Int J Adv Manuf Technol (2007) 32: 265–271
DOI 10.1007/s00170-005-0321-5

ORIGINAL ARTICLE

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Micro channel forming with ultra thin metallic foil by cold isostatic pressing

Received: 8 September 2004 / Accepted: 3 September 2005 / Published online: 16 March 2006

Abstract The objective of this study is to establish the limit of the metal forming process in terms of size and accuracy. In the present investigation, micro channel forming with ultra thin metallic foil by the sheet metal forming process was studied. In order to examine the fabrication limit of the process, both the channel size needed to be as small as possible and the sheet thickness to be as thin as possible. Copper foil 1.0 μm thick was made into 5.6 μm wide and 3.2 μm deep channels. The shapes of the channels were straight line, concentric circle, cross, and other curved shapes. Forming was done by cold isostatic pressing. Single crystal silicon wafer was used as the die material, and die grooves were made by micro machining techniques. The die, metallic foil, and plasticine as the pressure-transmitting medium were vacuum packed in a bag made of multilayered film. The forming was conducted with a cold hydrostatic press where the forming pressure was 240 MPa. The formed channels were examined in terms of their dimensions and surface qualities. Based on the examinations, channel formability was also discussed.

Keywords Micro channel · Forming · Foil · Isostatic pressing

1 Introduction

The trend of miniaturization in various industries requires manufacturing technologies that enable smaller parts to be produced with high accuracy and numbers. Metal forming is a potential technology that can fulfill this requirement considering the simplicity of the process and its high production capability. For this reason, many studies have been done on the various micro forming processes such as micro forging [1, 2], micro coining [3, 4], micro punching [5–7], micro incremental forming [8], and micro mold forming by isostatic pressing [9].

This paper dealt with micro forming of ultra thin metal sheet. The main goal of this study is to establish the limit of the forming process in terms of size and accuracy. Forming of micro channels with ultra thin metallic foil by cold isostatic pressing has been studied by the authors. In their previous study [10], flat rolled 3.0 μm thick copper foil was made into 12 μm wide and 9 μm deep channels as shown in Fig. 1. The shapes of the channels were straight line, concentric circle, cross and other curved shapes. Single crystal silicon wafer was used as the die material, and die grooves were made by micro machining techniques. Forming was done by a cold isostatic pressing process as shown in Fig. 2. The die, metallic foil, and plasticine as pressure-transmitting medium were vacuum packed in a bag made of multilayered film with the thickness of 80 μm. For easy separation of metallic foil from sticky plasticine after the forming process, a 0.9 μm thick polyester film was placed between the metallic foil and plasticine. The forming was conducted with a cold hydrostatic press and the forming pressure was set as 240 MPa.

In the present investigation, further miniaturization of channel size was carried out in order to examine the fabrication limit of the forming process. As the workpiece material, a 1.0 μm thick flat rolled copper foil was used, which is probably the thinnest rolled copper-made product, and it was formed into 5.6 μm wide and 3.2 μm deep channels of various shapes. Die grooves were made on single crystal silicon wafer by dry etching, and then appropriate shapes of die groove were produced through two different fabrication techniques. Both techniques produced 5.6 μm wide and 3.2 μm deep grooves with different die corner radii and wall slopes. The formed channels were examined in terms of their dimensions and surface qualities. Based on the examinations, the effect of die groove shape on the formability of metallic foil was discussed.

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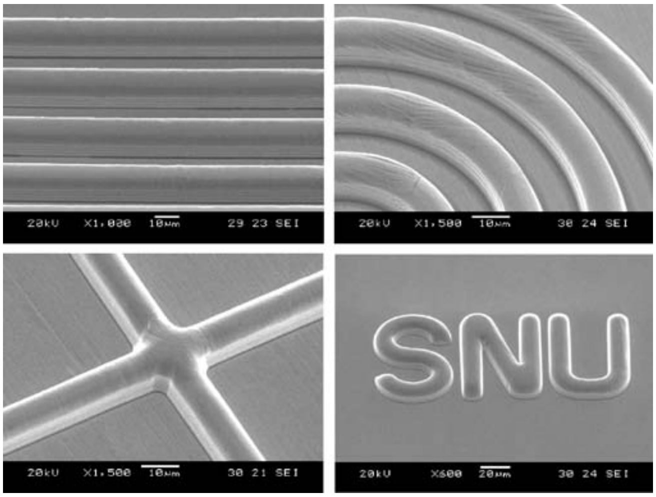

