Journal of Materials Processing Technology 230 (2016) 233–243

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

# Scale effect on springback behavior of pure titanium foils in microbending at elevated temperature

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ARTICLE INFO

*Article history:*
Received 27 April 2015
Received in revised form 5 October 2015
Accepted 28 November 2015
Available online 2 December 2015

*Keywords:*
Microbending
Elevated temperature
Pure titanium foils
Springback
Scale effect

ABSTRACT

The occurrence of size effects in microforming process influences the accuracy of the products significantly. To investigate the scale effect and the mechanism of springback behavior of thin pure titanium (Ti) foils bent at elevated temperatures, scaled microbending processes assisted by resistance heating are performed for the foils with different thickness of 0.02, 0.05, and 0.1 mm. It is found that the springback angle increases with decreasing foil thickness at room temperature. However, after bending at elevated temperatures, the springback angle is found to decrease with decreasing foil thickness. Due to the lower flow stress of surface, the influence of surface area is thought to be the dominating factor that results in the less springback of thinner foils at elevated temperatures. To confirm this and to predict the springback angles at elevated temperatures, a new theoretical model of surface area increasing with increasing temperature is proposed. The springback angles are calculated by theoretical analysis using conventional plastic theory and the proposed model. As temperature increases, the large reduction of springback angles compared to 298 K can be captured by using the proposed model successfully. The validity of the proposed model is confirmed.

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## 1. Introduction

Because of the high productivity, near-net-shape, and good properties of formed products, microforming process has been received much attention in the manufacture of microparts such as electronics, automobile components, and biomedical devices (Geiger et al., 2001). As the size is scaling down, the processes in micro scale are usually unpredictable because of the occurrence of size effects (Vollertsen et al., 2009). In micro upsetting tests by keeping the same grain size of the material, the flow stress was found to decrease with decreasing specimen size (Engel and Eckstein, 2002). The same phenomenon was observed in the geometrically tensile tests of micro sheet forming (Kals and Eckstein, 2000), which can be explained by the surface layer model. Not only the flow stress, but also the accuracy of the products is influenced by size effects.

Microbending is one of the major sheet forming processes used in the fabrication of micro sheet metal parts. As is well-known, the springback in bending process has significant influence on the accuracy of the products. Moreover, in microbending, thinner foils may indicate larger springback due to the size effect (Diehl et al., 2010) explained by strain gradient theory (Suzuki et al., 2009). Li et al. (2010) predicted the springback angles of pure aluminum foils by considering the influence of strain gradient. To reduce the springback and to improve the accuracy of microparts, a resistance-heating-assisted system was introduced to the microbending process by the authors (Aoyama et al., 2014). Compared with conventional furnace heating, resistance heating can achieve a rapid heating rate. Furthermore, the equipment of resistance heating system indicates simpler configuration (Mori, 2012).

By conducting the bending process assisted by resistance heating method, it is found that the springback angle decreases with increasing temperature (Aoyama et al., 2014) and with increasing current density (Green et al., 2009). In spite of the advantages of resistance-heating-assisted microbending process, the size effect of heat on the springback behavior for thin foils has not been investigated in detail. Thus, to improve the accuracy of the manufactured products by predicting the springback under heating, the mechanisms of springback behavior for thin foils bent at elevated temperatures should be investigated.

The objective of this study is to investigate the mechanisms of springback behavior for thin foils after microbending process assisted by resistance heating. Because of the widely use of titanium and its alloys in biomedical devices and implants, thin pure titanium (Ti) foils with different thickness of 0.02, 0.05, and 0.1 mm

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http://dx.doi.org/10.1016/j.jmatprotec.2015.11.025
0924-0136/© 2015 Published by Elsevier B.V.

are chosen for the present study. To obtain the tensile properties of the material for the analysis of springback, uniaxial tensile tests are first conducted for these thin pure Ti foils. Then, microbending tests assisted by resistance heating method are performed for the foils along 0° and 90° to the rolling direction and at different temperatures ranging from 298 to 723 K. To discuss about the springback behavior of thin pure Ti foils, the hardness of the blank in the cross section (rolling direction (RD)-normal direction (ND) plane) after bending at 298 and 723 K is measured. Finally, the springback angles of thin pure Ti foils bent at different temperatures are predicted by theoretical analysis. The mechanisms of springback behavior under heating are discussed.

## 2. Experiment

### 2.1. Materials

Pure Ti foils with different thickness ($h$) of 0.02, 0.05, and 0.1 mm are used in this study. To minimize the influence of yield stress on springback, the materials are annealed to keep the same hardness of 123.5–133.3 HV for each thickness foil. The Poisson's ratio $\nu$ is 0.4. The Young's Modulus $E$ is 107.9, 98.4, 88.0, and 76.0 GPa at temperatures of 298, 433, 573, and 723 K, respectively (Huang et al., 2006). Fig. 1 shows the scanning electron microscope (SEM) images in the cross-section (transverse direction (TD)-normal direction (ND) plane) of the foils after processed by focused ion beam (FIB). As shown in Fig. 1, the average grain size of 0.02, 0.05, 0.1 mm foils are estimated to be 2, 4, and 5 μm, respectively.

