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Research on the Shaving Mechanism of Sheet Metals with Punch and Die*

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Theoretical and experimental researches were performed on the shaving mechanism of sheet metals. From the experiment it was found that the shaving deformation processes of aluminum plates could be divided into three stages, indentation, chip formation and shear fracture. In the theoretical research, three slip line fields associated to the above stages were assumed, and the shaving load-punch penetration curves were calculated. Moreover, the influences of the shaving conditions (shaving depth, rake angle of die and metal temper) on the configuration of the shaved surface became clear.

1. Introduction

The purpose of shaving is to shave the edges of cut blanks with punch and die, and to get smooth, square and sharp edges. This working requires at least two or more operations to obtain the finished edges. Then, in an effort to displace these multiple operations by a single operation, several new techniques "the fine blanking", "the finish blanking" etc. have been developed. But, these techniques are accompanied with the decrease of tool life and the waste of sheet metal. In order to avoid these disadvantages the combination of blanking and shaving is frequently required.

In the shaving, it is most important to determine the suitable amount of shaving depth (depth of cut). The shaving depth is affected by the following factors: (i) clearance of blanking tool. (ii) physical properties of specimens (especially, ductility, work hardening and anisotropy). (iii) thickness. (iv) the configuration of the tool edge (rake angle, relief angle), and (v) operation speed. The object of this research is to investigate the influence of these factors and to determine the suitable shaving depth of sheet metals.

In this report, some experi-

mental investigations were carried out on the shaving mechanism of aluminum plates, of which the edges were finished square with cutting tools. Moreover applying the slip line theory to the shaving deformation processes of sheet metals, the shaving load and the configuration of the shaved edge were analyzed for various shaving depths, and the results compared with the experimental ones.

2. Experiment

2.1 Apparatus

The shaving apparatus of circular blanks in shown in Fig. 1 (a). Diameter of the die and the punch were 29.403 mm and 29.036 mm respectively.

Fig. 1 Shaving apparatus

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The location of the specimen was done by the guide pin ⑤. The apparatus was placed on a hydraulic type testing machine, and the punch penetration was measured by two dial gauges. The testing speed in no-load running was controlled at a constant speed 1mm/min.

In the case of the straight edged die, the shaving depth was controlled with the backup block ⑦ placed parallel to the cutting edge as shown in Fig. 1 (b). The relief angle of die was $\beta=4^\circ$ both in the circular and the straight edge, and the rake angle of die was $\alpha=0^\circ, 5^\circ, 10^\circ, 15^\circ$

Fig. 2 Stress-strain curve

Fig. 3 Shaving deformation processes of annealed aluminum plate

at the straight edged blank and $\alpha=0^\circ$ at the circular blank.

2.2 Test material

The material tested was a commercially available aluminum plate (3mm in thickness) which was annealed at 350°C for 30 min after machining the edges. The actual tensile stress-logarithmic strain diagram of the material is shown in Fig. 2. The dimensions of the specimen were determined in order that the shaving depth to thickness ratio h_0/t might be 3%, 5% and 10%. Besides, some experiments using un-annealed aluminum plates were carried out to check the influence of the temper condition.

3. Experimental results and discussion

3.1 Shaving deformation processes

3.1.1 When die rake angle is zero The shaving deformation processes of the annealed aluminum plate were divided into two stages as shown in Fig. 3, that is,

(i) Chip formation process Deformed region is defined in the vicinity of the die edge,

(a) Chip formation process

(b) Shear fractured process

Fig. 4 Fiber structure of annealed aluminium plate during the shaving deformation processes

and a triangular chip is formed [Fig. 3 (a)-(c)].

(ii) Shear fracture process Triangular chip slips along the surface connecting the cutting edges of punch and die, and cause ultimate rupture [Fig. 3 (d)-(e)].

Fig. 4 shows photomicrographs of fiber structures of specimens in the chip formation process and the shear fracture process obtained by etching the specimens in 5 % hydrofluoric acid after cutting on the meridian plane with the electro-spark machining and being polished by electrolytic polishing. In the chip formation process [Fig. 4 (a)], boundary CA between the undeformed region and the triangular chip nearly coincides with the direction of fiber structure, and this is similar in appearance to the transitional chip formation mechanism at the early stage in the orthogonal cutting⁽¹⁾. In the shear fracture process [Fig. 4 (b)], the direction of fiber structure nearly coincides with the plane DD' connecting the cutting edges of punch and die, and this is similar to the shearing mechanism with punch and die having null clearance.