Fig. 1 Various shapes of micro channels made on 3.0 μm thick copper foil

2 Micro channel forming process

2.1 Workpiece material

A 1.0 μm thick copper foil was used as the workpiece material. Foil was flat-rolled with a width of 60 mm and a length of 2 m (Toyo-Seihaku Corp., Japan.). The foil was found to be free of pin holes, and the thickness tolerance was met within ±0.15 μm. In order to improve the ductility of the foil, copper foil was annealed at 385°C in a vacuum on the order of 10^{-5} Torr. The heating and cooling rates of the annealer were set to be 10°C/min. In order to find the appropriate annealing time, several foil specimens were annealed for varying annealing time (5, 30, and 60 min), and in-plane grain structures of annealed specimens were observed. Specimens were etched in H_2O, HCl, Iron(III) chloride (=120 ml:30 ml:10 g) solution. It was assumed that the proper annealing would make grain structure homogeneous, but the grain-growth was minimized. It was observed that the 30 min- and 60 min-specimen became fully annealed, whereas the 5 min-specimen should have recrystallized such that 20 min was chosen as the proper annealing time. Figure 3 shows in-plane grain structure of 1.0 μm thick copper foil, and the average grain size was measured to be about 5 μm. In order to evaluate the mechanical property of annealed foil, a hardness test was carried out with a nano indenter. The indentation depth was 150 nm with the indentation load of 1,000 μN. Hardness was measured to be 1.1 GPa.

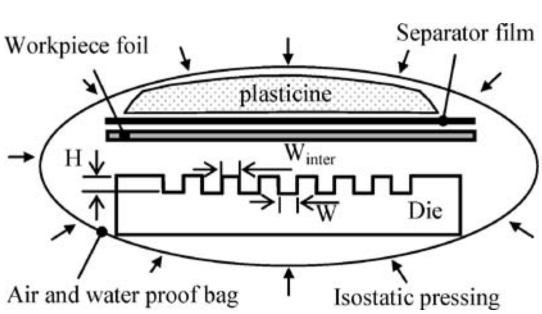

Fig. 2 Schematic of micro channel forming process

2.2 Die design and fabrication

A 4 inch [100]-oriented single crystal silicon wafer of 500 μm inch thickness was used as the die material. The silicon wafer was divided into a 12 mm×12 mm square zone. All geometric shapes within each zone comprised a forming die. Each zone contained 3.0 μm wide and 3.0~4.0 μm deep grooves with various shapes such as straight line, concentric circle, cross, and other curved shapes. Also, straight grooves and concentric circle grooves were spaced apart at an inter groove distance ranging from 3 to 17 μm, with an increment of 2 μm. For an inter groove distance, there were seven straight grooves of 1 mm in length, and five concentric circle grooves with the mean diameter of $W{+}2nW_{inter}$, where n=1, 2,…,5. Definitions of groove dimensions are given in Fig. 1. According to the designed groove shape, the dark field chrome mask with clear feature was made on a 5 inch sodalime glass.

After photolithography with positive photoresist, AZ-1512, two silicon wafers were dry etched by the deep reactive ion etching process with different etching times so that micro grooves of 3.0 μm in width and 3.0 μm in depth, and 3.0 μm in width and 4.0 μm in depth were made on each silicon wafer. Then, photoresists were ashed and stripped off. The dry etching process created vertical walls with sharp corners; but there were ripples (scallop) with amplitude of 0.3 μm and frequency of 0.5 μm on the dry etched wall as shown in Fig. 4a. In order to ensure feasible deformation of metallic foil, an appropriate profile of grooves were provided by two different fabrication techniques. Both the techniques brought about a change in the dimension of dry etched grooves, and produced 5.6 μm wide and 3.2 μm deep grooves with different die corner radii and wall slopes as shown in Table 1.

