6. Conclusion

As the result of experimental studies about the generating mechanism, the following conclusion was derived.

(1) The largest noise source is load fluctuations in the direction of line of contact.

(2) Sound intensity is proportional to fluctuating load and square of fluctuating frequency, except in the region of higher frequency.

(3) Tooth profile error has much effects upon noise, especially under the light load.

(4) Separation occurs at a certain speed for the roughly finished gear, dynamic load and noise suddenly increase, and a strange noise which has subharmonic frequency is occasionally produced.

7. Acknowledgement

The author would like to express hearty gratitude for the encouragements and helpful sugges-

tions to Dr. T. Nakada, Professor of Tokyo Institute of Technology, and Dr. J. Ishikawa, Professor of the same Institute. Gratitude is also extended for many helpful discussions to Dr. M. Akeyama, Dr. M. Utagawa and other members of Mechanical Engineering Research Laboratory of Hitachi Ltd. All experimental work was done with kind cooperation of Mr. Tanikawa, a member of the same Laboratory.

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The Effects of Lubrication on the Press Forming Limits of Sheet Metals*

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The results of mathematical analyses or experiments of punch-stretching and deep drawing have been examined to obtain a systematic understanding of lubrication effects on the press forming limits of sheet metals. For this purpose, the relations of lubrication effects to size and shape effects in press forming have mainly been investigated.

The limiting stretching depth depends strongly upon workhardenability of sheet metal, but the correlation between them is weakened by the presence of friction in the round-bottomed punch-stretching rather than in the flat-bottomed one.

In non-axisymmetric punch-stretching, there is the accumulation effect which is caused by the combination of whole and local geometries of a pressed part and is also affected by lubrication. In deep drawing, the lubrication effect on the limiting drawing ratio is complicated and is generally stronger in non-axisymmetric drawing than in axisymmetric one.

1. Introduction

Most of the already-published papers on lub-

rication have treated the fundamental mechanism of lubrication in press forming of simple shape⁽¹⁾⁻⁽⁶⁾. A sufficient explanation has not been given yet for the mechanism and effect of lubrication in press forming of complicated shape.

Lubrication effect is caused by the contact and relative displacement of a blank with a punch and a die, and is therefore affected by the type of

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forming and the applied place of lubrication. Each deforming region is connected with the lubrication effect as shown in Table 1 and with the forming shape as shown in Fig. 1.

Fig. 1 Deforming regions of a blank in a die cavity in axially symmetrical deformation

Fig. 2 Radial strain distribution models for combinations of workhardening and formed shape in pure punch-stretching at $\mu=0$

2. Lubrication effect in die cavity region

2.1 Forming shape and mechanical properties of sheet metal

The fundamental forming shape is here regarded as the combined shape of punch flat-bottom region, punch profile region and overhang region, according to Fig. 1.

The deformation of a blank in a die cavity is most strongly governed by the combined property of stress-strain relation, such as workhardening. On the basis of mathematical and experimental analyses⁽⁷⁾⁻⁽⁹⁾, Fig. 2 illustrates typical examples of the deformation mode of a blank in a die cavity in pure punch-stretching without the draw-in of the shrink flange region, with respect to forming shape and workhardening. These strain distribution models are given by radial strain ϵ_r and, for simplification of the models, the rupturing radial strain is assumed to be constant.

The forming depth is determined by the integrated quantity of ϵ_r and the geometrical coefficient of every region. In the absence of friction, the integrated quantity of ϵ_r in the die cavity is strongly and positively correlated with the workhardening of sheet metals, when the blank is ruptured. Therefore, the stretchability of sheet metals can be ranked by workhardening without influence of formed shape, when friction is absent or negligibly small.

2.2 Lubrication effect on deformation in die cavity

The direct effect of lubrication on the deforming behavior of a blank appears over the punch profile region. Inasmuch as the stress and strain distributions in

Table 1 Application and effect of lubrication

Place of lubrication		Effect of lubrication
Die cavity	Punch flat bottom region	Increase of deformation
	Punch profile region	Control of rupturing force
	Overhang region	
Die surface	Die profile region	Control of increase in transmitted stress
	Die face sliding region	Decrease of flange resistance to deformation
		Control of strain gradient

the flat-bottomed and overhang regions are mainly governed by the transmitted stress from the punch profile region, they are indirectly affected by friction.

