# Plastic Deformation of ⟨111⟩ Oriented Aluminum Single Crystals

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**Abstract**

It is known that an aluminum single crystal having ⟨111⟩ tensile orientation shows an initial rapid hardening, and that its flow stress increases gradually until failure. However, many problems pertaining to the deformation mechanism of the ⟨111⟩ oriented single crystal remain unsolved.

In the present study, to clarify the deformation mode of aluminum single crystals having multiple slip orientations, tensile test were performed at various temperatures on ⟨111⟩ oriented single crystals.

At room temperature, the ⟨111⟩ oriented single crystal deformed only by fine multiple slips, and the flow stress increased with an increase of strain until failure. On the other hand, the coarse wavy slips composed of {111} and {100} slips occurred at high temperatures, such as 473K.

In the single crystal having a tensile orientation deviated from ⟨111⟩ by a few degrees, the clustered slips were observed in addition to the fine multiple slips. It is concluded that the deformation mode and flow stress of the single crystal are very sensitive to the tensile oriention in the vicinity of ⟨111⟩.

## 1. Introduction

Generally, the stress-strain curve of a face-centered-cubic metal single crystal is devided into three regions, termed Stage I, Stage II and Stage III respectively, according to a change of the work hardening rate. The transition from Stage I to Stage II is caused by the activation of the secondary slip which interacts with the primary slip. The transition from Stage II to Stage III is caused by the appearance of a cross slip which is able to avoid barriers inside a crystal. The flow curves of f.c.c. metal single crystals have been studied by Lücke and Lange[1)2)] and many other research workers[3)-7)].

Therefore, it is well known that Stage II, characterized by a very high rate of

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work hardening, immediately follows the yield point in the deformation of a single crystal having a typical multiple-slip-orientation (⟨100⟩, ⟨111⟩ etc.). Stawbwasser[4] investigated the effect of crystallographic orientation on the stress-strain curve of aluminum single crystals. He reported that the flow stress of the ⟨100⟩ oriented crystal rarely increased at Stage Ⅲ, and that the stress-strain curve of a ⟨111⟩ oriented single crystal did not exhibit a distinct transition from Stage Ⅱ to Stage Ⅲ. Subsequently, Hosford et al.[8] and Kocks[9] studied the plastic deformation of aluminum single crystals having such an orientation. The deformation mode and mechanism of the ⟨100⟩ or ⟨111⟩ oriented single crystal have not yet been clarified sufficiently despite their works.

Recently, Saeki and Miura[10] studied the deformation mode of a ⟨100⟩ oriented aluminum single crystal. They found that only the fine multiple slip occurred with a rapid work hardening at Stage Ⅱ. Thereafter, a coarse slip accompanied by a prominent cross slip was activated to evade obstacles formed by the interaction of the slips. They also observed that the flow stress of the crystal hardly increased when the coarse slip propagated from both ends to center of the specimen. Hajif et al.[11][12]showd that the ⟨100⟩ oriented aluminum single crystal was deformed by slips on {110} instead of {111} at the initial stage of compressive deformation at high temperature.

However, the exact deformation mode and the effect of deformation temperature on the deformation mechanism of single crystal having ⟨111⟩ orientation are yet unknown.

In the present work, the defomation mode of a ⟨111⟩ oriented aluminum single crystal was studied carefully from yielding until failure, to clarify its deformation mechanism. The effects of the deformation temperature and of the deviation of the tensile direction from ⟨111⟩ on the deformation mechanism were also investigated circumstantially. Namely, it was newly found that the clustered slip was not observed in the ⟨111⟩ oriented single crystal, but in the single crystal having a tensile orientation deviated from ⟨111⟩ by a few degrees. The wavy coarse slip line not matching with {111} traces was observed at high temperature.

## 2. Experimental procedure

The material used in this experiment was 99.99% pure aluminum. Plates of single crystal, having an orientation controlled by seeding, were grown by the Bridgman method in a vacuum. Specimens with a gauge dimension of $2\times5\times15$ $mm^3$ were obtained from the single crystal plates by spark cutting and annealed at 823K for 3hrs. The specimens were polished mechanically and electrolytically in a solution of one part perchloric acid to four parts ethyl-alcohol before the tensile tests.

