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Micro-forming of Al-Si foil

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Materials

ABSTRACT

Purpose: of this paper is as below. The investigation of the ability of the cold micro-forming of non-metallic glass was purpose. The grain of the rapidly solidified aluminium alloy became fine. The aluminium alloy foil with fine grain was used, and the investigation of the micro-formability of this alloy was investigated. Moreover, increase of the forming speed was investigated. The increase of the forming speed was purpose of this study, too.

Design/methodology/approach: The nozzle pressing melt spinning method was used to attain the rapid solidification of the non-metallic grass. The Al-14mass%Si, which is hyper eutectic but is close to eutectic, was used. The roll contact surface was formed by V-groove. The cold rolling was adopted for forming. The V-groove was machined at the roll surface. The micro-forming was operated at the cold work.

Findings: Micro-forming of the crystal aluminium alloy was able by the cold work. The forming speed was 0.04S to form 10 μm height. The forming speed could be drastically increased.

Research limitations/implications: The angle of the V-groove, which was used in the present study, was only 60 degrees. The effect of the groove angle on the protrusion-height was not clear. The used material was only the Al-14mass%Si. Relationship between the material and protrusion-height was not clear.

Practical implications: The die for the micro-forming of the resin could be made from economy material by the conventional cold rolling process at short time. Therefore, the mass production of the economy die for resin may be obtained.

Originality/value: The micro-forming of the rapidly solidified non-metallic glass by cold work was original.

Keywords: Metallic alloys; Plastic forming; Micro forming; Melt spinning; Rapid solidification

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1. Introduction

They say that micro-forming of the crystal alloy is difficult, because the grain boundary makes the formed-surface worse. In the micro-forming, the grain size becomes larger than the size of the die. The metal could not be formed into the die-shape. Therefore, the metallic grass has been used for the micro-forming. The metallic glass could be formed into the die shape, and the surface of the formed part became smooth [1-4]. In the micro-forming of the metallic glass, the forming was operated at the temperature higher than glass temperature T_g. The micro-forming using the conventional alloy has not been investigated. However, the crystal alloys have the advantages, i.e. at the point of the cost and the mechanical properties. The micro-forming using the metal, which grain is small, may be used for the micro-forming as same as the metallic glass. However, the report about the micro-forming using the metal with small size grain is few. The melt spinning is useful as the method to get small grain metal. In the present study, the melt spinning was adopted to get fine grain. The thickness of the foil cast by the melt spinning is usually thinner than 50 μm. This thickness is too thin to form the metal.

The melt spinning was improved to cast the 200 µm-thick foil. The Al-14%Si alloy was used. Al-Si alloy is conventional and typical alloy for casting. Si content was decided at the point of the eutectic structure. It was thought that the eutectic structure was suitable for the micro-forming from the point of the fine grain.

The forming speed of the micro-forming is usually very slow. The increase of the forming speed was tried. The cold rolling was adopted for the forming process. The reason of the adaptation of the cold rolling was as below. The contact between the metal and roll is not face but the line. Therefore, load becomes small. As the result, the micro-forming of the wide area was could be operated. The rolling may be suitable for the forming of the foil than stamping. The rolling speed was from 0.5 mm/min to2 m/min. This speed was higher than the conventional micro-forming. In the conventional micro-forming, the UV process is usually used to make Si or Ni die. In the present study, the Ni-die was made by the machining.

The micro-forming of the rapidly solidified metallic Al-14mass%Si was tried using the mill equipped with the V-grooved roll at room temperature. The ability of micro-forming was reported in this paper.

2. Nozzle pressing melt spinning

2.1. Specification and experimental conditions

Figure 1 shows a schematic illustration and photograph of the melt spinning process of the present study. This process is nozzle pressing melt spinning method [5]. The specification and the experimental conditions of this melt spinning process are shown at Table 1.

Table 1.
Specification of melt spinning and experimental conditions

roll	material: copper diameter: 300mm width: 100mm speed: 10m/min polishing: #1200 emery paper
Nozzle-roll gap	initial: 0.1mm
Specimen	Al-14mass%Si 200g temperature: 630^{O}C ejection pressure : 10kPa
slit nozzle	width: 20mm gap: 1.0mm inclination angle: 30degrees coating: BN
nozzle pressing	50N

The property of the melt spinning of this study is the thickness of the foil. The foil cast by the conventional melt spinning or PFC (planer flow casting) is thinner 0.05 mm. The melt spinning of the present study could cast the foil of 0.2 mm thickness. Some devices were adopted to cast thick foil. The gap of slit-nozzle of this study was 1mm (ref. Fig. 1). The gap is usually 0.5 mm. The gap was wider than the conventional melt spinning to cast thick foil. The nozzle was inclined at 30degrees against the roll surface to prevent the back break of the melt. The nozzle is usually perpendicular to the roll surface. The back break of the melt occurred easier as the nozzle-roll gap became wider. The tip of the nozzle pressed the foil. The roll contact surface became flat by the pressing. When the press load was too large, the foil stuck at the nozzle-tip. The initial nozzle-roll clearance was 0.1mm, and the clearance became 0.2 mm while the casting as the foil lifted up the nozzle. The nozzle pressing made the better-heat-transfer condition between the strip and the roll. When the nozzle pressing was not operated, the foil was not cooled enough.