As the first technique, wet isotropic etching was used. A dry etched silicon wafer with 4.0 μm deep grooves was cut into 12 mm×12 mm square plates, and then die plates were isotropically etched in HNA solution (HF:HNO3: CH3COOH=3:5:3, CP4A etchant [11]). In order to find appropriate etching time, die plates were etched for 3, 4, 5 and 6 s, and the dimensions of etched grooves were measured at each time point. It was found that as the etching time increased, the groove width (W) and fillet radius (R_b) increased, while groove depth (H) and wall slope (θ) decreased, as shown in Fig. 4c. On the other hand, the die corer radii (R_t) remained sharp even after isotropic etching. Based on this experiment, it was decided that the appropriate etching time was 6 s, and values of W, H, R_b, and θ became 5.6 μm, 3.2 μm, 1.5 μm, and 76~77°, respectively. Also, the ripples made by dry etching disappeared, and R_{max} was measured to be 0.1 μm. Figure 4b shows the cross sections of die groove after isotropic etching. For the purpose of discussion, isotropically etched die was named $D_{Si,iso}$.

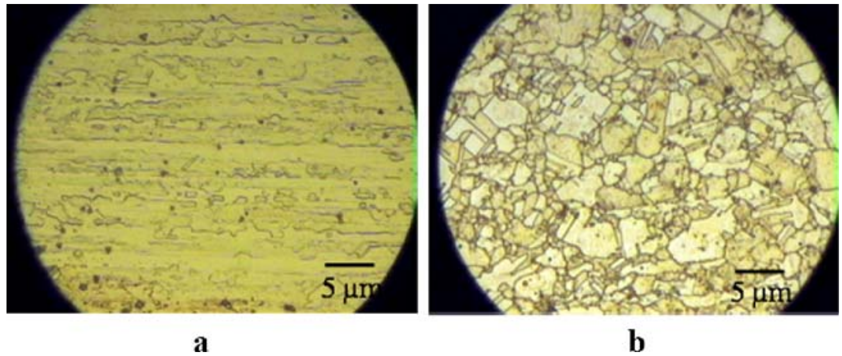

Fig. 3 In-plane grain structure of 1.0 μm thick copper foil. **a** Rolled. **b** Annealed at 385°C for 20 min

As the second technique, wet thermal oxidation was used, because it was assumed that the technique would make die corner round. The basic idea was that single crystal silicon would be more consumed at the sharp corner rather than at its adjacent regions, due to the differences of oxidant flux across the grown oxide layer at the sharp corner and its adjacent regions during wet thermal oxidation. A dry etched silicon wafer with 3.0 μm deep grooves was subject to wet thermal oxidation at 1,000°C, and the oxide thickness was set to be 2 μm. Then silicon dioxide was stripped off in a 7:1 BHF (40 NH_4F:HF=7:1) solution. Finally, a silicon wafer was cut into 12 mm by 12 mm die plates. Figure 5a shows the fabricated die groove, and enlarged view of the die corner. By wet thermal oxidation die corner became round, and the corner radius was measured to be 0.2 μm. Also, the values of *W*, *H*, R_b, and *θ* were measured to be 5.6 μm, 3.2 μm, 1.5 μm, and 83~84°, respectively. Ripples made by dry etching almost disappeared, and R_{max} was measured to be 0.06 μm. For the purpose of the discussion, the die subject to wet thermal oxidation and oxide strip was named $D_{Si,oxi}$. The same process was simulated with ATHENA-SSUPREM4 software, and the simulation result for die corner rounding is shown in Fig. 5b. The present corner radius of 0.2 μm was smaller than the simulated value of 0.7 μm. It is thought that the corner rounding effect by the present wet thermal oxidation is probably mostly wasted on the smoothing ripple of dry etched grooves at the corner seen in Fig. 4a. Further efforts should be made to make die corner round.

It was thought that $D_{Si,iso}$ and $D_{Si,oxi}$ have both merit and demerit for channel formability: die grooves of $D_{Si,iso}$ have wall slope of 76~77°, but sharp die corner, whereas $D_{Si,oxi}$ have somewhat rounded die corner, but relatively steep wall slope of 83~84°.

