Fundamental Characteristics of the Transformation Superplasticity in a Commercially-pure Titanium*

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Synopsis

The strain while undergoing allotropic transformation has been considered to be an important component for the transformation superplasticity. The fundamental characteristics of the strain due to a "both ways" passage through the $(\alpha + \beta)$ field under low stress, ε_{lr} , has been investigated for a commercially-pure titanium.

The remarkable strain was found to occur in certain temperature range during heating and also cooling, in which the transformation takes place. The amount of ε_{lr} was changed by the rate of heating and cooling, $\dot{T}$, showing a maximum at a rate of 0.1 K/s. The strain generating during heating was always larger than that during cooling in the present study. This has been considered to be attributed to the strain of the transformation itself. The values of ε_{lr} increased with an increase in the applied stress. It was also shown that the orientation between the stress axis and the rolling direction had an influence on ε_{lr} . This has been explainable qualitatively in terms of both the orientation dependence of ε_{lr} under stress free condition and also the texture of the specimen.

A possible mechanism for the transformation superplasticity will be discussed on the basis of the stress dependence of ε_{lr} .

Key words: transformation superplasticity; pure titanium; allotropic transformation; temperature cycle.

I. Introduction

The strain which generates due to a "both ways" passage through the $(\alpha + \beta)$ field under the application of the low stress, ε_{lr} , is not so large for metallic materials. However, the accumulation of the strain through a number of the temperature cycles, $\sum \varepsilon_{lr}$, results in achievement of an abnormally large strain. This phenomenon is well known as the transformation superplasticity.

Titanium alloys are characterized by their high strength. However, they are regarded, on the other hand, also as difficult materials to work because of the high flow stress and the narrow range of the optimum temperature for the hot working. Therefore, it has been expected that the hot working condition is improved for the titanium alloys. The transformation superplasticity has a probability of the improvement.

While many investigations of the transformation superplasticity have been carried out for iron and its alloys,¹⁻³⁾ a few studies have been made for titanium and its alloys.⁴⁻⁷⁾ In addition, it is not known systematically how ε_{lr} is influenced by the rate of heat-

ing or cooling, the applied stress and also the microstructure under a wide condition of the temperature cycle test.

In this paper, therefore, the relationship between the transformation and the total strain obtained in a temperature cycle, ε_t , has been examined first, and then the value of ε_{lr} is defined and evaluated under various conditions. Finally, the influences of the rate of heating and cooling, the applied stress, and the direction of the stress axis to the rolled direction on the amount of ε_{lr} have been investigated.

Pure titanium was selected as the specimen of the present study because the result had a very good possibility of providing the fundamentals of the superplasticity for titanium alloys.

II. Experimental Procedure

The test mode employed in the present study was compression because it was easy to obtain higher accuracy in measurements of the small displacement and also to quench the specimen quickly after an interruption of the test. The displacement under higher stress than 0.5 MPa was measured in a specially designed compression apparatus (SDCA), while the displacement under lower stress was determined by a thermomechanical analyzer (TMA) of RIGAKU CN-8096. Both instruments were used under constant load. The system including a high quality differential transformer was adopted in SDCA, the accuracy of which was within $\pm 2 \mu\text{m}$ of the displacement. The test temperature was regulated by a PID controller in an infrared ray furnace. The main part of SDCA was screened from atmosphere by a transparent quartz tube, which was swept and filled with a purified argon gas. In TMA, a differential dilatometric system in an air was adopted with an alumina bar as the reference specimen. The accuracy of measurement in TMA was $\pm 0.5 \mu\text{m}$.

