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Influence of Grain Size and Lubricant on Forming of Micro-parts by Forward-Backward Extrusion of 6063 Aluminum Alloy

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The recent trend towards miniaturization of products and technology has produced a strong demand for such metallic micro-parts with extremely small geometric features and high tolerances. Conventional forming technologies, such as extrusion and drawing, have encountered new challenges on the micro-scale due to the influence of 'size effects' that tend to be predominant at this level. One of the factors that shows a strong influence is friction. This paper focuses on the frictional behavior observed at various sample sizes during micro-extrusion with various lubricants. A novel experimental setup consisting of forming assembly and a loading stage has been developed to obtain the force-displacement response for the extrusion of pins made of aluminum. The paper also investigates the validity of grain size and lubricant to improve the tribological characteristics observed in micro-extrusion.

Keywords: *micro-extrusion, grain size, lubrication, tribology*

1. Introduction

The rapid advancement of miniaturization technology in recent years has made several novel products and applications that have had a significant impact on a variety of fields such as electronics, biotechnology, and high-precision optics. The field of micro-forming is one such miniaturization technology that has been receiving a lot of attention recently from industrial and academic communities. Micro-forming is the branch of manufacturing technology that deals with the fabrication of metallic micro-parts, i.e, parts that have at least two characteristic dimensions in the sub-millimeter range such as connector pins for electronics, lead frames for IC chips and micro-gears. Apart from feasibility, micro-forming focuses on the suitability of the manufacturing process to be employed in mass-production. So, research on plastic forming is very intense [1,2]. Conventional forming technologies, such as extrusion and drawing, have encountered new challenges at the micro-scale due to the influence of 'size effects' that tend to be predominant at this level. One of the most important aspects of size effects is seen in the behavior of friction at the micro-scale level. Some factors that exert a strong influence on the behavior of friction are the crystal organization of the material, lubricants and die coatings.

This paper focuses on the frictional behavior observed at various crystal sizes during micro-extrusion with various lubricants. A novel experimental setup consisting of forming assembly and a loading stage has been developed to obtain the force-displacement response for the extrusion of pins made of aluminum in the micro/meso scale range (from 0.1 mm to 10 mm). The paper also investigates the validity of grain size and lubricant to improve the tribological characteristics observed in micro-extrusion.

2. Experiment Method

2.1. Material

In this study, aluminum alloy (A6063) is used as the test material. The workpiece billets fabricated to 1.7 mm in diameter and 6 mm in length by hot extrusion and machining were non-annealed and heat-treated at 688K for 3 and 48 hours.

Fig. 1 shows microstructures of workpiece billets that annealed at 688K for 0, 3, and 48 hours.

Fig. 2 shows Vickers hardness (HV) of workpiece billets that annealed at 688K for 0, 3, and 48 hours.In the non-annealed billet, a fine grain structure by extrusion was observed, and the Vickers hardness (HV) value was measured to be about 50. In the billet annealed at 688K, a grain growth takes place by heat treatment, the approximate grain size is observed to be from 60 μm to 100 μm, and the HV value was about 30 regardless of the annealing time.

	Condition ①	Condition ②	Condition ③
	hot extrusion for 723K		hot extrusion for 753K
	Non-annealed	Billet annealed for 688K× 3 hours	Billet annealed for 688K× 48 hours
Grain size [μm]	45.45	63.49	105.45

