It is problematical to use p instead of P for the results of this test in which the contact load is supported by a hydrodynamic oil pressure. But if p is used more often than P for the basis of gear design, it will be necessary to arrange them in terms of $\eta(V_r/\rho)/p$.

(2) The measuring apparatus used is shown in append-Fig. 1. The shafts and the bearings were made to high accuracy, and both axes were set parallel to each other perfectly, and the bearings had no clearance at all. When the apparatus was set at the maximum magnifying power, the length of 0.1μ was found as the angular displacement of 3 degrees. But it is problematical to show the relation between h_0 and R by only one curve since the data points of h_0 disperse pretty wide by as shown in Fig. 15 (a). In this case, it is a problem to choose the value of voltage between disks.

The fluctuation of readings is small. The oscillograph record is shown in Fig. 18. In order to find out the accurate oil-film thickness between disks, not only the elastic deformation but also the variation of oil-viscosity owing to the variation of temperature and pressure between disks must be taken into consideration. Considering the elastic deformation, its effect on the oil-film thickness measured by this method is seen to be small, since the quantity

of oil participating in the measurement of electric resistance is not changed by the elastic deformation. The measured h_0 is larger than its theoretical value obtained from Eq. (2) and it is seen that the measured value gives the mean value of clearance contained in the roughness and the waviness.

(3) If we take a value of S intermediate between 0 and 0.01, the value of μ can be found in between the corresponding values, and it will become rather close to the value obtained at $S=0.01$, because the existence of sliding motion is the cause which produces the difference in the lubricating characteristic. Moreover, the value of S can not be measured accurately in the range of $S < 0.01$, so we did not test in this range.

We could not locate the chief cause which produces the maximum value of μ at $S=0.06$. The effect of oil temperature is seen to be small. It may be possible that the value of S which gives the maximum value of μ will be changed by the lubricant which has a different characteristic of viscosity depending on the temperature and the pressure.

It can not be said that the chief cause producing the pitting is the effect of the maximum friction at $S=0.06$, but it may be said that it is one of the causes.

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Pressure Lubricated Deep Drawing*

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In this paper, a method promoting a fluid lubrication in the deep drawing of sheet metals is introduced. Possibilities of this method are proved by laboratory scale experiments on aluminium and reported. It is shown that the process brought about many encouraging results for the improvement of the drawing ratio.

Some contributions are made to the practical development of this process by clarifying fully the pressure characteristic of this method which is an important key to its success.

Chapter I. Conception of the mechanism, characteristics and possibilities

1. Introduction

In the practice of deep drawing it is usually

tried, for the economical reason, to raise the drawing ratio attainable in a single operation as high as possible. However, in so far as we have recourse to the orthodox method, in which the ordinary rigid tools are used, there seems to be scarcely a possibility of improving it far above 2.0. Since the only way available was thought to be found in the field of lubrication, the papers pertaining to the

* Received 31st March 1958 and 8th April, 1960.

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application of the new lubricants have been appearing increasingly in the recent publications⁽¹⁾⁽²⁾. Yet, the conditions treated in them are limited almost to the cases of boundary lubrication. If it becomes possible to establish a fluid lubricating condition over the die surface, the frictional resistance will be reduced markedly with a consequent contribution to raising the drawing ratio. Moreover, the drawn component thus obtained will come to have a good surface appearance due to the protection from the inter-metallic contact between surfaces of the material and the die by a viscous insulating film of the lubricant. Besides these, if the various phenomena experienced in the case of zero friction of the die surface are able to be ascertained, the boundary frictional phenomena in the ordinary process will be clarified by comparing this case with the ordinary case. Considering the above, the authors attempted to introduce a pressure lubrication method in the deep drawing, and succeeded to an appreciable degree. This paper deals with this drawing method.

Hereafter, it should be noted that the pressure lubricated deep drawing process would be referred to simply as "the pressure process" and the ordinary drawing process as "the ordinary or the conventional process".

