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Experimental and numerical analysis of springback behavior under elevated temperatures in micro bending assisted by resistance heating

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Abstract

In the micro bending process, thinner foils may indicate larger springback due to the size effect of strain gradient. Heat-assisted micro bending is an effective process to reduce the springback and improve the accuracy of the products. In order to investigate the mechanism of springback behavior of pure titanium foils under elevated temperature, experimental and numerical analysis were carried out for different thickness foils (0.02, 0.05, and 0.1 mm) with the same hardness. The results show that the springback angle decreases with increasing temperature. In the experiments, it is observed that the springback angle increases with decreasing foil thickness at room temperature, while the springback angle decreases with decreasing foil thickness at temperatures of 300˚C or higher. This tendency cannot be found in the results from numerical analysis, which is explained by the surface layer model and strain gradient theory. It is suggested that the influence of surface grains on the properties of the material is the dominating factor for the less springback of thinner foils at elevated temperatures. This indicates better accuracy of the parts made by thin foils at elevated temperatures.

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Keywords: Micro bending; Elevated temperature; Springback; Surface layer model; Strain gradient

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1. Introduction

With the large demands for microparts in electronics, automobile components, and biomedical devices, microforming has been received much attention in recent decades. Micro bending is one of the major sheet forming processes used in the fabrication of micro sheet metal parts. In general, the occurrence of the springback in bending process affects the accuracy of the deformed parts significantly. Moreover, for micro bending process, thinner foils may indicate larger springback due to the size effect of strain gradient (Vollertsen et al., 2009; Diehl et al., 2010; Li et al., 2012; Jung et al., 2012). To reduce the springback and improve the accuracy of the microparts made by thin foils, a heat-assisted micro bending process was conducted by the authors (Aoyama et al., 2013). In this process, a resistance heating system was developed. Compared with conventional furnace heating, the equipment of resistance heating system became simpler, and the heating rate is rapid (Mori et al. 2012, 2013). By the resistance hating assisted bending process, it is found that the springback angle decreased with increasing temperature. However, to improve the accuracy of the deformed parts effectively, it is necessary to investigate the mechanism of the springback of thin foils at elevated temperatures and to predict it.

In this study, micro bending processes were first conducted for different thickness foils at different temperatures assisted by resistance heating method. Then numerical analysis was carried out by commercial software ABAQUS-6.12 to predict the springback of the foils. Finally, the springback behavior was discussed according to the results from experiments and numerical analysis.

2. Procedure of experiments and modelling for numerical analysis

2.1. Material properties

Pure titanium (Ti) foils, with different thickness of 0.02, 0.05, and 0.1 mm, were used. The hardness of each thickness foil is at the same value of 129.4-133.3 HV. The material of the tools (punch and die) is SKD-11 steel (JIS standard). The electrical resistivity of pure Ti and SKD-11 are 0.488 and 0.1 μΩ·m, respectively. The thermal, electrical, and elastic properties for pure Ti and SKD-11 are shown in Table 1 (Huang et al., 2006). Uniaxial tensile tests along rolling direction were performed to determine the plasticity for different thickness pure Ti foils at different temperatures (see Fig. 1).

Table 1. Thermal, electrical, and elastic properties for pure Ti and SKD-11.

Material		Thermal conductivity (W/m˚C)	Specific heat (J/kg˚C)	Young's modulus (GPa)	Poisson's ratio
Ti	25 ˚C	19.3	——	107.9	0.4
	100 ˚C	18.9	503	102	0.4
	200 ˚C	18.4	545	95	0.4
	300 ˚C	18	566	88	0.4
	400 ˚C	18	587	80	0.4
	500 ˚C	18	628	72.8	0.4
SKD-11		29.3	480	210	0.3

2.2. Experimental procedure

Fig. 2 shows the micro bending process assisted by resistance heating. Dies used as electrodes are connected to the power supply directly. By the contacting between the blank and the die, the current flows through the blank. The temperature of the blank is increased by Joule heating. To reduce the variation in temperature of the blank when the punch contacts, the punch was heated up by one pair of plate heater throughout the tests. To maintain a constant temperature of the blank, a thermosensor was used to measure the temperature at the center of the blank. Then the measured temperature was sent to the PC to control the output power by PID program.