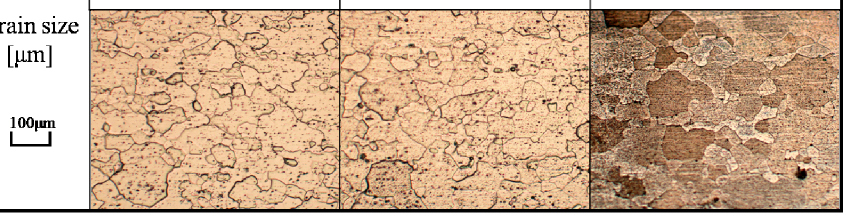

Fig. 1 Microstructures of workpiece billets

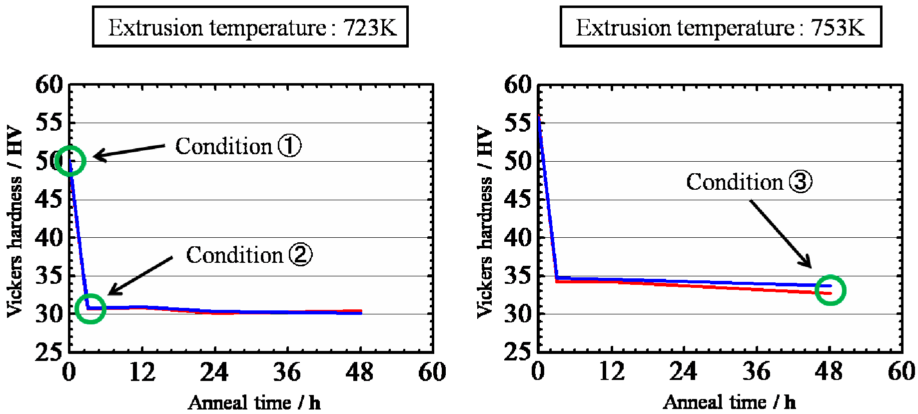

Fig. 2 Vickers hardness of workpiece billets

2.2. Experimental method for micro-extrusion

The die was segmented to facilitate the removal of the pins after extrusion. The segmented die was fabricated with a base diameter of 1.71 mm and the corresponding extruded diameter of 1.09 mm, and the diameter of the punch was 1.47 mm. This forming assembly was then placed inside a loading sub-stage that is equipped with a load cell (capacity 30 kN) and a displacement sensor to measure the extrusion force and the corresponding ram displacement.

Fig. 3 shows the novel experimental press for micro-extrusion consisting of forming assembly and a loading stage. The micro-extrusion experiments are carried out at room temperature, a ram speed of 0.1 mm/sec, a forming stroke of 3.5 mm, and with various lubricants. **Table 1** shows the kinematic viscosity etc. of the lubricants used in this experiment.

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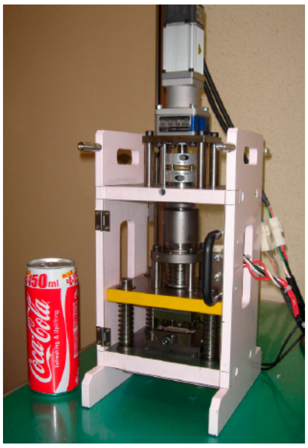
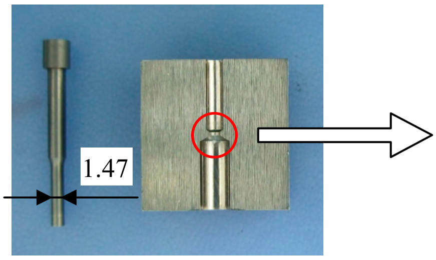
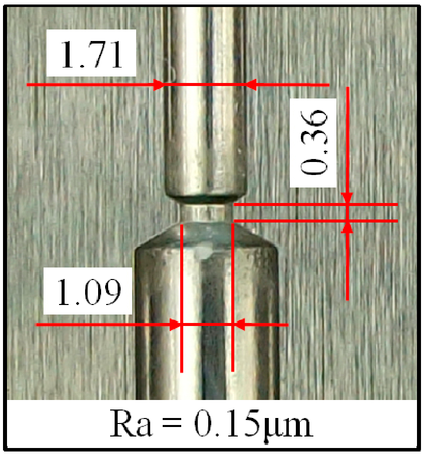
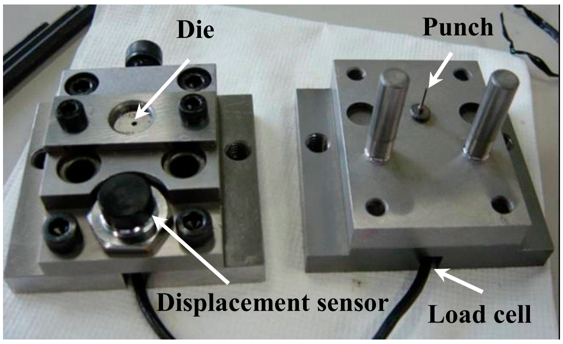


(a) Micro-extrusion press



(b) Segmented die and punch





(c) Forming assembly

***Fig.** 3Experimental apparatus for micro-extrusion*

***Table 1** Lubricants for micro-extrusion*

	Density (288 K) g/cm^3	Kinematic viscosity mm^2/s (313 K)	Flash point K
Lubricant A	0.7890	2.606	352
Lubricant B	0.8390	55.15	
Lubricant C	0.8629	150.2	
Lubricant D	0.7890	428.6	

3. Results and Discussion

Fig. 4 shows samples of the micro-pins obtained during forward-backward micro-extrusion using 6063 aluminum alloy workpiece billets.

