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Tensile properties and constitutive model of ultrathin pure titanium foils at elevated temperatures in microforming assisted by resistance heating method

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ABSTRACT

Pure titanium (Ti) is often used for microparts in biomedical devices and implants. Microforming is a promising technology for the manufacture of microparts. Owing to the occurrence of size effects in microforming, the material flow is nonhomogeneous and the process parameters exhibit considerable scattering. Heat-assisted microforming is an effective process for solving these problems. To improve the heating rate, the resistance heating method has been introduced into the microforming process. To design an effective resistance-heating-assisted microforming process, the relationship between the electric current and the flow stress of the material should be determined.

To achieve this, a tensile testing system incorporating the resistance heating method is developed in this study. The tensile properties of 0.05-mm-thick pure Ti foils are investigated by performing uniaxial tensile tests at elevated temperatures. The tensile tests are carried out at different angles (0°, 45°, and 90°) relative to the rolling direction, at various temperatures from room temperature (298 K) to 723 K, and under different strain rates from 10^{-4} to 10^{-1} s^{-1}. To contribute to the design of the resistance-heating-assisted microforming process, the effect of the temperature and electrical current density on the material properties of ultrathin pure Ti foils is discussed. A constitutive model based on the Fields–Bachofen (FB) equation is derived to describe the flow stress of ultrathin pure Ti under different forming conditions. The effect of the electrical current density on the work hardening and strain rate sensitivity is included in the derived constitutive model. The good agreement between the calculated and experimental results confirms the feasibility of the proposed constitutive model for resistance-heating-assisted microforming.

1. Introduction

Owing to the high specific strength, light weight, outstanding corrosion resistance, and biocompatibility of titanium and its alloys, they are widely used in electronics, automobile components, and biomedical devices [1–3]. In particular, pure titanium (Ti) is often used for microparts in biomedical devices and implants. In the last few decades, some investigations on the material properties and forming processes have been conducted for pure Ti [4–7]. Even though the mechanical properties of pure Ti sheets under tensile [5,7] and compression [6] conditions have been well studied, such properties are not suitable for the manufacture of microparts because of the occurrence of size effects in microforming [8].

Size effects may result in nonhomogeneous material characteristics and large scattering of the process parameters, which make the forming process unpredictable at the microscale [9,10]. To solve these problems, a heat-assisted microforming process was conducted by Egerer et al. [11,12]. By carrying out micro upsetting and backward extrusion tests at elevated temperatures with heating in a furnace, they found that the scattering of the process parameters was reduced and the material flow was more homogeneous. To improve the heating rate for heat-assisted microforming, a resistance heating system was developed and introduced into the microforming process by the authors [13]. This system has the advantages of improving the material formability, reducing the forming load, and improving the accuracy of the products while requiring much less energy [13,14]. As shown in Fig. 1, in the micro

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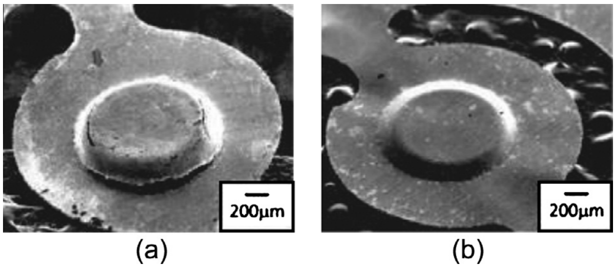

Fig. 1. Images of cups drawn by micro deep drawing process: (a) at room temperature, and (b) at a high temperature of 653 K assisted by resistance heating [13].

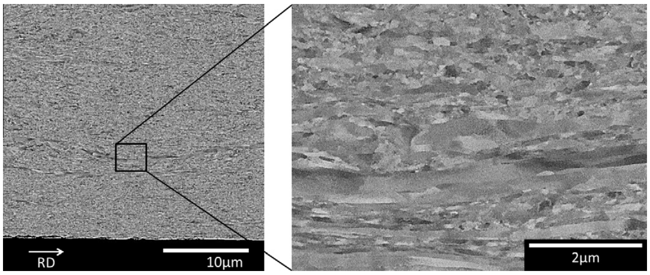

Fig. 2. Microstructure of pure Ti foil with thickness of 0.05 mm taken by SEM.

deep drawing process, for a given forming height, the material exhibits better formability at high temperatures than at room temperature. However, to design an effective resistance-heating-assisted microforming process, it is necessary to determine the relationship between the electric current and the flow stress of the material.