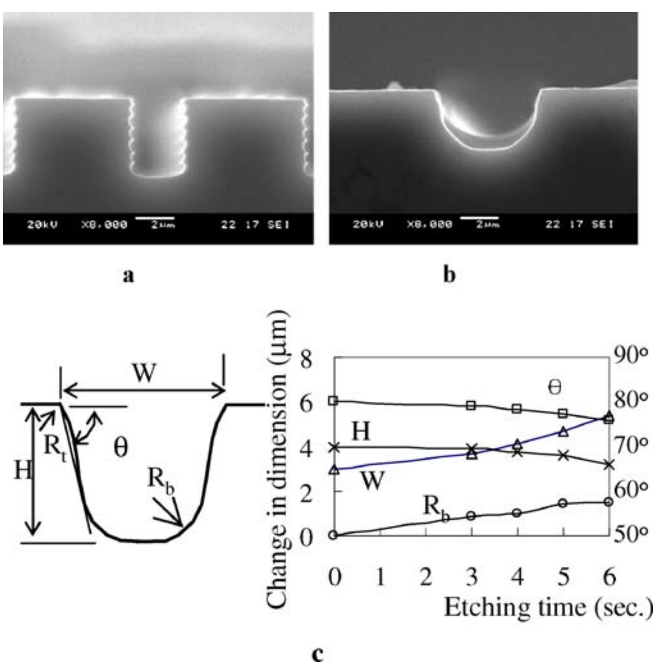

Fig. 4 Fabrication of silicon wafer die with isotropic etching technique. **a** Dry etched die groove. **b** Die groove after isotropic etching for 6 sec. **c** Dimension change of die groove vs. etching time

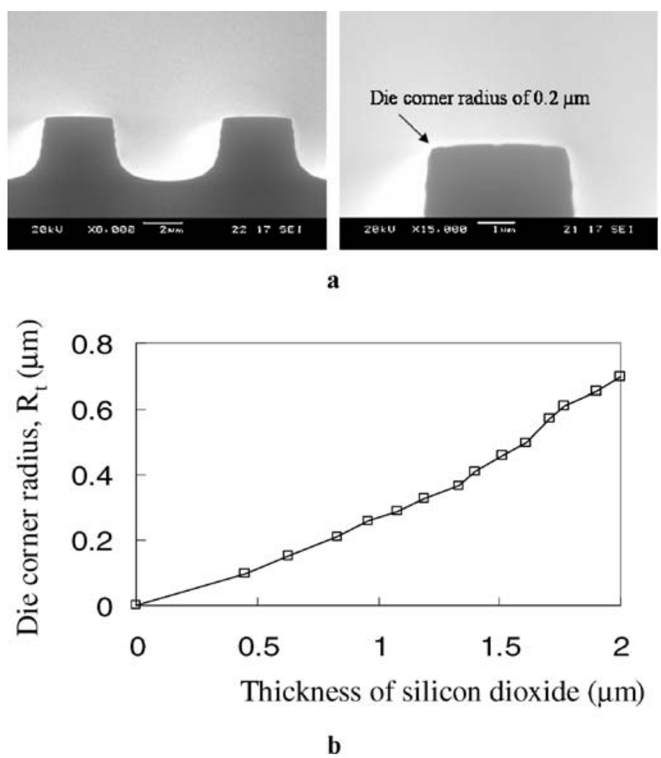

Fig. 5 Fabrication of silicon wafer die with wet thermal oxidation technique. **a** Die groove after wet thermal oxidation and oxide strip. **b** Die corner rounding vs. thickness of silicon dioxide (simulated by ATHENA)

2.3 Cold isostatic pressing as forming method

Forming was done by a cold isostatic pressing process as shown in Fig. 1. A stack composed of die-copper-separator-plasticine was made: the 1.0 µm thick copper foil was placed on the die plate ($D_{Si,iso}$ or $D_{Si,oxi}$), and then plasticine as the pressure-transmitting medium (black plasticine with the reported flow behavior of σ=0.208$\varepsilon^{0.133}$ MPa) with separator film (0.9 µm thick polyester film for easy separation of metallic foil from sticky plastcine after forming) was placed above the copper foil. The stack was then vacuum packed in an air- and water-proof bag made of multilayered films with the thickness of 80 µm. The packing was done under the vacuum state of 0.05 Torr.

Another type of stack composed of die-polyester-copper-separator-plasticne was also used. The only difference between the second stack and the first stack was that a 0.9 µm polyester film was inserted between the copper foil and die surface. Here $D_{Si,oxi}$ was used as the die plate. The purpose of the second stack was to improve the formability of metallic foil in such a way that the polyester film lying between copper and die surface would reduce the thinning of copper foil at sharp die corner.

The forming was conducted with a cold hydrostatic press. The applied forming pressure was 240 MPa for all forming processes. It should be noted that the formed copper foil was easily separated from the die surface, and no excessive force was necessary for separation.