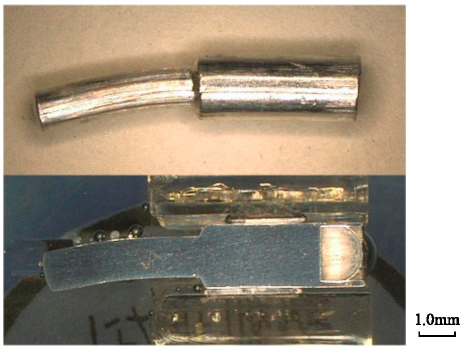


***Fig.**4 Samples of micro-pins obtained during forward-backward micro-extrusion*

3.1. Effects of lubrication and grain size of billets

In this research, to confirm reproducibility, it tests four times on all conditions.

Fig.5-7 shows a force - displacement diagram of condition 1-3. Extrusion conditions are the force-displacement diagrams in the non-lubricant state where the grain size is 45 micrometers, 63 micrometers, and 105 micrometers, respectively. The extrusion force decreases in the one with low hardness of the billet.

Fig.8-10 shows whats examine four times, pick up average data, and compare it. The comparison when non-lubricant, lubricant A, and lubricant D on each condition is shown. It turns out that effectiveness of lubricant A is good in condition.

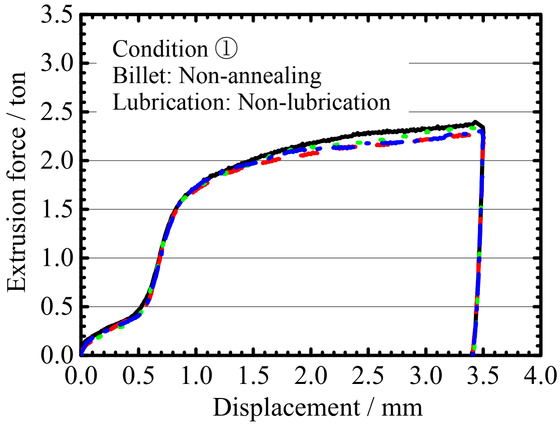


Fig. 5 *Force-displacement responses for non-annealed billets in non-lubrication*

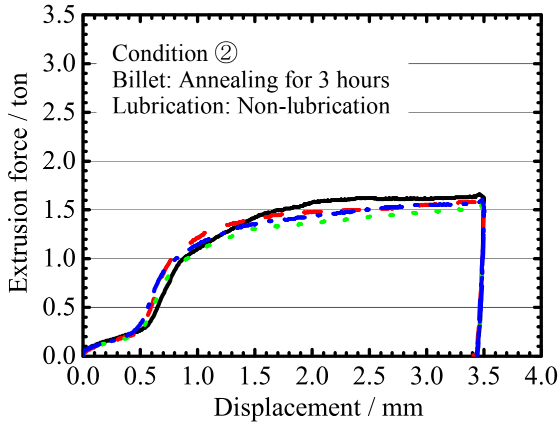


Fig. 6 *Force-displacement responses for billets Annealing for 3 hours in non-lubrication*

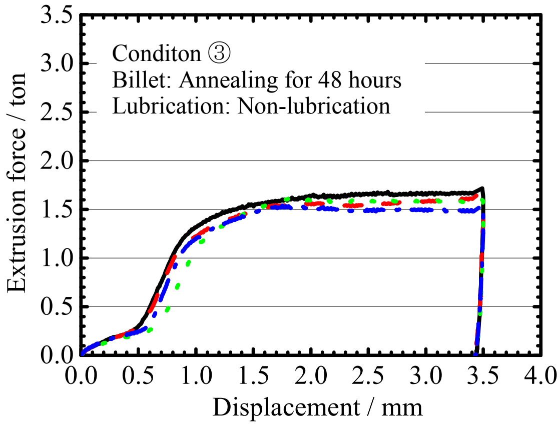


Fig. *7 Force-displacement responses for billets Annealing for 48 hours in non-lubrication*