Two series of the commercially-pure titanium plate, Ti-A and Ti-B, were prepared for specimens. These plates were 6 mm and about 30 mm in thickness, respectively. They had been annealed after hot rolling. Chemical compositions of these materials are shown in the Table 1. Cylindrical specimens for compression tests were machined from Ti-A and Ti-B plates

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Table 1. Chemical compositions of pure titanium used.
(wt. ppm)

	Elements				
	O	H	N	Fe	Ti
Ti-A	880	20.5	66	580	bal.
Ti-B	550	16	32	340	bal.

as the stress axis was parallel to the rolling direction, RD. Further specimens were prepared from Ti-B as the stress axis was in the long or the short transverse direction, LT or ST, respectively. All specimens were 5 mm in diameter, while length was 10 mm for SDCA and 19 mm for TMA.

Specimens were heated at rates of 2 and 8.30×10^{-2} K/s for tests in SDCA and TMA, respectively, followed by holding for 1.2 ks at 1 073 K before all tests of the temperature cycle. Both rates during heating and cooling were set to be equal and constant under each condition. The rate is represented by $\dot{T}$ hereinafter. Values of $\dot{T}$ and the applied stress ranged from 0.01 to 5 K/s and from 0 to 1.96 MPa, respectively. The range of the temperature cycle was about from 1 073 to 1 173 K.

III. Results and Discussion

1. Relationship between the Strain Occurring during Heating and Cooling and the Phase Transformation

Typical strain-temperature curves obtained are shown in Fig. 1, in which the strain is represented by the nominal value and positive in the compression direction. A remarkable strain is found in a linear part on each curve in Fig. 1, which is seen, for example, from about 1 120 to 1 150 K in the curve of $\dot{T}$ of 0.05 K/s. Optical and electron microstructures in the specimen quenched from several points on the curve of 0.05 K/s in Fig. 1 were observed and it was revealed that the steep slope indicated by the arrow mark corresponded to the $\alpha \rightleftharpoons \beta$ transformation.⁸⁾

It is shown in Fig. 1 that the region of the dual phase is about 30 K wide. The temperature range should depend on the impurity content in the commercially-pure titanium. It is suggested that iron and oxygen have a remarkable effect on the transformation temperature of pure titanium.⁹⁾ Figure 2 shows a phase diagram for Ti-rich region of the Ti-Fe system, which was reported by Matyka *et al.*¹⁰⁾ The α solvus is found to be 1 119 K for the specimen containing iron of 580 ppm. On the contrary, oxygen is known as an α stabilizer. Oxygen of 880 ppm is considered to raise the α solvus about 5 K.⁹⁾ Therefore, the α solvus of the present specimen may be estimated approximately to be 1 124 K, while the β transus is considered to be about 1 160 K.^{9,10)} It is concluded, therefore, that the temperature range of the dual phase region, obtained experimentally, is in good agreement with that estimated on a simple assumption of the effect of iron and oxygen contents on both the α solvus and the β transus of the present specimen. These results support strongly an idea that

Fig. 1. Typical strain-temperature curves obtained in a temperature cycle under a stress of 0.98 MPa and different rates of heating and cooling for Ti-A.

Fig. 2. Titanium rich region of the phase diagram for the Ti-Fe system.¹⁰⁾

the commercially-pure titanium should be regarded as a Ti-Fe-O ternary system alloy, especially concerning its phase transformation.

2. Evaluation of ϵ_{lr}

It has been confirmed that the significant strain for the transformation superplasticity appears actually in the steep slope on the strain-temperature curve as shown in Fig. 1. The amount of ϵ_{lr} is defined presently as drawn in Fig. 3, where ϵ_{lr-h} and ϵ_{lr-c} correspond to ϵ_{lr} during heating and cooling, respectively. The value of ϵ_{lr} in the definition is considered to be sum of both strains due to the transformation itself $\epsilon_{lr(0)}$ and the transformation under the stress $\epsilon_{lr(\sigma)}$, the latter of which is a characteristic strain for the superplasticity. According to this definition, ϵ_{lr} is recognized to be separated from any other strain which involves those due to the thermal expansion and to the creep deformation in a respective single phase region.

Fig. 3. Definition of ε_{tr-h} and ε_{tr-c} on the strain-temperature curve.

