acta physica slovaca 42 (1992), No. 1, 34–41

MECHANICAL TWINNING EFFECT ON WORK HARDENING RATE OF Cu-10 wt% Sn ALLOY

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The effects of mechanical twinning on tensile stress-strain behaviour of polycrystalline specimens of a Cu-10 wt% Sn alloy of different grain diameters were investigated at 623, 673, 723 and 773 K. It was found that the start of the twinning is accompanied by a decrease in the work hardening rate and that the concentration of deformation twins increases by increasing the working temperature. A drop in ductility was observed at elevated temperatures, and attributed to the formation of mechanical twins on intersecting planes. A value of 19.26 kJ/mole was obtained for the energy activating the process of twin formation.

I. INTRODUCTION

Many physical properties of a polycrystalline material are influenced by the grain size. The well-established Hall-Petch relationship [1,2] for grain size dependence of the yield stress is one of the numerous examples. Lui and Alers [3] had studied the effect of grain size on the rolling texture in a Cu-Sn alloy of different concentrations, and found that concentrated Cu-Sn alloys revealed abundant microtwins which reflect on the value of the measured Young's modulus. It has been also demonstrated by a number of investigators [4—10] that deformation twinning influences the mechanical response of fcc metals. However, the role that twinning plays in the development of the desirable properties in polycrystalline fcc metals has not been appreciated in literature. In the last decade two contradictory points of view were proposed. In one, due to Vöhringer [4—6], it is assumed that the formation of twins is accompanied by a decrease in the work hardening rate. In 1980 Krishnamurthy and Reed-Hill [11] confirmed in one part of their work on Cu-4.9 at. %Sn Vöhringer's proposition. The second point of view was due to Rémy [8] and Murr [10]. They assumed that twinning increases the flow stress due to the fact the twin boundaries increase the total grain boundary area per unit volume.

The present paper aims at obtaining a clearer understanding of the effect of deformation twinning on the stress-strain relations of a Cu—Sn alloy of various grain diameters. The effect of the working temperature was also taken into consideration. The copper-tin alloy was chosen for this study because in this alloy mechanical twins are resolvable in an optical microscope and are thus suitable for metallographic analysis.

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II. EXPERIMENTAL PROCEDURE

II. 1. Specimen Preparation

The Cu-10 wt% Sn alloy used in this work was prepared from cathodic copper of 99.99% purity and zone refined tin of 99.999% purity. The pre-weighted materials were melted in a graphite crucible. The as received cast obtained in the form of a rod 12 mm in diameter was first given a homogenization anneal at 773 K for 13 days, swaged and cold drawn into a rod of 8 mm in diameter. This rod was reduced in diameter in steps with intermediate anneals at 873 K for 2 h. The resulting test specimens were of 0.3 mm in diameter. Specimens of various grain diameters were prepared by suitable annealing treatments, usually for one hour at temperatures ranging from 823 K to 1093 K. To reveal the grains, the specimens were electropolished in a well stirred solution of 50 g $Cu(NO_3)_2)$—$3H_2O$, 5ml HNO_3, and 150 ml methanol maintained below 5°C. They were then etched in a solution of equal parts of water, HNO_3 and 25% glacial acetic acid. The grain diameter was measured by a linear intercept method in which the intersections with twin boundaries were neglected. For most determinations, over thirty grain boundaries were considered.

II. 2. Mechanical Tests

The stress-strain experiments for the annealed wires were done using a conventional type machine similar to that previously adopted by Youssef et al [12]. The wires were heated while clamped in the tensile testing machine. The samples were deformed at 623, 673, 723 and 773 K. The tensile tests were completed up to fracture. The fracture stress as well as the fracture strain percentage were determined. All the tensile experiments were made on specimens of a gauge length of 50 mm at a strain rate of 0.5 mm/min.