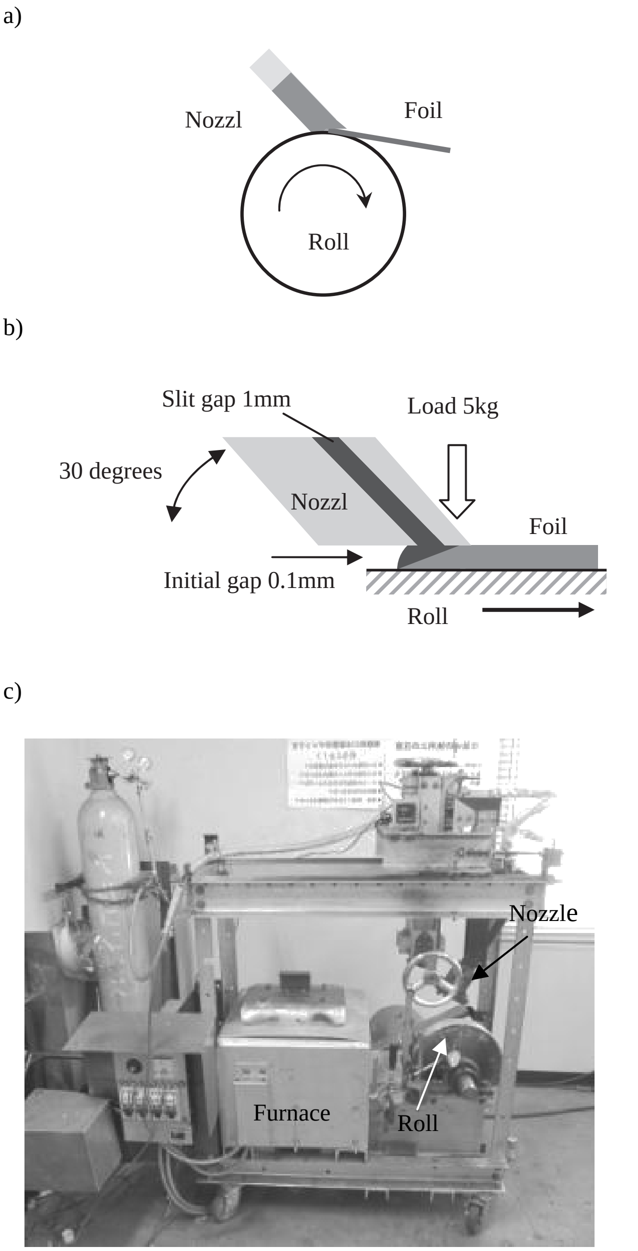


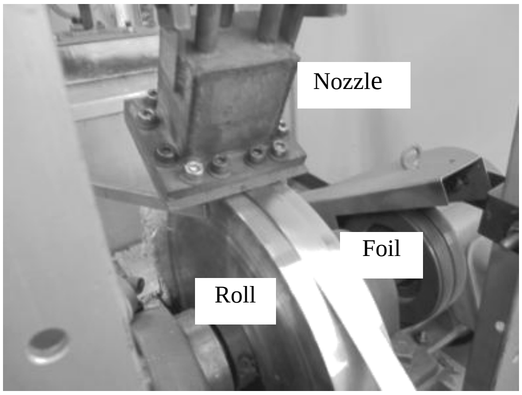
Fig. 1. Nozzle pressing melt spinning method: a) Schematic illustration of the nozzle pressing melt spinning, b) Schematic illustration of enlarged view around the nozzle tip, c) Photograph of the nozzle pressing melt spinning apparatus

Al-Si alloy is conventional alloy for casting. Therefore, Al-Si alloy has good casting ability at the melt spinning. Moreover, Al-Si alloy is economy. Al-12%Si is eutectic. The eutectic point shifts to the hyper side as the cooling rate increases. The Si content at eutectic was about 15mass% at the roll contact surface of the foil when the foil was cast by the nozzle pressing melt spinning method. The grain at eutectic became fine. However, the free solidified surface was not sound when the Si content was higher than 15mass%. In this reason, Al-14%Si, which was close to eutectic, it was chosen in the present study. It is though that the Al-14mass%Si is enough hard to use the mould die of the resin and his alloy has good wear-resistance.

