Experimental study on the coupling size effects in the ring compression test

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Abstract: During the scaling down of the manufacturing systems, the size effects in the fabrication of metallic components become significant and play a critical role in the performance of desktop factories. In this study, the ring compression tests (RCTs) were adopted to investigate the coupling size effects in micro/meso forming. The RCTs with various specimen dimensions and various lubricants were performed for comparison. The decrease in inner diameter (DID) for each specimen after the RCTs were measured to investigate the size effects. From the experimental results, the scaling down of the specimen led to the increase of the DID with MoS_2 lubricant. Using Teflon lubricant and no lubricant, however, the DID decreased with the reduction of the specimen size. Not only the frictional size effect but also the specimen/grain size effects were involved in the RCTs. The underlying mechanisms of the observed size effects were then discussed. This study provides an approach to investigate the coupling size effects in the micro/meso forming.

NOMENCLATURE

D_{out} = the initial outer diameter of the specimen
D_{in} = the initial inner diameter of the specimen
H = the initial height of the specimen
D_G = the average grain size of the specimen
$\lambda = (D_{out} - D_{in})/2D_G$

1. Introduction

With continuous trend towards miniaturization in fields such as micro electro mechanical systems (MEMS), microfactories, bio-medical, electronics, and renewable energy, there has been remarkable increase in demand of manufacturing the metallic products and features spanning the nano/micro/meso-scales [1]. Among various processes, micro/meso forming [2-4] is a promising approach for mass production of miniature metallic parts. During the scaling down of the manufacturing systems, the size effects in the fabrication of metallic components have drawn significant interests in both the academic research and the industrial applications [5-7]. The material flow, the friction behavior and the formability are remarkably affected by the size effects in the forming processes [5], which clearly play a significant role in the performance of desktop factories.

In the micro/meso forming, not only the flow stress [8-10] but also the tribology [11-13] is subject to the size effect. In several cases, it may be difficult to specially investigate only one type of the size effect and exclude the influence of other effects, since various types of the size effects are usually coupled together. The ring compression test (RCT) and the double cup extrusion test (DCET) are typically adopted to evaluate the friction in metal forming, and are also used to investigate the frictional size effect when the forming process scales down to micro/meso forming [11]. However, the RCT and the DCET themselves are also metal forming, and may subject to other types of size effects. Then, it becomes questionable that the size effects identified in the RCT or the DCET indeed originates from the frictional size effect.

In this study, the RCT was adopted to investigate the coupling size effects in the micro/meso forming. Ring-shape specimens with various dimensions and a consistent shape ratio were prepared. The RCTs were performed without lubricant, with Teflon lubricant and with liquid lubricant. After the RCTs, the decrease in inner diameter (DID) for each specimen was measured to investigate the size effects. By comparing the size effects among various lubricants, the source of the size effect was identified.

2. A state-of-the-art survey

In the micro/meso metal forming, it has been experimentally found that the flow stress is significantly affected by the feature dimension [14,15]. Besides the size effect on flow stress, the tribological condition in the microforming is also subject to the size effect [16]. The lubricant pocket model [11] is a widely-accepted model to account for the frictional size effect. In this model, the lubrication condition in the die−specimen interfaces is classified into the open lubricant pockets (OLPs) and the closed lubricant pockets (CLPs). For the OLPs, the roughness valleys have a connection to the edge of the surface, which cannot keep the lubricant. The lubricant escapes and is not able to support the forming load with high normal pressure, resulting in a higher friction. The CLPs, on the other hand, do not have a connection to the edge of the surface. Clearly, the CLPs rather than the OLPs reduce the friction, and the friction factor significantly depends on the ratio of the OLPs to the CLPs. Since the depth of the OLPs is nearly unchanged during the scaling down of the process, the ratio of the OLPs to the CLPs increases in the scaling down, leading to an increased friction in the micro/meso scale.

