Effect of punch surface grooves on micro-extrudability of micro backward extrusion of AA6063

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Abstract

In order to apply conventional forming processes to microscale, the size effects caused by material properties and frictional effects must be taken into account. In this research, the effect of tool surface properties such as punch surface grooves on micro-extrudability, including extrusion force, shape of the extrusion and Vickers hardness, was investigated using a AA6063 billet. Microscale grooves of 5 to 10 µm were fabricated on the punch surface. The extrusion force increased rapidly as the stroke progressed for all the grooves. Comparing the product geometries, the smaller the groove size, the lower the adhesion and the longer the backward extrusion length. The results of material analysis using EBSD showed that a 5 µm groove depth punch improved the material flowability and introduced more strain uniformly. On the other hand, material flowability was reduced and strain was applied non-uniformly when a mirror-finish tool was used. Therefore, the tribology between the tool and the material was controlled by changing the surface properties of the punch to improve the formability.

Keywords: micro extrusion, size effect, micro texture, grain size, aluminium alloy

1. Introduction

In recent years, the improvement of productivity of micro-scale parts using plasticity processing technology has attracted attention in various fields such as medicine, electronics, and chemistry [1]. Among them, micro extrusion processing has attracted a lot of attention from industry as one of the micro-component forming processing technologies. When conventional macro-scale processing technologies such as extrusion are applied to the micro-scale, problems arise in terms of repeatability and accuracy. Engel et al. clarified the effect of decreasing the product size on tribology by double-cup extrusion tests at the micro scale, and found that, as the product size decreased, there were fewer pockets in the tool-billet contact area to hold lubricant. It was reported that as the product size decreases, the pockets that hold lubricant decrease in the tool-billet contact area and the direct contact area increases, resulting in higher friction [2]. We also investigated the processing temperature suitable for micro forming, and showed that stable forming is possible when processing at high temperatures, where dislocation migration becomes active, and that the variation in product accuracy due to size effects is reduced [3].

In a series of studies on micro-extrusion [4-6], Cao et al. investigated the effects of microstructure and interface conditions, such as grain size, shape and orientation of the billet, on processing. The deformation behaviors of different grain sizes in micro-extrusion were evaluated, and it was shown that the larger the grain size, the more easily the extruded part was bent due to non-uniform deformation, and that the difference in grain size affected the formability. In addition, the effectiveness of a hard coating was investigated to stabilize the friction during processing. Ngail et al. [7] designed a tool for ultrasonic micro-extrusion molding and investigated the effect of forming load and surface finish. Fu et al.[8, 9] reported that the analysis of micro forming can accurately predict the deformation behavior of the material by considering several influencing factors such as the flow pattern of the material, the state of the interface, and the flow stress curve.

In micro forming, it is difficult to prepare the surface properties suitable for micro size, and it is essential to find the optimum tool surface condition to reduce friction and improve formability. In the case of microscale forming, the surface becomes relatively rough in relation to the processing scale. It has been shown that the roughness of the surface causes a large variation in friction and forming behavior [11]. In the field of micro-machining, micro-texturing has been applied to reduce the friction on the tool surface and to enlarge the lubrication pocket area, and the results have been satisfactory [12-13]. The micro texture is expected to reduce the tool contact area and stabilize the formability by retaining lubricant.

These researches show that, in micro-extrusion, grain size control and tribology at the tool-material interface have a significant effect on formability, such as forming force and material flow. In this study, backward extrusion of micro parts has been investigated to realize micro forming technology. The textured tool is used to reduce the tool contact area and to stabilize the formability by retaining lubricant. Microscale grooves were added to the punch surface, and the effect of the punch surface properties was investigated. The effect of the grooves on the micro extrudability was observed from the extrusion force, the shape of the extrusion, the amount of adhesion to the punches, and the microstructure analysis of the extrusion.

2. Experimental setup

Fig. 1 shows the micro-extrusion device and the outline of the device. The micro extruder is a servomotor-driven screw press. It controls the forming speed and position of a punch connected to the screw shaft via a load cell. The maximum output of the machine is 30 kN and the maximum stroke is 11.0 mm. The extrusion force and the punch stroke are fed back to the controller from the load cell and displacement meter, and the respective data can be obtained.