The oriention of these single crystal specimens are shown in Fig. 1(a). In these specimens, the tensile direction (z axis) is ⟨111⟩ exact, and the geometric relations between the tensile direction and their six active slip systems are identical, respectively. A single crystal, having a tensile direction deviated from ⟨111⟩ by a few degrees, was also prepared so as to compare it with a ⟨111⟩ oriented single crystal. This single crystal is termed as a near ⟨111⟩ oriented single crystal in this paper.

Tensile test were carried out by using an Instron-type testing machine with a

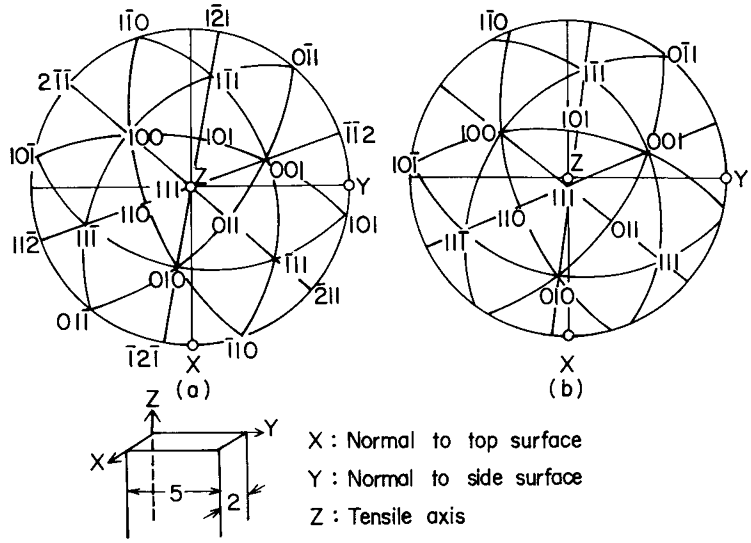



Fig. 1 Oriention of single crystal specimens.

strain rate of $4\times10^{-5}$ $sec^{-1}$ in atmosphere at 293±2K and in silicon oil at 373±2K and 473±2K. After the specimen was stretched by a proper strain, it was unloaded and slip line observations were performed on its top surface. The change in orientation of the specimen axis during the plastic deformation was also studied by the back-reflection X-ray Laue method. For the convenience of the slip line observation, the specimen surface was electically polished from time to time.

Moreover, Fig. 1(b) shows the crystallographic orientation of a single crystal, termed as a near ⟨111⟩ oriented single crystal.

## 3. Results and discussion

### 3.1 Slip line observation

#### 3.1.1 ⟨111⟩ oriented single crystal

##### (a) Deformation at room temperature (293K)

Fine multiple slips begin to be observed immediately after the yielding in the whole of the specimen (Fig. 2). The expression "Strain p-q (%)" in the figure indicates that the top surface of the specimen was electrolytically polished at a strain of p%, and the surface observation was performed at a strain of q%. It is considered that the individual slip line of multiple slip lines corresponds to one among the slip traces of the three active slip planes:(111), $(11\bar{1})$ and $(1\bar{1}1)$. Despite the proceeding of deformation, only the fine triple slip keeps occurring, and it becomes more fine and more intimate until failure.

In the ⟨111⟩ oriented single crystal, the geometric relations between the tensile

