Occurrence of Grain Subdivision reduces Springback in Microtube Press Bending Process

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Abstract - With the ongoing miniaturization of products, springback is a dominant effect because material behavior greatly varies in the microtube press bending process. The present investigation experimentally addresses the effect of grain size on the press bending process of seamless stainless microtubes. The problem was approached in two stages. First, the microtubes were annealed to examine the grain size effect on mechanical properties by performing a tensile test. Second, a microtube press bending system was developed to observe springback behavior. Consequently, the occurrence of grain subdivision, induced by strain hardening, reduced the springback amount. The criterion of grain subdivision occurrence may be determined by observing the reaction force with respect to the stroke of the press and bending angle.

Keywords - springback, tube, press, bending.

I. INTRODUCTION

Miniaturization is a trend in product development [1-3]. This trend encourages researchers to verify the feasibility of applying conventional macro-scale analysis methods to the micro-scale metal forming process. To date, many researches have focused on first-order size effects, which can be accounted for using conventional models. Researches have also explored second-order size effects that cannot be explained using conventional models. In the studies of first-order size effects, the influence factors include the grain size effect, grain boundary effect, free surface effect, grain statistics effect, and processing induced size effect [4-6].

For example, the contribution of frictional force to the total force is significant when miniaturizing the deep drawing process. In a study of second-order size effects, all important process dimensions were scaled down due to the observance of geometric similarity. A length scale was designated corresponding to a sheet thickness between 1 and 0.1 mm in the tensile test. As a result, the occurrence of second-order size effects was found to be expressed by the decreased flow stress, vertical strain anisotropy, and ductility [7].

Tensile and air bending testing have demonstrated that the grain size effect influences the deformability [8]. Tensile test showed that yield strength decreases upon the decrease of specimen thickness at a constant grain size in tensile tests. The material used was Al 2S. However, the bending experimental results showed that yield strength increases with decreasing grain size. Also, T/D (thickness/average grain diameter) ratio has been used to examined the influence of size effects on flow stress and formability [9,10]. It was found that yield strength, tensile strength and ultimate strain can be expressed as a function of the T/D ratio. In a three-point bending application, in addition to thickness, springback can also be expressed by the T/D ratio. In this study, the T/D ratio was adopted as an indicator for determining whether the conventional model is adoptable for the microtube press bending process.

Thus far, there have been no reports on the material behavior of microtubes in the press bending process. Since microtubes are among the most important microcomponents, and have been used in many microdevices such as microsensors and micro-heat exchangers, their material behavior is of great interest. In addition, because the ductility of material is an important parameter determining the formability of the press bending process, its evaluation is essential.

In this study, two experiments were carried out in the microtube press bending process. One prepared constant wall thickness (450 μm) with different average grain sizes and the other approached the average grain size of 10 μm with thickness variation. The relationship between the heat treatment condition and grain growth tendency was reported. A microtube press bending system was developed to examine the effect of grain size on the springback amount.

II. MATERIAL AND METHODS

A. Grain Size Control

To examine the grain size effect in the press bending test, heat treatment was carried out for 100 mm long seamless stainless microtubes (SUS 304). The specimen was prepared by annealing treatment in two ways: first, by changing the grain size at a constant wall thickness (450 μm), and second, by reducing the wall thickness of the microtube at a constant grain size (10 μm). Grain images were captured using an optical microscope and a fixed CCD camera. For grain analysis, representative samples of the batches were polished and etched. An aqua regia solution was used to etch the specimens. Average grain sizes were determined from the specimens' cross-section in accordance with the ASTM-E112 standard [11]. Each batch used 12 samples to check the reliability of the experiments.

For changing the average grain size at a constant wall thickness, grain growth tendency was analyzed as shown in Table 1. The T/D ratio denotes the ratio of specimen thickness and average grain size. Each specimen was heated from room temperature to the temperature of batch request. The temperature was maintained for one hour and each specimen was cooled in an oven. Because the heat treatment was conducted in a vacuum condition, no oxidation layer was formed.

To change wall thickness with a constant average grain size, the aim of this experiment was to examine the influence of the final bending angle in relation to thickness variation. The annealing treatment parameters, which consisted of temperature and heating time, were obtained by trial and error. These parameters are listed in Table 2. The thicknesses of the specimen were 150, 300, 450, and 600 µm. For each batch, 12 samples were used to calculate the average grain size. We were unable to obtain a microtube with an exact average grain size of 10 µm ; thus, deviation was used to present the range of results.

