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Effect of Deformation Temperature on the Stage IV Deformation in ⟨100⟩ Oriented Aluminum Single Crystal

By

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Abstract

It is known that at room temperature the tensile stress-strain curve of an aluminum single having ⟨100⟩ tensile orientation becomes flat after about a two percent elongation. (This flat region of the stress-strain curve is named Stage IV). In the previous paper, the propagation of a clustered slip accompanied by a prominent cross slip was observed in the Stage IV region of curve.

In the present study, ⟨100⟩ oriented aluminum single crystals were tested in tension at various temperatures so as to clarify the influence of temperature on the deformation mechanisms in Stage IV.

At 203K, a few clustered slip lines accompanied by a prominent cross slip occurred, but they did not propagate in the entire region of the specimen. The stress-strain curve became flat only from about a ten percent elongation. In the crystal stretched at 77K, the cluster did not propagate at all from either end of the specimen, and so the stress-strain curve did not become flat.

On the other hand, a wavy coarse slip was observed and the curve became flat from about a 0.5 percent elongation at 473K. It was suggested that these wavy slip lines were produced by a frequent repetition of the cross slip on two {111} planes and also possidly on a {110} plane having the same slip direction.

It was confirmed that the occurrence of Stage IV is caused by the of the clustered slip accompanied by a prominent cross slip, and is much influenced by the temperature of deformation due to the easiness of the cross slip.

1. Introduction

It has been observed by many research workers[1)-6)] that the tensile flow curve of an aluminum single crystal having a ⟨100⟩ tensile orientation becomes flat after an elongation of a few percent strain at room temperature. Kocks[6)] termed the flat region of the curve as Stage IV, but a deformation mechanism at Stage IV has not yet

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been sufficiently clarified. It was also reported that a similar Stage IV region exists in the ⟨100⟩ oriented gold single crystals deformed at room temperature[7] and in the ⟨100⟩ silver single crystals at a high temperature[8].

Saeki and Miura[6] reported the exact deformation mode of a ⟨100⟩ oriented aluminum single crystal deformed at room temperature. In the plastic deformation of the single crystal, a clustered slip accompanied by a cross slip begins to occur at about 2% strain. It propagates from the both ends to the centre of the specimen, similar to a propagation of the Lüders band.

Also, Miura et al.[9] studied the plastic deformation of a ⟨100⟩ oriented copper single crystal. A clustered slip occurs only at both ends of a specimen, but it never propagates in the case of a copper single crystal. The clustered slip in the copper single crystal is not accompanied by a prominent cross slip, since the occurrence of a cross slip in copper is more difficult than that in aluminum having a higher stacking fault energy. Therefore, the stress-strain curve of a ⟨100⟩ oriented copper single crystal deformed at room temperature does not show any Stage IV.

It is considered that the stability of the flow stress is caused by a propagation of the deformation bands of such sorts as Lüders band. It is obvious that the deformation band in the case of Stage IV is the clustered slip accompanied by a prominent cross slip. These results suggest that the Stage IV deformation is closely related to a difficulty with the cross slip, but the relation is not established.

In this paper, ⟨100⟩ oriented aluminum single crystals are tested in tension at various deformation temperatures. The effect of a deformation temperature on the Stage IV deformation is studied in order to establish the relation between Stage IV and the cross slip.

2. Experimental procedure

The material used in this experiment was 99.99% pure aluminum. A single crystal having an orientation controlled by seeding was grown by the Bridgman method in a vacuum. The maximum temperature and the vertical moving rate of the furnace were 1073K and 50 mm/h respectively. Specimens with a gauge dimension of $2\times2\times15\text{mm}^3$ were cut from the single crystal plate by spark cutting and then annealed at 823K for 3hrs. All the specimens were polished mechanically before the tensile tests. The orientation of the single crystal specimens is shown in Fig. 1. The accuracy of the orientation of the single crystals could be controlled to within $\pm1°$.