II. 3. Experimental Results and Observations

The tensile stress-strain curves for the annealed wires tested at 623, 673, 723 and 773 K are shown in Fig. 1. As no yield point effect occurred, the yield stress was taken as that corresponding to the first deviation from linearity in the stress strain curves. The Petch—Cottrell relations [2,13,14] proved to be valid for the studied wires. This was deduced from the linear dependence of yield and fracture stress on $d^{-1/2}$ (d is the grain diameter) shown in Figs. 2 and 3. It is clear from these figures that: (a) the friction stress, σ_0, is nearly the same for all relations independent of the working temperature, and (b) the Petch slope K_y decreased by increasing

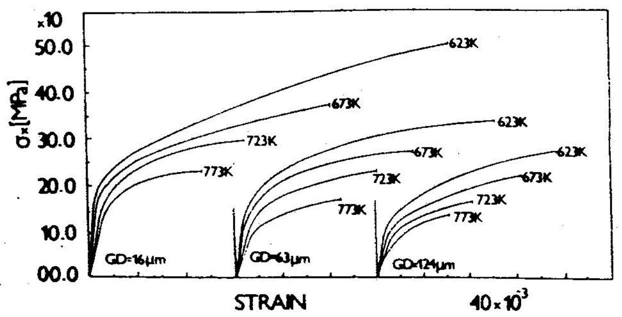

Fig. 1. Representative stress-strain curves for Cu-10% Sn wires of grain diameters of 0.016, 0.063 and 0.124 mm, the working temperatures are indicated.

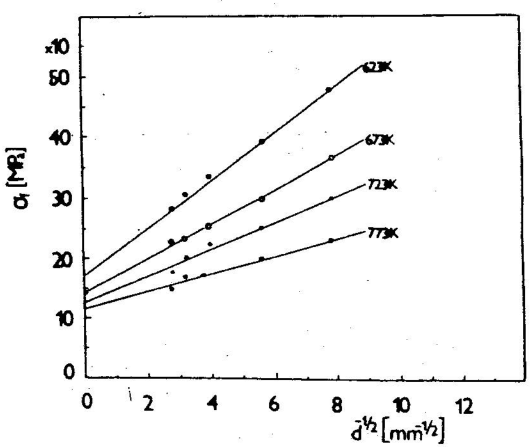

Fig. 2. Dependence of the yield stress σ_y for wire specimens on $d^{-1/2}$ at different working temperatures, d being the grain diameter.

working temperature. From the stress-strain relations it was observed that as the working temperature increases the strain at which fracture occurs decreases. The dependence of the fracture strain percent ε_f on the working temperature is shown in Fig. 4. Figs. 5 and 6 are photomicrographs which show the mechanical twins found at grain boundaries and at triple points in a test sample deformed to 2% strain at 623 K and 723 K respectively.

Comparison of Figs. 5 and 6 indicates that the concentration of the deformation twins increased by the rise of working temperature. To study the functional form of the curved part of the stress-strain curves immediately after yielding, plots of $\partial\varepsilon/\partial\sigma$ versus σ for different grain diameters were made. The results obtained are shown in Fig. 8a, b and c, at working temperatures 623, 723 and 773 K respectively. As

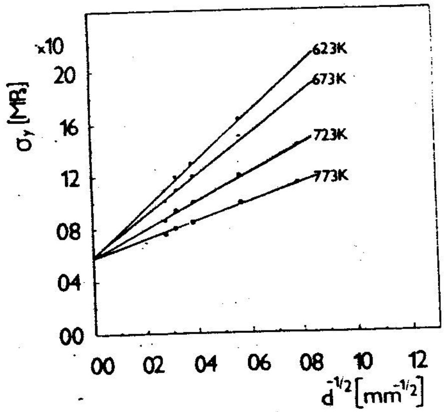

Fig. 3. Dependence of fracture stress σ_f for wire specimens on $d^{-1/2}$ at different working temperatures, d being the grain diameter.

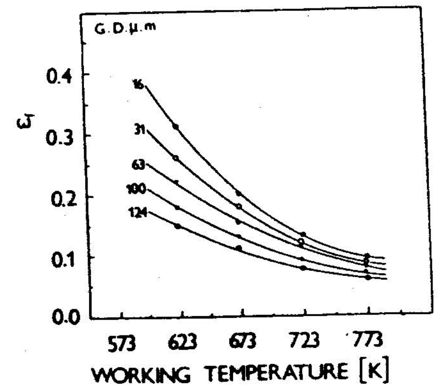

Fig. 4. Effect of working temperature on the fracture strain ε_f for different grain diameters of wire specimens.