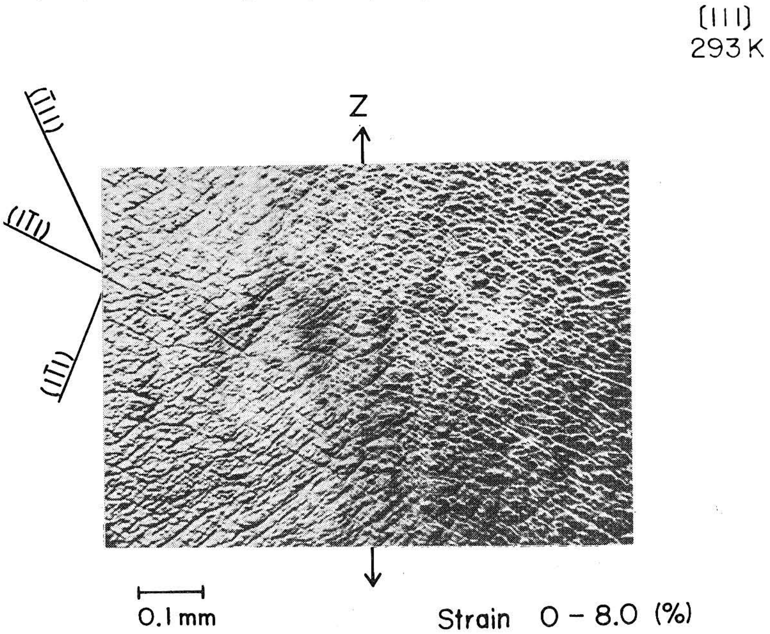



Fig. 2 Multiple slip lines observed in a ⟨111⟩ oriented single crystal stretched by 8.0% at 293 K; (The expression "Strain p–q(%)"in the photographs in the present study indicates that the slip lines appearing on the top surface of the specimen which had been electrolytically polished after strain of p% were observed at a strain of q%.)

direction and the three {111} active slip planes are identical, and the dislocations on these slip planes begin to move simultaneously by applied stress. As a result of the interaction between these glide dislocations, numberless obstacles such as the Lomer-Cottrell sessile dislocations are formed. Since the movement of glide dislocations is impeded frequently, the slip lines are very short and fine. It was reported that the ⟨100⟩ oriented single crystal, in which obstacles are formed similar to the ⟨111⟩ oriented single crystal, is deformed by the fine quadruple slip at the initial stage of plastic deformation, after a few percent strain, deformed by the coarse slip accompanied by prominent cross slips by Saeki and Miura[10]

Miura et al.[13] studied the orientation dependence of the stress required to make a cross slip which indicates the easiness of a cross slip. They showed that it depends on the ratio: M of the shear stress on the cross slip system: $\tau_{cross}$ to that of the primary slip system: $\tau_{pri.}$, that is $M=\tau_{cross}/\tau_{pri.}$. The axial orientation of the specimen used in this study is ⟨111⟩ where the value of M is −1, and M is 1 at ⟨100⟩ ,if one takes into account the direction of the resolved shear stress on the cross slip plane. It is said that the ⟨111⟩ axial orientation is the one where a cross slip is most difficult to occur. Therefore, in the ⟨111⟩ oriented single crystal, the glide dislocation can not transfer to a cross slip plane from a plane, and more numerous barriers are produced as the defomation proceeds, resulting in a more fine triple slip (Fig. 3).

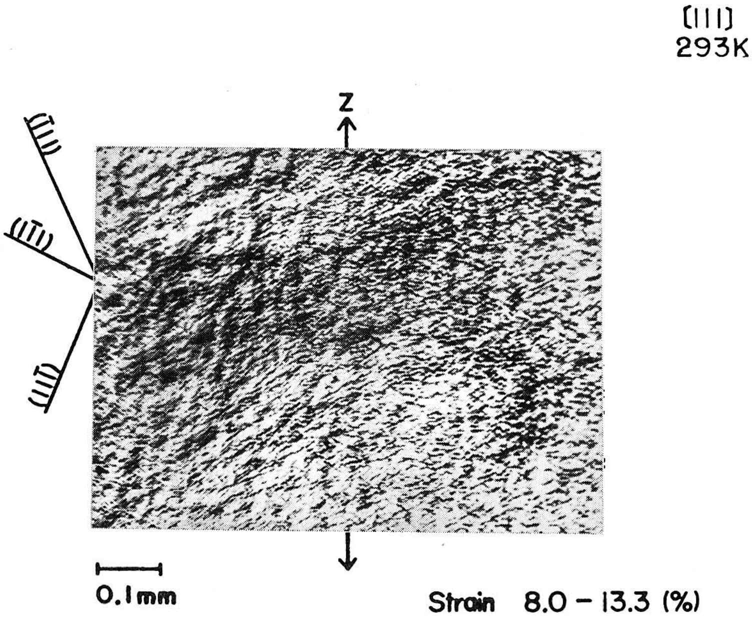



Fig. 3 Multiple slip lines observed in a ⟨111⟩ oriented single crystal stretched by 13.3% at 293 K.