3 Experimental results and discussions

Various shapes of micro channels were made on 1.0 µm thick copper foil by using the present process. The formed channels were examined in terms of their dimensions and surface quality. First, surface quality of both sides of formed foils (die-contacted side and plasticine-contacted side) was investigated with a scanning electron microscope, and surface roughness was measured with a non-contact surface profiler (SIS-1200, SNU Precision Co., South Korea) with nanometer resolution. Second, dimensional accuracy was investigated by sectioning the straight channels. For this, specimens were mounted and carefully polished. Measurements of the thickness were done along the arc of deformed channels, and thickness strains were calculated with measured thickness values.

Table 1 Dimensions of fabricated micro forming dies

Name	$D_{Si,iso}$	$D_{Si,oxi}$
W(µm)	5.6	5.6
H(µm)	3.2	3.2
θ(°)	76~77	83~84
R_b(µm)	1.5	1.5
R_t(µm)	sharp	0.2

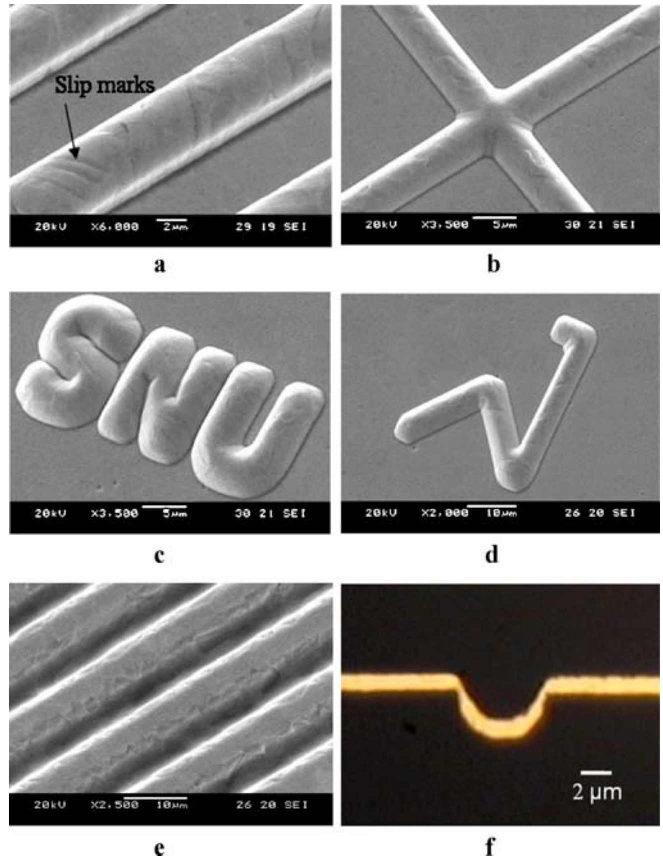

Fig. 6 Channels made on 1.0 µm thick copper foil with silicon wafer die, $D_{Si,iso}$. **a**–**d** Viewed at the die-contacted side. **e** Viewed at plasticine-contacted side. **f** Section of formed channel

Figure 6 shows formed channels made on 1.0 µm thick copper foil with silicon wafer die, $D_{Si,iso}$. Channels were fully formed into various shapes such as straight, cross, letters 'SNU', and the Seoul National University emblem, as shown in Fig. 6a–d, respectively. The maximum forming heights were measured to be the same as the depth of die grooves, 3.2 µm. First, surface quality of the formed foil at the die-contacted side was investigated. The peripheries of the deformed surface were flat because they were firmly pressurized by plasticine and flat die surface. The surface roughness, R_a, in these regions was measured to be 20 nm. It appeared that there were slip marks induced by stretching deformation at the ridge of deformed surface as shown in Fig. 6a. R_a was measured to be about 50 nm, and it is assumed that the surface roughness was influenced by such deformation-induced marks. Second, surface quality at the plasticine-contacted side was investigated. As seen in Fig. 6e, the surface was found to be relatively rough, and R_a was measured to be about 100~150 nm. Figure 6f shows the section of a formed channel. The lower profile of the section resembled the profile of die groove seen in Fig. 4. Channel width and depth were measured to be 5.6 µm and 3.2 µm, respectively. Also, the thickness strains at the die corner and the bottom were measured to be about 63% and 15%, respectively, as shown in Fig. 8b. Figure 7 shows formed channels made on 1.0 μm thick copper foil with silicon wafer die, $D_{Si,oxi}$. 5.6 μm wide and 3.2 μm deep channels were made, but it was found that foil tearing took place at the die corners. In the section of formed channel shown in Fig. 7c, foil tearing took place at the left die corner, and the thickness strain at the right die corner was measured to be about 74%. From this, it could be concluded that the different shapes of die grooves of $D_{Si,iso}$ and $D_{Si,oxi}$ demonstrated different thinning behaviors of metallic foil.