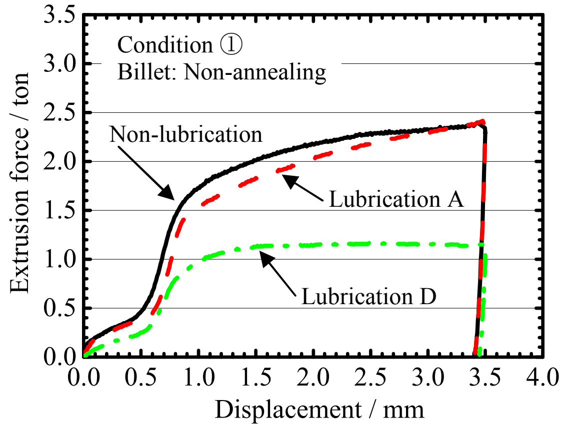


Fig. 8 *Force-displacement responses for different lubrication*

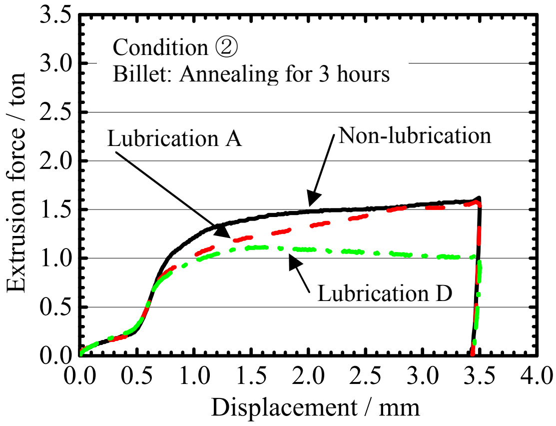


Fig. 9 *Force-displacement responses for different lubrication*

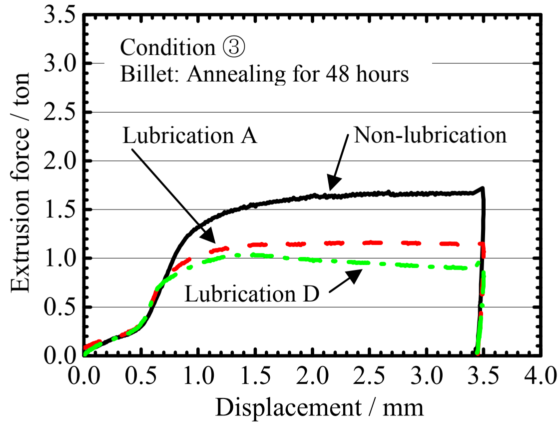


Fig. 10 *Force-displacement responses for different lubrication*

Reproducibility is able to be confirmed from these results. Moreover, the force-displacement diagram of the same tendency was obtained on all the conditions. The increase in the force of the stroke to near 0.5mm is the force by a metal being full in a container. Moreover, the increase in the load of the stroke to near 0.7mm is force in case a metal is full into a bearing. Afterwards, the extrusion advances forward and backward. The force increases gradually though friction decreases by the extrusion forward. It is because friction is caused by the extrusion to the rear side between the container and the billet. If the lubricant is used, the force becomes the maximum when the stroke becomes at about 1.5mm. Afterwards, the force decreases gradually. It is thought that the reason for this factor is that the friction of the container and the billet in the rear side decreased with the lubricant.