Air bending processes at different temperatures (from room temperature to 450 ˚C) along the rolling direction were conducted by using this micro bending system. As shown in Fig. 2(b), the process mainly consists of three steps, heating, bending and springback. In the heating step (Step 1), the punch contacts with the blank, and the power is turned on to flow the current through the die to the punch and the blank. When the desirable temperature of the blank is obtained, the bending process is conducted (Step 2). Finally, the springback behavior of the blank is observed and the springback angle is measured according to Step 3. To obtain the same maximum strain for different thickness foils, a scaled experimental setup is utilized. The process parameters are summarized in Table 2. The width of all the blank is 5 mm. For the accuracy and repeatability, the bending tests were conducted five times for each condition.

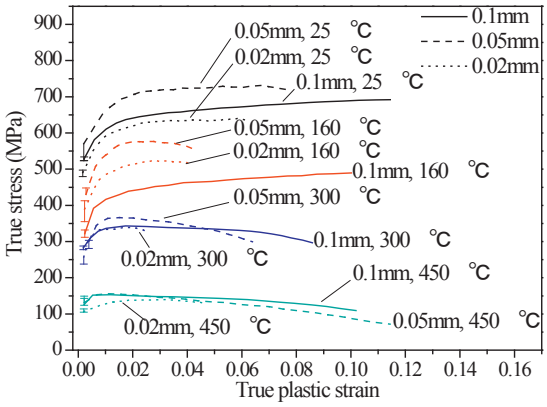

Fig. 1. True stress-true plastic strain curves of different thickness pure Ti foils at different temperatures.

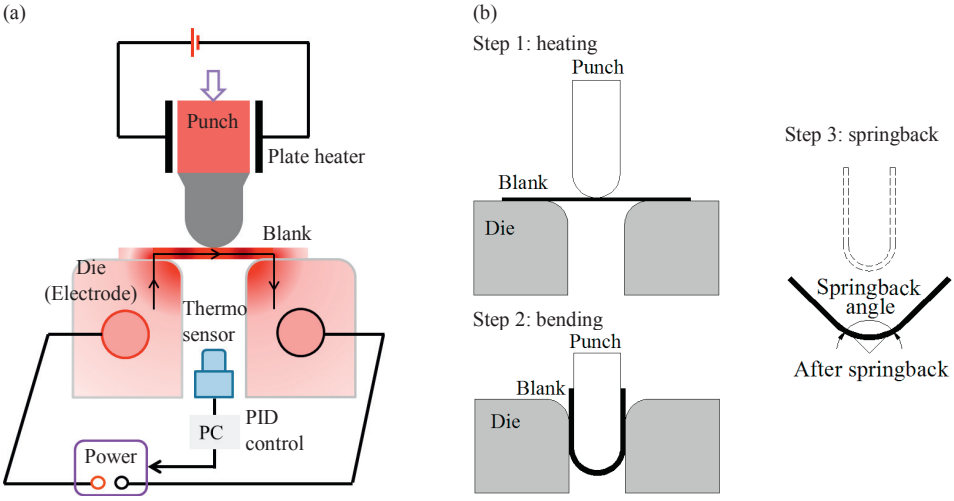

Fig. 2. Illustration of micro bending process assisted by resistance heating: (a) micro bending system, and (b) micro bending process.

2.3. Modelling for numerical analysis

2-D plane-strain model was used in numerical analysis. The analysis was done for the three steps in bending process (see Fig. 2(b)) by using ABAQUS 6.12. The material properties in Table 1 and Fig.1 were input. In Step 1, coupled thermal-electrical procedure was conducted for the analysis of the temperature distribution of the blank. The blank is discretized with 4-node linear coupled thermal-electrical quadrilateral elements, using five elements

through the thickness. The same element type as blank is also used for punch and die. In Step 2, coupled thermal-displacement dynamic explicit procedure was used for the micro bending process, and the temperature distributions of the blank and tools calculated from Step 1 were imported to the model. 4-node plane strain thermally coupled quadrilateral, bilinear displacement and temperature, reduced integration element was used for the blank, punch and die. Based on these two analysed models, static implicit procedure was carried out for the analysis of springback behaviour. For Step 2 and Step 3, the von Mises yield criterion was used. The process conditions for all of the analysis are the same as the experiment.

Table 2. Process parameters in air bending assisted by resistance heating.