Clearly, the lubricant pocket model only applies to the cases using liquid lubricants. For the cases with dry lubricants or no lubricants, the experimental findings of the frictional size effect are controversial [5]. When the specimen size decreases, the friction is found to increase [17], decrease [18], or have no observable size effects [19] in various studies. Vollertsen et al. considered that a general size effect, as described in lubricated friction, does not exist for dry friction [5].

3. Experimental setup and procedures

The experimental setup used to investigate the size effects in the RCTs is shown in Fig. 1. The experimental setup consists of a material testing system (WDW-100E, Time Group Inc.), a punch and a die. The displacement and the load in the tests are measured by the sensors in the material testing system. Aluminum alloy 6061 was used as the material of the specimen in this study. As-received aluminum tubes were cut into required lengths by wire electrical discharge machining. All the specimens were annealed at 413 °C for 2 hours to remove the prior work hardening effects. The photograph of the prepared ring-shape specimens before tests was shown in Fig. 2, and the dimensions of the specimens were summarized in Table 1. The ratio of the outer diameter (D_{out}), the inner diameter (D_{in}) and the height (H) is 6:3:2 for all the specimens, which is a typical ratio in RCTs [20-22].

The RCTs were conducted at room temperature with a strain rate of 0.01 s^{-1}. The specimens were deformed to a half of the original height for all the specimen sizes. The specimen heights were measured by a millimeter caliper. The RCTs with MoS_2 lubricant, Teflon lubricant and no lubricant were investigated and compared. Each test was repeated at least three times for the same condition.

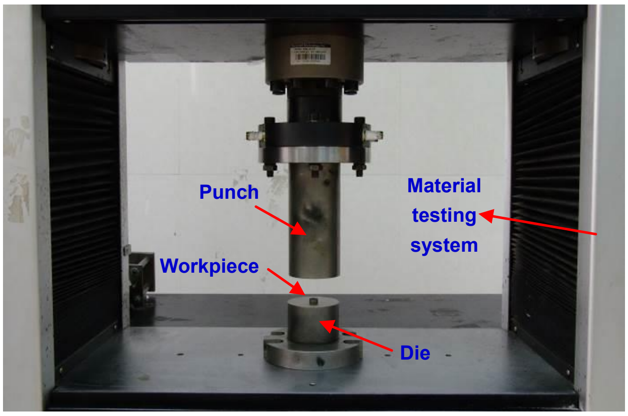


Fig. 1 Experimental setup for the ring compression tests

Fig. 2 Specimens for the ring compression tests

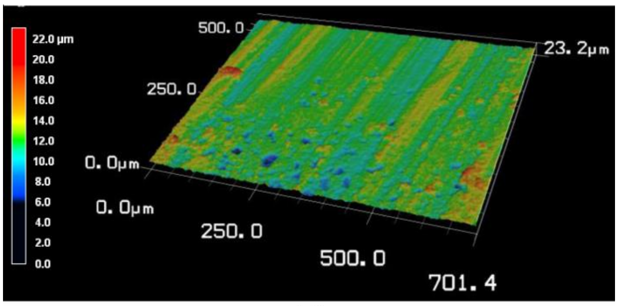
Table 1 Specimen dimensions in the ring compression tests

No.	D_{out} (mm)	D_{in} (mm)	H (mm)
1	12	6	4
2	8	4	2.7
3	6	3	2
4	4	2	1.3

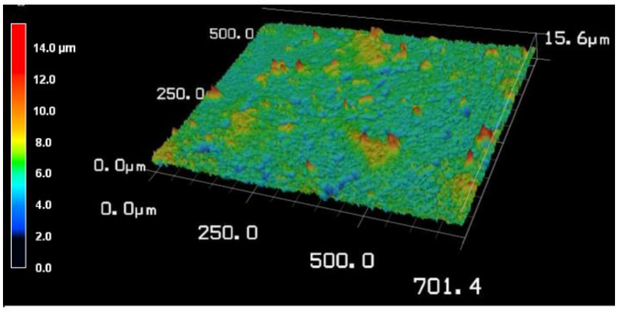
4. Experimental results

After the RCTs, the surface topography of the formed specimens was scanned by a 3D laser scanning microscope (VK-X200, Keyence). Typical surface topography of the formed specimens with and without lubrication is shown in Fig. 3, and the average surface roughness of the formed specimens is around Ra 0.9 μm.