As for the forming limit, lubrication causes some effects on the rupturing punch force as well as average ductility*.

The forming shape in the die cavity is divided into horizontal and vertical shapes, for consideration of lubrication. Vertical shape: The stress and strain distributions over the punch profile region, in the case of punch-stretching using a round-bottomed punch in the presence of friction, are schematically shown in Fig. 3 in accordance with the results of the mathematical analyses⁽⁹⁾. These figures relate to different values of frictional coefficient μ with stresses being constant at the top of the punch. With increasing μ , the maximum points of σ_r and ϵ_r approach, from the top of the punch, the boundary between the punch-blank contact region and the overhang region. The same but weaker tendency is observed in the σ_θ and ϵ_θ distributions.

Fig. 4 illustrates two examples of the relations that exist between workhardenableity and ϵ_r distribution at $\mu \neq 0$, one for the flat-bottomed shape and another for the round-bottomed shape. In the round-bottomed punch-stretching, the presence of friction tends to produce a state where the region of strain in negative correlation with workhard-

enability remains in the middle of the blank even at the moment of rupture. In the flat-bottomed punch-stretching, there is no remarkable difference between $\mu=0$ and $\mu \neq 0$. It may therefore be said that the stretching limit of the flat-bottomed punch can hardly be affected by friction, and that it is significantly in positive correlation with workhardenableity.

Horizontal shape: While the displacement of every portion in a blank takes place along the radial direction only, in the axisymmetric punch-stretching, the displacement occurs in the radial and circumferential directions in the non-axisymmetric punch-stretching, so the lubrication effect is present in the circumferential direction as well as in the radial direction. In general, it may be said that the decrease of friction increases the circumferential displacement of the material from the region of larger radius of curvature to the region of smaller one in the horizontal cross section of the punch. Lubrication may be effective to regulate the local concentration of deformation as the occasion demands.

2.3 Forming force and lubrication effect

Fig. 5 illustrates examples of lubrication effect on the curve of punch load to punch travel in pure punch-stretching with flat-bottomed punches of various shapes. The presence of friction tends to control and localize the deformation of the blank and therefore to increase the required punch load at the same depth. The increase of the maximum punch load due to lubrication becomes larger with increasing axisymmetry of the punch cross section.

3. Lubrication effect in the sliding region on die surface

3.1 Lubrication in die profile region

The behavior of lubrication in the die profile region may be similar to that in the punch profile region. For control of wrinkling in the die profile

Fig. 3 Effect of friction on stress and strain distributions in a punch-blank contact region over a round-bottomed punch

* Average ductility means the average strain over all the deformed areas at the forming limit of rupture.

Fig. 4 Radial strain distribution models for different workhardenableities at $\mu \neq 0$, in flat- and round-bottomed punch-stretchings

region, it may be impractical to increase the die profile radius beyond a certain extent in actual press forming.

The restraint of circumferential displacement in the die profile region is relieved by improving lubrication. In contrast to the punch profile region, lubrication makes easier the displacement of the material from the region of smaller radius of curvature to the region of larger one in the die profile region.

3.2 Lubrication effect on deformation on die surface

A required force for shrink-flange deformation is determined by the average deforming strength

of the flange and the frictional resistance between the blank and the die surface. The decrease of the friction tends to produce the flange wrinkling and increase the required blank holding force.

In non-axisymmetric punch-stretching, it may be expected sometimes that the strain gradient in the circumferential direction is relieved with increasing friction and thereby the deforming strength of the flange is varied, while the deformation behavior of the blank is less affected by varying the flange frictional resistance.

It has been found as a general tendency that the decrease of the required punch load due to decreasing friction is more remarkable in the non-axisymmetric shape than in the axisymmetric.

