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Recrystallization Behavior of Commercially Pure Titanium During Hot Rolling

Masayuki Hayashi*1 Hirofumi Yoshimura*2
Mitsuo Ishii*2 Hisaaki Harada*3

Abstract:

This paper describes the results of investigation made of the restoration process, i.e., recovery and recrystallization, of commercially pure titanium during hot rolling. During hot rolling, recrystallization proceeds with greater ease in the α-region (near 1,073K), and the deformed structure including the lamellar deformation twin changes to the recrystallized structure as the rolling reduction increases. This recrystallization is considered to be static immediately after hot rolling and is influenced by strain and strain rate in addition to the rolling temperature. In the low-temperature region (near 837K), the deformed structure including the lenticular deformation twin changes to the recovery structure. Material with coarse cast structure exhibits a similar behavior, but in this case recovery and recrystallization tend to be sluggish.

1. Introduction

Commercially pure titanium is manufactured generally by a process comprising ingot forging or slabbing, hot rolling, annealing, pickling, cold rolling, and final annealing. Problems characteristic of titanium are concerned with such surface defects as oxidation and seizure that occur because titanium is a reactive metal and those associated with anisotropy of plasticity that occur because titanium is a hexagonal close-packed (hcp) metal. These problems conspicuously appear in the hot rolling step where slabs are reheated in air and heavily reduced. Many studies have been traditionally made on the texture and deformation twins related to the plastic anisotropy of titanium and on the general microstructure of titanium.

Studies concerning the hot working of titanium may be classified by subject into the following groups: (1) deformation mode and texture evolution[1,2]; (2) deformation strength[3,4]; and (3) hot-rolled sheet and plate properties[5]. Studies have been relatively few, however, about the metallurgically important recrystallization behavior of titanium during hot rolling.

This article describes the restoration process, i.e., recovery and recrystallization during hot rolling as experimentally investigated by hot rolling ingots of commercially pure titanium into slabs and slabs into sheets.

2. Experimental Method

A titanium material equivalent to JIS Grade 2 commercially pure titanium was vacuum arc remelted, cast into ingots, slabbed, and hot rolled into sheet. A typical chemical composition of the test material is given in **Table 1**. The initial average grain size was about 10,000 μm in the as-cast condition and about 40 μm in the slabbed condition.

The ingots and slabs were test rolled at medium or high temperatures. The specimen geometry and rolling procedure are illustrated in **Fig. 1**[6]. A wedge-shaped specimen was machined from each test ingot or slab in the direction parallel to the casting or slabbing direction as shown in **Fig. 1(a)**. The specimen was reheated at a temperature of 673 to 1,373 K for 3.6 ks and hot rolled in a single pass on a two-high mill as shown in **Fig. 1(b)**. As soon as it was hot rolled, the specimen was water quenched

*1 Formerly Technical Development Bureau
*2 Technical Development Bureau
*3 Hikari Works

Table 1 Main chemical components of test material (mass%)

Fe	O	N	C	H
0.038	0.095	0.014	0.005	0.0006

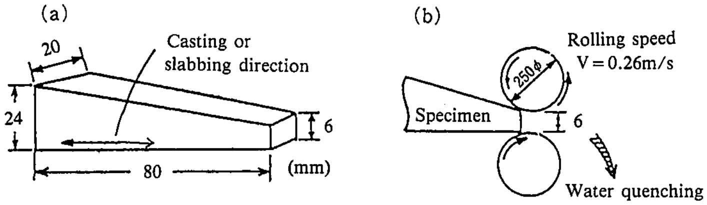

Fig. 1 Geometry of small tapered specimen (a) and rolling procedure (b)

