Flow behaviour of $\beta$-Sn single crystals

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The flow behaviour of $\beta$-Sn single crystals by tension test was studied as a function of orientation and strain rate. It was found that the flow stress curves were strongly dependent on crystal orientation and strain rate. In addition, while the slip traces change with the strain rate, there was not any detectable effect of crystal orientation.

Plastic deformation has been the subject of continued scientific and technical interest in order to ensure the appropriate conditions during material processing and to predict the performance of components during service. Corresponding to this, it has been shown that the flow stress behaviour of crystals which is comprehensively represented by the stress-strain curves is governed by the thermally activated movement of dislocations within a wide range of temperatures and stresses. An attempt to describe the macroscopic plastic flow behaviour of crystals in terms of the dynamics and interaction of dislocations and the nature of the collective motion of dislocations has been proposed by Haasen. He proved experimentally and theoretically that the stress-strain curves of crystals are very sensitive to temperature and strain rate ($\dot{\varepsilon}$) and, in addition, those are sensitive to the value of the dislocation density. Also, it has been shown that the yield stress of some crystals exhibits a positive temperature dependence in a certain temperature region, known as the yield stress anomaly. Both dislocation locking by interstitial impurities and dislocation dynamics have been used to explain various aspects of the yield phenomenon in body-centred-cubic (bcc) metals. On the other hand, Rosáles et al. showed that the $\{110\}$ and $\{111\}$ specimens showed pronounced yield points followed by a decrease in the flow stress. This pronounced yield point has been explained by the absence of a sufficiently high density of mobile dislocations.

Another important characteristic of plastic deformation is the strain-rate dependence of flow stress in the anomalous temperature region. Takeuchi and Kuramoto and Umakoshi et al. showed that the flow stress was almost independent of strain rate. However, a small but finite strain rate dependence flow stress has recently been reported by some researchers. The small strain rate sensitivity has been explained by considering the thermally activated locking and unlocking dislocations or the superkink motion. Meanwhile, it has been found that the flow stress increases with increasing temperature to a peak value and then deformation occurs by the movement of super lattice dislocation pairs.

Studies on plastic deformation under a constant strain-rate in $\beta$-Sn single crystals which have a body centered tetragonal structure above 13.2 °C have been carried out by several workers in addition to instructive studies of deformation under a constant applied stress, i.e., creep tests. It has already been indicated that dislocation boundaries play an important role in plastic deformation. Also, Hirokawa et al. showed that moving dislocations are obstructed by dislocation boundaries, and as a result, the crystal strength is increased. In particular, although a few data have been published on yield point and flow stress behaviour in $\beta$-Sn single crystals, there is still little information on plastic deformation in this metal as compared with those in bcc and face-centred-cubic (fcc) metals. To understand the plastic deformation of this material more clearly, it is necessary to understand the behaviour of the crystal under different temperatures, strain-rate and orientation. The main purpose of present study is to find the effect of orientation and strain-rate on the stress-strain curves.

**Experimental Procedure**

$\beta$-Sn ingots used in this study were of 99.99 % purity and were grown in a glass tube with a speed of...
15 mm/h using a modified Bridgman method under 10^{-4} torr pressure. The crystals 6 mm diameter and 50 to 60 mm in length were grown from melt and their orientations were determined by the Laue back reflection method. The crystal orientations which are tensile axes are \langle 001 \rangle, \langle 110 \rangle and \langle 110 \rangle are shown in the unit triangle (Figs 1 and 2). In order to observe slip lines, the crystals were chemically polished for one hour with a solution consisting of 1 part 65\% HNO_3, 1 part CH_3COOH and 4 parts glycerine. The crystals were pulled along the growth direction with an Instron 4204 test machine. The test machine, with two hooks and digital electromechanics, had 5 kN capacity in the pulling velocity 0.5-250 mm/min and 25 kN capacity in the pulling velocity 25-500 mm/min. Tensile experiments were performed in an etching solution to avoid oxidation. Slip traces on the surfaces were observed by metal microscope (Nikon; Optiphot 22962) having three magnifications of \times 500, \times 1000 and \times 2000. Load and elongation curves were recorded during tensile tests. Resolved shear stress-strain curves were calculated from load-elongation curves and plotted for crystals having various orientation. Further experimental details are described elsewhere.

Results and Discussion

Fig. 1 shows stress-strain curves of \beta-Sn single crystals obtained at a strain rate 10^{-4} s^{-1} for three different orientations at room temperature. The flow stress strongly depends upon crystal orientations. Especially for \langle 001 \rangle orientation, there is a pronounced yield point. The flow stress increases rapidly on loading and quickly reaches a peak, followed by gradual decrease and finally followed by a gradual increase in the stress with strain. Murayama et al.\textsuperscript{32} and Yoshimi et al.\textsuperscript{33} have found a similar behaviour in polycrystalline Nb_3Al and in tetragonal single crystals Mo_3Si, respectively. It was attributed to dynamic recrystallization and to the absence of a sufficiently high density of mobile dislocations. Also, it is found that the observed pronounced yield point is consistent with the displacement jumps in Mo_3Si at room temperature\textsuperscript{34}. For the \langle 110 \rangle and \langle 110 \rangle oriented crystals, yielding occurs gradually without a yield drop and is followed by almost linear work hardening. This linear work-hardening region can be considered to be a steady state of plastic deformation.

As a selected example, Fig. 2 shows the stress-strain curves of \langle 001 \rangle oriented crystal obtained during tension at different strain rates at room temperature. At high strain rates, the flow stress increases rapidly on loading and quickly reaches a peak, followed by a gradual decrease. With decreasing strain-rate, there is no remarkable yield drop. And also, at room temperature, the stress drops when strain rate is decreased. The flow curve changed from work softening to the steady state flow. It can be said that the crystals have a very low dislocation density and a high stress needed for multiplication of dislocations. A similar stress-strain behaviour has been observed for Mo_3Si single crystals\textsuperscript{35}, single crystal nickel-base superalloy\textsuperscript{35}, and some semiconductors\textsuperscript{36,37}.

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**Fig. 1**—Effect of crystal orientation on stress-strain curves of \beta-Sn single crystals. The crystal orientations are shown in the unit triangle.

**Fig. 2**—Effect of strain rate on stress-strain curves of \beta-Sn single crystals.
In addition, slip traces were observed on single crystals with three orientations indicated in the unit triangle (Fig. 1) at room temperature. The slip trace analysis showed that slip occurred on {121}, {100}, {011} and {01̅1} planes. In considering the slip trace analysis, there were no major differences in nature and distribution of slip traces between three orientations. Figs 3a and 3b show the optical micrographs of slip traces on the {121} surface of $<001>$ specimen for two different strain rates at room temperature. Slip lines are always long and straight, but they become much finer as the yield point decreases with decreasing strain rate.

**Conclusions**

In conclusion, we may say that the deformation characteristics in present study for $\beta$-Sn single crystals are in good agreement with results of early deformation studies on other single crystals. The stress-strain curves depend on the crystal orientation and strain-rate.

**References**