Tabata et al.[14] analyzed the plastic deformation of ⟨111⟩ oriented aluminum single crystals using a high voltage electron microscope. In these crystals, the tangle of dislocations is made uniformly by the interaction of glide dislocations on different slip systems. It grows into the cell-wall disturbing the movement of glide dislocations. No deviation of the tensile direction in this specimen during the plastic deformation corresponds with the equilibrium of the slip-activity in the six slip systems in the whole stage of the plastic deformation.

**(b) Deformation at high temperature (373K, 473K)**

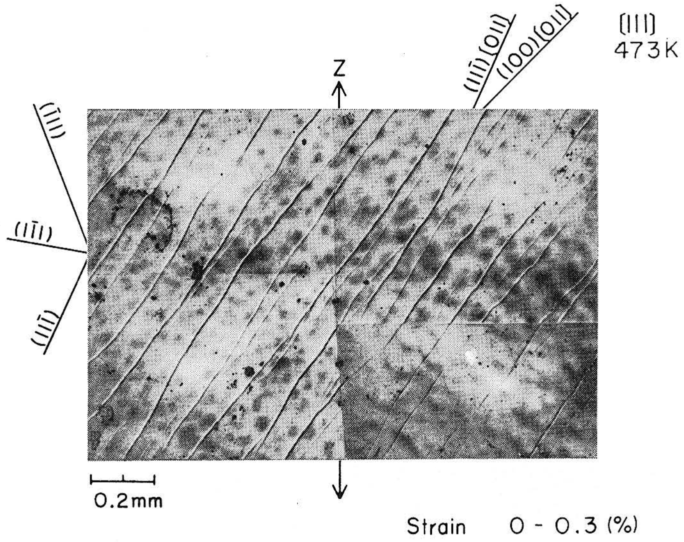



Fig. 4 Multiple slip lines and wavy slip lines observed in a 〈111〉 oriented single crystal stretched by 0.3% at 473 K.

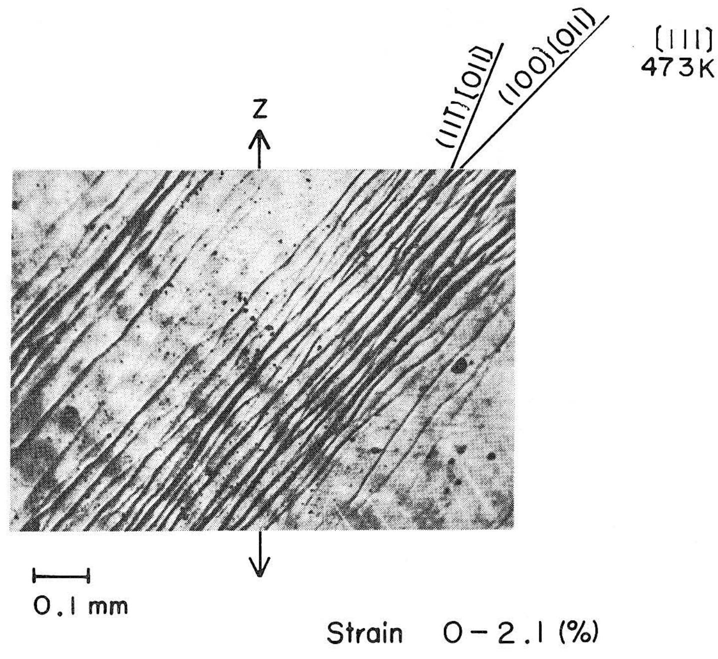



Fig. 5 Multiple slip lines and wavy slip lines observed in a 〈111〉 oriented single crystal stretched by 2.1% at 473 K.