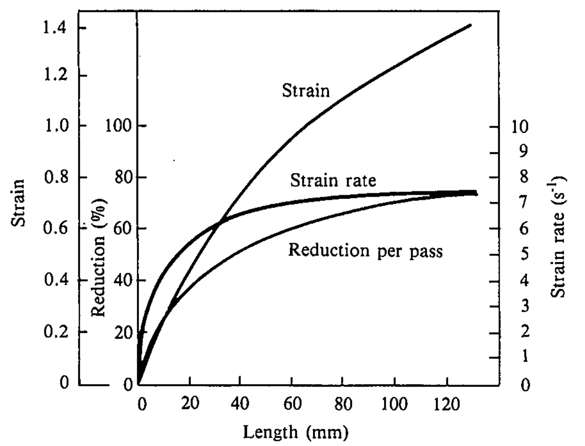

Fig. 2 Estimation of reduction and strain rate along length of rolled tapered specimen

to retain the hot-rolled structure. This quench took 2 to 3 s. The reduction and strain of the specimen in respective positions were calculated from the specimen shape and the mill roll diameter, and the strain rate of the specimen was calculated considering the rolling speed. The calculated values of reduction, strain, and strain rate are as shown in **Fig. 2**. The strain was calculated by ln t/6 where t is the larger thickness of the specimen before hot rolling (the thickness of 24 mm in **Fig. 1(a)**). The hot-rolled sheet thus obtained was tested for hardness at room temperature and structurally examined by optical microscopy on the longitudinal section parallel to the rolling direction and normal to the plate surface. Vickers hardness was measured at almost the mid-thickness position of the specimen under a load of 5 kg. The specimen was etched in an aqueous solution of nitric acid and hydrofluoric acid and was closely examined by optical microscopy for the deformed, recovered and recrystallized structures.

3. Experimental Results

3.1 Effects of hot rolling temperature and reduction on hardness after hot rolling

Fig. 3 shows the effects of the slab reheating temperature and rolling reduction on the hardness of the longitudinal section of the hot-rolled plates. The hardness values considerably vary, but indicate the following general trend. The hardness increases as the slab reheating temperature decreases from 1,173K to 673K. The hardness remains unchanged or slightly decreases as the reduction rate increases in the reheating temperature region of 1,073 to 1,173K, and slightly increases as the reduction rate increases in the reheating temperature region of 673 to 973K.

3.2 Effects of hot rolling temperature and reduction on structure after hot rolling

Photo 1 shows typical changes in the structure of the longitudinal section of palates hot rolled from slabs according to the reheating temperature and reduction. On cooling after hot rolling at the high-temperature side of the β region, the specimen exhibits a sawtooth structure due to the $\beta \rightarrow \alpha'$ transformation. At 1,173K, β grains are elongated by rolling, and recrystallized grains form in a fringe pattern at β grain boundaries **(Photo 1(a)** to **1(d))**. At 1,073 and less in the α region, deformation twins are introduced. Lamellar deformation twins are predominant at temperatures above 973K **(Photo 1(f))**, and lenticular deformation twins are predominant at temperatures below 973K **(Photo 1(j))**. As the reduction rate increases at 1,073K, lamellar deformation twins increase, slip deformation is added, and a recrystallized structure partially appears at a reductions rate of 40% or higher **(Photo 1(e)** to **1(h))**. Recrystallization is initiated in twins

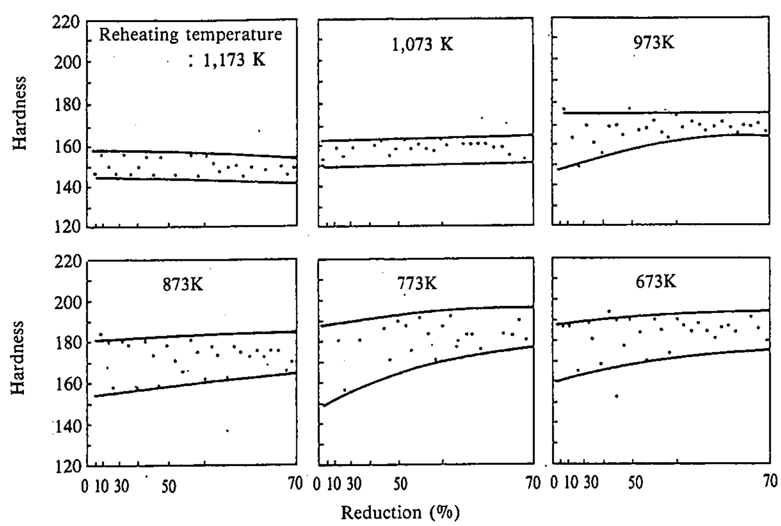

Fig. 3 Change in hardness at room temperature with reheating temperature and reduction