2.2. Melt spun foil

The casting of the foil by the nozzle-pressing method is shown in Fig. 2.

a)

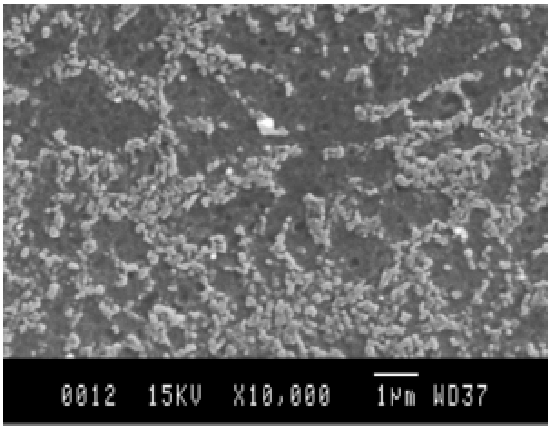


b)

Fig. 2. Melt spinning and Al-14mass% foil. (a) Melt spinning in operation, (b) Melt spun Al-14mass%foil

The microstructure of as-cast foil is shown in Fig. 3. The position of the microstructure shown in Fig. 3 (a) is 10μm from the free solidified surface. The primary Al was existed and the primary Si was not existed in spite of the Al-14mass%Si was hyper eutectic. This reason is thought that the eutectic point shifted to hyper side by the effect of the rapid solidification. The position of the microstructure shown in the Fig. 3 (b) was 10μm from the roll contact surface. The white particle was eutectic Si. The size of the eutectic Si was smaller than 0.4μm.

a)



b)

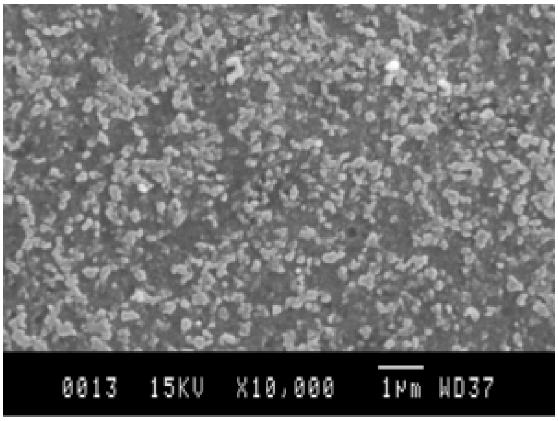


Fig. 3. SEM image of the as-cast Al-14mass% foil. a) 10μm from the free solidified surface, b) 10μm from the roll contact surface

2.3. Smoothing of the melt spun foil

Figure 4 shows process of the foil-casting, the flattening of the surface of the foil and micro-forming by the cold rolling. The surface of the roll contact surfaces of the Al-14mass%Si foil at the conditions of as-cast, cold rolling by Cr-plate roll and after buff-polishing are shown in Fig. 5. The roll contact surface of the as-cast foil was not flat. The unevenness of the surface is thought to be caused by the unevenness of the wetting condition between the molten metal and the roll. The surface of the as-cast strip was too rough to operate the micro-forming. The cold rolling using Cr-plate roll was operated to make the surface flat. The as-cast foil was annealed for 4 hours at 250^{O}C before cold rolling. The unevenness was improved by cold rolling as shown in Fig. 5 (b).

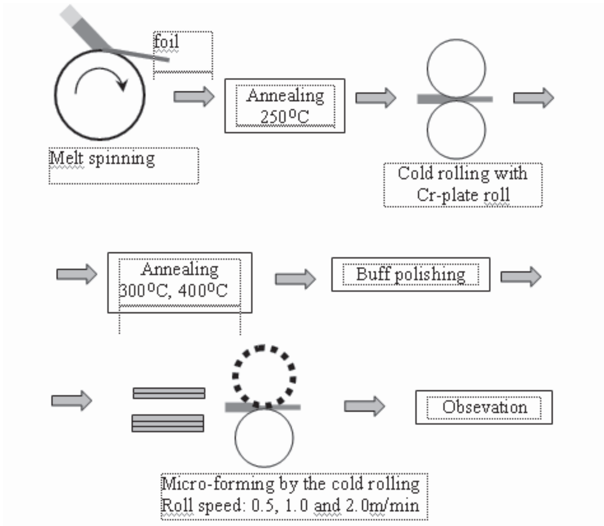


Fig. 4. Schematic illustration showing the process of the foil-casting, the flattening of the foil-surface and micro-forming by the cold rolling

a)

b)

c)