In order to discuss the effect of die groove shape on channel formability, the forming of 5.6 μm wide and 3.2 μm deep straight channels with inter channel distance of 8.0 μm were simulated with the rigid-plastic finite element program, DEFORM2D, assuming the plane strain deformations. Both blank and die lying between the two geometrical symmetries (the center of die groove width and the center of the inter groove distance) were modeled such that the initial blank size was 6.8 μm in length and 1.0 μm in thickness. The element number of the blank was 1,000. Two rigid dies with the same groove width and depth, but different wall slopes and die corner radii, were modeled based on the fabricated dimensions of $D_{Si,iso}$ and $D_{Si,oxi}$. The wall slope angles and die corner radii of $D_{Si,iso}$ and $D_{Si,oxi}$ were assumed to be 77°, 0.15 μm, and 84°, 0.3 μm, respectively. They were named $(D_{Si,iso})_{sim}$ and $(D_{Si,oxi})_{sim}$. As the flow stress curve of the blank, $\overline{\sigma}= 532\overline{\varepsilon}^{0.133}(MPa)$, which was the flow stress curve of annealed copper foil [12], was used. At the symmetric planes of the blank, the material velocities were set to be zero. As the pressure boundary condition, constant pressure of 240 MPa was applied on the top surface of the blank. Since friction condition between blank and die surface was not known, Coulomb friction coefficient μ at the die wall including die corner was to be varied from 0.0 to 0.9 with an increment of 0.1, and at the

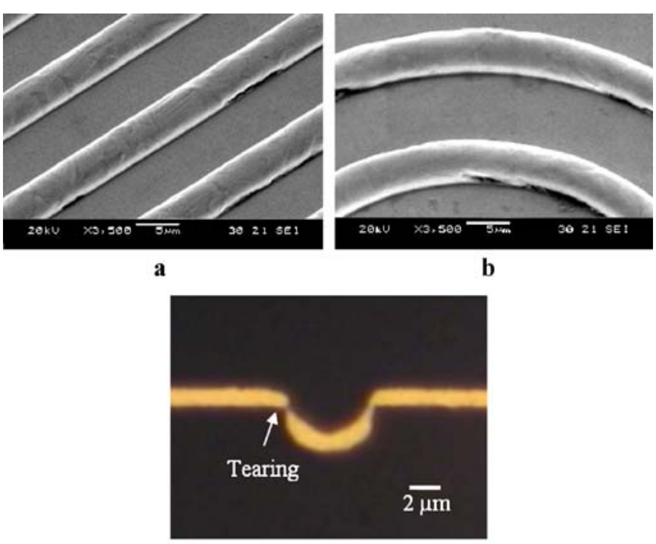

Fig. 7 Channels made on 1.0 μm thick copper foil with silicon wafer die, $D_{Si,oxi}$. **a**, **b** Viewed at the die-contacted side. **c** Section of formed channel

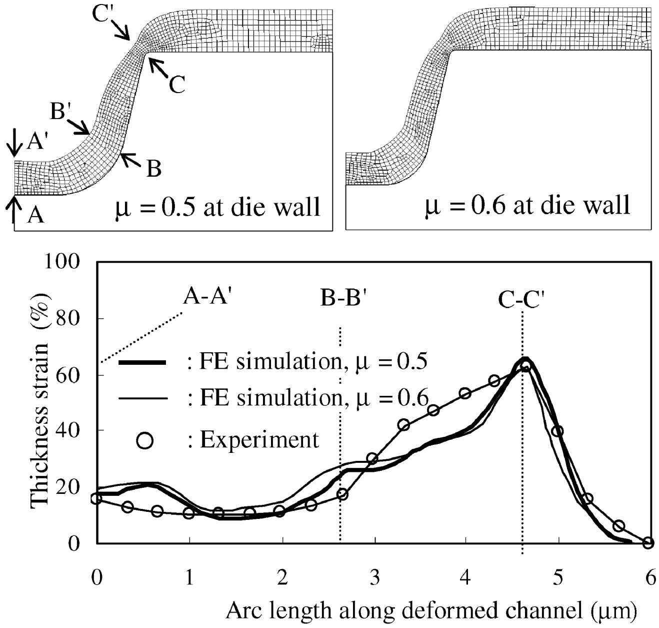

Fig. 8 Simulated thickness distributions of straight channel formed with $(D_{Si,iso})_{sim}$