3. Dependence of ε_{tr} on $\dot{T}$

In order to examine $\dot{T}$ dependence of ε_{tr} , temperature cycle tests were carried out under conditions of a given stress of 0.98 MPa and of various rates of heating and cooling for one cycle. As seen in Fig. 4, each curve has a maximum at $\dot{T}$ of near 0.1 K/s. Dependence of ε_{tr-c} on $\dot{T}$ was similar to that of ε_{tr-h} . The value of ε_{tr-c} was smaller than the other under all rates examined. The tendency obtained in Fig. 4 may be closely related to periods required to reach the transformation temperature region and also to pass through the region. During the former period, microstructural change such as grain growth may take place under a small $\dot{T}$, while the latter has a reasonably close relation to the amount of ε_{tr} . Therefore, this tendency should be discussed with informations on microstructural and temperature dependence of ε_{tr} . Here, reason for a definite difference between ε_{tr-h} and ε_{tr-c} in Fig. 4 is discussed in detail with information on their stress dependence in the next section.

4. Dependence of ε_{tr} on the Applied Stress and the Orientation of the Stress Axis to the Rolling Direction of the Specimen

The relationship between ε_{tr} and the applied stress for Ti-A under a constant $\dot{T}$ of 0.05 K/s is seen in Fig. 5. Values of ε_{tr} increased with an increase in the stress. The relationship can not be regarded as linear, in contrast to previous results.¹¹⁻¹⁴⁾ Under stress free condition, deviation from the origin to the positive side (contraction) or the negative side (expansion) takes place in the curves of ε_{tr-h} or ε_{tr-c} , respectively. These deviations may be attributed to $\varepsilon_{tr(0)}$, as discussed below.

Texture of the rolled or the recrystallized titanium was studied by Keeler and Geisler¹⁵⁾ and Barrett and Massalski.¹⁶⁾ For the preferred orientation of the annealed plate after hot rolling, they suggested that $[10\bar{1}0]$ was oriented in $\pm 14\sim 20^\circ$ from the rolling direction on the rolling plane and also in $\pm 14\sim 20^\circ$ from the transverse direction, and that (0001) pole was oriented in $\pm 25\sim 40^\circ$ from the rolling direction. On the other hand, the Burgers' relation was reported

Fig. 4. Influence of $\dot{T}$ on ε_{tr-h} and ε_{tr-c} at a stress of 0.98 MPa for Ti-A.

Fig. 5. Influence of the applied stress on ε_{tr} at a heating and cooling rate of 0.05 K/s for Ti-A.

to be held in crystallographic change during the transformation in titanium, which is $\{110\}_\beta // \{0001\}_\alpha$ and $\langle 111 \rangle_\beta // \langle 11\bar{2}0 \rangle_\alpha$.^{17,18)} According to this relation, possible values of $\varepsilon_{tr(0)}$ on simple orientations are estimated as follows, contractions of 0.43 % for $\langle 0001 \rangle_\alpha \rightarrow \langle 110 \rangle_\beta$ and 8.8 % for $\langle 1010 \rangle_\alpha \rightarrow \langle 110 \rangle_\beta$, and expansion of 11.5 % for $\langle 1120 \rangle_\alpha \rightarrow \langle 110 \rangle_\beta$.

Therefore, the presence of both contraction during heating and the expansion during cooling under stress free condition is considered to be explainable qualitatively in terms of both the orientation dependence of $\varepsilon_{tr(0)}$ and the preferred orientation of the specimen.

In order to examine the above concept, influence of the orientation relationship between the stress axis and the rolling direction on ε_{tr} has been investigated for the thicker plate of Ti-B under the condition of $\dot{T} = 0.2$ K/s. Results are shown in Fig. 6, in which

Fig. 6. Influence of the applied stress and its orientation dependence between the stress axis and the rolling direction of the specimen on ε_{tr} at a heating and cooling rate of 0.2 K/s for Ti-B.

the largest ε_{tr-h} is obtained in RD, while the minimum in ST. On the contrary, it has been found that larger values of ε_{tr-c} are shown in ST, while the lowest in RD. The difference between them is not so marked, especially in ST, compared with the case of ε_{tr-h} .