Recently, the effect of the electric current on the material deformation behavior during forming has been studied in terms of the dislocation slipping velocity [15] and energy balance [16]. In addition, Gallo et al. [17] proposed a viscoplastic constitutive model that successfully described the material behavior of an aluminum alloy and copper alloy subjected to a combination of mechanical loading and a high-intensity electric current. Magargee et al. [18] used modified Hollomon and Johnson–Cook models to predict the magnitude of stress reduction caused by an electric current and the associated temperature increased by Joule heating during electrically assisted tension experiments. However, some of these models only focused on predicting the material behavior from the electric current for conventional macroscale plastic forming but not for microforming. Other models predicted the flow stress for microforming without considering the effect of the strain rate. As is well known, the temperature of a material increases because of Joule heating when an electric current is applied. Once the material is deformed at an elevated temperature, the strain rate has a significant effect on the mechanical properties. Thus, to design an effective microforming process assisted by resistance heating, the flow stress of the material should be predicted by an effective constitutive model considering not only the electric current but also the effect of the strain rate on the material properties.

The objective of this study is to obtain the effective constitutive model mentioned above to contribute to the design of the resistance-heating-assisted microforming process. To achieve this, a tensile testing system incorporating the resistance heating method is first developed. Then, uniaxial tensile tests are carried out to obtain the mechanical properties of ultrathin pure Ti foils with a thickness of 0.05 mm. The tensile properties of the Ti foils are discussed. Finally, a constitutive model based on the Fields–Bachofen (FB) equation is derived to describe the relationship between the electric current and the flow stress of the foils. To predict the change in flow stress with the strain and strain rate, the effect of the temperature and electrical current density (ECD) on the work hardening and strain rate sensitivity is included in the derived constitutive model.

2. Experiment

2.1. Materials

As-received pure Ti foils (JIS TR270C-H) with a thickness of 0.05 mm are used in this study. Fig. 2 shows the microstructure (rolling direction (RD)-normal direction (ND) plane) of the foil taken by scanning electron microscope (SEM; HITACHI, SU-70) after ion milling (HITACHI, IM-4000). Due to the high rolling reduction, elongated grains in the rolling direction can be observed. The grain size in the normal direction of the foil is in sub micrometer range. This is thought to be caused by the pre-annealing process before rolling to an ultrathin thickness of 0.05 mm.

2.2. Development of tensile testing system incorporating resistance heating method

Fig. 3 shows an image of the tensile testing system incorporating resistance heating. This system was developed on the basis of a commercial tensile testing machine (Autograph AG–IS 50 kN, Shimadzu Corp.) as shown in Fig. 3(a). The system mainly consists of five parts, a direct current (DC) power supply, a controlling personal computer (PC), a thermosensor, an optical extensometer, and a tensile test machine. By applying current using the DC power supply, the material is heated by its own resistance. To maintain a constant specimen temperature during the test, a feedback system was developed. The temperature at the center of the tensile specimen is measured by the thermosensor, and is sent back to the PC to control the output power via a proportion integration differentiation (PID) program. During the tensile test, the strain is measured optically by a noncontact extensometer (DVE-201, Shimadzu Corp.). To flow the electric current from the power supply to the specimen and to insulate the tensile machine from the electricity in the specimen, a tensile fixture is designed that consists of an electrode, insulating plates, and a holding jig (see Fig. 3(b)). The electrode is embedded in the tensile fixture so that the current can flow directly from the power supply to the specimen. The insulating plates, which are made of glass fiber, are used to insulate the tensile machine from the electricity and heat in the specimen. The holding jig is used to mount the tensile fixture on the tensile machine.

To validate the temperature of the specimen before the tensile test, the history of temperature variations was recorded at a heating temperature of 573 K, and the temperatures at several positions along the gauge length of the tensile specimen were measured by thermocouples to obtain the temperature distribution.

Fig. 4 shows the history of the temperature variations before the tensile test at the center of the specimen. The temperature variations show three periods, an increase in temperature, PID control, and a stable period. The increasing rate of the temperature is relatively high, which indicates the high efficiency of the resistance heating method. The PID controlling program enables a stable temperature to be obtained in 1 min. After the period of PID control, the temperature can be kept stable within a range of ±3 K.

Fig. 5 shows the temperature distribution along the gauge length of the specimen before the tensile test. The results show that the temperature at the center tends to be higher than that at the edge. This is attributed to the difference in ECD at each position. When applying the electric current, ECD along the gauge length is higher than that in the clamping area. Thus, the area with