The tensile tests, using an Instron type testing machine were performed in liquid nitrogen at 77K, in a solution of ethyl-alcohol cooled with liquid nitrogen at 203 ± 2 K, in atmosphere at 293 ± 2K and in silicon oil at 473 ± 2K. The strain rate was $4\times10^{-5}\text{sec}^{-1}$ for all tests. After giving a proper strain to the specimen, the load was

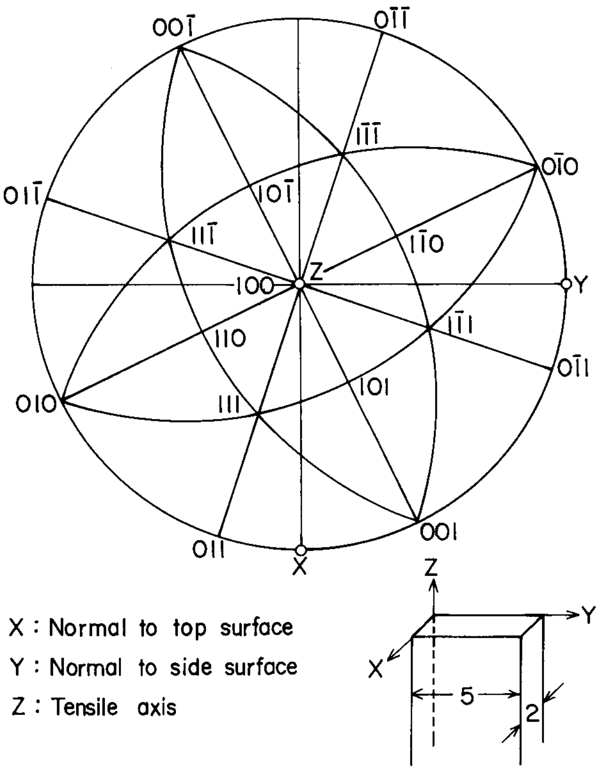

Fig. 1 Orientation of single crystal specimens.

removed and slip line observations were made on the top surface of the specimen.

3. Results and discussion

3. 1 Effect of the deformation temperature on the stress-strain curve

The stress-strain curves of the ⟨100⟩ oriented aluminum single crystals, deformed at 77K, 203K, 293K and 473K, are shown in Fig. 2.

The stress-strain curve at 293K has well known features, i. e. its flow stress increases rapidly from the yielding to a 2% strain, but hardly increases thereafter. Namely, Stage IV is obtained at a strain of more than 2%.

The flow stress at 203K rises with a higher work hardening rate than that at 293 K in the initial stage of plastic deformation. As the deformation proceeds, the work hardening rate decreases and the stress-strain curve exhibits Stage IV after an elongation of a 10% strain. At 77K, the flow stress increases rapidly to be proportional to a plastic strain from the yielding to a 2.5% strain. Subsequently, an increase of the flow stress becomes moderate step by step as the plastic deformation proceeds, but does not stop even at a large strain. Namely, Stage IV is not obtained

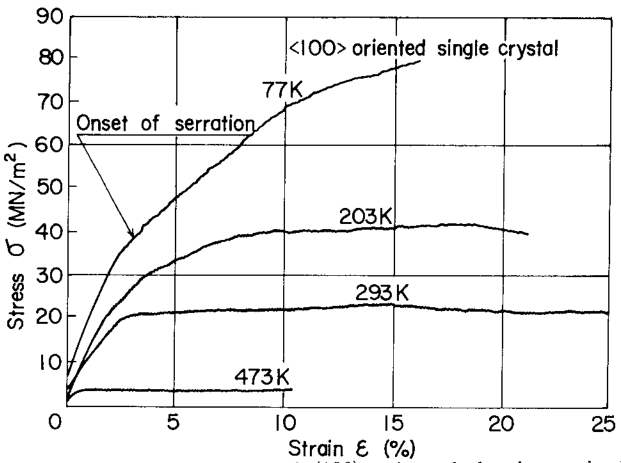

Fig. 2 Stress–strain curves of ⟨100⟩ oriented aluminum single crystals deformed at various temperatures.

at the 77K defomation.

On the other hand, the ⟨100⟩ oriented aluminum single crystal deformed at 473 K scarcely hardens after an elongation of 2%.