top surface of die μ was fixed to be zero. It was found that when μ=0.5 and 0.6 simulation results agreed with experimental results. It was thought that in the present process high friction conditions arose between workpiece foil and die surface because the channels were deformed by high isostatic pressure without any lubrication. As shown in Fig. 8, when $(D_{Si,iso})_{sim}$ was used, the thickness strains of the blank at the die corner were calculated to be 65% at μ=0.5, and 62% at μ=0.6, respectively. Also, as shown in Fig. 9, when $(D_{Si,oxi})_{sim}$ was used, the thickness strains of the blank at the die corner were calculated to be 90% at μ=0.5, and 71% at μ=0.6, respectively. These results show that die groove with gentle wall slope is capable of improving the thinning of the blank at the die corner, and that the present die corner radii were too sharp. Simulation results also show that high friction condition at the die wall can improve the thinning of the blank at the sharp die corner, which was not in accordance with the common sense of less friction and better formability in the sheet metal drawing. However, it should be noted that the present process differed from the conventional sheet metal drawing, where the blank at the periphery of die corner is drawn into the die cavity. Since in the present forming process the in-plane dimension of metallic foil was very much larger than the die groove width and the entire surface of metallic foil was firmly pressurized, the workpiece material at the periphery of the die groove could not be easily drawn into the die groove. Rather only the flat regions of metallic foil just above the die grooves could be bent and stretched. In the case of low friction at the die wall, the workpiece material bent below the die corner slides down, while the material lying on the top surface of the die was firmly held by pressurizing so that the necking could take place at the sharp die corner. In the case of high friction at the die wall, however, the

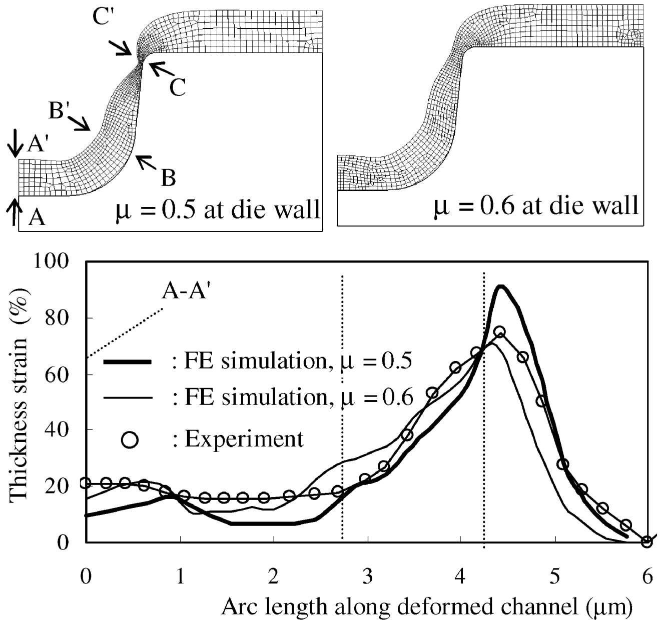

Fig. 9 Simulated thickness distributions of straight channel formed with $(D_{Si,oxi})_{sim}$

possible necking could be prevented, because the workpiece material bent below the die corner could not easily slide down, and instead it stretched. It is thought that wall slope was too steep for $D_{Si,oxi}$ so that large amounts of thinning of workpiece material must have taken place at the sharp die corner before such friction effect worked, but $D_{Si,iso}$ had relatively gentle wall slope so that channels were formed without tearing.

