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Deformation behavior of pure titanium at a wide range of strain rates

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Abstract. Plastic deformation behavior of pure titanium has been investigated using a tensile test at a various range of strain rates. Flow stress curves reveal that the work hardening behavior depends on the strain rates. The higher strain rates, the more work hardening. Dislocation cell structure has been developed after the deformation at a low strain rate. At a high strain rate, in addition to that, microstructure of twinning is well evolved. Much occurrence of twinning at the high strain rate leads the pronounced work hardening.

1. Introduction
Outstanding properties of titanium such as excellent strength-to-weight ratio, corrosion resistance, prominent biocompatibility are giving itself wide spread applications. The deformation behavior of titanium with an hcp structure can be more complex than that of common cubic metals. Slips with a-type Burgers vectors are the most favorable system. Despite the requirement of five independent slip system for polycrystalline to adapt an arbitrary plastic strain, only four slip systems exist. The occurrence of deformation twin plays an important role.

Regarding work hardening behavior, titanium displays substantial rate sensitivity [1] and exhibits several different stages, as reported from compression material tests [2-5]. Formation of deformation twin increase the strain hardening, and a number of attempts have been paid to elucidate the structure of the deformation twin [6-8]. Almost all of the previous investigations are discussed based on compression tests. The purpose of this study is conducting tensile tests at a various range of strain rates and clarifying the tensile plastic deformation behavior regarding to the strain rate sensitivity.

2. Experiments
In this investigation, Grade 1 quality CP-Ti ingots were used. The ingots were cold-rolled from 9 to 1 mm in thickness. Tensile test pieces were cut out from the cold-rolled sheet using an electric discharge machine in a way to coincide the tensile direction with the rolling direction. The test pieces were subjected to heat treatments in vacuum furnaces at a temperature of 923 K for 10 min, 1 h and 10 h. The test pieces were recrystallized by annealing for 1 h and 10 h, and yielding equiaxed grain sizes were 14.3 µm and 25.8 µm, respectively. The test pieces annealed for 10 min were partially recrystallized and we could not evaluate the grain size of them. The tensile test with various strain rates at room temperature were performed using a dynamometer sensing block type high deformation speed material testing machine (HMH206, Saginomiya Seisakusho Inc., Jpn). The rate-dependent mechanical behavior of the CP-Ti was studied over a strain rate range of $10^{-3}$ to $10^3$ /s. TEM samples
were sectioned from the position near a grip end in order to avoid sectioning samples from the necking region. TEM thin foils were prepared by electro-polishing to perforation. These foils were examined using a JEOL JEM-3010 transmission electron microscope operating at 300 kV.

3. Experimental results

3.1. Mechanical behavior

Figure 1 reveals the dependence of the proof stress on the strain rate. Even though the existence of wide dispersion, it seems to be a slight correlation between the strain rate and the proof stress for all of the heat treatment periods. The annealing period gives no effect on the change of the proof stress, or the wide range of dispersion of the proof stress may mask the grain size effect.

The flow stress curves are shown in figure 2. Wavy curves for a $10^3$ /s strain rate have arisen from stress vibration which occurs when an elastic wave caused by an impact from a hummer in the test machine is propagated through the test sample and detected by the load cell. The wavy shape of the curves is due to the inherent problem of the test machine and is not essential for the mechanical behavior. The true stresses at some constant strain increase with the strain rate for all of the heat treatment periods. Significant difference between the heat treatment periods cannot be recognized. Only in the case of a low strain rate, the sample annealed for 10 min, partially recrystallized, obtain higher tensile strength and elongation (figure 2(a)). For the medium strain rate ($10^6$/s) the elongation becomes lower than those for the lower strain rates. For further high strain rates, however, the elongation increases with the strain rates. This phenomena have been found not only hexagonal crystal but also cubic iron (both bcc and fcc structures) [9], and the reason of the reduction in elongation for the medium strain rate is still vague for all kind of crystal structure.

3.2. Microstructure

As anticipated from the flow stress curves, dimple structure has been seen on the fractured surfaces after the tensile test for all of the specimens by SEM observation. No significant difference in the dimple structure was detected regarding the effects of the strain rates and the annealing periods.