3.2 Effect of the deformation temperature on the deformation mode

The deformation mode of the ⟨100⟩ oriented aluminum single crystal deformed at room temperature was reported by Saeki and Miura[6]. The quadruple slip characteristic of the ⟨100⟩ tensile axis takes place almost homogeneously in the whole region of the specimen immediately after the yielding, and obstacles such as the Lomer–Cottrell sessile dislocation are formed due to the interaction of the slips. As the obstacle occasionally impedes a movement of the glide dislocations, the moving distance of the glide dislocation is very short. Namely, only fine quadruple slips are observed. After an elongation of about 1.5%, a clustered slip which can break out of such obstacles, is activated by a highly applied stress at both ends of a specimen. Therefore, the clustered slip propagates accompaning the prominent cross slip to the centre of the specimen with an increase of the plastic strain (Fig. 3) .

Even at the 203K deformation of the ⟨100⟩ oriented single crystal, when the plastic deformation starts, only the fine quadruple slip is observed initially (about a 2% strain) and the clustered slip accompanied by a cross slip of the (111) $[10\bar{1}]$ slip system and the $(1\bar{1}1)$ $[10\bar{1}]$ slip system takes place at both ends of the specimen subsequently (Fig. 4) . The clustered slip spreads with an increase of the plastic strain, but does not reach the central region of the specimen until failure (Fig. 5) . The occurrence of the prominent cross slip at 203K is sufficiently less than at 293K.

The deformation mode of the ⟨100⟩ oriented single crystal stretched at 77K is

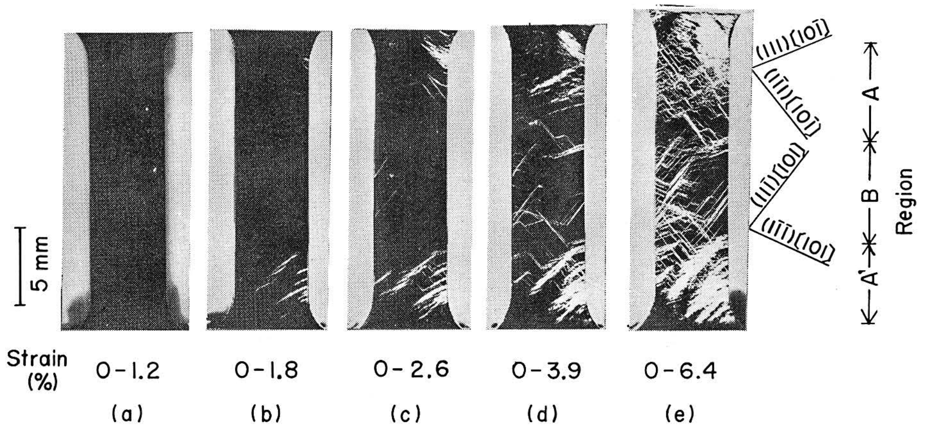

Fig. 3 Propagation of a clustered slip accompanied by a prominent cross slip in a specimen deformed at 293 K. (after Y. Saeki and S. Miura[6])

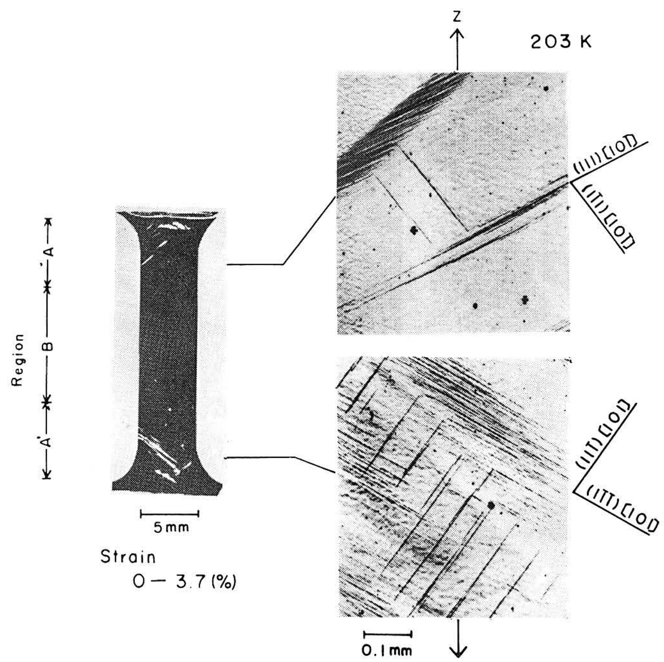

Fig. 4 Multiple slip lines and clustered slip lines accompanied by prominent cross slips in a specimen stretched by a 3.7% strain at 203 K.