The shaving deformation processes of straight edged specimens are shown in Fig. 5. In the case of annealed aluminum plate of Fig. 5 (a), the same triangular chip is yielded as Fig. 3 (d). Thus, the shaving deformation processes for the straight edged blank are almost the same as those found for the circular blank, provided that the diameter of specimen is out of proportion to the thickness (diameter-thickness ratio is 10 in this experiment). On the other hand, in the case of unannealed aluminum plate of Fig. 5 (b), flow-type chips are yielded as in the orthogonal cutting.*

3.1.2 When die rake angle is not zero

Judging from Fig. 6, the shaving deformation processes of the annealed aluminum plate can be divided into three stages.

(i) Indentation process This stage is similar to the indentation of a rigid wedge into a semi-infinite medium. During the indentation the entire configuration of the deformed region remains geometrically similar.

(ii) Chip formation process In this stage, the triangular chip grows as shown in Fig. 6 (a), (b), (c). When the shaving depth is small, the flow-type chip formation process appears in succession.

(iii) Shear fracture process Fig. 6 (d), same as 3.1.1 (ii).

3.2 Shaving load

* On the shaving of annealed aluminum plate, the flow-type chip is formed when the ratio of shaving depth to sheet thickness is small (see Appendix).

The shaving load-punch penetration curves of the annealed aluminum plates are shown in Fig. 7. It is found that if the ratio of shaving depth to thickness h_0/t is constant, almost the

$h_0/t=0.042$ $s/t=0.66$
(a) Annealed aluminum plate

$h_0/t=0.042$ $s/t=0.66$
(b) Un-annealed aluminum plate

Fig. 5. Influence of temper condition on the shaving deformation process ($\alpha=0^\circ$, straight edged blank)

(a) $s/t=0.107$

(b) $s/t=0.315$

(c) $s/t=0.578$

(d) $s/t=0.798$

Fig. 6 Shaving deformation processes of annealed aluminum plate ($\alpha=15^\circ$, $h_0/t=0.057$)

same load-penetration curves appear in both cases of circular blank and straight edged blank. If the ratio h_0/t increases, the punch penetration up to the maximum load point decreases and the maximum load increases. If the ratio h_0/t is constant and the die rake angle increases, the punch penetration up to the maximum load point increases and the maximum load decreases.

3.3 Shaved surface

The shaved surface of the annealed aluminum plate consists of "obtuse plane", "bright plane", "shear fractured plane" and "secondary bright plane" as shown in Fig. 8.

(i) The obtuse plane b_1 is formed in an early stage when the cutting edge of die begins to penetrate into the material, and increases with increasing shaving depth.

(ii) The bright plane b_2 is formed in the chip formation process and decreases with increasing shaving depth.

(iii) The shear fractured plane b_3 and the secondary bright plane b_4 . In the shear fracture process, large shearing strain occurs along a plane connecting the cutting edges of punch and die. Accordingly, cracks develop at an angle to the plane of shear, and the shear fractured plane b_3 is formed. After that, the secondary shearing phenomenon occurs as if the triangular chip is sheared using tools having zero clearance, and the secondary bright plane b_4 is formed. After this, we call (b_3+b_4) the ruptured plane.

The relationships between the shaved surface

Fig. 7 Shaving load-penetration curves of annealed aluminum plates

and the shaving depth are represented for different rake angles in Fig. 9. The ruptured plane (b_3+b_4) reduces with an increase of die rake angle, while the decrease of shaving depth reduces the plane. Thus, it was found that an accurately finished surface could be obtained by using large rake angle and small shaving depth.

4. Theoretical analysis

To simplify the analytical treatment of the problem, the following assumptions are adopted.

(1) The material is a perfectly plastic-rigid body.

(2) The obtuse plane formed in the early stage of the shaving is negligible.

(3) The contact between the die rake face and the chip is under a condition of the stick-slip (this is suggested by several experimental results with respect to the steady-orthogonal cutting).