A possible reason for these results is considered to be found in the difference of $\varepsilon_{tr(0)}$. During heating of RD and LT, it appears in positive (compression), while in negative (expansion) for ST. By plotting $\varepsilon_{tr(a)} (= \varepsilon_{tr} - \varepsilon_{tr(0)})$ against applied stress, Fig. 7 is obtained, showing less difference among RD, LT and ST specimens. It means that the level of ε_{tr-h} and ε_{tr-c} is determined mostly by the amount of $\varepsilon_{tr(0)}$. Although the absolute values of $\varepsilon_{tr(0)}$ may be much smaller than the estimated ones mentioned above, the experimental results of orientation dependence of $\varepsilon_{tr(0)}$ are considered to be consistent qualitatively with that estimated. It is still unknown the reason for the quantitative disagreement, but the variety of the microstructure and the different sharpness of the texture may be associated with these discrepancy.

The reason for the stress dependence of ε_{tr} has been investigated by examination of the stress exponent of the strain rate, n ($\dot{\varepsilon} = K'\sigma^n$, where $\dot{\varepsilon}$ is the strain rate, σ the stress and K' a constant). The value of n equals to the reciprocal of m which is referred to as a significant parameter for the fine grain superplasticity.¹⁹⁾ Presently, the stress can be expressed as follows, $\sigma = K\dot{\varepsilon}_{tr}^m$, where $\dot{\varepsilon}_{tr}$ is the strain rate evaluated from the slope on the strain-time curve and K is a constant. Figure 8 shows the relationship between $\dot{\varepsilon}_{tr}$ and stress in double logarithmic plot. The value of m evaluated from the slope was found to be nearly equal to unity. These were consistent with the results reported by Oelschlägel and Weiss²⁰⁾ and Nishihara *et al.*¹⁴⁾ It is very possible that deformation in the transformation superplasticity is controlled by a diffusional process, such as the diffusional creep²¹⁻²³⁾ and the grain

Fig. 7. Relationship between the applied stress and $\varepsilon_{tr(a)}$ ($= \varepsilon_{tr} - \varepsilon_{tr(0)}$) for Ti-B.

boundary sliding^{24,25)} at the vicinity of the advancing boundaries during the phase transformation.

IV. Conclusions

In order to clarify the fundamental characteristics of the transformation superplasticity for a commercially-pure titanium, influences of the heating and cooling rate, the applied stress and the orientation of the stress axis to the rolling direction on the strain while undergoing the transformation for a temperature cycle, ε_{tr} have been investigated. The results are summarized as follows,

- (1) The remarkable strain was found in certain temperature range during heating and also cooling, in which the transformation takes place.
- (2) The amount of ε_{tr} was changed by heating or

Fig. 8. Relationship between the applied stress and the strain rate during the phase transformation under stresses above 0.5 MPa and a heating and cooling rate of 0.05 K/s for Ti-A.

cooling rate, $\dot{T}$, showing a maximum at a rate of 0.1 K/s. Values of ε_{tr} during heating were always larger than those during cooling. This difference has been considered to be attributed to the strain of the transformation itself.

(3) The values of ε_{tr} during heating and cooling increased with an increase in the applied stress. The orientation between the stress axis and the rolling direction has an influence on ε_{tr} . These are considered to be explainable qualitatively in terms of both the orientation dependence of ε_{tr} under stress free condition and also the texture of the specimen.

(4) The relationship between the strain rate and the stress while undergoing the allotropic transformation was to be nearly equal to unity. This implies a possibility that the deformation in the transformation superplasticity is controlled by a diffusional process.

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