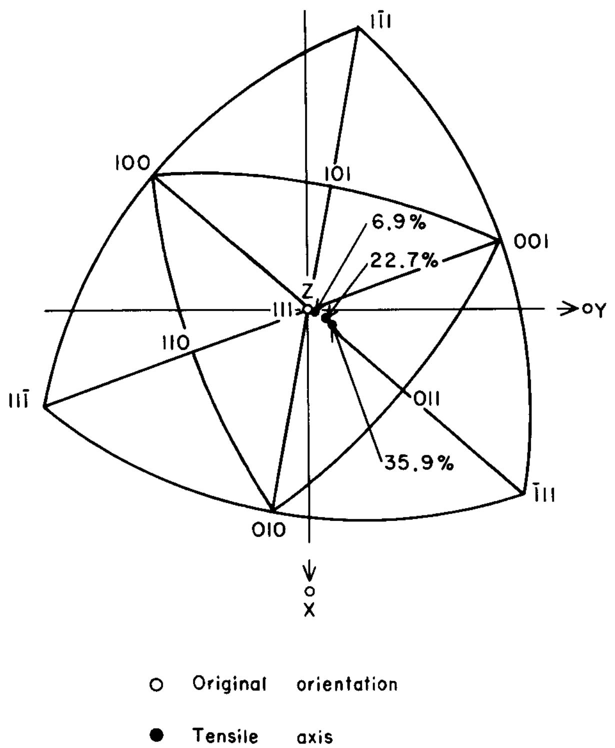


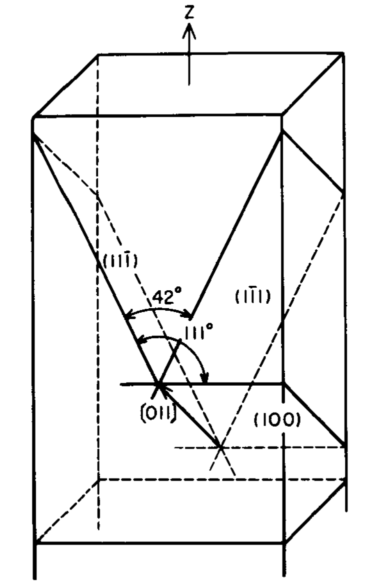

Fig. 6 Changes in tensile orientation in a ⟨111⟩ oriented single crystal during deformation at 473 K.

In the ⟨111⟩ oriented single crystal deformed at 373K, the fine triple slip, the same as the one observed at room temperature, occurs immediately after yield. After a strain of about 2%, a coarse wavy slip, not matching with any traces of {111} planes: $(\bar{1}11)$, $(1\bar{1}1)$ and (111), takes place at both ends of the specimen. However, the coarse locally and does not spread into another region of the specimen.

In deformation at 473K, the coarse wavy slips, shown in Fig. 4, are obsersed in the whole region of the specimen. The wavy slip line also does not agree with any traces on the observed surface of the three {111} slip planes, and it has an incline between those of the (111) trace and the (100) trace on the observed surface. With the proceeding of plastic deformation, the coarse wavy slip increases, as shown in Fig. 5, and no other sort of slip ever occurs. Therefore, the deformation mode consisted of a multiplication of the coarse wavy slip kept to the failure of the specimen.

The tensile orientation of the specimen at 473K diverges by several degrees towards [011] from [111] along the [111] - [011] symmetry line, as shown in Fig. 6, in contrast to the stability of that of the specimen defomed at room temperature. It is suggested by the result that the slip direction of the coarse wavy slip is [011] which is contained in both $(1\bar{1}1)$ and (100). Taking these into account, it is considered that the coarse wavy slip, shown in Figs. 4 and 5, is composed of the alternate repetitions of the short distance cross slip between $(11\bar{1})$ and (100).

The aluminum, one of the face-centered-cubic metal, is commonly deformed by the slip in {111} , closest-packed planes, but a slip in {100} , secondary-close-packed plane, is also observed additionally in an aluminum crystal deformed at a higher




| Slip system | Schmid factor |
|---|---|
| $(11\bar{1})$ (011) | 0.272 |
| $(1\bar{1}1)$ (011) | 0.272 |
| (100) (011) | 0.472 |

Fig. 7 Schematic illustration of slip planes having the same slip direction of [011] in a ⟨111⟩ oriented single crystal.

temperature than 723K[15] and which deformed impulsively[16]. In the plastic deformation of the ⟨111⟩ oriented aluminum single crystal, obstacles against movements of dislocations, such as the sessile dislocation, are formed immediately after the yielding, because the glide dislocations on the three slip planes begin to move equally and simultaneously. Therefore, a fairly higher stress is required to proceed with the plastic deformation of the ⟨111⟩ oriented single crystal, due to the obstacles.