4.1 Non-hardening perfectly plastic-rigid body

b_1 : obtuse plane b_2 : bright plane
 b_3 : shear fractured plane
 b_4 : secondary bright plane
 (b_3+b_4) : ruptured plane

Fig. 8 Shaved surface of annealed aluminum plate ($\alpha = 0^\circ$)

Fig. 9 Relations between shaved surface and shaving depth (material: annealed aluminum plate)

4.1.1 When die rake angle is zero

(i) Chip formation process From the above assumption (3), a slip-line field as shown in Fig. 10 is assumed for the chip formation process. When the die having zero rake angle penetrates into the material by s with the shaving depth h_0 , a triangular chip grows on the free surface. Assuming the chip segment AB to be a straight line, the first and second slip-lines⁽²⁾ which intersect the segment AB in the triangular region ABD become straight respectively, and the stress distribution is uniform in the triangle ABD. Therefore, from the assumption (3) and the Hencky's equation, the mean normal stress N and the tangential stress T acting on the rake face of die are

$$N = k(1 + 2\phi), \quad T = k \dots\dots\dots (1)$$

where k is the yield shearing stress.

Let us now consider the velocity distribution, assuming that the punch and the rigid region of the material are moving with velocity U and the die is at rest. Fig. 11 expresses the velocity components in the slip-line field of Fig. 10 with respect to a cylindrical coordinate. From Fig. 11, velocity components along the first and second

Fig. 10 Chip formation process ($\alpha = 0^\circ$)

Fig. 11

slip-lines are obtained as follows:

$$\left. \begin{aligned} v_1 (=v_r) &= U \sin \theta \\ v_2 (=v_\theta) &= U(1 - \cos \theta) \end{aligned} \right\} \dots\dots\dots (2)$$

Next, let us determine the relations between the punch penetration s , the chip contact length l and the fan angle ϕ for the different shaving depths h_0 . l and s are determined in view of the geometric relations and the volume-constancy of Fig. 10 as follows:

$$\left. \begin{aligned} l &= \frac{h_0}{1 + \sin \phi - \cos \phi} \\ s &= \frac{h_0 \cos 2\phi}{2(1 + \sin \phi - \cos \phi)^2} \end{aligned} \right\} \dots\dots\dots (3)$$

By eliminating ϕ in Eqs. (3), l is uniquely determined in terms of s and h_0 .

Consequently, the shaving load (per unit sheet width) is given as follows:

$$F = kl(1 + 2\phi) \dots\dots\dots (4)$$

(ii) Shear fracture process Fig. 12 is provided as the slip-line field in this stage. Assuming that the material below DD' line connecting the cutting edges of punch and die is at rest and the material above DD' line is rigidly moving with the same velocity U as the punch, the line DD' becomes a slip-line, so the shaving load (per unit width of sheet) is given as follows:

$$F = k(t - s) \dots\dots\dots (5)$$

Fig. 12 Shear fracture process ($\alpha = 0^\circ$)

Fig. 13 Indentation process ($\alpha \neq 0^\circ$)

4.1.2 When rake angle is not zero

(i) Indentation process Considering that the deformation mode in the indentation process is analogous to that in the indentation of a rigid wedge into a semi-infinite medium⁽³⁾, the slip-line field becomes as shown in Fig. 13. Here O is the starting point of die indentation. Assuming that the segment BC raised on the free surface is straight, the stress distribution becomes uniform in the triangle BCE, and from the above assumption (3), the die rake face directly makes contact with the centered fan region CDE. Hence, denoting by ϕ_0 the fan angle, the mean normal stress N and the tangential stress T acting on the rake face of die is given as follows:

$$N = k(1 + 2\phi_0), \quad T = k \dots \dots \dots (6)$$

Let us now consider the velocity distribution. Since the punch and the rigid region in the material are moving with velocity U and the die is at rest, the velocity components are obtained in a similar way to 4.1.1 from Fig. 11.

$$\left. \begin{aligned} v_1 (=v_r) &= U \sin \theta \\ v_2 (=v_\theta) &= U(\cos \alpha - \cos \theta) \end{aligned} \right\} \dots \dots \dots (7)$$

In order that the entire configuration of the plastic region in this stage may remain geometrically, it is necessary that the following relation between α and ϕ_0 holds

$$\frac{\sin \phi_0 + \cos \phi_0}{\sin \alpha - \sin(\phi_0 + \alpha) - \cos(\phi_0 + \alpha)} = \cos \alpha - \cos(\phi_0 + \alpha) + \sin(\phi_0 + \alpha) \dots \dots \dots (8)$$

and moreover, the following relation between l and s holds

$$\frac{l}{s} = \frac{\cos \alpha}{\sin \alpha - \sin(\phi_0 + \alpha) - \cos(\phi_0 + \alpha)} \dots \dots \dots (9)$$