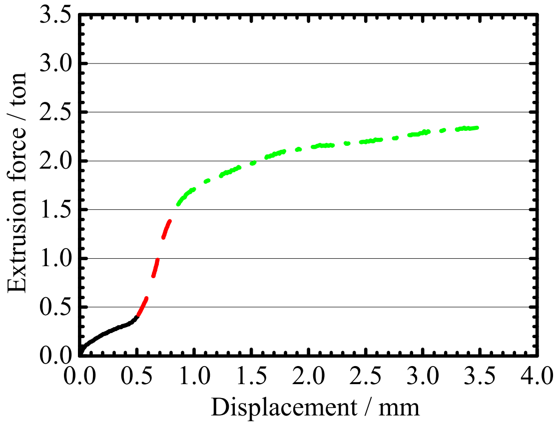


***Fig. 11** Force-displacement responses (Non-lubrication)*

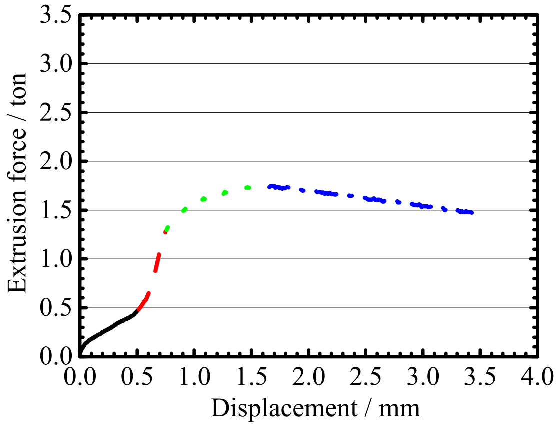


***Fig. 12** Force-displacement responses (Lubrication D)*

Fig.13-14 show what compared the back of the extruded billet in each conditions. **Fig.13** is a comparison of the crystal grain diameters. The lubricant is not used. **Fig.14** is compared using Lubricant D. In **Fig.14**, when the grain size became large, a result to which the extrusion stroke by backward becomes short was brought.

It is thought that it is because it becomes difficult to be extruded backward when the grain size grows because the thickness of a rear extrusion molding part is 120μm.

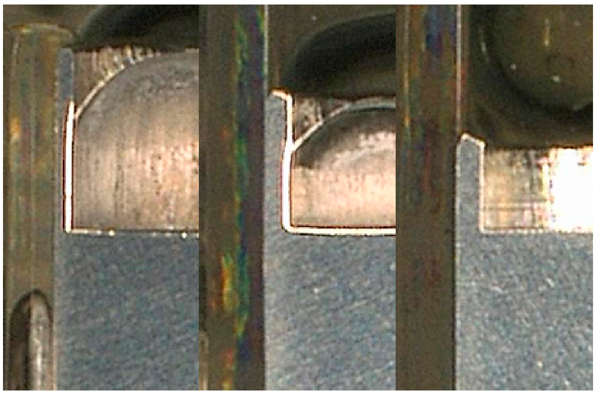


***Fig. 13** Backwad ewtrusion (Non-lubrication)*

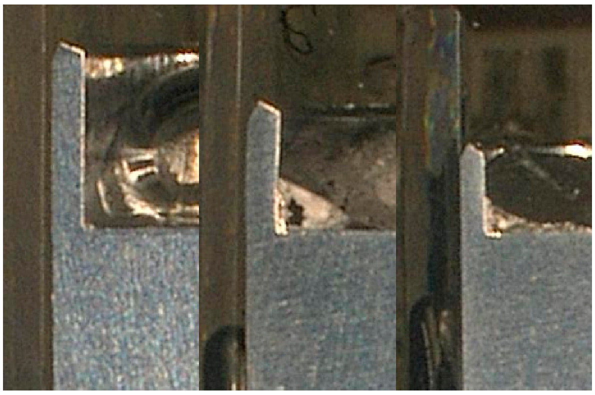


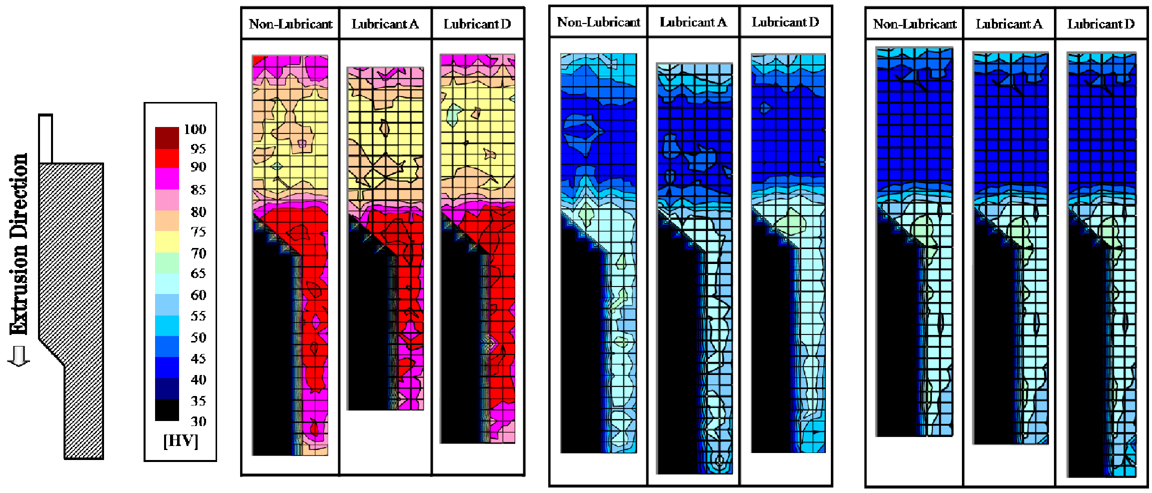
***Fig. 14** Backwad ewtrusion (Llubrication D)*