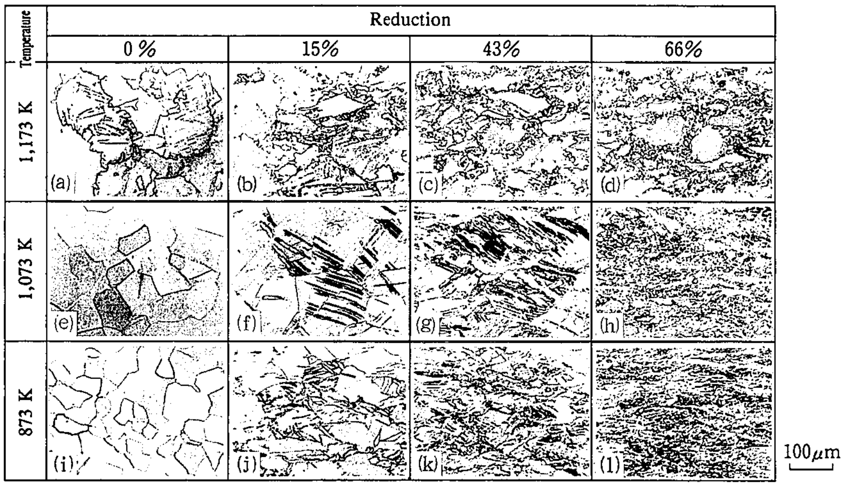

Photo 1 Change in structure with hot rolling temperature and reduction (material: Rolled slab)

or twin intersections where the dislocation density is high, and recrystallized grains are uniformly fine and equiaxed. As the reheating temperature decreases to 873K, slip deformation adds to lenticular deformation twins even when the hot rolling temperature decreases, but recrystallized grains are observed locally (**Photo 1(i)** to **1(l)**). As the hot rolling temperature decreases in this way, the recrystallized structure is replaced by the deformed structure. This agrees with the hardness change shown in **Fig. 3**.

The structure changes with the hot rolling temperature and reduction as described above. These changes are quantitatively shown in terms of recrystallization ratio and recrystallized grain size in **Fig. 4(a)**. It should be noted that the region where recrystallization proceeds to the greatest extent, that is, the so-called nose of recrystallization, is present between 1,073K and the β transformation temperature or at the high-temperature side of the α region. As the temperature drops further, recrystallization is retarded even under increased reduction, and the recrystallized grains are reduced in size. As evident from **Fig. 4(a)**, recrystallization hardly occurs at temperatures of 873K or lower.

The hot-rolled structure of the ingot material is arranged by the hot rolling temperature and reduction in **Fig. 4(b)** as done for the slab material (**Fig. 4(a)**). When the two figures are compared to clarify the effects of the hot rolling material microstructure, the ingot material with a coarse structure exhibits a shifting of the recrystallization region toward the higher temperature side, which means that recrystallization is retarded, compared with the slab material having relatively fine initial grains. Also, the ingot material is larger in the recrystallization grain size than the slab material.

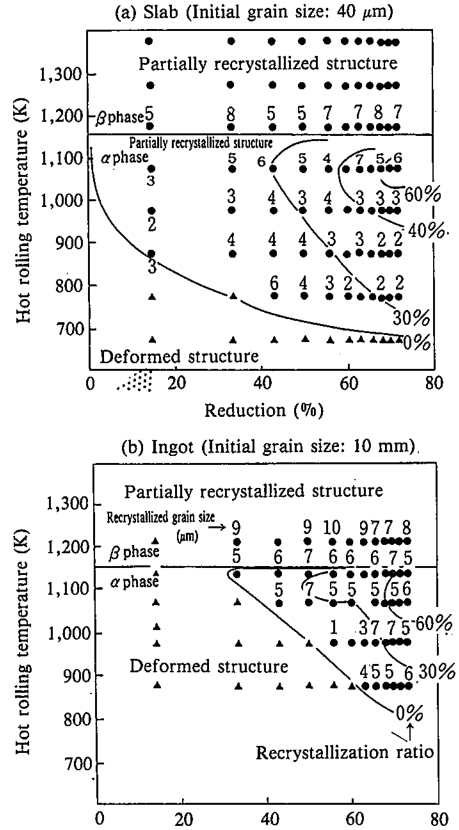

Fig. 4 Effects of hot rolling temperature and reduction on recrystallization ratio and recrystallized grain size