As it is considered that the geometric similarity of the slip line field continues up to the punch penetration s_1 where the point B coincides with B_0 in Fig. 13, the indentation stage holds in the range of the following punch penetration

$$s \leq s_1 = \frac{h_0(\sin \phi_0 + \cos \phi_0)}{\{\cos \alpha - \cos(\phi_0 + \alpha) + \sin(\phi_0 + \alpha)\}^2} \dots \dots \dots (10)$$

The slip-line field at the punch penetration $s = s_1$ is expressed with the dotted line $B_0C_0D_0$ in Fig. 14. At this time, $B_0C_0 (=a)$ is given by

$$a = \frac{\sqrt{2} h_0}{\cos \alpha - \cos(\phi_0 + \alpha) + \sin(\phi_0 + \alpha)}.$$

Consequently, the shaving load F (per unit sheet width) in the indentation process is given as follows:

$$F = kl(1 + 2\phi_0 + \tan \alpha) \dots \dots \dots (11)$$

(ii) Chip formation process The slip-line field in this stage is assumed as shown in Fig. 14.

Let us now give an arbitrary point C on the die rake face to the punch penetrations s . In these circumstances, the velocity vector in the triangular region ACE fluctuates with an increase of s , but it is apparent from Eqs. (7) that the velocity distribution at every moment of penetration does not vary. Hence, the relative displacement vector between any two points on the segment B_0C_0 to the co-ordinate origin remains the same independently of the increase of s . Therefore, $\overline{B_0C_0} \parallel \overline{BC}$, $\overline{B_0C_0} = \overline{BC}$. Let us draw a straight line with a length of $\sqrt{2} \times \overline{CD}$ from the point C to the working surface and obtain the point of intersection A. Next, a point E may be determined to satisfy the condition of $\angle ACE = \angle CAE = 45^\circ$. Lastly, re-examine the point C about whether the volume constancy condition is satisfied during the deformation process or not. In this way, the slip-line field shown in Fig. 14 can be constructed with the trial and error-method.

In this case, the plastic region also consists of the triangular region and the region of the centered fan, and the stress and velocity components in the slip-line field can be calculated in a similar way to those of the indentation process. Thus, the mean normal stress N and the tangential stress T acting on the rake face of die are

$$N = k(1 + 2\phi), \quad T = k \dots \dots \dots (12)$$

where ϕ is the fan angle, and the shaving load F (per unit sheet width) is given as follows:

$$F = kl(1 + 2\phi + \tan \alpha) \dots \dots \dots (13)$$

Let us determine the relations between the chip contact length l , the punch penetration s and the fan angle ϕ in terms of the shaving depth h_0 and the die rake angle α . From the relations of geometrical configuration of the slip-line field and the volume constancy condition, the chip contact

Fig. 14 Chip formation process ($\alpha \neq 0^\circ$)

is,

$$w = \int_0^{\varepsilon_{eq}} \sigma_t d\varepsilon_t \dots\dots\dots (22)$$

From the assumption (2) of 4.2 the stress-strain curve is given by

$$\left. \begin{aligned} \sigma_t &= H\varepsilon_t^n & (\varepsilon_t \leq \varepsilon_m) \\ \sigma_t &= -\sigma_m(2 - e^{-\varepsilon_m})e^{-\varepsilon_t} + 2\sigma_m e^{-\varepsilon_m} & (\varepsilon_t > \varepsilon_m) \end{aligned} \right\} \dots\dots\dots (23)$$

where σ_m and ε_m are the values when a local contraction of area appears.