Fig. 2 shows the outline of the die and punch. The die is divided at the center to take out the billet after extrusion. The die has a container inner diameter of φ1.71 mm. The arithmetic mean roughness inside the container is Ra = 0.18 μm. The punch was selected for backward extrusion, and the diameter of the forming part is φ1.47 mm.

Fig. 3 shows the punches used in this study. The grooves were measured using a non-contact three-dimensional roughness measurement system. Fig. 3.(a) shows a punch with a ground surface and a mirror finish. Fig. 3.(b) is a punch with a groove of 10 μm made by using 140 grit abrasive paper on Fig. 3(a). Fig. 3.(c) shows the punches with grooves of about 5 μm in depth and pitch of about 100 μm on Fig. 3(a) using 400-grit abrasive paper.

The test billets were cut from A6063 aluminum alloy round wire φ1.70 mm and finished to a length of 4.0 mm. **Table 1** shows the shape dimensions, grain size, mechanical properties, and microstructure of the billets. The average grain size of the billets was 23.3 μm. The relationship between the true stress σ and the true strain ε of the billet can be expressed by the hardening equation (1), which is the power of the plasticity factor *F* [MPa] and the work hardening index *n*.

$$\sigma = F\varepsilon^{n} \quad (1)$$

The plasticity factor of the billet is the *F* value and the work hardening finger is the *n* value.

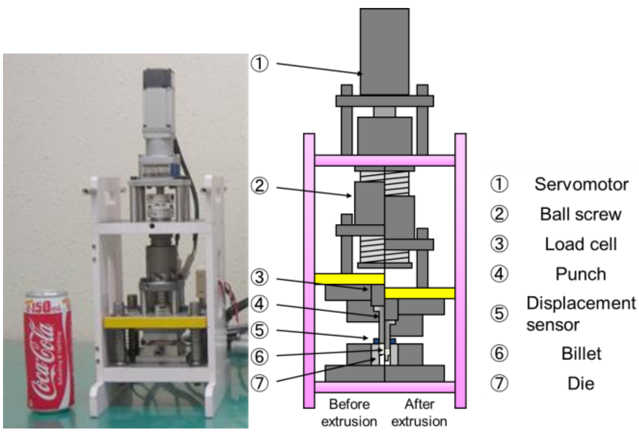


Fig. 1 (a) Photograph of the experimental setup for micro extrusion; (b) Schematic diagram of extrusion apparatus

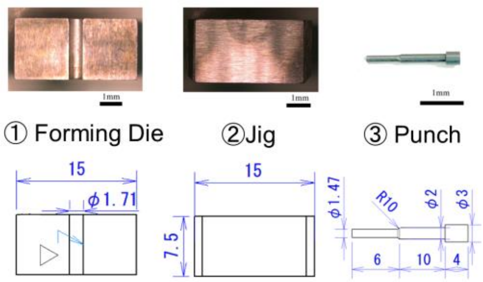


Fig. 2 Dimensions of die and punch

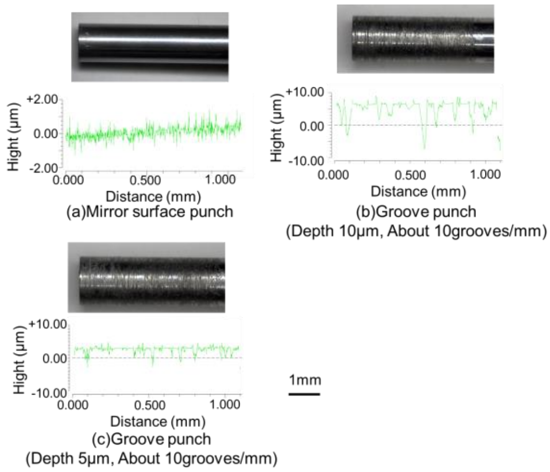
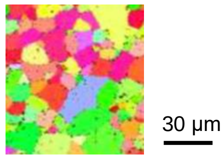
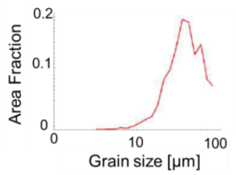


Fig. 3 Grooved punches

Table 1 Dimension and properties of billet

Billet Shape	φ1.70×4mm
Vickers Hardness	33.2 HV
F	169.0
N	0.29
Micro structure	 30 μm
Grain Distribution	
Average Grain size	23.3 μm

The extrusion conditions were set at room temperature with a ram speed of 0.1 mm/s and a ram stroke of 1.5 mm. In this experiment, the extrusion test was repeated four times with each billet to confirm the repeatability. Electron Probe Micro Analyzer (EPMA) was used to evaluate the adhesion to the punches. Electron Back Scattered Diffraction Pattern (EBSD) was used for product microstructure analysis.