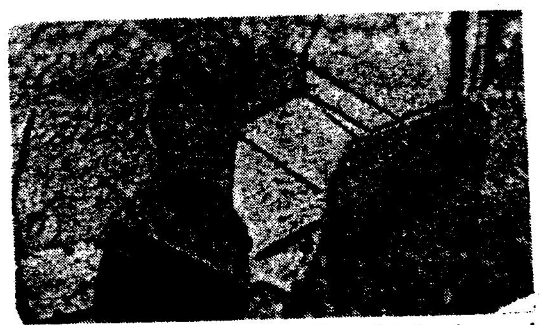

Fig. 5. Photomicrograph showing the formation of twins in specimens of the alloy deformed to 2% by tension at 623 K, 140×.

evident from these figs., the curves describing the variation of $\partial\varepsilon/\partial\sigma$ as a function of σ can be divided into four stages. Significant changes due to variations of the effective parameters such as grain diameter and/or working temperature could be obtained particularly in the second stage. Thus we will be interested only in the second stage.

III. DISCUSSION

The wire texture of this alloy is basically a mixture of grains with orientations close to ⟨111⟩ and ⟨100⟩, which is typical of that normally observed in fcc metals [15]. As noted from the stress-strain curves (Fig. 1), the strain increases by an

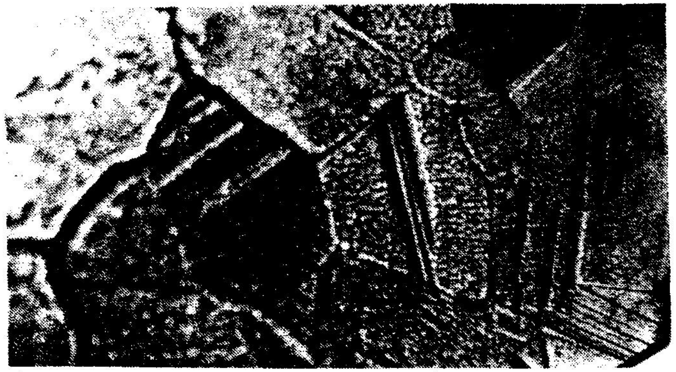

Fig. 6. Photomicrograph showing the formation of twins in specimens of the alloy deformed to 2% by tension at 723 K, 140 x.

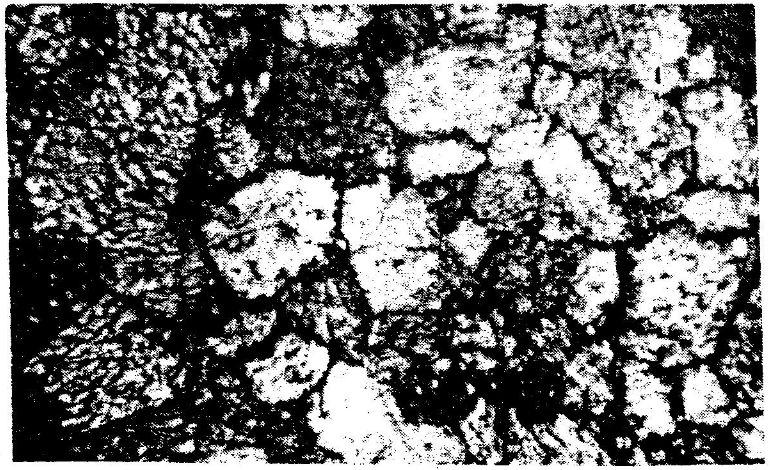

Fig. 7. Photomicrograph showing the initial microstructure of the specimen before straining.

increasing stress with an increasing rate, $\partial\varepsilon/\partial\sigma$. It is clear from Fig. 8 a, b and c that there is a sharp upward bend the beginning of which depends on the grain diameter as well as on the working temperature. This abrupt increase in $\partial\varepsilon/\partial\sigma$ can be accounted for by the beginning of the twin formation. Thus it can be assumed that the formation of twin adds an increase of the strain but does not influence the flow stress. In other words, the work hardening rate decreases once the twinning

begins.