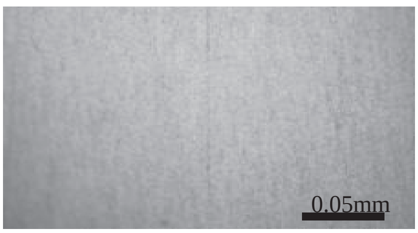
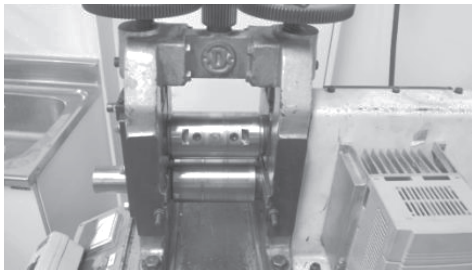


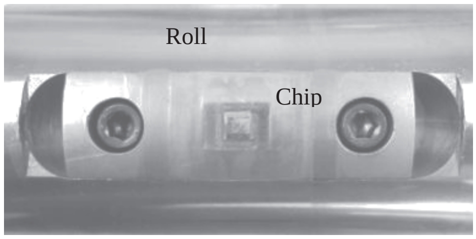
Fig. 5. Surface and roughness of the foil at as-cast, after cold rolling and after buff polishing: a) as-cast condition, roughness Ra: 0.8μm, b) after cold rolling by Cr-plated roll, roughness Ra : 0.5μm, c) after buffing, roughness Ra: 0.3 μm

However, the evenness was not sufficient for micro-forming yet. Therefore, buffing was operated on the surface of the as-rolled foil to improve the evenness. The annealing was operated at 300^{O}C and 400^{O}C before the micro-forming. The micro-forming was operated on the surface after the buffing at the roll speeds of 0.5, 1.0 and 2.0 m/min.

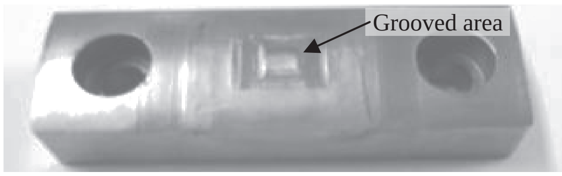
a)



b)



c)



d)

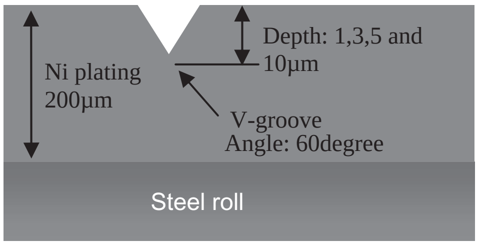


Fig. 6. V-grooved chip attached to the roll: a) small mill equipped with 70mm diameter rolls, b) chip attached to the roll, c) area where V-grooves were machined, d) schematic illustration showing the V-grooves

3. Roll used for micro-forming

The stamping is usually used for the micro-forming. However, the cold rolling was chosen as process for the micro-forming in the present study. The contact condition is face-contact in the stamping. In the rolling, the contact condition is line-contact. The load of against the die of-line-contact is smaller than that of face-contact. This is the advantage. In the micro-forming, the forming speed is very slow, i.e. 500s/10μm. The forming speed of the rolling could be set much higher (i.e. 0.08s/10 μm) than that of stamping (press forming). The roll speed was set up to 2 m/min. The rolling was operated at the condition of the cold working.