The geometrical relation of two {111} planes and a {100} plane containing a same slip direction: [011] in the ⟨111⟩ oriented single crystal, is illustrated schematically in Fig. 7. Also, the Schmid factor of the three slip systems: $(11\bar{1})$ [011], $(1\bar{1}1)$ [011] and (100) [011] is listed in the figure. It is obvious that the cross slip between $(11\bar{1})$ and $(1\bar{1}1)$ requires stress of the opposite direction, and that the resolved stress by the applied stress of (100) [011] slip system is higher than that of the $(1\bar{1}1)$ [011] slip system. Therefore, geometrically the cross slip between $(11\bar{1})$ and (100) is easier than that between $(11\bar{1})$ and $(1\bar{1}1)$.

At a higher temperature, it is expected that the thermal kinetic enery raises the possibility of a slip in (100). In the ⟨111⟩ oriented single crystal deformed at 473K, it is considered that the occurrence of a cross slip between $(11\bar{1})$ and (100) is sufficiently possible by the assistance of thermal energy, since the cross slip between two {111} planes having a same burgers vector is very difficult[13]. It is concluded that the coarse wavy slip, shown in Figs. 4 and 5, is the one observed macroscopically as a result of frequent alternative cross slips between $(11\bar{1})$ and (100).

### 3.1.2 The single crystal having a tensile orientation deviated from ⟨111⟩ by a few degrees (The near ⟨111⟩ oriented single crystal)

In the plastic deformation of the single crystal having a crystal orientation,


Fig. 8 Clustered slips observed in a near ⟨111⟩ oriented single crystal stretched by 2.1% at 293 K.

shown in Fig. 1(b), a few clustered slips of $(1\bar{1}1)$ [110] are observed in addition to the fine triple slip (Fig. 8). They are observed at the deformation of a ⟨111⟩ oriented single crystal deformed at room temperature, immediately after the yielding. However, the occurence of the clustered slip is restricted within the initial stage of the deformation, and only the fine triple slips consisting of slips on $(\bar{1}11)$. $(11\bar{1})$ and $(1\bar{1}1)$ occurs after a strain of 2%.

Hosford et al.[8] observed a clustered slip, similar to that observed in this study, in their ⟨111⟩ oriented single crystal stretched at room temperature. However, it is corroborated by the present study that the ⟨111⟩ oriented single crystal is deformed only by the fine triple slip from the yielding until the failure. Also, such a clustered slip takes place at the deformation of the single crystal having a tensile direction deviated from ⟨111⟩ by a few degrees.

The resolved shear stress of the $(1\bar{1}1)$ [110] slip system by applied stress is slightly higher than those of the other five slip systems in the near ⟨111⟩ oriented single crystal, taking account of the crystal orientation. Owing to the slight advantage on stress, slips of the $(1\bar{1}1)$ [110] slip system are activated concentratively in the form of clustered slips breaking throught obstacles such as the sessile dislocation at the initial stage of plastic deformation. As the stress increases, slips of the other slip systems are also activated sufficiently. Since the obstacles due to those multiple slips increase and are stabilized, even the slips of $(1\bar{1}1)$ [110] can not break through those obstacles. Consequently, it is supposed that only the fine triple slip is observed after a strain of a few percent.

### 3.2 Stress-strain curves

The stress-strain curves of the ⟨111⟩ oriented single crystal stretched at room temperature, 373K and 473K, and of the near ⟨111⟩ oriented single crystal stretched at room temperature (a broken line) are given in Fig. 9.

The flow stress of the ⟨111⟩ oriented single crystal deformed at room temperature increases most furiously immediately after the yielding, and keeps increasing until failure, according to the high stability of the triple slip and the difficulty of the cross slip. Tabata et al.[14] studied the flow stress of an ⟨111⟩ oriented aluminum single crystal deformed in HVEM. They found that the flow stress and the averaged diameter of cells formed in the crystal satisfied the Hall-Petch relation. Therefore, they suggested that the process of work hardening was similar to that of a polycrystal, deformed by the multiple slip consistently. This similarity is confirmed in this investigation because of the consistency of the triple slip in the ⟨111⟩ oriented single crystal.