Thickness (mm)	Length of blank (mm)	Radius of punch and die (mm)	Clearance between punch and die (mm)	Velocity of punch (mm/s)
0.1	20	2.5	0.2	10
0.05	10	1.25	0.1	5
0.02	4	0.5	0.04	2

3. Results and discussion

3.1. Results from experiments and numerical analysis

Fig. 3 shows the shapes of the blank after springback at different forming temperatures. The springback decreases with increasing bending temperature as expected, which indicates the better accuracy of the parts deformed at elevated temperatures. To obtain the differences of the tendency in springback for different thickness foils, the springback angles were measured from the experiments and numerical analysis as shown in Fig. 4. From experimental results (see Fig. 4(a)), 0.02 mm-thickness foils indicate the largest springback angle at room temperature. At temperatures of 300 ˚C or higher, this tendency is changed to that the 0.02 mm-thickness foils indicate the smallest springback. However, such phenomenon cannot be found in the results from the numerical analysis as shown in Fig. 4(b). To observe the differences in the springback angle between the experimental results and numerical analysis for each thickness foil, the comparison of the results is shown in Fig. 5. The results show good agreement for 0.1 mm-thickness foils, while a more decrease in springback angle from experiments is observed for 0.05 and 0.02-mm thickness foils.

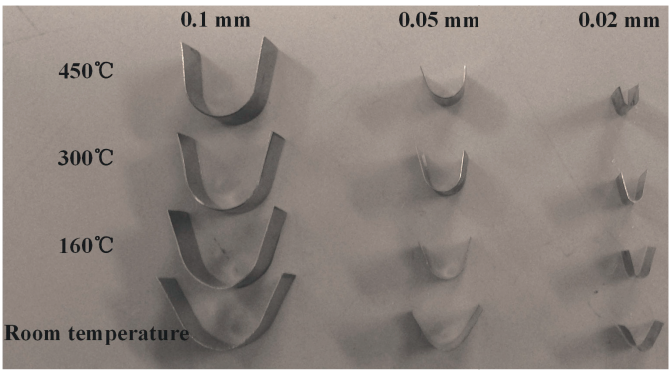

Fig. 3. Shapes of blank after springback at different forming temperatures.

3.2. Discussion

In microscale, the flow stress decreases with decreasing sheet thickness from the tensile test results at room temperature when the grain size is the same (Kals et al. 2000). This can be explained by the lower stress due to the less constraint in the surface grains of the specimen, the model of which is called surface layer model. Instead of

surface layer model, strain gradient theory is generally used to explain the reason for the larger springback of thinner foils in micro bending process (Diehl et al., 2008; Li et al., 2010). In this theory, it is thought that the thinner foils show more strain gradient when bending at room temperature, which results in larger springback (Suzuki et al., 2009).

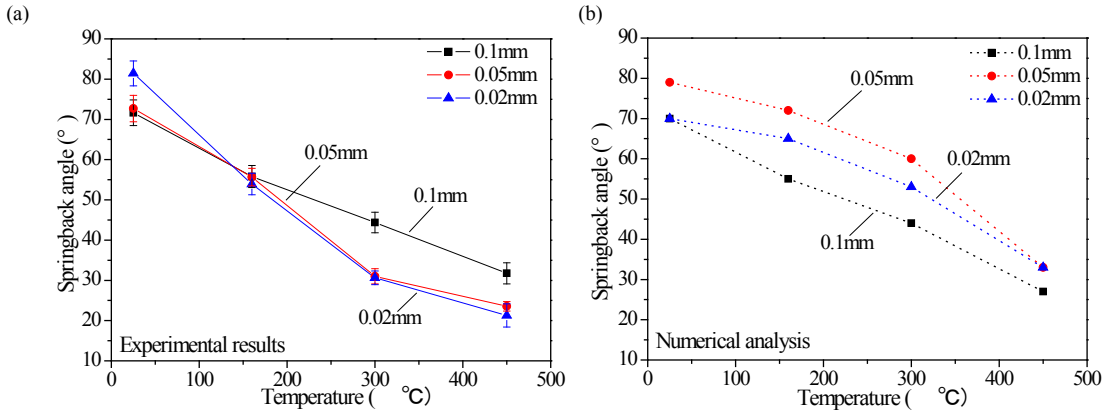

Fig. 4. Spingback angles obtained from experiments and numerical analysis at different forming temperatures for different thickness foils: (a) experimental results, and (b) numerical analysis.