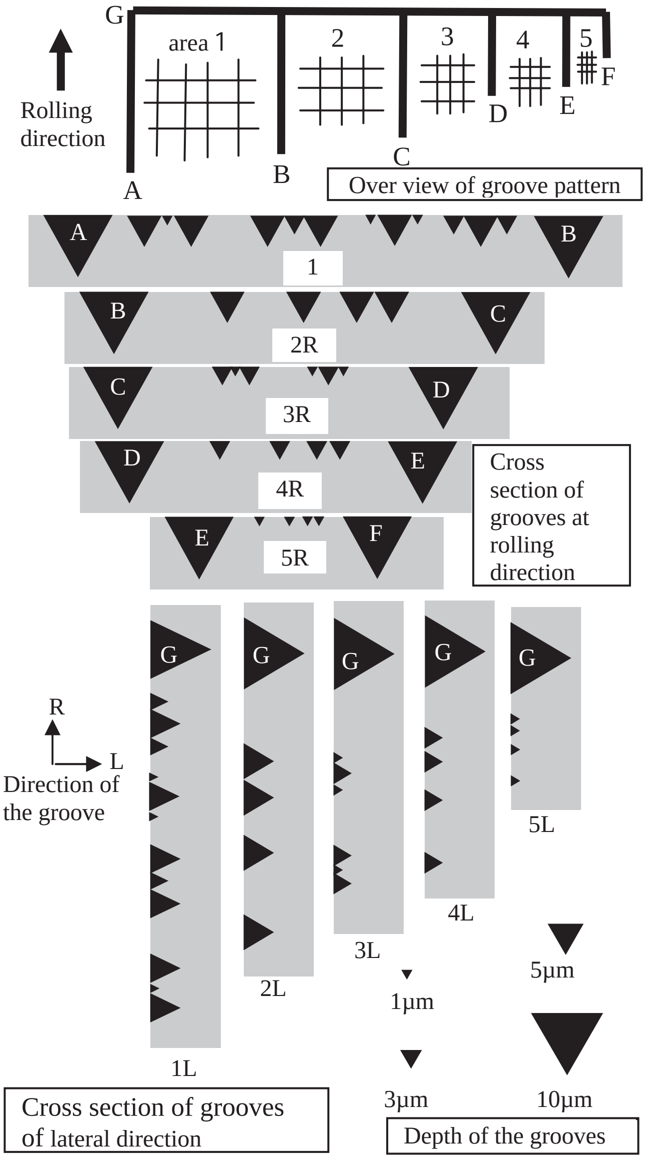


Fig. 7. Schematic illustration showing the pattern of the grooves of the die machined on the chip attached to the roll. R and L show the direction of the groove. Numbers from 1 to 5 show the areas. A, B, C, D, E, F and G show the 10μm-depth groove

The 200 μm-thick Ni plating was operated on the tip. The V-grooves for the die were machined on the surface of Ni plating. The tip was attached to the roll. The shape of the cross of the groove was shown in Fig. 6. The angle of the V-groove was 60 degrees. The depth of the V-groove was 1, 3, 5, and 10 μm. The diameter of the roll of the mill was 70mm.

The pattern of the groove was shown in Fig. 7. There were five areas of from 1 to 5. The depths of the grooves were different at each area. The directions of the grooves were rolling direction and lateral direction.

The LSCM (laser scanning confocal microscopy) image of the V-grooves on the chip is shown in Fig. 8. The grooves were machined by FANUC ROBONANO α-O*i*B. A, B, C, D, E, F and G show the 10 μm-depth groove.

The thickness of the strip after buff-polishing was about 0.1 mm. The setting of the roll-bite-clearance is thinner than 0.1 mm was difficult. Therefore, two or three foils were superimposed when the micro-forming was operated by the cold rolling to prevent the broken of the grooves.

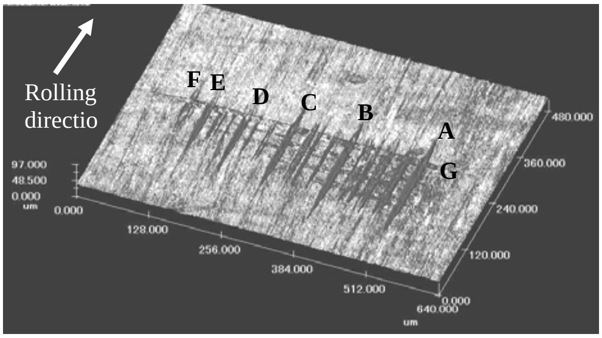
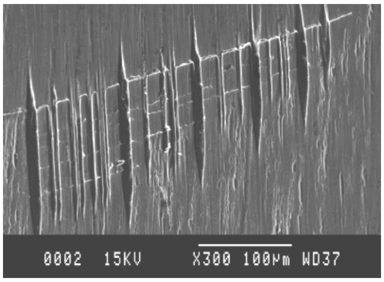


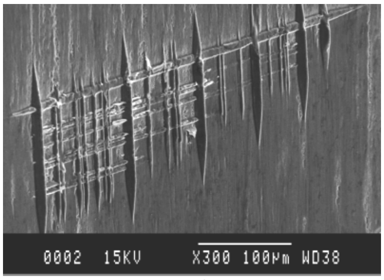
Fig. 8 LSCM (laser scanning confocal microscopy) image of the V-grooves on the chip. A, B, C, D, E, F and G show the 10 μm-depth groove