3. Experiment results

3.1 Extrusion force-ram stroke diagram and metal flow during micro backward extrusion

Fig. 4 shows the extrusion force-stroke diagram when using a mirror punch, a 10 μm groove punch, and a 5 μm groove punch. The extrusion force was 5.2 kN with the mirror surface punch, 4.1 kN with the 10 μm groove punch, and 3.0 kN with the 5 μm groove punch.

Fig. 5 shows the cross-sectional shape after micro backward extrusion for each punch and the backward extrusion length (lb) for each product at a ram stroke of 1.5 mm. The backward extrusion lengths (lb) were 1.95 mm, 2.19 mm, and 2.63 mm for the mirror, 10 μm groove, and 10 μm groove punches, respectively, indicating that the micro-scale texture on the punches increased the backward extrusion length by reducing the true contact area between the billet and the tool. This indicates that the addition of texture to the tool reduces the contact area and thus the friction. It is thought that this will result in smoother plastic flow and a longer backward extrusion length. The reason for the shorter backward extrusion length of the 10µm groove punch than that of the 5µm groove punch is that there are two flows: one in the backward extrusion direction and one that enters the groove of the tool. By reducing the texture depth, the aluminum adhesion of the punch is broken up and the friction is reduced. As a result, the plastic flow becomes smoother and the backward extrusion length becomes longer. Therefore, it is considered that the friction reduction effect can be obtained by reducing the texture depth in micro-scale forming.

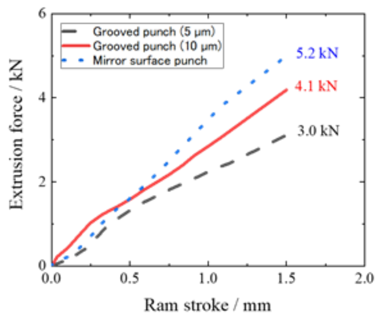


Fig. 4 Extrusion force－Ram stroke curve in each punch

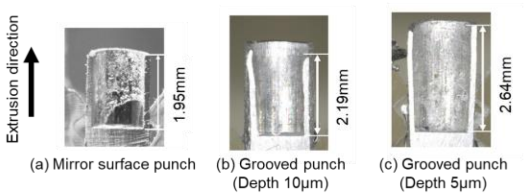


Fig. 5 Cross-sectional images of the extrusion

3.2 Evaluation of adhesion to punch

Fig. 6 shows the amount of adhesion on the surface of the punches after machining with different surface properties of the mirror punch, 10 µm groove punch, and 5 µm groove punch. EPMA was used to analyze the punch surface.

The experimental results show that the aluminum enters the circumferential grooves and the adhesion is divided. In addition, when the amount of adhesion was compared between two punches with different sizes of textured grooves on the tool surface, the amount of condensation was smaller in the 5 µm groove punch than in the 10 µm groove punch. This is thought to be due to the fact that the smaller the groove size, the smaller the pockets into which the material flows, and the finer of the deposition. It is also considered that the frictional force is reduced by breaking up the adhesion, and the force is reduced.

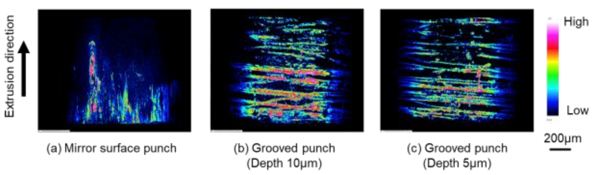


Fig. 6 Evaluation of adhesion to punch by EPMA

3.3 Microstructure analysis of the extrusion

Fig. 7 shows the results of Inverse Pole Figure (IPF Map) when using a mirror punch and a 5 µm groove punch. The IPF Map is defined by the crystal plane and is a measurement method to determine the crystal orientation by color. In the case of the mirror punch, the grain size at the tip of the extrudate is not sheared and flows out as it is. At the end of the extrusion, the material is sheared in the longitudinal direction and the grain size is extended. Near the center of the extrusion, the grain size before processing is slightly collapsed into an oval shape. The color of the crystal orientation is uneven, indicating that the crystal state is changing due to the shear force in the extrusion direction. Near the rear end of the extrudate, the crystal is elongated in the longitudinal direction. Compared to the mirror punch, the 5 µm groove punch has a longer grain size and more noise in the longitudinal direction. It is thought that the stronger strain than the mirror punch may have increased the noise in the measurement.