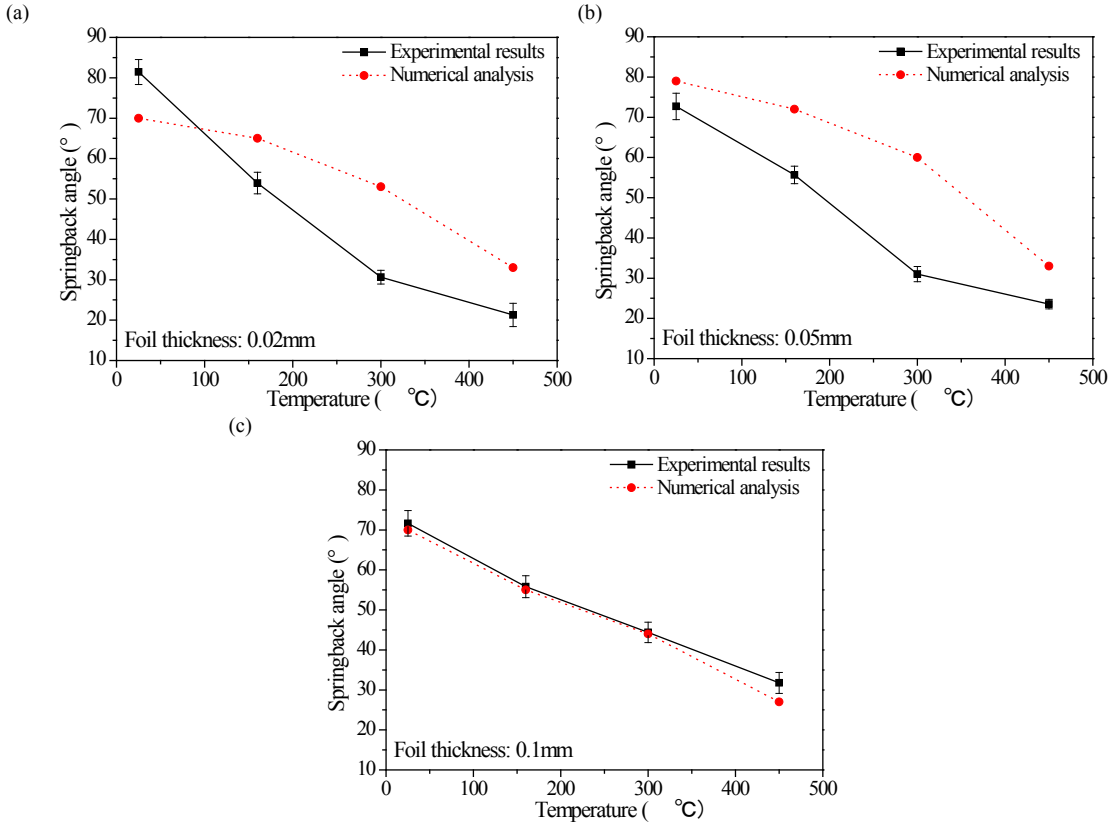

Fig. 5. Comparison of springback angles between experimental results and numerical analysis for each thickness foil: (a) 0.1 mm, (b) 0.05 mm, and (c) 0.02 mm.

In our study, larger springback angle for thinner foils at room temperature can be explained by the strain gradient theory. However, at elevated temperatures, the dislocation density in the surface layer may indicate a more decrease than inner material. Meanwhile, it is suggested that with increasing temperature, the influence of strain gradient decreases more significantly for thinner foils than thicker ones. Thus, the influence of surface grains may be the dominating factor for the larger decrease in springback of thinner foils.

Since the surface layer model and strain gradient theory are not considered in the modelling for the numerical analysis, the less decrease of the springback for 0.02 and 0.05-mm thickness foils from numerical analysis is observed from Fig. 5. Thus, to predict the springback for thinner foils precisely, it is necessary to apply the material constitutive model by the combination of surface layer model and strain gradient theory to the numerical analysis. To achieve this, a new constitutive model including the influence of temperature, strain rate, grain size and strain gradient will be established first, then a subroutine VUMAT will be developed for the analysis of bending process.

4. Conclusion

In this study, the mechanism of springback was investigated by experimental and numerical analysis for different thickness thin foils with the same hardness at different temperatures along rolling direction in micro bending process assisted by resistance heating. The results showed that the springback decreased with increasing temperature rapidly. From the experimental results, springback angle increased with decreasing foil thickness at room temperature, while the springback angle decreased with decreasing foil thickness at temperatures of 300 ˚C or higher. However, this tendency cannot be found in the results from the numerical analysis, which was not considered the effect of surface grains and strain gradient. At room temperature, the strain gradient is the dominating factor for the larger springback of thinner foils. At elevated temperatures, the influence of the surface grains is dominating for the less springback of thinner foils. This may indicate better accuracy of the parts made by thin foils at elevated temperatures. In the future, to design a resistance heating assisted micro bending process by predicting the springback precisely, the combination of surface layer model and strain gradient theory will be applied for further analytical calculation and numerical analysis of the springback.

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