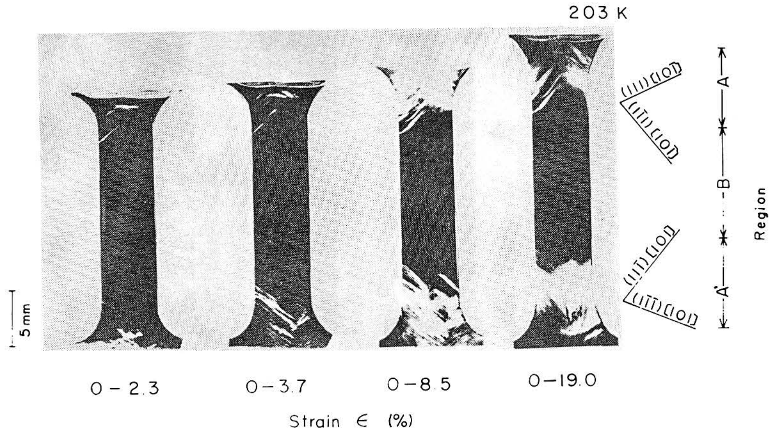

Fig. 5 Propagation of a clustered slip accompanied by a prominent cross slip in a specimen deformed at 203 K.

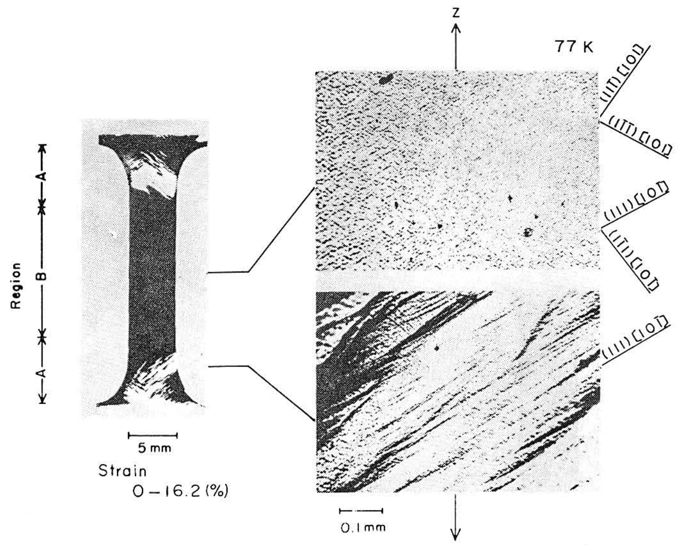

Fig. 6 Macroscopic observation of a deformation mode in a speci men deformed at 77 K.

almost similar to that at 203K, i. e. the fine quadruple slip takes place at first, and the clustered slip is activated subsequently at both ends of the specimen after an elongation of 2. 5% (Fig. 6) . However, the occurrence of the clustered slip is restricted to within both ends of the specimen, the stress-concentrated regions, even at the final stage of deformation. Figure 7 shows that the clustered slip which occurred at 77K is hardly accompanied by a prominent cross slip, differing from that at 293K or 203K.

A fine quadruple slip is also observed at the initial stage of the 473K deformation. But in this case, a wavy coarse slip, as shown in Fig. 8, takes place at 0.5% strain, and it spreads to the whole region of the specimen thereafter. The trace of this wavy slip does not correspond to any traces of the {111} planes, but it is close to the trace of the (101) plane, and lies between the traces of the (111) and (11$\bar{1}$) planes.