4. Discussion

4.1 Analysis of recrystallized structure by Zener-Hollomon parameter

The Zener-Hollomon (Z) parameter (see the equation below) that is the strain rate compensated for temperature is often used to minutely analyze the recrystallization behavior during hot rolling.

$$Z = \dot{\varepsilon}\exp(Q/RT)$$

where $\dot{\varepsilon}$ is strain rate; Q is activation energy; R is constant; and T is temperature.

The values of recrystallized grain size obtained in the experiment may be arranged by the Z parameter as shown in **Fig. 5**. The activation energy Q is put at 185 kJ/mol[7]. With dynamic recrystallization, the recrystallized grain size is uniquely determined by the Z parameter. The results of this experiment show that the recrystallized grain size cannot be arranged by the Z parameter alone. When the strain $\dot{\varepsilon}$ is considered in addition to the Z parameter or strain rate and temperature, the recrystallized

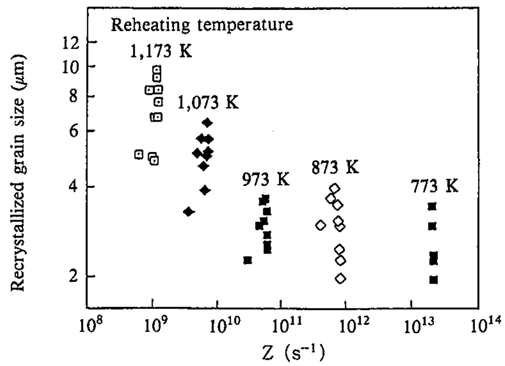

Fig. 5 Relationship of Z parameter and recrystallized grain size

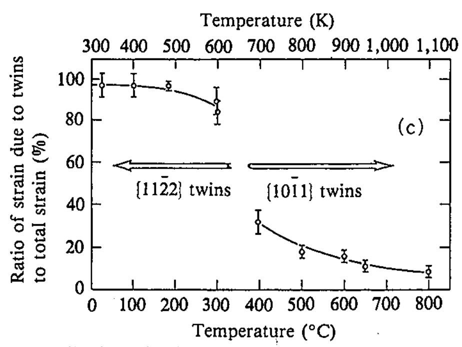

Fig. 6 Contribution of twin deformation during compression test of single titanium crystals (direction of compression: transverse)[1)]

grain size d may be arranged by the following equation:

$$d = 10^{-0.102} \varepsilon^{-0.917} Z^{-0.012} d_i^{0.357}$$

where d_i is initial grain size.

The recrystallized structure obtained in this study also depends on the strain ε. This characteristic suggests that the recrystallized structure results not from dynamic recrystallization but from static recrystallization immediately after hot rolling. This behavior closely resembles the recrystallization behavior of ferritic and austenitic stainless steels during hot rolling[6,8)].

4.2 Deformed structure containing deformation twins

The deformed structure of hot-rolled commercially pure titanium consists of deformation twins and deformation bands. It is known that the deformation twins prominently occur at 300 K or lower and that the way they occur has a large effect on the mechanical properties of titanium[9)]. As the working temperature is raised, slip deformation becomes predominant and twin deformation diminishes its role. Concerning the formation of deformation twins during high-temperature deformation, Paton and Backofen[1)] compression tested single titanium crystals. The results are shown in **Fig. 6**. As shown, the twins formed when the titanium single crystal is compressed at 573K or lower are {11$\bar{2}$2} twins, and those formed when the titanium single crystal is compressed at 673K or higher are {10$\bar{1}$1} twins. The two types of twins are morphologically characteristic in that they are shaped like wide lenses and narrow plates, respectively.

The deformation twins observed in the experiment are classified from this standpoint. Generally, the type of deformation twin to be formed varies according to whether the deformation mode is compression or tension. Since this experiment involves a deformation mode similar to that in a compression test, the abovementioned data of Paton and Backofen may be safely used as they are.