To obtain the tensile properties of the foils, uniaxial tensile tests are performed at various temperatures ranging from 298 to 723 K under different strain rates of $10^{-3}$, $10^{-2}$, and $10^{-1}$ $s^{-1}$ along the rolling direction. The dimensions of tensile specimen are the same as the previous study reported in Zheng et al. (2014b). The tensile testing system incorporating resistance heating method (Zheng et al., 2014b) is utilized to conduct the tensile tests. The tensile tests are conducted three times for each condition. Fig. 2 shows an example of the true stress-true strain curves of the foils with different thickness. At temperatures of 298 and 433 K, the patterns of the flow stress for the foils show relatively large difference. However, at temperatures of 573 and 723 K, the materials exhibit almost the same strain hardening patterns before necking. This is attributed to the more homogenous material flow as the temperature increases. Taking 0.05 mm-thick foils as an example, the influence of strain rate on the true stress is shown in Fig. 3. The strain rate has more influence on the flow stress at elevated temperatures. The flow stress increases with increasing strain rate significantly when the temperature is 573 K or higher. This is caused by the thermal softening behavior (Zheng et al., 2014b).

To describe the relationship among true stress, true strain, and strain rate, Fields-Bachofen (FB) equation as shown in Eq. (1) is used.

$$\sigma = K\varepsilon^n \dot{\varepsilon}^m \quad (1),$$

where $\sigma$ is the true stress, $K$ is the strength coefficient, $\varepsilon$ is the true strain, $n$ is the strain hardening exponent, $\dot{\varepsilon}$ is the strain rate,

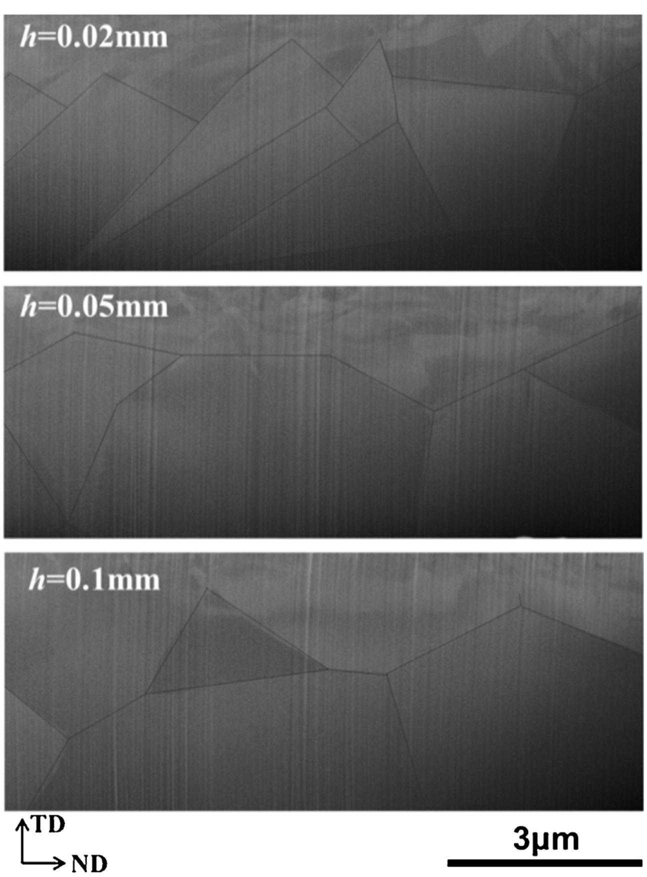


**Fig. 1.** SEM images of microstructure in the cross-section for pure Ti foils with different thickness.

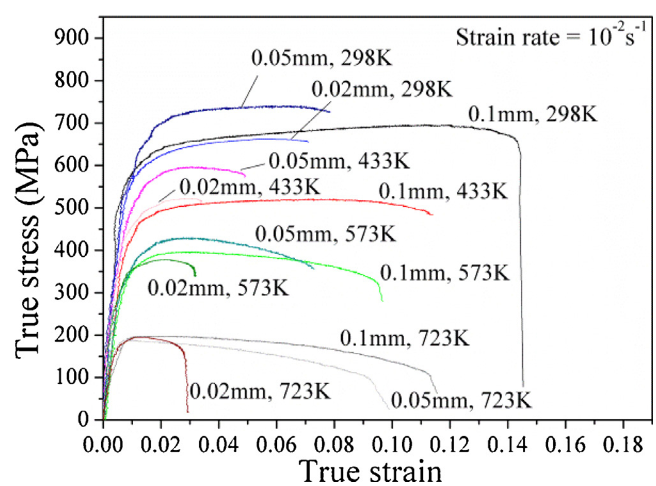


**Fig. 2.** True stress–true strain curves of pure Ti foils with different thickness at different temperatures under the strain rate of $10^{-2}$ $s^{-1}$.

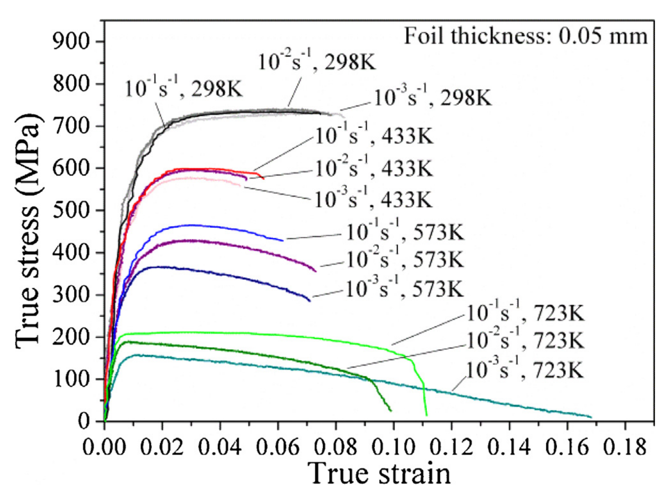


**Fig. 3.** True stress-true strain curves of 0.05 mm-thick pure Ti foils at different temperatures under different strain rates.

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