The outer and inner diameters of the formed specimens were measured by a digital microscope (VHX-100, Keyence). Then, the DIDs with various specimen dimensions and various lubrication conditions were calculated and summarized in Fig. 4.



(a)



(b)

Fig. 3 Typical surface topography of the formed specimens: (a) no lubricant, and (b) $MoSi_2$ lubricant

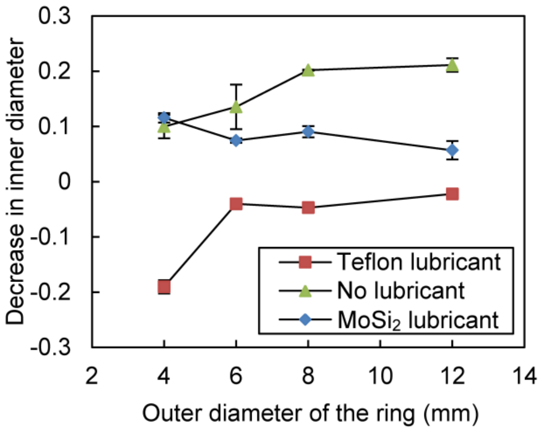


Fig. 4 The decreases in inner diameter with various dimensions and various lubricants in the ring compression tests

As demonstrated in Fig. 4, the DID decreases with the reduction of the specimen size using the Teflon lubricant. Teflon lubrication is using polytetrafluoroethylene (PTFE) films between the die–specimen interfaces. The Teflon film is a commonly used lubricant which significantly reduces the friction influence so that the plastic deformation can be considered to take place without friction [23]. The quite low DIDs for specimens with Teflon lubrication shown in Fig. 4 support the friction reduction effect of the Teflon. Therefore, it is reasonable to consider that the size effect with Teflon lubricant observed in Fig. 4 has nothing to do with the friction. This size effect must originate from the material deformation itself. Since the specimens with various dimensions are made from the same material and the same heat treatment process, the grain sizes with various dimensions should be similar. In the scaling down of the specimen, the ratio of the grain sizes to the specimen dimensions increases, which may lead to size effects. Due to the source of this size effect, it is predicted that the size effect observed in Teflon lubrication is also present in other lubrication conditions.

As shown in Fig. 4, the trend of the size effect without lubricant is similar with the one with Teflon lubricant, though the values of DIDs are all significantly larger. There is still no widely-accepted model available to support a frictional size effect without lubricant. As reviewed by Vollertsen et al [5], a general frictional size effect does not exist for dry friction. Therefore, it is considered that the size effect without lubricant observed in Fig. 4 also originates from the material flow, which is the same as the size effect with Teflon lubricant mentioned above.

The scaling down of the specimen leads to an increase of the DID with MoS_2 lubricant, as illustrated in Fig. 4, which is different from the other two conditions. The observed size effect with MoS_2 lubricant (liquid lubricant) can be explained by the frictional size effect using the lubricant pocket model [11]. The scaling down of the specimen leads to the increase in the ratio of the OLPs to the CLPs, and therefore, results in an increased friction. Due to the characteristics of the RCTs, the increase of the friction will lead to an increase of the DID. Regarding the results introduced above, not only the frictional size effect but also the size effect in material flow is involved in the RCTs. Furthermore, the size effect in material flow partially offsets the frictional size effect, though the frictional size effect is still dominant in the coupling size effects.