In order to investigate the effect of die corner radii on formability, similar simulations were conducted with die grooves, $(D_{Si,oxi})_{sim}$, by varying die corner radii from 0.4 μm to 1.0 μm. Friction condition μ=0.5 at the die wall was used. It was found that as the die corner radii increased, the maximum thickness strain of the blank at the die corner decreased. The maximum thickness strains of the blank at the die corner were obtained to be 72% at R_t=0.4 μm, 64% at R_t=0.5 μm, 56% at R_t=0.6 μm, 54% at R_t=0.7 μm, 53% at R_t=0.8 μm, 52% at R_t=0.9 μm, and 51% at R_t=1.0 μm. It was also found that when the die corner radii were large enough, low friction between blank and die surface reduced the thinning at the die corner. For example, when the die corner radius was 1.0 μm, friction-free condition μ=0 at the die wall led to the thickness strain of 42% at the die corner, while μ=0.5 led to the thickness strain of 51% at the die corner. Theses results showed that in order to improve the formability, the die corner rounding technique was highly demanded and also the friction-reducing technique needed to be developed.

Figure 10a,b shows formed channels made on 1.0 μm thick cooper foil when a 0.9 μm thick polyester film was placed between copper foil and die, $D_{Si,oxi}$. It was observed that the channels were formed without foil tearing, but the surface quality of the die-contacted side became lower compared with that of the previous channels. Surface roughness R_a at the ridge of channels was measured to be 80~100 nm, and 40~50 nm at the valley. Moreover, slip marks were not observed. It was thought that the surface quality of formed channels was influenced by the surface quality of polyester film. Figure 10c shows the section of straight channel. In order to show the degree of deformation, two separate images of the sectioned channel and die groove were superimposed onto one image. The thickness strain at the die corner was measured to be 30~40%. It was thought that the polyester film lying between workpiece foil and die surface must have acted as the round die corner such that thinning at the die corner could be reduced. Also, it was found that dimensions of formed channel differed from dimensions of die groove. Channel width (W_{foil}) was widened up to 6.5 μm, wall slope angle (θ_{foil}) became 64~65°, fillet radius ($R_{b,foil}$) was 2.5 μm, and corner radius ($R_{t,foil}$) was about 1.0 μm. It was thought that such differences in dimensions of formed channel and die groove are correlated with deformation of the polyester film. This change in dimensions, such as $R_{b,foil}$ of 2.5 μm and $R_{t,foil}$ of 1.0 μm, made sense because the thickness of polyester film, die corner radius, and die fillet radius were 0.9 μm, 0.2 μm, and 1.5 μm, respectively.

4 Conclusions

In this paper, forming of micro channel with ultra thin metallic foil by cold isostatic pressing was studied. 5.6 μm wide and 3.2 μm deep channels were made on 1.0 μm thick copper foil. Based on the present investigations, it was found that surface quality of formed channel is influenced by deformation-induced marks, formability by the die groove shape such as wall slope and corner radii, and the friction condition. Also, it was found that introducing a polymer layer between foil and die surface could improve the formability. To ensure better formability, die fabrication

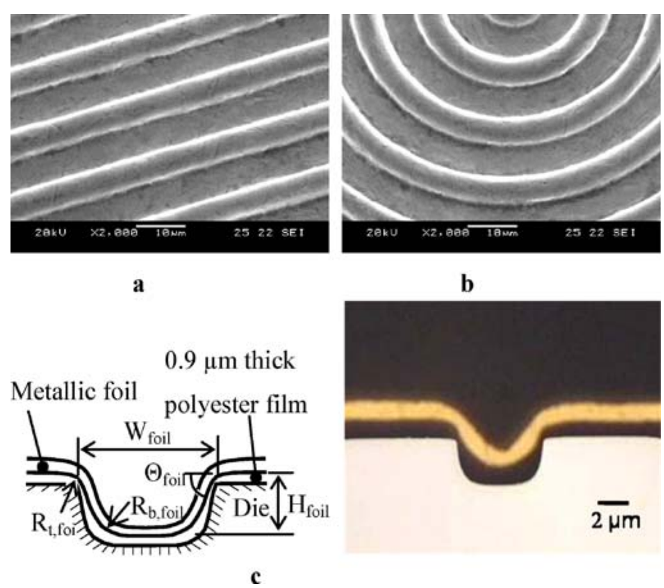

Fig. 10 Channels made on 1.0 μm thick copper foil when a 0.9 μm thick polyester film was placed between foil and die. **a**–**b** Viewed at the die-contacted side. **c** Section of formed channel

techniques to provide proper die corner radii need to be developed.

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