4. Illustrations of lubrication effects in press forming

4.1 Lubrication effect in punch-stretching

Fig. 6 illustrates the relation between the n value, which is a test value of work-hardensability of sheet metals, and the $h_{\max}$ under the usual lubricating condition.

When the overhang region ($r_2 - r_1$) increases, the correlation of the n value with $h_{\max}$ becomes stronger both in the flat- and round-bottomed punch stretchings. With the decreasing overhang region, the said correlation is strongly weakened or becomes negative in the round-bottomed punch-stretching, while it is hardly affected in the flat-bottomed.

Fig. 7 illustrates the relation between the n value and $h_{\max}$ for various r_p and lubricating conditions.

In such experimental conditions as described in Fig. 7, among the n value, lubrication and r_p , $h_{\max}$ is most strongly affected by change in r_p , next by the value and last by lubrication. The lubrication effect on $h_{\max}$ is effective at r_p being more than three times sheet thickness, and is increased by increasing r_p . It is also increased with increasing n value.

Among materials of small difference in n value, the correlation between n value and $h_{\max}$ is disturbed in the presence of friction which increases with increasing r_p .

Material: 0.9 mm thick Al-stabilized mild steel $n=0.216$, $r=1.60$
 Broken line: no lubrication
 Full line: perfect lubrication with polythene and lubricant oil
 Clamping dia.: approx. 340 mm

Fig. 5 Curves of punch load-punch travel in pure punch-stretching

Fig. 6 Relation of limiting stretching depth with n value Fig. 7 Relations between limiting stretching depth and n value for various punch profile radii and lubricating conditions in pure punch-stretching

Materials: 0.9 mm thick, $2r_1 = 20$ mm, $2r_2 = 23$ mm, Clamping dia.: 33 mm
 ---x--- No lubrication, ---△--- High-viscosity oil, ---○--- Perfect lubrication

Fig. 8 Rupturing force and rupturing diameter

4.2 Punch-stretching test and lubricating ability test

For rating the stretchability of sheet metals in various forming conditions, it is necessary to employ a series of tests consisting of the combination of fundamental shape and flange restraint conditions, as described in the authors' other report⁽¹⁰⁾. In comparison with the round-bottomed punch, the flat-bottomed punch-stretching test is superior because it corresponds to the round-bottomed punch-stretching under perfect lubrication and represents the formability of high universality.

In contrast to this, as for the lubricating ability test of lubricant, it may be desirable to employ

the round-bottomed punch-stretching test and the material of high n value for more sensitive discrimination of lubricating ability.

4.3 Rupturing force and lubrication effect

Generally, the rupturing force tends to increase with increase of the stretching limiting depth, because the angle between the direction of punch travel and the tangential direction of the overhang region is decreased as the limiting stretching depth increases.

Fig. 8 illustrates the relation between the rupturing diameter and $P_{\max}/P_b$ ($P_{\max}$: maximum punch load, P_b : $2\pi r_1 t_0 \sigma_B$). When r_p is large, for

Material: 0.9 mm thick Al-stabilized steel
 $n=0.216$, $r=1.60$
 Clamping dia.: approx. 340 mm

Fig. 9 Effect of change in horizontal punch contour on $h_{\max}$ for different lubricating conditions

(a) Strain distributions in pure stretching of square punch with 5 mm corner radius

(b) Strain distributions in pure stretching of square punch with 25 mm corner radius

(d) Strain distributions in pure stretching of elliptic punch with 25 mm least radius of curvature

(c) Strain distributions in pure stretching of elliptic punch with 15 mm least radius of curvature

Fig. 10-2

example, $r_p=10$ mm, $P_{\max}/P_b$ is rather small probably because of the said angle being large. At $r_p=1$ mm, it is lowered by the effect of severe bending. The bending effect on the maximum punch load is almost negligible at r_p =more than 3 times sheet thickness.

4.4 Horizontal shape and lubrication effect

Fig. 9 gives the relations between the limiting stretching depth and the smallest radius of curvature, for illustrating the horizontal shape effect and the lubrication in non-axisymmetric punch stretching.