5. Discussion

During the frictionless RCTs, whether the material flows outwards or inwards only depends on the material properties. If the same homogeneous material is used, the DIDs should be consistent. The observed size effects in Fig. 4 with Teflon lubricant indicate that the material in the sample with D_{out} = 4 mm cannot be considered to be homogeneous. The underlying mechanisms of this size effects are still unclear. There are various models proposed to account for the size-dependent flow stress, including the composite model [14], the passivation layer model [24], the strain gradient model [25], the surface grain model [15] and the transition area model [26]. In this study, an explanation to the observed size effect is provided regarding the specimen/grain size.

To quantitatively describe the relative size of the grains compared to the specimen dimensions, a size ratio, λ, is defined as below

$$\lambda = (D_{out} - D_{in})/2D_G,$$

where, D_G is the average grain size of the specimen. The grain size is very small compared to the specimen with $\lambda >> 1$, then it is reasonable to consider the ring-shape specimen to be homogeneous in the compression. On the other hand, the grain size is comparable to the specimen dimensions when λ is close to 1. The effect of individual grains may become significant, and the material might no longer be homogeneous.

A simple diagram of the grain and the grain boundary is shown in Fig. 5. Grain boundaries are planar defects between adjacent grains. At low temperatures, grain boundaries act as barriers to dislocation motion, thus strengthening the material. The more grain boundaries that exist, the higher the strength becomes. Reducing the grain sizes leads to the increase in the amount of grain boundary, and improves the material strength, which is known as the Hall–Petch relation [27].

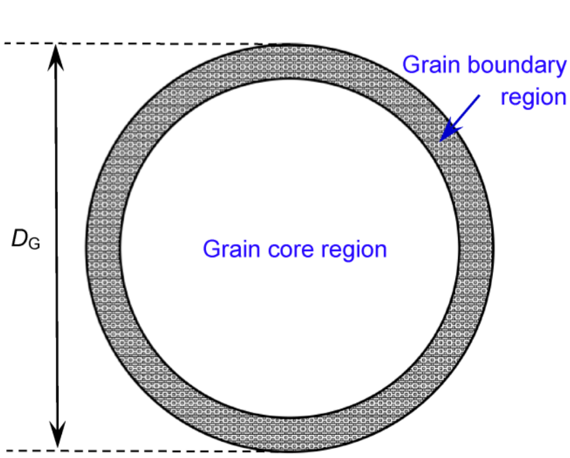


Fig. 5 Diagram of the grain and the grain boundary

Diagrams of the grains after the ring compression tests are shown in Fig. 6. When λ is large (Fig. 6a), there are a large amount of grains in either the inner boundary or outer boundary. Since the average grain sizes are almost uniform in the sample after annealing, the densities of the grain boundaries in the inner or the outer boundary should be similar. When $\lambda = 1$ (Fig. 6b), there is only one grain between the inner and the outer boundary. The grains are elongated along the radial direction in the compression process. Clearly seen from Fig. 6b, the density of the grain boundaries in the inner boundary is larger than the one in the outer boundary. In the view of energy, the relatively large density of the grain boundaries in the inner boundary hinders the material flow inwards. Therefore, the DID decreases when the specimen scales down to the size comparable to the grain sizes.

It is known that a higher DID represents a higher friction factor in typical RCTs. Due to this characteristic, the RCT becomes a convenient approach for friction evaluation in conventional metal forming. However, the experimental results shown in this study have revealed that the RCT might not be suitable to be used in investigating the frictional size effect, since the RCT itself may be subject to the specimen/grain size effect.