The work hardening rate of the ⟨111⟩ oriented single crystal deformed at 473K is fairly high until a strain of about 0.5%. However, it decreases rapidly with an increase of strain thereafter, and becomes almost zero from a strain of 3%. This

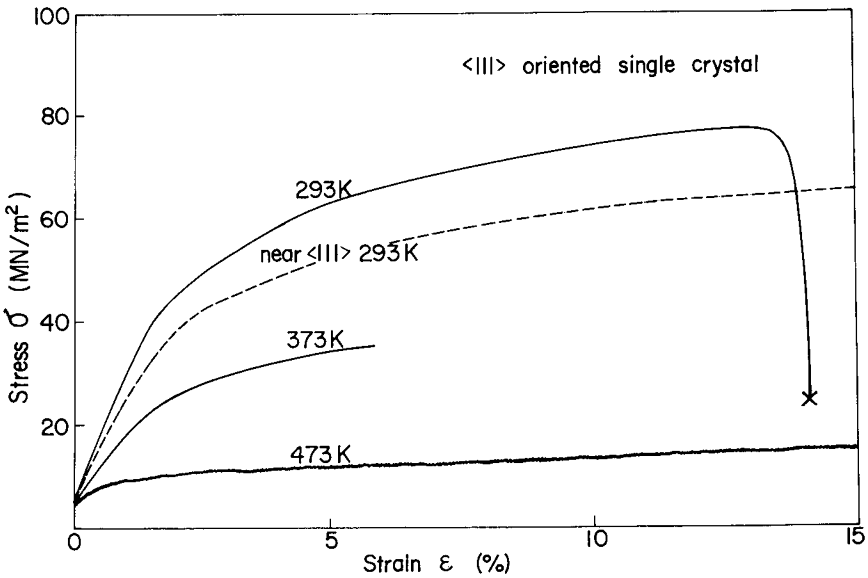



Fig. 9 Effect of deformation on the stress-strain curves of ⟨111⟩ and near- ⟨111⟩ oriented aluminum single crystals.

phenomenon is caused by the propagation of a coarse wavy slip consisting of the frequent cross slips between $(11\bar{1})$ and (100) which originated from a sufficient applied stress. Also, the serration on the flow curve of this single clystal is thought to be owing to the relaxation of the stress by these cross slips.

The stress-strain curve of the near ⟨111⟩ oriented single crystal has almost the same peculiarity, but its flow stress is slightly lower than that of the ⟨111⟩ oriented single crystal throughout the whole process of plastic deformation. There is a difference of both flow stresses in about 5. 5MN/m$^2$ at 1% strain and 11 MN/m$^2$ at 5% strain. This difference is considered to originate from the occurrence of the clustered slip on the $(\bar{1}11)$ [110] slip system. As a result, it is concluded that the deformation mode and the stress of a crystal having a tensile orientation deviated from ⟨111⟩ by an angle within a few degrees are very sensitive to a crystallographic orientation.

## 4. Conclusion

The deformation mechanism of the ⟨111⟩ oriented aluminum single crystal, especially the effects of the deformation temperature and of the deviation on tensile orientation, were studied. The results are summarized as follows:

(1) The ⟨111⟩ oriented single crystal is deformed by the triple slip which is specific for the ⟨111⟩ orientation from yielding until failure at room temperature. Therefore, the tensile orientation is fixed, and its flow stress keeps increasing throughout the plastic deformation.

(2) The coarse wavy slip is observed in the deformation of a ⟨111⟩ oriented single crystal stretched at 473K. It is considered that the coarse wavy slip is caused by frequent alternative cross slips between {111} plane and {100} plane.

(3) In the deformation of a single crystal having a tensile direction deviated from ⟨111⟩ by a few degrees at room temperature, a clustered slip occurs in addition to the fine triple slip and its flow stress is considerably lower than that of the ⟨111⟩ oriented single crystal. It is obvious that the deformation mode and the flow stress of a single crystal are very sensitive to a crystallographic orientation, when the tensile orientation is near ⟨111⟩

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