Table 2 Classification of deformation twins formed during hot rolling

Hot rolling temperature	Deformation twins
673-873K	{11$\bar{2}$2} twins
973-1,073K	{10$\bar{1}$1} twins

The classification results are given in **Table 2**. The boundary temperature between the {11$\bar{2}$2} twins and the {10$\bar{1}$1} twins lies in the neighborhood of 923K. This temperature is 300K higher than the 623K reported by Paton and Backofen, probably because of the difference in the deformation rate. The strain rate is 4×10^{-3}/s for the compression test of Paton and Backofen and is 2/s, or greater by a factor of about 5×10^3, for the present experiment at the reduction of 15%.

4.3 Recovery and recrystallization during hot rolling

The change in structure with the hot rolling temperature and reduction may be schematically illustrated as shown in **Fig. 7.** When titanium is hot rolled in the β region, recrystallized grains appear at the β grain boundaries in a fringe pattern. A uniformly recrystallized structure cannot be obtained even if the reduction rate is increased.

When titanium is hot rolled in the α region, lamellar {10$\bar{1}$1} deformation twins appear first at the high end of the temperature range. Next comes a structural change through the following steps: addition of slip deformation, increase in dislocation density due to intersection of deformation twins, static formation of recrystallization nuclei, and grain growth. As the hot rolling temperature drops, the hot-rolled titanium undergoes a similar process after introduction of the lenticular {11$\bar{2}$2} deformation twins. Recovery becomes predominant, and recrystallization does not occur unless the reduction rate is raised considerably. This agrees well with the hot rolling temperature dependence of the hardness of hot-rolled sheet shown in **Fig. 3**. The lowest temperature at which recrystallized grains are recognized is 873K, which is in approximate accord with the static recrystallization start temperature of commercially pure titanium during annealing[10)]. The reheating temperature dependence of the recrystallized grain size may be explained by the difference in the material temperature in the static recrystallization process immediately after hot rolling.

When the hot-rolled structure of commercially pure titanium

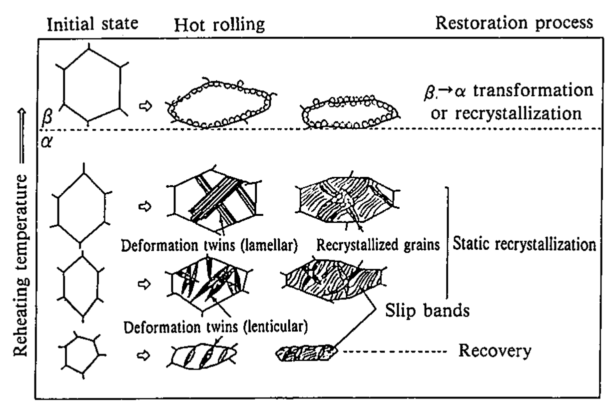

Fig. 7 Schematic illustration of structural change during hot rolling

is coarse grained as its cast structure is, it generally exhibits similar recovery and recrystallization behaviors. Since the initial grain size is large, however, the deformation twins and slip bands are not uniformly introduced by working, making it difficult for recrystallization to proceed.

5. Conclusions

Concerning the recrystallization behavior of commercially pure titanium during hot rolling, the hardness and structure of hot-rolled titanium plates were minutely examined as described above. The results obtained may be summarized as follows:

(1) When the hot rolling temperature is high (1,073K), hardness scarcely changes with increasing reduction. When the hot rolling temperature is low (873 to 973K), hardness slightly increases with increasing reduction.

(2) As for structural change during hot rolling, a recrystallization nose exists at the high-temperature side (near 1,073K) of the α region. When a commercially pure titanium slab is rolled in this temperature region, a recrystallized structure gradually appears from the deformed structure containing lamellar deformation twins as the reduction rate is increased. At the lower-temperature side (873K), a recovered structure appears where deformation bands containing lenticular deformation twins are formed. The recovery and recrystallization processes do not readily proceed when the microstructure of the titanium material is coarse grained.

(3) The recrystallized structure observed in this study is considered to have resulted from static recrystallization immediately after hot rolling, and is influenced by strain as well as temperature and strain rate.

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