4. Result and discussion

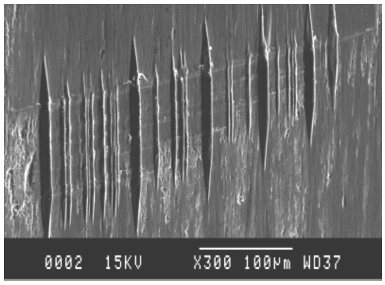
The cold rolling was operated, and the result of micro-forming was shown by the SEM image in Fig. 9. Effects of the annealing temperature, rolling speed and number of superimposed foils on the micro-forming are shown. Fig. 9 is the over view of the micro-formed area. It is clear that micro-forming of the Al-14%Si aluminium alloy by the cold rolling was not unable. The protrusion was formed at the rolling direction. However, the height of the protrusion was low at lateral direction. The forming ability was affected by the direction. The protrusion at the rolling direction was not drastically affected by the conditions of rolling speed, annealing temperature and the number of the superimposed foils at the forming by the grooves deeper than 3μm. The forming of protrusion by 1 μm-depth groove was affected the number of the super imposed foils. When the two pieces of foils were superimposed, the protrusion could be formed by the 1μm-depth groove as shown in Fig. 13 (m) and (o). When the 2 grooves of 1μm-depth were side by side without clearance, the protrusions were formed at side by side.



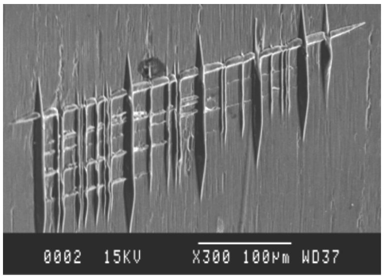
(a) V: 0.5m/min, T: 300°C, 3 pieces



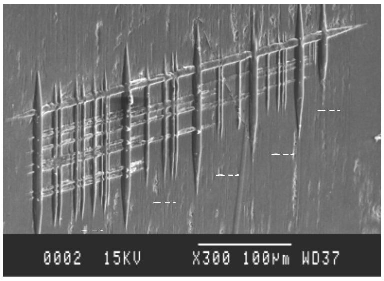
(b) V: 1.0m/min, T: 300^{O}C, 3 pieces



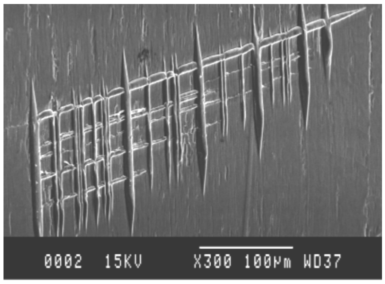
(c) V: 2.0m/min, T: 300^{O}C, 3 pieces



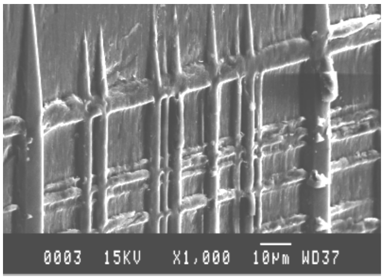
(d) V: 1.0m/min, T: 400°C, 3



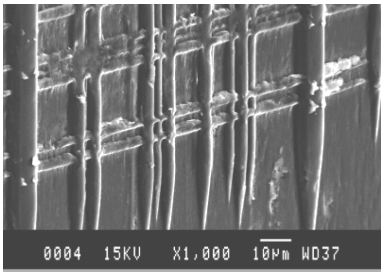
(e) V: 1.0m/min, T: 300^{O}C, 2 pieces



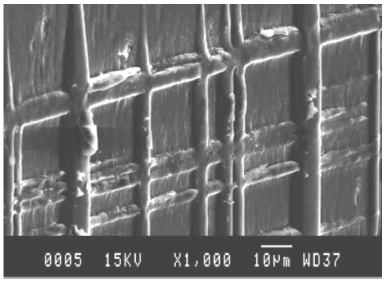
(f) V: 1.0m/min, T: 400^{O}C, 2 pieces



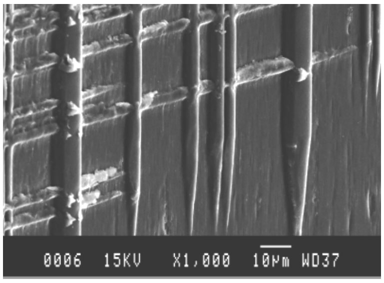
(g) enlarged view of upper part of area 1 of (e)



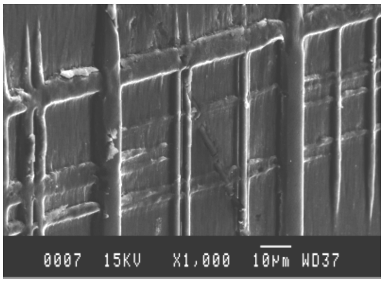
(h) enlarged view of lower part of area 1 of (e)



