Development of Friction-Assisted Extrusion Process for Producing Thin Metal Strips*

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A new concept of "friction-assisted extrusion" to produce a thin metal strip was proposed. In this process, a rectangular prismatic workpiece inserted into the container is compressed by a punch against an anvil, and the anvil is forced to move horizontally. A thin strip can be extruded through the gap by exerting a high friction force over the anvil surface. Very thin strips of aluminum up to about $15\text{ }\mu\text{m}$ in thickness could be formed up to the extrusion ratio $R=667$ with a considerably low punch pressure ratio $p/2k=1\sim 2$ (p : punch pressure, k : yield shear stress), which agreed with the theoretical value estimated by the upper bound approach analysis. The friction-assisted extrusion process was applied to a forming of thin strips from aluminum powder. The thin strips formed from the aluminum powder have superior mechanical properties to those formed from bulk aluminum materials.

Key Words: Plastic Forming, Tribology, Friction-Assisted Extrusion, Thin Metal Strip, Powder Forming, Aluminum, Aluminum Powder, Punch Pressure

1. Introduction

One of the authors has developed several new processes of "friction-assisted extrusion", in which the friction drag on the tool surface enforces plastic flow of the workmetal, and thereby a higher reduction in area Re can be attained with a considerably low working pressure. Friction-assisted extrusion processes for producing a thin-wall cup and a thin-wall tube were reported, and it has been confirmed that the punch pressure in the tribo-extrusion with $Re=70\sim 97\%$ was much lower than that in the conventional extrusion⁽¹⁾⁻⁽⁴⁾.

In the present paper, a new concept of "friction-assisted extrusion" to produce a thin metal strip is proposed. In the process, a rectangular prismatic workpiece inserted into the container is compressed by a punch against an anvil, and the anvil is forced to

move horizontally. A thin strip can be extruded through the die gap by exerting a high friction force over the anvil surface. Moreover, the friction-assisted extrusion process is applied to the forming of a thin metal strip from aluminum powder.

2. Principle of Friction-Assisted Extrusion Process of Thin Strip

A schema showing the principle of the friction-assisted extrusion process of a thin strip is presented in Fig.1. A rectangular prismatic workpiece (1) inserted into the container (5) is compressed by a punch (4) against an anvil (2) at a certain pressure. When the anvil (2) is forced to move horizontally, a thin strip (1a) can be extruded through the gap between the anvil (2) and the die (3) by exerting a high friction force over the anvil surface.

To utilize effectively the friction force on the anvil surface, the frictional shear stress $\tau_A=m_Ak$ should be increased up to the yield shear stress of the workmetal k (namely $m_A=1$) and the thin strip (1a) must flow out at the same velocity as the anvil.

Figure 2 shows the kinematically admissible velocity field and the hodograph for the friction-assisted extrusion process as shown in Fig.1. The

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upper bound solution for the velocity field as shown in Fig. 2 gives the relative punch pressure $p/2k$ described with the following equation.

$$p/2k = (R+1)/2R - (m_A/2)R + m_c(L_c/H + 1/2R) \quad (1)$$

Here, R is extrusion ratio H/h , m_c is the friction shear factor, and L_c is the contact length of the workmetal on the container wall.

The relative punch pressure $p/2k$ given by Eq. (1) is indicated by the solid lines in Fig. 3, where $m_c = 1$ and $L_c/H + 1/2R = 1$ were assumed. The dotted line shows the relative punch pressure $p/2k$ for the conventional extrusion process, described by the following equation (after Hirst and Ursell⁽⁶⁾).

$$p/2k = 0.47 + 1.2(\ln R) \quad (2)$$

The $p/2k$ in the conventional extrusion process increases linearly with the extrusion ratio $\ln R$ and reaches about 7 at $R=200$. On the other hand, the

$p/2k$ in the friction-assisted extrusion process gradually decreases and approaches a constant value of about 1, when the friction shear factor m_A on the anvil surface equals 1.