Using TEM observations, we have found the difference in the microstructures between low and high strain rate deformations. Figure 3(a) shows the microstructure after the tensile test with the low strain rate of $10^3$ /s. A large number of dislocations can be seen, and the parallel band that is marked
Figure 3. (a) TEM micrograph of the deformation microstructure after the tensile test of 1 h annealed titanium with the strain rate of $10^{-3}$/s, (b) [01 $\bar{T}$] zone axis SAED pattern, (c, d) CBED patterns taken from the positions "c" and "d" as indicated in figure 3(a).

"d" in the right side of the TEM image seems to be a twin plate at first glance. The crystal orientation relation between "c" and "d" is not twin but almost the same orientation. Kikuchi lines in figure 3(d) are moved from the position in figure 3(c) to the [2 $\bar{T}$ 0] direction. The movement of the Kikuchi pattern equals to $2G_{27}$ that means the tilt angle between them is 0.8°. The boundary dividing the crystal orientation is a small angle tilt boundary composed of tangled dislocations, and the microstructure after the low strain rate deformation is mainly dislocation cell structure. Deformations twins occur with a low frequency. A remarkable point on the diffraction patterns is that the movement of Kikuchi pattern is just lateral [0 1 1 2] direction which contains only a-axes direction in the hexagonal crystal. The tangled dislocations making the small angle boundary have proven to be with a-type Burgers vectors only.

For the deformation at a high strain rate, many dislocations and small angle boundaries have been seen as well as the case of the deformation at low strain rate. In addition, twin boundaries have been observed. Figure 4(a) shows the microstructure after the tensile deformation at the strain rate of $10^{3}$/s. Dense dislocations are formed in the twin plate and horizontal twin plates are seen as indicated "c" in figure 4(a). This twin plane is almost parallel with the direction of a $10^3$ $\bar{T}$ diffraction spot. Using the relation between Miller-Bravais index and 4-dimensional index [10], we can calculate the index of the twin plane. The twin is formed on a $[0211]$ plane. It is well known that the $[0211]$ twin compensate the tensile stress along the c-axis. Those twins will obstruct the motion of dislocations. Therefore, much work hardening behavior has been measured at the high strain rate tensile test.

4. Discussion

Many papers pointed out that the behavior of work hardening in compression test shows a distinctive 3-stage pattern in the change of work hardening rate [2-5]. Many difficulties attended our attempt to differentiate the flow stress curves due to the wavy fluctuation for high strain rates. On the other hand, we can analyze the stress flow curves simply based on a Hollomon's equation. n-values (work hardening exponent) obtained from the Hollomon's equation have been consistent with uniform
Figure 5. (a) Effect of the tensile strain rate on the work hardening exponent, $n$, and the true strain, $\varepsilon_T^*$ satisfying the necking condition, (b) effect of the strain rate on the true stress, $\sigma_T^*$ and the ultimate tensile true stress.

elongations derived from the criterion of plastic instability. The exponent, $n$ and $\varepsilon_T^*$; the true strain when starting plastic instability, are shown in figure 5(a). As mentioned before, elongations decrease for the medium strain rate. When the plastic instability is held, the work hardening rate coincide with the true stress, $\sigma_T^*$, which should correspond to the ultimate tensile strength (UTS). Relation between the tensile strengths and the strain rate is shown in figure 5(b). At a high strain rate, the tensile strength significantly increases since the deformation twins have a role of the obstacles against the dislocation motion.

5. Conclusion
Findings from the tensile tests at a various range of strain rates and the following TEM observations after deformation are summarized as follows.
1. The higher tensile strain rates, the more work hardening.
2. The microstructure developed after a low-rate deformation mainly exhibits the dislocation cell structure.
3. The microstructure developed after a high-rate deformation reveals the deformation twinning in addition to the dislocation cell structure.
4. Analyses of the flow stress curves are successfully performed based on the Hollomon's equation.
5. The formation of twinning at a high-rate deformation seems to enhance the work hardening.

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