In the cylindrical-to-square punch series, the $h_{\max}$ and the lubrication effect (a difference in the $h_{\max}$) are both the largest in the axisymmetrical cylindrical punch and, in the square punches, both decrease along with the decrease in the corner radius. In contrast to the square punch, in the cylindrical-to-elliptic punch series, the relations of the $h_{\max}$ and the lubrication effect with the smallest radius of curvature are not so simple.

Fig. 10 illustrates the strain distributions, in the punch-stretching with square and elliptic punches, which have been obtained as the result of investigation into the reason why the stretch forming characteristics of elliptic punches are different from those of square punches.

In the middle portion of the punch bottom in the case of square punch-stretching, there is a state of equibiaxial tensions the same as in the bottom of the cylindrical punch. In the peripheral regions of the flat-bottom, there is a state of biaxial tensions in the straight region thereof where the tension in the direction perpendicular to the periphery is predominant, while there exists a state of deformation somewhat similar to what

happens in the case of cylindrical stretching, though there is a state of stress and strain gradients in the corner region. These deformation modes are schematically shown in Fig. 11.

In the elliptic punch-stretching, there does not exist a state of equibiaxial tensions in the flat-bottom, but there is instead a state of biaxial tensions, accompanying a larger stress along the minor axis over all the bottom surface of the punch. The reason why the stretching limit is not in agreement with the severity of geometrical shape may be that, at the portion of the smallest radius of curvature, the displacement of every portion in the direction of the major axis is accumulated due to the deformation component of the major axis direction accompanying the tensile deformation thereof in the direction of the minor axis, and this accumulation effect mollifies the severity of deformation. Thus, it has been made

Fig. 11 Schematic representation of deformation mode in square punch-stretching

(b) Cylindrical-square punch series
Material: 0.9 mm thick Al-stabilized mild steel
Fig. 12 Lubrication effect on deep drawing limit

clear that it is inadequate to make forming classification or severity classification simply on the basis of classification of geometrical shapes.

4.5 Lubrication effect in deep drawing

Fig. 12 illustrates the lubrication effect on the deep drawing limit of cylindrical, square and elliptic punches for a square-shaped blank.

While L_1/l_1 is the largest at $r_1/l_1=0.15$ under lubrication with ordinary oil except on the punch bottom, according to the already-published report, the two lubricating conditions under perfect lubrication with polythene film and viscous lubricant give different effects on drawing limit respectively for various shapes of punches.

The drawing limit is remarkably increased by improving lubrication especially in the deep drawing of square punches with such a small corner radius as $r_1/l_1=0.05$.

According to these experimental results, it may be clear that, in such a non-axisymmetric deep drawing as the square, the concentration of shrink-flange deformation into the corner region is relieved by improving lubrication and thereby the resistance to deformation in the flange corner region is reduced.

As the effective lubrication makes possible the press forming of a deep pressed part, a new kind of rupture which is called "Wall breakage" tends to take place in the wall at the corner region in the deep drawing of a square punch or at the region of smallest radius of curvature in an elliptic punch⁽¹¹⁾.

This new type of rupture suggests that it will be necessary to find new techniques for preventing such breakages as the above and to establish a new severity classification with respect to new types of rupture and forming techniques, with the progress of lubrication technique.

5. Conclusion

Friction between a blank and press forming

tools in press forming of sheet metals exerts very complicated effects on press performances in connection with mechanical properties of sheet metal, forming shape and size, and forming type. It may be necessary to make further investigations into the lubrication effects on stress and strain distributions in press forming of various shapes, in order to obtain the accurate understanding of complicated lubrication effect.

The shape and size effect in press forming may be regarded as a kind of forming techniques including lubrication. Therefore, the severity classification of pressed parts can not easily be made by simply classifying geometrical shapes. It may be said that the selection of sheet metal to be used can hardly be standardized without considering the lubrication effect.

Although a trial is made to establish the systematic understanding of lubrication in press forming, it is still insufficient in this paper. It will sometime be possible to establish the lubrication technique which relates more closely the fundamental forming techniques with mechanical properties of sheet metals and thereby improve the press performances during the step of planning the forming process.

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