B. Press bending system

The principle of the proposed press bending system consists of three bearings, a pair of supports and a press as shown in Fig. 1. A pair of bearings (symbol 2 and 3) is fixed on the supports of the base and one bearing (symbol 1) is fixed by the battering ram of the press. For the bending to occur, a microtube (symbol 4) is placed on the pair of bearings (symbol 2 and 3), as the press moves vertically on the microtube causing it to deform . The bending radius and bending angle of the microtube can be controlled by adjusting the distance of the two supports (symbol x) and the displacement of the press (symbol h). All bearings need to be machined with a U-groove by using the wire Electrical Discharge Machining (EDM) process for contacting with the microtube. The radius of the U-groove is proportional to the diameter of the microtube. The purpose of using a bearing with a U-groove on the punch and support is to eliminate the friction effect and constrain the microtube in the groove during the press bending process.

The advantage of the proposed system is that it can produce different bending radiuses without changing the bearings, because the bending radius does not depend on the radius of the bearing, but on the position of the three bearings. On the other hand, the disadvantage of this procedure is that the bending radius is determined indirectly using quotes h and x, and it is a little more difficult to adjust.

III. RESULTS AND DISCUSSION

A. T/D ratio and mechanical properties

Table 1 presents the experimental results of average grain size with standard deviation for the specimen with constant wall thickness. From the perspective of constant thickness, the T/D ratio proportionally increases as annealing temperature increases. Table 2 shows the annealing parameter, average grain size, and T/D ratios for the specimens with varying thicknesses. As can be seen, the average grain size of each batch was well controlled within a deviation of 1 µm . It was found that the grains of batch CT1 grew rapidly when the annealing temperature was 1050°C, resulting in an average diameter larger than 10µm . Therefore, the annealing temperature was set to be 1000°C and maintained for 0.8 hours. As a result, the average grain size of each batch was nearly 10µm.

Table 3 presents the effect of the T/D ratio on mechanical properties including yield stress, Young's modulus, strength coefficient, and strain hardening component. Observation of batches AT1 to AT4 shows that the mechanical properties decrease as T/D ratio decreases. In other words, the mechanical properties decrease as the average grain diameter increases. Observation of CT1 to CT2 shows that the mechanical properties decrease with an increasing T/D ratio, except for the strain hardening component. This reveals that the mechanical properties decrease as the wall thickness of the microtube increases when the average grain diameter is 10µm.

B. Press bending system

To examine the springback behavior of the microstructured specimens, this study successfully developed a microtube press bending system. The developed system consists of a load frame incorporated into a micro-stepper driving stage that receives one pulse for 1µm of movement. The load frame is composed of a load-cell, a bearing punch and a pair of bearing supports. The purpose of using a load-cell is to investigate the variation of the reaction force with respect to the bending angle. In addition, a pair of CCD cameras was used to observe the alignment of U-groove channel and microtube, and record the press bending process as shown in Fig. 2. According to the experimental result, the microtube springs out of the original position when the punch touches it at a speed of 12 mm/s. The outer and inner diameters of the bearing were 5 mm and 2.8 mm, respectively. The fabricated channel and the radius of U-groove coincided with the radius of the microtube, as shown in Fig. 3

C. Springback

In this study, springback behavior was investigated and expressing the springback amount by using T/D ratio. As is generally known, springback is due to the uneven distribution of stress states in the loading configuration. The springback behavior of the microtubes in the press bending process occurs because the press force releases and induces the stress balance due to tension on the outside of the bend and compression on the inside of the bend. Accordingly, the wall thickness of the microtube on the inside and outside of the bend thickens and thins out due to compressive and tensile stress, respectively.

Figure 4 represents the springback amount of the experimental results. In Fig.4 (a), the springback amounts decrease with the decreased T/D ratio. In other words, the larger the average grain size, the smaller the springback amount. The springback amounts significantly decreased at batch of AT4. The reason may be interpreted by observing the microstructure of the micro-tubular cross-section of the bend. Fig. 4(b) shows the springback amount of the annealed microtube with a constant average grain size of 10 µm. The springback amounts moderately decrease as the T/D ratio increases. This reveals that the thicker the wall thickness of the microtube, the smaller the springback amount when they have the same average grain size.