2. Mechanism of the pressure lubrication and conditions of the experiment

To forcibly lubricate the die surface we might introduce one of the many pressure lubricators available. But, as might be expected, attachment of a hydraulic pressure unit would certainly complicate the apparatus. So, we accepted a very simple method of the pressure lubrication which was as follows: Suppose a mechanism as shown in Fig. 1, in which back of the die hole is closed so as to compose a pressure chamber and filled with a lubricating fluid. If the punch plunges into this die chamber together with the material, a pressure

Fig. 1

will naturally be generated in the fluid closed by the die chamber and the deforming material. And, if the compressibility of the fluid is small, the fluid displaced by the punch and the material will have to escape over the die radius into the upper side clearance between the die and the flange part of the blank. Thus, over the die surface an almost perfectly fluid lubrication may be established.

Fig. 2 shows the constitution of the hydraulic system of this process which was constructed for the subsequent experiments. When the working starts in this drawing unit, the punch ① ascends forcing the blank (not specified in the figure) into the die chamber ④ in which a fluid pressure is generated. In this unit, the generated pressure is taken up either by a measuring diaphragm ⑨ or by a pressure gauge ⑧. But, for the purpose of pressure recording, the deflection of the diaphragm ⑨ was optically magnified by an auto-collimating principle and recorded on an oscillograph paper together with the punch load and the holding force simultaneously⁽³⁾.

For the purpose of driving the die unit (the punch was fixed in this case) an Olsen type testing machine converted to attach the unit was used.

The tools and the materials used for the characteristic tests are as those in Table 1.

① punch	⑤ lead pipe
② die	⑥ three way joint
③ blank holder plate	⑦ relief valve
④ pressure chamber of the die	⑧ pressure gauge
	⑨ pressure measuring diaphragm

Fig. 2

3. Estimation of the necessary pressure

On constructing the above unit, in order to determine the size of tools and connections, we had to at least be able to predict the maximum pressure necessary to accomplish the process. In this instance, the point to be considered might be that: If the generated pressure could not overcome the pressure on the die radius exerted by the material during deformation, the continuous viscous flow of the lubricant would not be established throughout the die surface. Under this circumstance, the necessary and attainable maximum pressure must be determined by the maximum pressure on the die radius due to material deformation. For simplicity, if the material behaves as though a perfectly flexible membrane, the maximum pressure on the die radius will be represented by

$$p_{d\max} = t \left(\frac{\sigma_r}{r_d} - \frac{\sigma_\theta}{R_1} \right) \dots \dots \dots (1)$$

approximately. Where t =material thickness in mm, σ_r =radial stress in kg/mm², σ_θ =circumferential stress in kg/mm², r_d =radius of the die profile in mm, and R_1 =radius of the die hole in mm. Using, as the approximate condition of yielding, $\sigma_r - \sigma_\theta = 2k$, where k =yield stress in simple shear of the material, the approximate maximum radial stress at the die radius may be written as $\sigma_r = 2k \ln \beta$, where β =drawing ratio. Assuming that the material thickness does not change, Eq. (1) yields, with above σ_r ,

$$p_{d\max} = 2k \left[\frac{1}{\rho_d} \ln \beta + \frac{2}{\delta} (1 - \ln \beta) \right] \dots \dots \dots (2)$$

where $\rho_d = r_d/t_0$, t_0 =blank thickness in mm and $\delta = 2R_1/t_0$.

In the case of $\beta = 2.5 \sim 2.6$ the second term in the right hand side of Eq. (2) will become a

relatively small quantity. Neglecting this term in the equation, the necessary forcing pressure of lubrication will be

$$q = p_{d\max} \doteq \frac{2k}{\rho_d} \ln \beta \dots \dots \dots (3)$$

approximately. For example, with the values $t_0 = 0.3$ mm, $r_d = 1.0 \sim 2.5$ mm, $2k = 10$ kg/mm² and $\ln \beta = 1.0$ in accordance with the experiment, we have to expect a pressure $q \doteq 120 \sim 300$ kg/cm² from Eq. (3).

4. Fundamental results

4.1 The pressure and the load diagrams recorded during working, and the surface quality of the drawn component

Fig. 3 shows an example of the experimental records. The points identified by A in the figure show that at this instant the lubricant penetrates through the die surface for the first time. The points identified by B indicate the instant when the outer rim of the blank starts to leave the holder plate and is drawn into the radius of the die. At point A, the pressure and the punch load curves sharpen and thereafter drop to balanced values. Generally speaking, both curves increase monotonously from the instant immediately after the penetration point A to the ultimate point B.