3. Experimental Procedures

The experimental apparatus as shown in Fig. 4 was set on a multi-axis hydraulic press with inner ram 200 kN, outer ram 150 kN, and horizontal ram 100 kN. The die holder was fixed on the press bed, and the container was compressed and cramped on the die holder by the outer ram. The friction-assisted extrusion of a rectangular solid blank was carried out based on the process as mentioned above, while the conventional extrusion was carried out under the condition wherein the anvil was fixed. The powder metal was compacted in the container cavity by the

Fig. 1 Schema showing principle of friction-assisted extrusion

Fig. 2 Kinematically admissible velocity field and hodograph for friction-assisted extrusion of thin strip

Fig. 3 Relationship between relative punch pressure and extrusion ratio given by upper bound solution in friction-assisted extrusion and the equation of Hirst et al. in conventional extrusion (Theoretical results)

Fig. 4 Main apparatus for friction-assisted extrusion experiments

punch, and then the compacted green part was extruded using the same process as that for the solid blank. The punch load P_p , the anvil load P_A and the cramping load of container P_H were recorded during the forming of thin strips.

Table 1 shows the experimental conditions. The container is made of cemented carbide (V 4 in JIS). The cross-sectional area of the container cavity is $10 \times 10 \text{ mm}^2$. The die opening is 10 mm in width, and the gap of the opening h was varied, ranging from 0.5 mm to 2 mm, with which the extrusion ratio could be changed, ranging from 5 to 200. The anvil is made of cemented carbide (V4), and its surface roughness R_a is $0.047 \mu\text{m}$. The anvil velocity is low at 0.1 mm/s, and the maximum anvil stroke is about 40 mm. The friction-assisted extrusion process was carried out under the dry friction condition on the anvil surface to utilize the friction force effectively, while conventional extrusion process is carried out under the condition of lubrication with MoS_2 wax.

A commercially pure aluminum sheet A 1050 F was used as the workmetal, as shown in Table 2(a). The workpiece was cut into cubes measuring $10 \times 10 \times$

10 mm^3 . Commercially pure aluminum powder atomized with -100 mesh was used as the metal powder, as shown in Table 2(b). The aluminum powder was compacted in the die cavity with a relative density of more than 95% under punch pressure higher than 400 MPa.

Tensile tests were conducted with a testpiece of 8 mm in gage length and 8 mm in width. Hardness was tested by a micro-Vickers hardness tester with a load of 25 g.

4. Forming of Thin Strips from Aluminum Bulk Workpiece

Strips ranging from 2 mm to 0.05 mm in thickness were extruded by the conventional extrusion process. However, the punch pressure p increases remarkably with an increase of the extrusion ratio R , and reached 1 GPa at $R=200$. The friction-assisted extrusion process could extrude strips ranging from 2 mm to 0.015 mm in thickness, and the punch pressure p maintained a lower value of about 200 MPa even at every high extrusion ratio $R=667$.

The experimental points indicated by the solid circles in Fig. 5 show the relative punch pressure $p/2k$ in the case of friction-assisted extrusion. The yield stress $2k$ is obtained by $2k=(2/\sqrt{3})\sigma_Y=143 \text{ MPa}$, where σ_Y equals uniaxial yield stress at the strain $\epsilon=1$ given by the compression test. The values of $p/2k$ are fairly low at about 1 and agree with the theoretical curve for $m_A=1$. The foil thickness was very thin (about $50 \mu\text{m}$) at the extrusion ratio $R=200$.

On the other hand, the experimental points indicated by the solid triangles show the $p/2k$ in the case of conventional extrusion. The experimental values of $p/2k$ agree with the theoretical values indicated by the dotted line, and increase linearly with R , reaching 7 at $R=200$.