D. Microstructure

When a microtube is formed on the press bending system, bending deformation mainly occurrs in the area near the bending plane. According to the deformation features of microtubes, two typical deformation zones can be defined as the axial and lateral planes, as shown in Fig. 5. Figures 6(a) and (b) present the microstructure of the bend in the axial and lateral plane, respectively. Both show the boundaries as dark lines, a so-called "flat etch", and the grain size morphologies. Fig. 6 (a) shows that the inside bend of the lateral plane contains a lot of ultrafine grain formed in the range from about 100-200 nm diameters, indicated by the arrowheads. The region where the ultrafine grain appeared, as shown in Fig. 6(a), was the same region as that of the maximum von Mises strain, as illustrated in Fig. 6(a). This reveals that the compressive stress exceeded the allowable stress of grains, inducing the occurrence of a grain subdivision and therefore releasing compressive stress. No grain subdivision can be found on the outside bend of the lateral plane. Further, ultrafine grains can also be found on the outside bend of the axial plane, as shown in Fig. 6(b). The region in Fig. 6(b) represents tensile stress. This phenomenon, the effect of plastic deformation enhancing the grain subdivision, agrees with Ueji's report [12].

In this study, the occurrence of grain subdivision reduced the springback amount because of continued straining. The formation mechanism of grain subdivision induced by plastic straining is, in fact, not yet well understood. From an experimental point of view, the effect of high strain rates on formation of grain refinement is obvious. The criterion of grain subdivision occurrence in the microtube bending process may be obtained by observing the reaction force with respect to the stroke of the press. Figure 7 represents the press reaction force history of batch AT4 with a bending angle of 90°. It is evident that the deformation is composed of elasticity (region I) and plasticity (region II and III). As for plasticity, the press reaction force significantly increases, indicated by symbol R, when the bending angle exceeds 64°. Symbol R indicates the end of press bending. The reaction force decreased when the press released.

Hence, two specimens of batch AT4 then put through the press bending process with angles of 60° and 70° to investigate the microstructure, respectively. It was found that a few ultrafine grains can be observed in the microstructure of the inside bend of the lateral plane in the specimen with a bending angle of 70°. The phenomenon of grain subdivision cannot be found in the specimen with a bending angle of 60°.

VI CONCLUSION

It is known that springback is a function of the ratio between material flow stress and Young's modulus; such a ratio certainly depends on material behavior. Previous studies have reviewed the above attempt to optimize, compensate for, or at least reduce springback in the tube metal forming of automotive and electric device applications. However, the influence of grain size on the occurrence of springback has not been examined. In this study, a microtube press bending system was fully developed to evaluate the material behavior of an annealed microtube. This study carried out two experiments. Based on the results of this study, the following conclusions for SUS 304 seamless stainless steel microtubes can be drawn:

1. For microtubes with the constant wall thickness and varying average grain size, the springback amount decreases as the T/D ratio decreases. For the microtubes with a constant average grain size of 10 μm, the springback amount decreases as the T/D ratio increases.
2. Grain subdivision occurred and resulted in ultrafine grain in the range of 100-200 nm. The occurrence of grain subdivision reduced the springback amount.
3. Ultrafine grains occurred at the inside bend of the lateral plane (compressive stress) and the outside bend of the axial plane (tensile stress).
4. The criterion of grain subdivision occurrence may be determined by observing the reaction force with respect to the stroke of the press.

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TABLE 1. Average grain sizes with standard deviation and T/D ratios for the first experimental specimens.

Batch no.	Annealing parameter	Average grain size (μm)	T/D
AT1	950ºC, 1h	3.07±0.03	146.6
AT2	1000ºC, 1h	6.17±0.1	72.3
AT3	1050ºC, 1h	9.95±0.08	45.2
AT4	1100ºC, 1h	12.04±0.05	37.4

TABLE 2. Annealing parameters and T/D ratios for the specimens with constant average grain diameter.

Batch #	Thickness (μm)	Annealing parameter	Average grain size	T/D
CT1	150	1000 ºC, 0.8h	9.89±0.02	15.2
CT2	300	1050ºC, 0.75h	10.04±0.05	29.9
CT3	450	1050ºC, 1h	9.95±0.08	45.2
CT4	600	1050 ºC, 1.2h	9.93±0.07	60.4

TABLE 3. Mechanical properties for each batch.