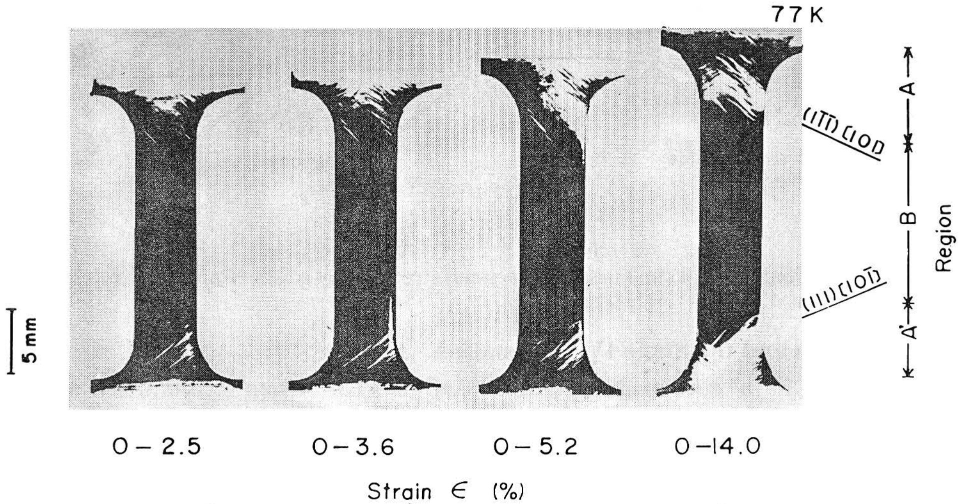

Fig. 7 Multiple slip lines in a specimen stretched by a 16.2% strain at 77 K.

Saeki and Miura[6] also observed a slip trace corresponding to a trace of the {110} plane, and concluded that it was apparently made by the alternate repetitions of a short distance cross slip on two {111} planes. On the other hand, Hajif et al.[10][11] reported the occurrence of a {110} ⟨110⟩ slip in a ⟨100⟩ oriented aluminum single crystal tested by compression at high temperature. Miura and Hamashima stated that an ⟨111⟩ oriented aluminum single crystal is deformed by a coarse wavy slip, caused by a frequent cross slip a {111} plane and a {100} plane at 473K[12]. The coarse wavy slip, shown in Fig. 8, is not similar to the one observed by Saeki and Miura, but one observed in the ⟨111⟩ oriented single crystal.

In the ⟨100⟩ oriented crystal, the Schmid factor of (101) [10$\bar{1}$] has a possible maximum value (0.5). It it thought that the slip of (101) [10$\bar{1}$] is activated by the thermal energy, and that the frequent repetitions of a short distance cross slip between (101) and (111) or (1$\bar{1}$1) are regarded macroscopically as such a coarse wavy slip.

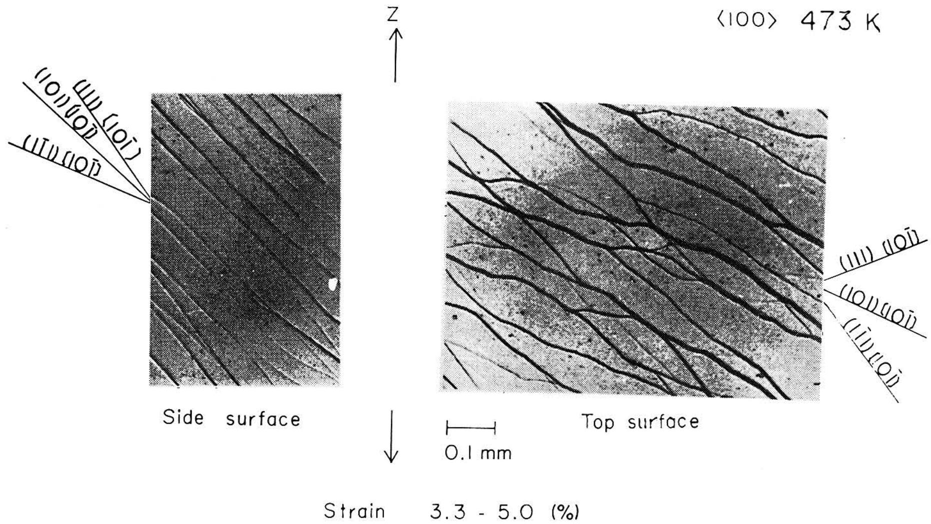

Fig. 8 Coarse wavy slip lines in a specimen stretched by a 5.0% strain at 473K.