Fig.15 show the hardness distribution of the extruded billet. **Fig.15 (a)** is compared by the Lubricated condition in the hardness distribution of the extrusion in non-annealing. **Fig.15(b)** is compared by the extrusion for billets annealing for 3 hours. **Fig.15(c)** is compared by the extrusion for billets annealing for 48 hours. **Fig.16** shows the grain size in the part where hardness has changed greatly in **Fig.15**.

Hardness had changed, and the grain size in the rear side of the container, the center of the container, the bearing, and the extrusion forward part was observed. The grain size in the rear side of the container, the bearing, and the extrusion forward part where hardness had increased was able to be observed to be transformed into side and length.

It is thought that the strain enters by this transformation and the work hardening was done.

Because the change in hardness was not seen, changing the grain size was not seen at the center of the container.



(a) Condition ① (b) Condition ② (c) Condition ③

Fig.15 *Comparison of distributions of Vickers hardness (Hv) after forward-backward micro-extrusion*

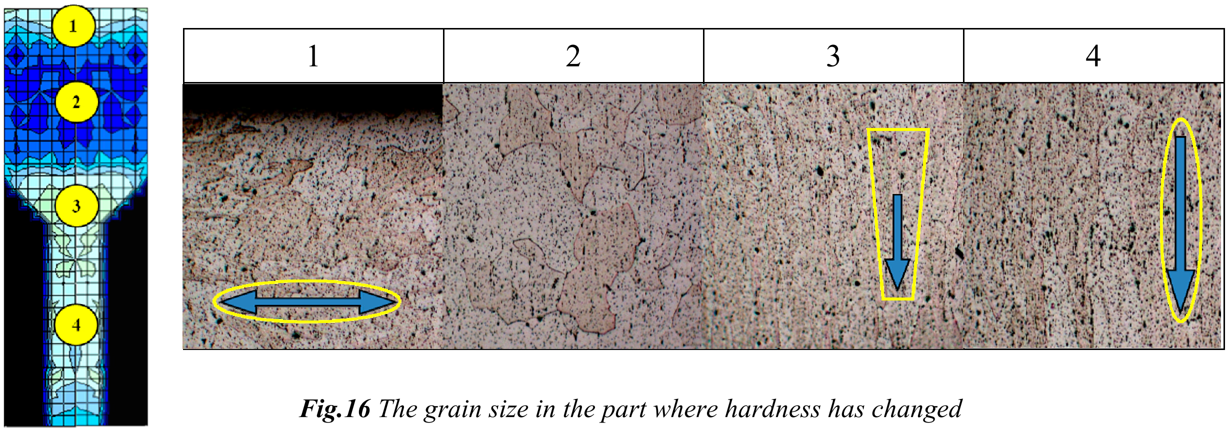


Fig.16 *The grain size in the part where hardness has changed*

4. Conclusions

In this paper, a novel micro-extrusion apparatus is used to perform experiments on aluminum alloy samples (A6063) having an initial billet diameter of 1.71 mm, a final forward-extruded diameter of 1.09 mm, and a backward-extruded inside diameter of 1.47 mm. This micro-extrusion apparatus enabled the authors to record the force-displacement response of the extrusion process.

As a result, the following conclusions were obtained.

(1) In micro extrusion, the big grain size is effective with the low lubricant of the motion viscosity.
(2) The extrusion length to backward changed with the gain size.
(3) The influence on hardness of the extrusion material by the change in the lubricated condition in the die was not seen.
(4) Vickers hardness test reached the value that looked like in each lubricated condition.

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