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Rate-dependent hardening model for pure titanium considering the effect of deformation twinning

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ABSTRACT

This paper is concerned with the strain hardening behavior of commercially pure titanium for a wide range of strain rates. Pure titanium has been described as having three stages of strain hardening behavior during compressive deformation. The stress–strain curve of pure titanium can be divided into three stages according to the strain hardening rate, and the strain hardening rate can be determined by the slope of the stress–strain curve. In the first stage, the strain hardening rate decreases as deformation continues due to dynamic recovery. The strain hardening rate shows a trend similar to general industrial metals. In the second stage, however, the strain hardening rate begins to increase as deformation continues. Following the second stage, the strain hardening rate decreases again in the third stage. Many researchers have determined that a sudden increase in the strain hardening rate in the second stage is caused by the generation of deformation twins, and the strain hardening behavior of pure titanium is influenced by the tendency of twin generation and evolution. In this paper, the effect of deformation twinning on the strain hardening behavior of pure titanium is investigated using OIM (Orientation Imaging Microscopy) analyses. EBSD (Electron Backscatter Diffraction) analyses are conducted to quantitatively observe the generation and evolution of deformation twins. The strain rate effect on the strain hardening is also investigated. Both tensile and compressive tests are conducted at strain rates ranging from 0.001/s to 10/s, and the effect of the strain rate on the three stages of the strain hardening behavior is quantified by observing the micro-structures of deformed specimens at the various strain rates. A novel rate-dependent hardening model is proposed by keeping trace of deformation twins with increase in the compressive strain, which induces the variation of the strain hardening rate. The proposed model is defined with a function of the plastic strain and the strain rate based on OIM results in terms of twin volume fraction and grain size distribution. The three stages of strain hardening behavior of titanium for a wide range of strain rates can be represented by one equation, and this equation can provide useful and simple way that can be applied to the numerical analysis.

1. Introduction

It is well known that the three stages of strain hardening behavior are observed during the compressive deformation of pure titanium. Kailas et al. [1] suggested that the stress–strain curve of pure titanium can be divided into three stages according to the tendency of the strain hardening rate. The strain hardening rate can be defined as the slope of the stress–strain curve. In the earlier plastic strain region after yielding, the strain hardening rate decreases as deformation continues. As the plastic strain increases, the flow stress increases via the strain hardening mechanism, but the slope of the stress–strain curve decreases. This decrease is due to dynamic recovery, and general industrial metals show dynamic recovery with an increase in the plastic strain. Following this region, however, a sudden increase in the strain hardening rate is observed in the second stage. Both the flow stress and its slope increase as the plastic strain increases. In the third stage, the strain hardening rate decreases again as the plastic strain increases. Nemat-Nasser et al. [2] also reported the three stages of the strain hardening behavior of pure titanium observed from compressive tests at room temperature and suggested that the cause of the second stage is dynamic strain aging. According to the research of Doner et al. [3], however, dynamic strain aging in pure titanium is only observed at strain rates ranging from 3×10^{-5}/s to 3×10^{-2}/s and at temperatures ranging from 600 K to 850 K. It can be the clear evidence that the increase in the strain hardening rate in the second stage is not due to dynamic strain aging because the