Accordingly, the shaving load (per unit sheet width) for the strain-hardening material is given from Eqs. (20) to (23) as follows.

$$F = y_A \left\{ \frac{H\varepsilon_m^{n+1}}{n+1} + 2\sigma_m(\varepsilon_{eq} - \varepsilon_m)e^{-\varepsilon_m} + \sigma_m(2 - e^{-\varepsilon_m})e^{\varepsilon_m - \varepsilon_{eq}} \right\} \dots\dots\dots (24)$$

Here y_A is given as follows:

when the rake angle of die $\alpha = 0^\circ$, $y_A = h_0$ and when the rake angle of die $\alpha \neq 0^\circ$

$$y_A = l \left\{ 1 + \frac{\sqrt{2}}{\cos \alpha} \sin \left(\alpha + \phi_0 - \frac{\pi}{4} \right) \right\} \quad (s \leq s_1)$$

$$y_A = h_0 \quad (s \geq s_1)$$

(ii) Shear fracture process In this stage, only the material in a thin layer region of the slip-line DD' of Fig. 12 yields the plastic strain, and the shearing strain on the slip-line DD' becomes infinity. Hence, with an infinitely increasing the tensile logarithmic strain corresponding to this shearing strain, the actual stress σ_t infinitely tends to $2\sigma_m e^{-\varepsilon_m}$, that is, when the shearing strain is infinity, the shearing stress becomes $(2/\sqrt{3}) \times \sigma_m e^{-\varepsilon_m}$. Accordingly, the shaving load (per unit width) for the strain-hardening material becomes as follows:

Fig. 17 Relations between chip contact length of die rake face and punch penetration (material: annealed aluminum plate)

$$F = \frac{2}{\sqrt{3}} \sigma_m e^{-\varepsilon_m} (t-s) \dots\dots\dots (25)$$

5. Comparison between theoretical results and experimental results

Relations between punch penetration s and contact length of chip l are shown in Fig. 17. Solid lines and dotted lines show the results calculated from Eqs. (3), (9), (14) and (15) to (18). The calculated values coincide with the experimental results fairly well.

The relations between the shaving load and the punch penetration are calculated from Eqs. (24) and (25) as shown in Fig. 18, and these also coincide with the experimental results of Fig. 7. From the results it becomes clear that the shaving load has the maximum value at the transition point from the chip formation process. In the calculation of Fig. 18, the fan angle ϕ decreases with an increasing punch penetration s and reduces to zero as h_0/t becomes small in the chip formation process of Fig. 14. After ϕ becomes zero, it is natural to assume that the steady orthogonal cutting process keeping the relation of $\phi = 0^\circ$ continues for the increase of s . Thus, a flat part appears on the shaving load-punch penetration curve from some stage of the chip formation process. This is found in the case of $\alpha = 15^\circ$, $h_0/t = 0.03, 0.05$ in Fig. 18.

Relations between the shaving depth and the shaved surface for different die rake angles are shown in Fig. 19. Solid lines show the results calculated from the punch penetration at which Eqs. (24) is equal to Eqs. (25), that is, at the

Fig. 18 Relations between shaving load and punch penetration (material: annealed aluminum plate)

transition point from the chip formation process to the shear fracture process. The calculated values coincide with experimental results fairly well. From the above results it becomes clear that shear cracks initiate in the material as soon as the shear fracture process starts, and that the increase of the die rake angle effectively decreases the ruptured plane within the shaved surface, especially, its effect is remarkable in the small range of the shaving depth.

6. Conclusions

The authors applied the theory of ship-line

Fig. 19 Relations between shaved surface and shaving depth (material: annealed aluminum plate)

Fig. 20 Relation between die rake angle α and shaving depth h_0/t forming flow-type chip (material: annealed aluminum plate)

field to the analysis of shaving mechanism, and compared the calculated results with the experiments.

(1) The shaving deformation processes can be divided into three stages, that is, the indentation process, the chip formation process and the shear fracture process. But, no indentation process appears in the case of the die rake angle $\alpha=0^\circ$, and the steady orthogonal cutting process appears in the case when the shaving depth is remarkably small.

(2) The shaving load-penetration curves were calculated by assuming three slip-line fields associated to the three stages described above. Moreover, the ruptured plane, calculated from the assumption that cracks initiate from the cutting edge of die as soon as the punch penetration reaches the shear fracture process, coincide with the experimental results fairly well.

(3) If the shaving depth decreases and the die rake angle increases, the maximum shaving load decreases and the length of the ruptured plane also decreases. The effect of the die rake angle is remarkable in the small range of the shaving depth.

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7. Appendix

On the shaving of the annealed aluminum plate, with the shaving depth decreased, a flat part appears on the shaving load-punch penetration curve, and the flow-type chip is formed. The relations between h_0/t and the limits of α , for which the steady cutting process appears, are shown in Fig. 20.

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