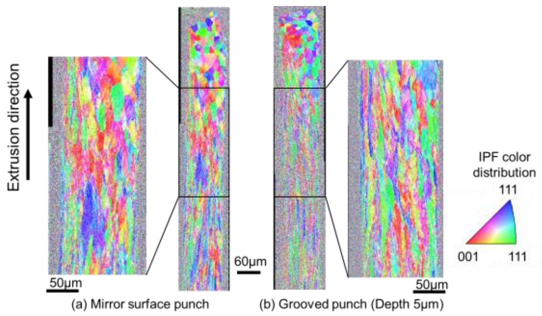
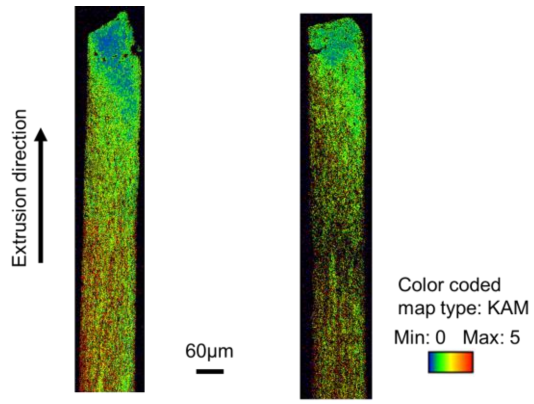


Fig. 7 IPF Map of the extrusion by EBSD

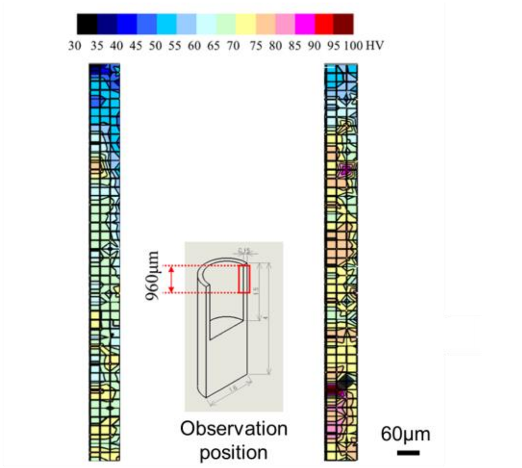
Fig. 8 shows the results of Kernel Average Misorientation (KAM Map), which is a measurement method to quantitatively evaluate the residual strain inside the measured sample based on the orientation difference information. In the mirror punch, the tip of the material is dominated by green and yellow with an orientation difference of 1 to 2°, while the rear end of the material is dominated by red and yellow with an orientation difference of 3 to 5°. In contrast, the 5 µm groove punch shows a uniform strain of more than 3~5° from the middle to the end of the material. This suggests that the 5 µm groove punch reduced the friction and facilitated the material flow, resulting in uniform strain and accelerated machining progress. On the other hand, for the mirror punch, the friction was higher and the material flow was more difficult, resulting in non-uniform strain accumulation.

Although the KAM Map is a useful measurement method for processes that apply local strain such as shearing, it has been pointed out that the internal strain distribution is affected by the grinding state for processes that apply large deformation overall such as forging. Therefore, the hardness was measured using a Vickers hardness tester to support the KAM Map. **Fig. 9** shows the Vickers hardness distribution in the longitudinal section of the product when a mirror punch and a 5 µm groove punch were used. It can be seen that the hardness of the specular punch is about 75 HV at the rear end of the material, while the hardness of the 5 µm groove punch is 70-90 HV. This indicates that the 5 µm groove punches are more work hardened due to strain. This result suggests that the noise observed in the 5 µm groove punches in the IPF and KAM Map is not only noise due to the difference in the surface condition of the polish, but is also likely to be noise caused by a large number of dislocations. In addition, the KAM Map showed that there was a lot of strain on the left side of the material, the surface in contact with the punch. In the present Vickers hardness test, the left side of the surface was work-hardened more than the right side for both punches, suggesting that the same tendency as in the KAM Map was observed.