Batch #	Yield stress (MPa)	Young's modulus (MPa)	Strength coefficient (MPa)	Strain hardening component	T/D
AT1	284.27	1070.1	15150.4	0.385	146.6
AT2	270.181	1045.3	14463.6	0.378	72.9
AT3	246.601	938.3	13216.8	0.362	45.2
AT4	217.134	918.7	11912.5	0.334	37.4
CT1	453.6	24375.1	1277.7	0.272	15.2
CT2	301.2	15448.8	1042.4	0.344	29.9
CT3	244.3	13150.4	970.1	0.346	45.2
CT4	229.5	12967.7	947.9	0.349	60.4

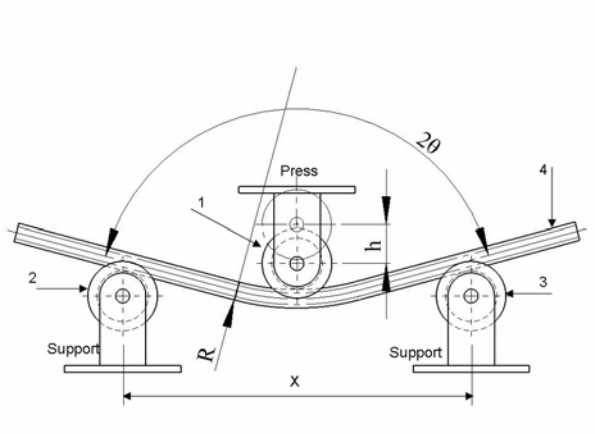


Fig. 1 Illustration of the microtube press bending principle.

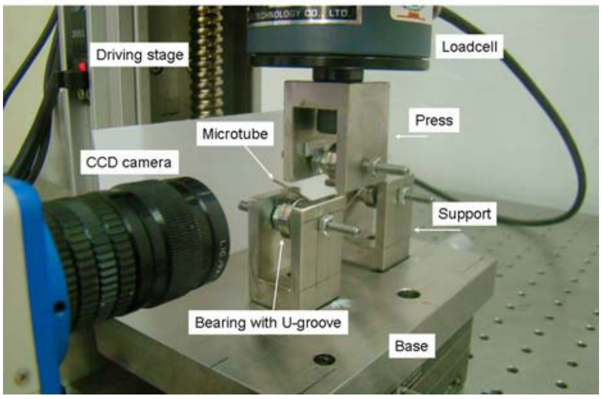


Fig. 2 Illustration of the microtube press bending principle.

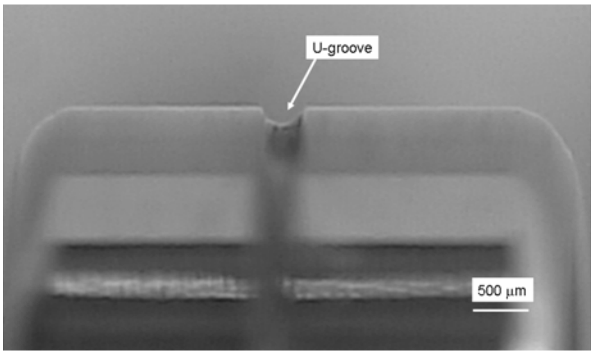
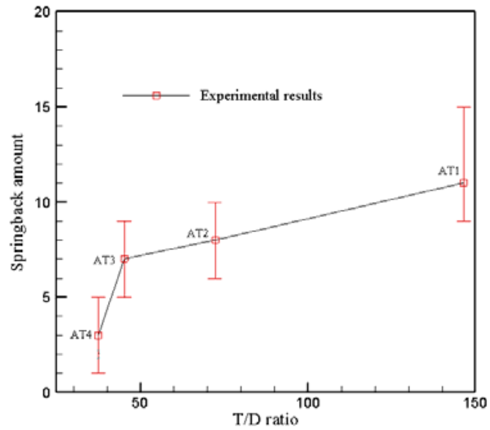
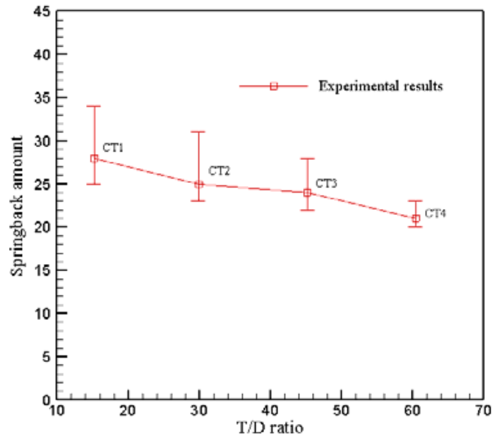


Fig.3 Bearing with U-groove (radius: 300 μm).