The metallographic examination of the undeformed specimens revealed no twins as shown in Fig. 7, while the examination of specimens deformed to a 2% strain at 623 and 723 K showed the development of the twinned structure, (Figs. 5 and 6). This indicated that the appearing twins in Figs. 5 and 6 are certainly deformation twins. Thus the abrupt increase of $\partial\varepsilon/\partial\sigma$ could be ascribed as being due to twin formation. Careful inspection of Figs. 5 and 6 showed that as the working temperature was increased the twin concentration increased. This may

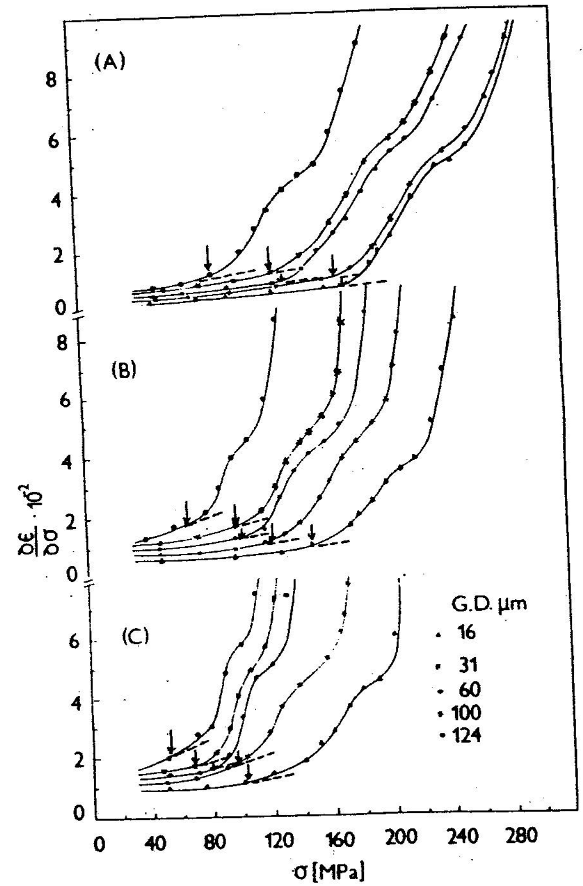

Fig. 8. Relation between $\partial\varepsilon/\partial\sigma$ vs. σ for wire specimens of different grain diameters at working temperatures: (a) 623, (b) 723 and (c) 773 K. The grain diameters are indicated.

lead to a decrease of the work hardening rate. This conclusion is in consistence with Vöringer's work [1—4] on the polycrystalline Cu-4.9 at % Sn alloy (which is nearly equal to the concentration of the present alloy).

It has been observed from Fig. 4 that for a certain grain diameter the strain at which the specimen fractures was decreased by increasing working temperatures. This indicates that the ductility of the material under investigation is prone to embrittlement (ductility drop) at elevated temperature. Elevated temperature embrittlement has been observed during deformation of steel and was attributed to dynamic strain, aging or strain induced precipitation [16]. Since none of these mechanisms occurs in the present alloy under the considered working conditions, one may propose that by increasing working temperature twins may occur preferentially on intersecting planes. This should influence the work hardening rate leading to an earlier fracture rather than to an increase of the flow stress. Such an earlier fracture may be considered in view of the assumption that formation of twins of intersecting planes creates microcracks at locations where a concentration of twin-induced stress exists. This is clearly seen in Fig. 6 where mechanical twins are concentrated at the grain boundaries.