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conditions proposed by Nemat-Nasser et al. do not correspond with the conditions proposed by Doner et al. Salem et al. [4–7] suggested in their series of studies that the second stage for commercially pure titanium is caused by the occurrence of deformation twinning. The authors used high-purity titanium to remove the possibility of dynamic strain aging and demonstrated that three distinct stages of strain hardening behavior were still observed. They also investigated the microstructure of commercially pure titanium during the compression process and demonstrated that the onset of the second stage is correlated with the onset of deformation twinning. The occurrence of deformation twinning in commercially pure titanium has been reported together with its role in strain hardening. Strain hardening of pure titanium is noted to be influenced by the generation and evolution of deformation twins [8–11]. In accordance with Kalidindi et al. [12], the sudden increase in the strain hardening rate in the second stage is due to the combination of several hardening mechanisms caused by deformation twinning. Precise physical connections between deformation twinning and strain hardening have not yet been established. Kalidindi et al. assumed that the strain hardening of pure titanium changes via the Hall–Petch hardening and texture hardening mechanisms. The material is hardened through the Hall–Petch mechanism because the effective slip length is reduced when deformation twins are generated. Additionally, these authors showed, using OIM (Orientation Imaging Microscopy), that the orientation of a twinned region is rotated with respect to the matrix region. The change in the texture orientation induces the change in the yield stress, and it provides clear evidence that the strain hardening of the material changes due to the texture hardening mechanism when deformation twins are generated [13–15]. The complex strain hardening behavior of commercially pure titanium can be understood as a result of the combination of the Hall–Petch hardening and texture hardening mechanisms. Ahn et al. [16] proposed a phenomenological strain hardening model that can represent the three stages of strain hardening behavior of pure titanium based on the investigation of the microstructures during compressive deformation. By measuring the quantitative tendencies of the initiation and evolution of deformation twins using the EBSD analyses, the effect of deformation twinning on the strain hardening of pure titanium was quantified at a quasi-static condition. The role of the initiation and evolution of deformation twins was included into the strain hardening model in terms of the Hall–Petch hardening and texture hardening mechanisms to account for the three stages hardening behavior during the compressive deformation of pure titanium.

It has been reported that the generation and evolution of deformation twins are influenced by the strain rate. Chichili et al. [17] investigated the effect of the strain rate on deformation twinning by conducting split Hopkinson pressure bar tests of commercially pure titanium at a strain rate higher than 3×10^3/s. The results showed that the density of the twins at the same strain condition increases as the strain rate increases. These tests can provide the qualitative results that indicate the twin density increases with an increasing strain rate.

In this paper, the compressive tests of commercially pure titanium are conducted at various strain rates ranging from 0.001/s to 10/s to investigate the effect of the strain rate on the three stages of strain hardening behavior induced by the evolution of deformation twinning. The universal testing machine (INSTRON5583) is utilized for the compressive tests at strain rates ranging from 0.001/s to 0.1/s, and the Gleeble3800 system is used for the strain rate ranging from 0.1/s to 10/s. Tensile tests are also conducted at the same strain rates as the compressive tests to compare the strain hardening behavior with and without deformation twinning because it is reported that very little deformation twinning is generated during tensile deformation [18,19]. The strain rate effect on the three stages of the strain hardening behavior during compressive deformation is quantitatively investigated from the test results at the various strain rates. OIM analyses based on the EBSD are conducted to examine the three stages of strain hardening behavior of titanium. The generation and evolution of deformation twins with increase in the compressive plastic strain are quantitatively investigated. The strain rate effect on the three stages of strain hardening behavior is also investigated by observing the microstructures of the deformed titanium for a wide range of strain rates and by quantifying the strain rate effect on the generation and evolution of deformation twinning. Using the results of the compressive tests and the microscopic investigations, a rate-dependent strain hardening model is proposed. The model is developed based on the investigated effect of deformation twinning on the strain hardening behavior of titanium and its strain rate dependency. The model is capable of representing the three stages of strain hardening for a wide range of strain rates. The purpose of the model is to suggest an applicable form of the strain hardening representation for commercially pure titanium that can be applied to numerical analysis, and the model is shown to accurately represent the strain hardening behavior. The applicability of the model to strain rate conditions higher than thousands/s is also verified by applying the model to the additional SHPB tests.

2. Experiments

2.1. Material

CP (commercially pure) titanium is usually divided into four grades according to its chemical composition and strength. A lower grade of CP titanium indicates higher purity and lower strength.

Table 1
Inspection certificate of the tested titanium (Aichi Steel Corporation).

Product	Titanium round bars	Date of issue	30-10-2007		
Applicable Spec.	JIS H 4650 (2001)	Finish	Hot rolled, annealed and turned		
Material	TB340H				
Size	(MM) 12				
Items	Mechanical properties				
	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Hardness (HV)
Min	215	340	23		110
Max	–	510	–	–	–
Results	304	435	33	56	166
Elements	Chemical composition (%)				
	H	O	N	Fe	C
Min	–	–	–	–	–
Max	0.013	0.20	0.03	0.25	0.08
Results	0.0008	0.112	0.004	0.034	0.003