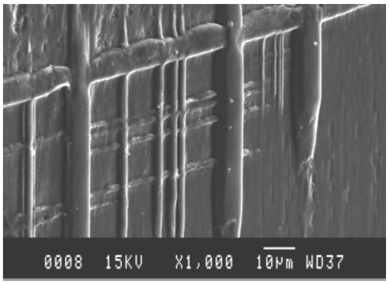
(i) enlarged view of upper part of area 2 of (e)



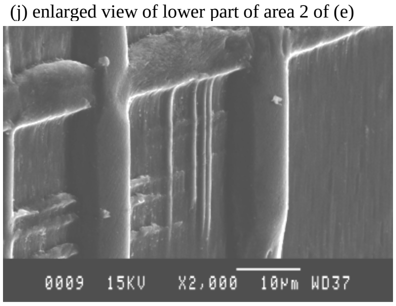
(j) enlarged view of lower part of area 2 of (e)



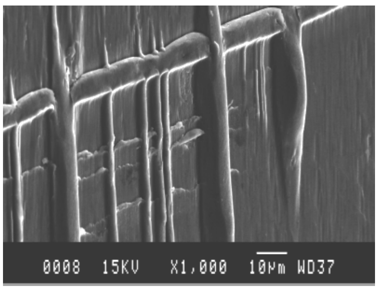
(k) enlarged view of area 3 of (e)



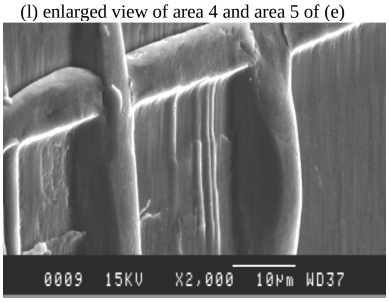
(l) enlarged view of area 4 and area 5 of (e)



(m) enlarged view of area 5 of (e)



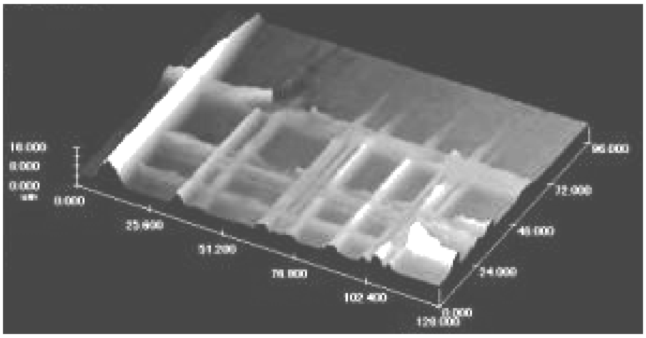
(n) enlarged view of area 4 and area 5 of (f)



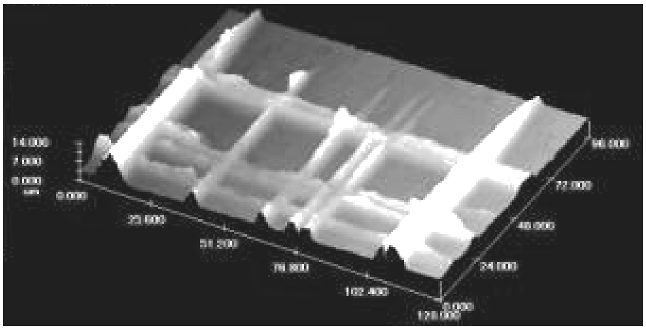
(o) enlarged view of area 5 of (f)

Fig . 9. SEM images of micro-formed surface of the foil. “V” shows rolling speed, “pieces” shows number of superimposed foils at rolling, “T” shows annealed temperature before buffing (i.e. Fig . 4), “area” is shown in Fig . 4 and Fig. 9 (e)

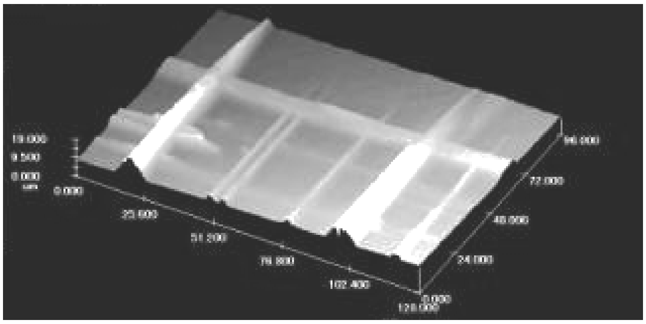
a) area 1



b) area 2



c) area 3



d) area 4 and area 5

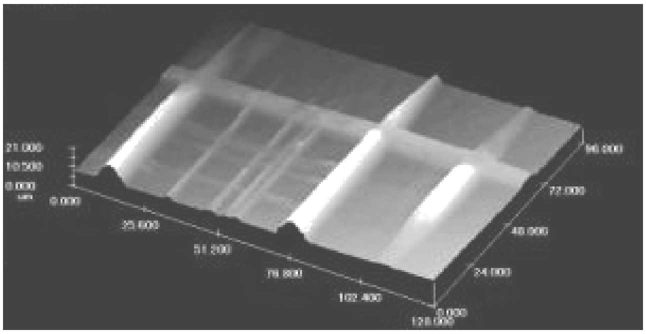


Fig. 10. LSCM (laser scanning confocal microscopy) image of the micro-formed surface. " area" is shown in Fig. 4