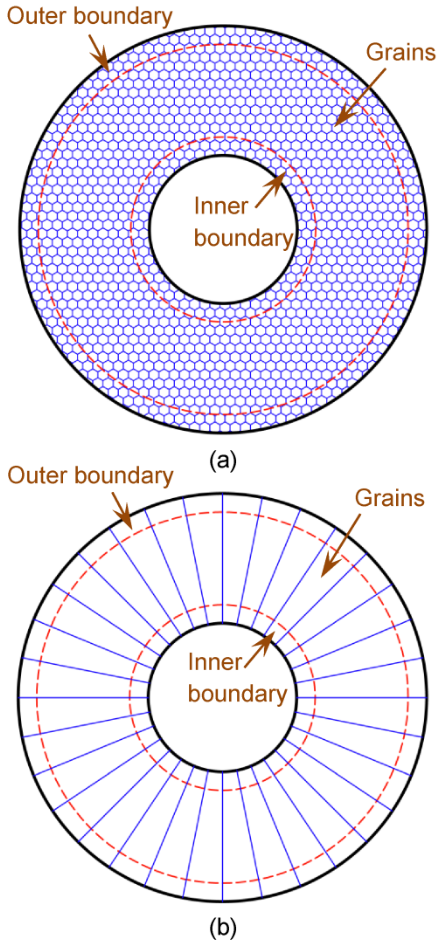


Fig. 6 Diagrams of the grains after the ring compression tests: (a) $\lambda > 10$; and (b) $\lambda = 1$.

5. Conclusions

In this study, ring compression tests (RCTs) with various specimen dimensions were performed to understand the size effects in the RCTs. Teflon lubricant, MoS_2 lubricant and no lubricant were used in the tests. The frictional size effect and the specimen/grain size effect were clearly identified and analyzed in the RCTs. With the reduction of the specimen size in the experiments, the DID decreased with Teflon lubricant and no lubricant, but increased with MoS_2 lubricant. The major source of the size effects in the RCTs can be explained by a combined effect of the frictional size effect and the specimen/grain size effect. The specimen/grain size effect existed in the tests with all the lubrication conditions, while the frictional size effect only appeared with MoS_2 lubricant (liquid lubricant). The specimen/grain size effect may be due to the difference in the density of the grain boundaries between the inner boundary and the outer boundary. This study provides an approach to investigate the coupling size effects in the micro/meso forming.