Fig. 5 Relationship between relative punch pressure and extrusion ratio in the case of friction-assisted extrusion and that of conventional extrusion from bulk material (Experimental results)

Table 1 Experimental conditions

(a) Tool

	Material	Mechanical properties	Surface roughness
Die	Cemented carbide V4	Hardness HRA: about 85	$R_{\max}=0.2 \mu\text{m}$
Anvil	Cemented carbide V4	Hardness HRA: about 85	$R_{\max}=0.2 \mu\text{m}$ $R_a=0.047 \mu\text{m}$

(b) Working conditions

Cross section of container: $10 \times 10 \text{ mm}^2$
Extruded thickness: 2, 1, 0.5, 0.25, 0.1, 0.05 mm
Extrusion ratio: 5, 10, 20, 40, 100, 200
Anvil velocity: about 0.1 mm/s
Anvil stroke: about 40 mm
Lubricant of container: Molybdenum disulfide
Lubrication condition of anvil surface: Dry

Table 2 Work materials used

(a) Aluminum bulk material

Aluminum sheet A 1050-F Thickness 10 mm	Stress-strain relation $\sigma=124 \epsilon^{0.29} \text{ MPa}$	Surface roughness $R_{\max}=5 \mu\text{m}$
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(b) Aluminum powder

Element	Al	Si	Fe	Cu	Mn	Ti+V	Other
wt %	99.75	0.09	0.16	tr.	tr.	tr.	tr.
Mesh	+100	100~200	200~350				-350
wt %	0.1	84.4	12.6				2.9

Figure 6 shows some examples of strips extruded by the friction-assisted extrusion. The strips of $R=20$ (or $h=0.5$ mm) was extruded successfully, so the flatness was good except for the front portion. However, the strip of $R=667$ or $h=15$ μm was severely warped.

Figure 7 shows the distribution of the thickness for strips extruded by friction-assisted extrusion. The thicknesses h are thicker than the die opening gap by $0\sim 20$ μm , and the scattering of thickness values is about $10\sim 20$ μm .

The surface roughness on the anvil side of the strip extruded by the friction-assisted extrusion process was relatively smooth, that is, less than $Ra=0.3$ μm , because the anvil side surface of the strip can be formed without relative slip at the interface between the anvil and workpiece. On the other hand, the surface roughness on the die side of the strip deteriorated due to a seizure phenomenon at the die opening.

Figure 8 shows the tensile strength S_T and the Vickers hardness HV of the strip extruded by friction-assisted extrusion. The values of S_T and HV increase with an increase of the extrusion ratio R , and reach 240 MPa and 77 at $R=200$, respectively.

It has been confirmed that a commercially pure copper also can be successfully extruded similarly to the aluminum.

(a) Extrusion ratio $R=20$
Strip thickness $h=0.5$ mm

(b) Extrusion ratio $R=667$
Strip thickness $h=15$ μm

Fig. 6 Some examples of strip extruded by friction-assisted extrusion from bulk material

5. Forming of Strips from Aluminum Powder

The aluminum powder was compacted in the container at the punch pressure $p=400$ MPa, and the compacted density ratio of about 95 % was obtained. The compacted green parts could be extruded successfully into thin strips ranging from 2 mm to 0.05 mm in thickness at the punch pressure $p=200\sim 500$ MPa by friction-assisted extrusion.

The experimental results indicated by the open circles and triangles in Fig. 9 show the lower and upper values of the relative punch pressure $p/2k$ in the friction-assisted extrusion process, respectively. The yield shear stress k is assumed to be 160 MPa, which is estimated from the tensile strength or Vickers hardness. The experimental values of $p/2k$ are considerably close to the theoretical curve for $m_A=1$ in

Fig. 7 Distribution of thickness for strips extruded by friction-assisted extrusion from bulk material

Fig. 8 Tensile strength and Vickers hardness of strips extruded by friction-assisted extrusion from bulk material

the friction-assisted extrusion process.