(a) Constant wall thickness (450 μm)



(b) Constant average grain size (10μm)

Fig. 4 Springback amount vs. T/D ratio.

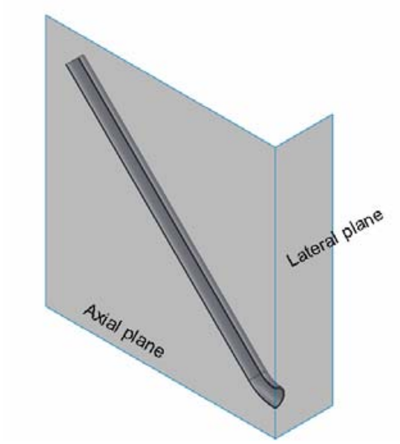


Fig. 5 Illustration of axial and lateral plane.

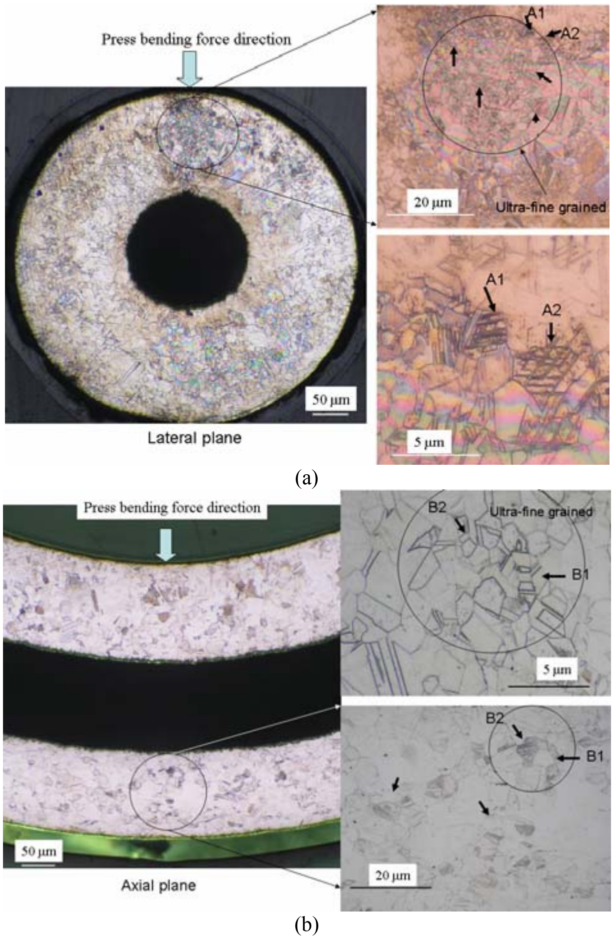


Fig. 6 Microstructure of batch AT4. (a) Microstructure of lateral plane and (b) Microstructure of axial plane.

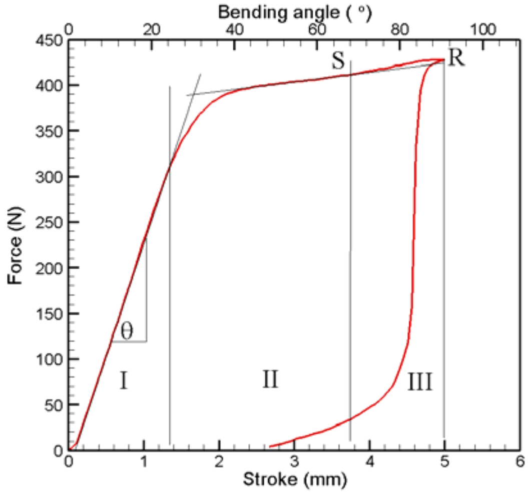


Fig. 7 Reaction force history of press vs. stroke.