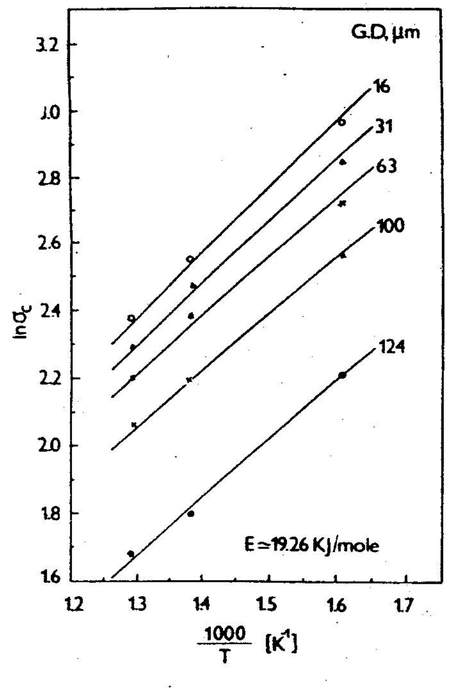

Fig. 9 Arrhenius plot of $\ln(\sigma_c)$ as a function of the working temperature T(k), the relation gave an activation energy for twin formation $\approx$ 19.26KJ/mole.

From Fig. 8 it is clear that a sudden change in $\partial\varepsilon/\partial\sigma$ took place. The stress

σ_c—indicated by arrows on the figure—at which this change takes place was determined by smoothly extrapolating the curve describing the first stage, i.e., as if this first stage continued to proceed smoothly as illustrated on the curves by the dashed lines. The point at which the second stage deviates from the first stage determines σ_c. σ_c was found to depend on the grain diameter as well as on the working temperature, and was accounted for by the start of twin formation. The activation energy of this process was calculated from an Arrhenius plot relating $\ln\sigma_c$ versus $1000/T$ (Fig. 9) and was found to have a value of 19.26 kJ/mole.

REFERENCES

[1] Hall, E. O.: Proc. Phys. Soc. *64B* (1951), 747.
[2] Petch, N. J.: J. Iron Steel Inst. *174* (1953), 25.
[3] Lui, Y. C., Alers, G. A.: Metallurgical Transactions *1491* (1973), 4.
[4] Vöhringer, O., Mater, S.: Eng. *3*, (1968/1969), 299.
[5] Vöhringer, O.: *Second Int., Conf. On Strength of Metals and Alloys* pp. 294 — 98, ASM. Metals Park, OH, 1970.
[6] Vöhringer, O., Z. Metalk: *67*, (1976), 518.
[7] Mahajan, S., Chin, G. Y.: Acta Met., *21*, (1973), 173.
[8] Remy, L.: Acta Met. *26*, (1978), 443.
[9] LaRouche and Mikkola, D. E.: Scr. Met., *12*, (1978), 1031.
[10] Murr, L. E., Moin, B., Grelich, F., Staudhammer, K. P.: Scr. Met., *12*, (1978), 1031.
[11] Krishnamurthy, S., Reed—Hill, R. E.: Metallurgical Transactions *11* A, (1980), 565.
[12] Youssef, T. H., Saad, G.: Phil. Mg., *42* A, (1980), 212.
[13] Petch, N. J.: Phil Mag., 3, (1958), 1098.
[14] Cottrell, A. H. *"Conference on Fracture" Swanpscott* (1959).
[15] Barrett, C. S., Masssalski, T. S.: *Structure of metals*, 3rd ed., P. 569, Mc. Graw—Hill Book Company, NY, (1966).
[16] GlenJ., J. Iron Steel Inst. (London) *190*, (1958), 30.

Received February 14th, 1990
Accepted for Publication July 18th, 1990

ЭФФЕКТ МЕЦХАНИЧЕСКОГО ДВОЙНИКОВАНИЯ ПРИ ЗАКАЛЬКЕ СПЛАВА Cu-10%Sn

В работе исследуется эффект влияния механического двойникования на свойства ударного растьяжения поликристалических образцов сплава содержащего 10 весовых процентов Cu с разным диаметром зерн. Исследования проводились при 623, 723 и 773 K. Показано, что начало двойникования сопровождается уменшением скорости отверждения когда концентрация деформации паров нарастает с увеличением рабочей температуры. Падение растяжимости наблюдается также при повышенной температуре, что можно отнести к формированию механического спаривания в пересекающихся плоскостях. Полученное значение энергии активации формирования двойникования составляет 19,26 кДж/мол.