Figure 10 shows some examples of strips extruded from powder aluminum by friction-assisted extrusion. The strip for $R=20$ (or $h=0.5$ mm) can be extruded successfully and the flatness is very good. However, the strip of $R=200$ (or $h=80$ μm) is warped and has cracks at the front portion.

Figure 11 shows the distribution of the thickness for strips extruded by friction-assisted extrusion. The thicknesses h are thicker than the die opening gap by 0~20 μm , and the scattering of thickness values is about 10 μm .

Fig. 9 Relationship between relative punch pressure and extrusion ratio in friction-assisted extrusion from powder aluminum (Experimental results)

(a) Extrusion ratio $R=20$
Strip thickness $h=0.5$ mm

(b) Extrusion ratio $R=200$
Strip thickness $h=0.08$ mm

Fig. 10 Some examples of strip extruded by friction-assisted extrusion from powder aluminum

The surface roughness on the anvil side of the strip extruded by friction-assisted extrusion was relatively smooth, that is, $Ra=0.1\sim0.25$ μm , because the anvil side surface of the strip can be formed without relative slip at the interface between the anvil and workpiece. On the other hand, the surface roughness on the die side of the strip deteriorated due to a seizure phenomenon at the die opening.

Figure 12 shows the Vickers hardness HV of the strip extruded by friction-assisted extrusion. The values for the strip made from aluminum powder, designated by the open circles, are higher than those for the strip made from bulk material, designated by the chain line. The values for the strip annealed at 400°C for 1 hour are also higher than the fully annealed commercially pure aluminum, that is, about

Fig. 11 Distribution of thickness for strips extruded by friction-assisted extrusion from powder aluminum

Fig. 12 Vickers hardness of strips extruded by friction-assisted extrusion from powder aluminum

Fig. 13 Tensile strength of strips extruded by friction-assisted extrusion from powder aluminum

Fig. 14 Relationship between total elongation and extrusion ratio for strips extruded by friction-assisted extrusion from bulk and powder aluminum

$HV=20\sim24$.

Figure 13 shows the tensile strength S_T of the strip extruded by friction-assisted extrusion. The values for the strip made from aluminum powder, designated by the solid circles, are higher than those for the strip made from bulk material, designated by the chain line. The values for the strip annealed at 400°C for 1 hour also are higher than the fully annealed commercially pure aluminum, that is, about $S_T=100$ MPa.

Figure 14 shows the relationship between the total elongation e_T and the extrusion ratio R . The values for the strip made from aluminum powder, designated by the solid symbols, are larger than those for the strip made from bulk material, designated by the chain line, when R is higher than 20. When the strips are annealed at 400°C for 1 h, the e_T increases to a value higher than 5%.

6. Conclusions

A friction-assisted extrusion process for producing thin metal strips was proposed and analyzed theoretically by the upper bound approach. The process was applied successfully to the forming of thin aluminum strips from a bulk material and an aluminum powder. As a result, the following was determined.

(1) The relative punch pressure $p/2k$ (p : punch pressure, k : yield shear stress) obtained by the upper bound approach decreased gradually with an increase of the extrusion ratio R and maintained values lower

than 1 under the stick friction condition of $m_A=1$ at the anvil surface.

(2) Very thin strips of aluminum up to about $15\ \mu\text{m}$ in thickness could be extruded successfully from bulk material at the extrusion ratio $R=667$ with a considerably low punch pressure ratio $p/2k=1\sim2$, which agreed with the theoretical value estimated by the upper bound approach. It has been confirmed that the strips extruded have good dimensional accuracy for thickness and smooth surface roughness $Ra=0.047\ \mu\text{m}$.

(3) Very thin strips of up to about $50\ \mu\text{m}$ could be extruded successfully from aluminum powder with a considerably low punch pressure ratio $p/2k=1\sim2$. The thin strips extruded from the aluminum powder have superior mechanical properties to those extruded from bulk aluminum material.

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