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REFERENCES

1. Jeswiet J., Geiger M., Engel U., Kleiner M., Schikorra M., Duflou J., Neugebauer R., Bariani P., Bruschi S., “Metal forming progress since 2000,” CIRP J Manuf Sci Tech, Vol. 1, No. 1, pp. 2-17, 2008.
2. Vollertsen F., Niehoff H. S., Hu Z., “State of the art in micro forming,” Int J Mach Tool Manu, Vol. 46, No. 11, pp. 1172-1179, 2006.
3. Engel U., Eckstein R., “Microforming - from basic research to its realization,” J Mater Process Tech, Vol. 125-126, pp. 35-44, 2002.
4. Ehmann K. F., DeVor R. E., Kapoor S. G., “Micro/meso-scale mechanical manufacturing - opportunities and challenges -,”JSME/ASME International Conference on Materials and Processing, Honolulu, HI, USA, 2002,
5. Vollertsen F., Biermann D., Hansen H. N., Jawahir I. S., Kuzman K., “Size effects in manufacturing of metallic components,” CIRP Ann-Manuf Tech, Vol. 58, No. 2, pp. 566-587, 2009.
6. Cao J., Krishnan N., Wang Z., Lu H. S., Liu W. K., Swanson A., “Microforming: Experimental investigation of the extrusion process for micropins and its numerical simulation using RKEM,” J Manuf Sci Eng-T ASME, Vol. 126, No. 4, pp. 642-652, 2004.
7. Kim G. Y., Koc M., Ni J., “Experimental and numerical investigations on microcoining of stainless steel 304,” J Manuf Sci Eng-T ASME, Vol. 130, No. 4, pp. 0410171-0410176, 2008.
8. Kim G.-Y., Ni J., Koc M., “Modeling of the size effects on the behavior of metals in microscale deformation processes,” J Manuf Sci Eng-T ASME, Vol. 129, No. 3, pp. 470-476, 2007.
9. Chan W. L., Fu M. W., Yang B., “Study of size effect in micro-extrusion process of pure copper,” Mater Des, Vol. 32, No. 7, pp. 3772-3782, 2011.
10. Jain A., Duygulu O., Brown D. W., Tome C. N., Agnew S. R., “Grain size effects on the tensile properties and deformation mechanisms of a magnesium alloy, AZ31B, sheet,” Mater Sci Eng A-Struct, Vol. 486, No. 1-2, pp. 545-555, 2008.
11. Engel U., “Tribology in microforming,” Wear, Vol. 260, No. 3, pp. 265-273, 2004.
12. Deng J. H., Fu M. W., Chan W. L., “Size effect on material surface deformation behavior in micro-forming process,” Mater Sci Eng A-Struct, Vol. 528, No. 13-14, pp. 4799-4806, 2011.
13. Jeon J., Bramley A. N., “A friction model for microforming,” Int J Adv Manuf Tech, Vol. 33, No. 1-2, pp. 125-129, 2007.
14. Hoffmann H., Hong S., “Tensile test of very thin sheet metal and determination of flow stress considering the scaling effect,” CIRP Ann-Manuf Tech, Vol. 55, No. 1, pp. 263-266, 2006.
15. Peng L. F., Liu F., Ni J., Lai X. M., “Size effects in thin sheet metal forming and its elastic-plastic constitutive model,” Mater Des, Vol. 28, No. 5, pp. 1731-1736, 2007.
16. Krishnan N., Cao J., Dohda K., “Study of the size effects on friction conditions in microextrusion - Part I: microextrusion experiments and analysis,” J Manuf Sci Eng-T ASME, Vol. 129, No. 4, pp. 669-676, 2007.
17. Geiger M., Messner A., Engel U., “Production of microparts—size effects in bulk metal forming, similarity theory,” Production Engineering, Vol. 4, No. 1, pp. 55-58, 1997.
18. Behrens B., Doege E., Hundertmark A., “Modelling of size-effects in bulk metal forming processes,” Strahltechnik, Vol. 24, pp. 49-56, 2003.
19. Messner A., Engel U., Kals R., Vollertsen F., “Size Effect in the FE-Simulation of Micro-Forming Processes,” J Mater Process Tech, Vol. 45, No. 1-4, pp. 371-376, 1994.
20. Wang J. P., Lin F. L., Huang B. C., Yun C. C., “A new experimental approach to evaluate friction in ring test,” J Mater Process Tech, Vol. 197, No. 1-3, pp. 68-76, 2008.
21. Rudkins N. T., Hartley P., Pillinger I., Petty D., “Friction modelling and experimental observations in hot ring compression tests,” J Mater Process Tech, Vol. 60, No. 1-4, pp. 349-353, 1996.
22. Sofuoglu H., Rasty J., “On the measurement of friction coefficient utilizing the ring compression test,” Tribol Int, Vol. 32, No. 6, pp. 327-335, 1999.
23. Bugini A., Maccarini G., Giardini C., Pacagnella R., Levi R., “The evaluation of flow stress and friction in upsetting of rings and cylinders,” CIRP Ann-Manuf Tech, Vol. 42, No. 1, pp. 335-338, 1993.
24. Xiang Y., Vlassak J. J., “Bauschinger and size effects in thin-film plasticity,” Acta Mater, Vol. 54, No. 20, pp. 5449-5460, 2006.
25. Nix W. D., Gao H. J., “Indentation size effects in crystalline materials: A law for strain gradient plasticity,” J Mech Phys Solids, Vol. 46, No. 3, pp. 411-425, 1998.
26. Justinger H., Hirt G., “Estimation of grain size and grain orientation influence in microforming processes by Taylor factor considerations,” J Mater Process Tech, Vol. 209, No. 4, pp. 2111-2121, 2009.
27. Hansen N., “Hall-Petch relation and boundary strengthening,” Scripta Mater, Vol. 51, No. 8, pp. 801-806, 2004.