Figure 11 shows the image of LSCM (laser scanning confocal microscopy) at the micro-formed surface. The forming of the protrusion can be confirmed from Fig. 11, too.

The foil was prolonged to the direction of the rolling. Therefore, the foil speed at outlet Vf is higher than the rolling speed Vr as shown in Fig. 11. The protrusion of lateral direction is pushed by Force F from wall of V-groove. This trace could be seen in SEM images of Fig. 9. Some protrusions of lateral direction might be planed off. Proper roll speed and reduction to form protrusion of lateral direction was not clear.

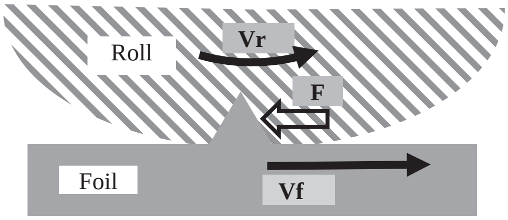


Fig. 11. Schematic illustration showing the relationship between the roll speed and foil speed at outlet. Roll speed Vr is larger than foil speed Vf. F is the pushing force from wall of V-groove to protrusion

The forming speed was 0.08 s/10 µm, 0.04 s/10 µm and 0.02s/10µm at the roll speeds of 0.5 m/min, 1.0 m/min and 2.0m/min, respectively. The forming speed means that the time taken for forming of 10µm height protrusion. In the conventional micro-forming of the metallic glass, the forming speed is, for example, 500 s/10 µm. In this way, the forming time of the method of the present study was very short.

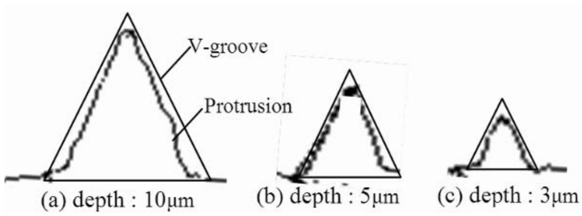


Fig. 12. Schematic illustration shows the relationship between the V-groove and protrusion. The shape of the protrusion was measured by LSCM (laser scanning confocal microscopy). The direction of the protrusion is rolling direction

Table 2.
The height of the protrusion formed by the V-groove. The direction of the protrusion is rolling direction

Depth of V-groove	1 µm	3 µm	5 µm	10 µm
Height of formed metal	0.7 µm	2.8 µm	4.8 µm	9.7 µm

The shape of the protrusion measured by the LSCM (laser scanning confocal microscopy) is shown in Fig. 12. The height of the protrusion is shown at Table 2, too. The direction of the measured protrusion is rolling direction. The V-groove was not filled by the metal. The width of protrusion was narrower than that of the V-groove. The foil was prolonged and the width of protrusion might become narrow. The difference between the between the depth of the V-groove and the height of the protrusion was less than 0.3µm. It is thought this result is sufficient.

5. Conclusions

The micro-forming was tried on the surface of the rapidly solidified Al-14mass%Si crystalline foil by the cold rolling. The nozzle pressing melt spinning method was used to cast the rapidly solidified foil which thick was 0.2 mm and surface was flat. The V-groove was used as the micro-die. The V-groove was machined on the Ni plate which thickness was 0.2 mm. The angle of the V-groove was 60 degrees and depth was 1, 3, 5 and 10 µm. The rolling speed was 0.5, 1.0 and 2.0 m/min. In this rolling speed, the forming time of 10 µm-height protrusion was 0.08 s, 0.04 s and 0.02 s, respectively. The protrusion parallel to the rolling direction could be formed. However, the protrusion perpendicular to the rolling direction could not be formed. It is thought this was concern to elongation the foil by the rolling. The two or three pieces of superimposed foils were cold rolled. The forming of the protrusion was better at the two pieces of imposed foils. The 1m/min of rolling speed was better. This reason was not clear. The annealing temperature did not affect the forming of the protrusion.

The ability of the micro-forming of crystalline aluminum alloy with fine grain by the cold rolling could be shown in this study.

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