal emf; curve 1 corresponds to unidirectional twisting of a sample having a grain size on the order of 0.1 mm, while curve 2 corresponds to a grain size of 0.001 mm. This figure clearly shows the easy-hardening stage for the fine-grain sample. We also see from these results that an increase in the deformation rate raises the induced thermal emf (curves 1 and 2).

CONCLUSIONS

1. The restoration of macroscopic shear observed previously during alternating twisting corresponds to a reduction of the induced thermal emf, apparently due to some local adjustment of the lattice.

2. During alternating twisting of polycrystalline materials at low deformation amplitudes, there may be successive, separate shear formation in different crystallographic slip systems in order of hardening.

3. The effects of the grain size and deformation rate on the hardening during static twisting are consistent with previous results, but the structural features of the deformation process are expressed more clearly in the measured induced thermal emf.

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