(a) Mirror surface punch (b) Grooved punch (Depth 5μm)

Fig. 8 KAM Map of the extrusion by EBSD



(a) Mirror surface punch (b) Grooved punch (Depth 5μm)

Fig. 9 Distribution of the Vickers hardness of the extrusion

In conclusion, micro-sized texturing was more effective in terms of formability and friction reduction stabilization in micro forming. By reducing the true contact area between the billet and the tool, the material flowability was improved and the backward extrusion length was increased. This suggests that adding texture to the tool can reduce the contact area and reduce friction.

5. Conclusions

(1) The extrusion force-stroke diagram of the micro backward extrusion process increased gradually with increasing stroke. The extrusion force was reduced by adding micro-scale grooves.

(2) In the shape of the extrusion, the backward extrusion length became shorter under the condition of high extrusion force. In the case of punches with small groove depths, the material flowability was improved and the backward extrusion length became longer.

(3) From the evaluation of adhesion on the punch surface by EPMA, it became possible to break up the adhesion size to a state suitable for the processing scale by adding micro-scale grooves to the punch surface. Therefore, the microgrooves had a good friction reduction effect and good formability in micro forming.

(4) According to the IPF Map and KAM Map by EBSD and the Vickers hardness distribution, the micro-scale grooves on the punch improved the material flowability and the strain distribution inside the extrusion became more uniform.

In future research, we will investigate the effect of surface properties on the nanoscale by applying various scales of texture to the punch surface, including nano-texture, which is smaller than the micro-scale. In addition, we will apply this method to the forming of biomaterials such as magnesium and titanium.

References

[1] J. Jeseiet et al., "Metal forming progress since 2000," CIRP J. Manuf. Sci. Technol., 1-1; 2008; 2-17.

[2] E. Egerer et al., "Microforming – from basic research to its realization," J. Mater. Tech., 125-126; 2002; 35-44.

[3] S. Geißdörfer, et al., "Process characterization and material flow in microforming at elevated temperatures," Int. J. Meter. Form., 1-1; 2008; 455-458. J. Mater. Tech., 125-126; 2002; 35-44.

[4] J. Cao, et al., "Microforming Experimental Investigation of the Extrusion Process for Micropins and its Numerical Simulation Using RKEM," ASME J. Manuf. Sci. ENG., 126-4; 2004; 642-652.

[5] S. A. Parasiz, et al., "Investigation of Deformation Size Effects During Microextrusion," ASME J. Manuf. Sci. ENG., 129-4; 2007; 690-697.

[6] S. A. Parasiz, et al., "Effect of specimen size and grain size on deformation in microextrusion," J. Manuf. Process., 13-2; 2011; 153-159.

[7] N. Krishnan, et al., "Study of the Size Effect on Friction Conditions in Microextrusion Part I Microextrusion Experiments and Analysis," ASME J. Manuf. Sci. ENG., 129; 2007; 669-676.

[8] C. Bunge, et al., "Influence of ultrasonic vibration on micro-extrusion," Ultrasonics, 51-5; 2011; 606-616.

[9] W. L. Chan, et al., "Experimental and simulation study of deformation behavior in micro-compound extrusion process," J.: Mater. Des., 32-2; 2011; 525-534.

[10] W. L. Chan, et al., "Study of size effect in micro-extrusion process of pure copper," Mater. Des., 32-7; 2011; 3772-3782.

[11] M. W. Fu, et al., "A review on the state-of-the-art microforming technologies.", Int. J. Advanced Manuf. Tech., 67-9-12; 2013; 2411-2437.

[12] T. Obikawa, et al., "Micro-texture at the coated tool face for high performance cutting.", Int. J. Machine Tools and Manuf., 51-12; 2011; 966-972.

[13] N. Kawasegi, et al., "Development and machining performance of a textured diamond cutting tool fabricated with a focused ion beam and heat treatment.", Precision Engineering, 47; 2017; 311-320.