3.3 Cross slip and the Stage IV deformation

Saeki and Miura[6] supposed that Stage IV of the ⟨100⟩ oriented aluminum single crystal deformed at room temperature, obtained after an elongation of 2%, was because of the propagation of the clustered slip accompanied by a prominent cross slip. The flow curve of the same single crystal deformed at 203K exhibits Stage IV after an elongation of 10%. The late appearance of Stage IV corresponds to a later occurrence of the clustered slip and the lower frequency of the prominent cross slip. Stage IV is not found at the 77K deformation. The absence of Stage IV answers well to the localized occurrence of the clustered slip and the absence of the prominent cross slip.

The ratio of shear stress on the cross slip system to that on the primary slip system indicates the easiness of the cross slip[13]. The value of this ratio in the ⟨100⟩ oriented single crystal is maximum, if one takes into account the direction of the resolved shear stress on the cross slip plane. Therefore, the prominent cross slip, to be able to evade obstacles in a specimen, occurs comparatively easily in the ⟨100⟩ oriented single crystal deformed at room temperature. Also, the clustered slip propagates successively accompaning the prominent cross slip in such a condition. However, the lower the deformation temperdture is, the more difficult is the activation of a prominent cross slip in a single crystal. At a lower deformation temperature such as 77K, the clustered slip in a single crystal can not propagate due to the impossibility of a prominent cross slip.

At a higher temperature, since the movement of dislocation is favored by the thermal energy, an operation of a slip on some {110} planes becomes possible in the ⟨100⟩ oriented single crystal. Therefore, the single crystal tested at 473K is deformed by the coarse wavy slip which is composed of frequent repetitions of short distance crosss slips on two {111} planes and a {110} plane having the same slip direction from a strain of 5% until failure. The coarse wavy slip occurs in the whole region of the specimen, and it multiplies as the deformation proceeds. But the work hardening and the dynamical recovery of the single crystal deformed at 473K are equivalent, because the coarse wavy slip always evades the obstacles to cause the work hardening. The flow stress of a single crystal deformed by the coarse wavy slip does not increase owing to the equivalence.

In the deformation of a ⟨100⟩ oriented copper single crystal, a clustered slip occurred only at both ends of a specimen and a prominent cross slip hardly occurred[9], thus being similar to that observed in the 77K deformation in this study. Hence, Stage IV is not obtained because the clustered slip does not propagate. It is concluded that the difficulty of a cross slip in copper is due to the lower stacking fault energy.

Taking these results into consideration, it is obvious that Stage IV of a ⟨100⟩ oriented aluminum single crystal deformed at a comparatively high temperature is caused by the propagation of the clustered slip accompanied by a cross slip. As the easiness of a cross slip is governed by the deformation temperature, it is concluded that both the existence and the extent of Stage IV of a ⟨100⟩ oriented aluminum single crystal are controlled by the deformation temperature.

4. conclusion

To clarify the effect of the deformation temperature on the Stage IV deformation, ⟨100⟩ oriented aluminum single crystals are tested in tension at 77K, 203K 293K and 473K. The results are summarized as follows:

(1) At room temperature, a clustered slip accompanied by a prominent cross slip takes place at a 1.5% strain, and Stage IV appears after an elongation of about 2%.

(2) A clustered slip accompanied by a prominent cross slip occurs after an elongation of about 3% even at 203 K. However, its frequency is relatively low and Stage IV is confined to about a 10% stramin. At the 77K deformation, the prominent cross slip is not observed and Stage IV does not appear.

(3) At 473K, the coarse slip consisting of frequent cross slips between two {111} planes and a {110} plane takes place, and the flow stress becomes constant due to the dynamical recovery, from about a 0.5% strain.

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