The blank holder plate is loaded by an elastic

A sample record

Fig. 3

Table 1

Tools	Die		Punch		
	Diameter	25.00 mm (hole dia.)	24.01 mm (outer dia.)		
	Radius	1.0, 1.5, 2.5, 4.0, 6.0 mm	2.5, 4.0, 8.0, 12.0 mm		
Blank	Material	Aluminium (Specification class 3)	Half hard, smooth finished sheet, annealed in a salt bath for an hour at 400°C, after the treatment the hardness $H_v = 20 \sim 23$		
	Size	Thickness 0.2, 0.3 mm Diameter 44, 62 mm	Drawing ratio 1.83, 2.58		
Lubricants	For pressure lubrication	Coefficient of viscosity (at 20°C)	# 30 Motorex oil about 450 cs	Rape oil about 80 cs	#120 Cylinder oil about 2000 cs
	For boundary lubrication	Tallow Sulphurized machine oil	Before working, either of these lubrications were applied on both sides of the blank		

Drawing speed 1 mm/sec

Conventional process
Blank diameter $D_0=44$ mm,
Die radius $r_d=2.5$ mm,
Drawing ratio $\beta=1.83$

Pressure process
Punch radius $r_p=4$ mm,
Blank thickness $t_0=0.298$ mm,
Lubricant; Tallow & #30 Motorex oil
(a)

Conventional process

Pressure process

(b)
Fig. 4

diaphragm having a spring constant of $k_s=1936$ kg/mm in this apparatus. At the instant A , the lubricant penetrates from the die chamber through the die face into the free air forcibly opening its way between the material and the die face. This causes the holder plate to be pushed back to some degree with a consequent increase in the spring load of the diaphragm. The sudden increase in the holding force in Fig. 3 shows this effect, and the amount of increase in the holding force naturally corresponds to the thickness of the lubricating film formed in the case.

Fig. 4 (a) shows a comparison between two components drawn by the conventional process (left) and this process (right). And, Fig. 4. (b) shows the comparison of the surface quality.

4.2 Component of the drawing load due to die friction

Fig. 5 (a) shows a comparison between the two experimental records. The dashed lines correspond to the pressure process and the full lines to the conventional process. The difference in the holding force of both cases refers to the difference in the film thickness of the lubricant. However, at point B' in the figure, the relatively thick film of the pressure process seems virtually to disappear.

The punch load in the case of the pressure process is essentially higher than that of the

ordinary process. This is due to the resistance caused by the generated pressure in the die chamber, so that the effective punch load P_e necessary for deforming solely the material will be obtained by subtracting this resistance of hydraulic pressure from the actually recorded punch load P_p . If the die friction is zero in the case of the pressure process, P_e will not contain any frictional resistance of the die surface. Therefore, the difference of the actual punch load P_e in the ordinary case from P_e will be recognized as a frictional component of drawing force in the conventional drawing. This frictional component is shown by the difference between the full line and the dashed line in Fig. 5 (b). In the figure, both curves intersect at point B'' . Yet, it should never be thought that at this point the die friction in the ordinary case might become zero. In this circumstance, the frictional resistance of the die surface seems to be included rather in P_e itself due to failure of the lubricating condition prior to this stage of the pressure process.

4.3 Effect of the holding force

In Fig. 6, a comparison is made between the recorded diagrams of the processes in which various holding forces are applied. As already mentioned, the displacement of the holder plate immediately after the point A is recorded as a sudden increase

in the holding force in the figure. It may also be thought as a thickness of the lubricating film formed, and in fact it is measured as 0.03 to 0.04 mm in these cases. This film thickness is also estimated theoretically by the equation of viscous flow through a clearance between parallel walls. When the notations shown in Fig. 7 are used, the equation of the pressure distribution may be written as

$$-r \frac{dq}{dr} = \frac{6\mu Q}{\pi h^3} \quad \dots\dots\dots (4)$$

assuming a laminar and axially symmetric flow and h to be independent of r . Since the summation of the pressure q over the flat part of the die must be equal to the holding force, the following relation exists,

$$2\pi \int_{R_2}^R q r dr = H_0 + k_s h \quad \dots\dots\dots (5)$$

where μ = viscosity of the lubricant in kg sec/mm², Q = volume of flow per unit time in mm³/sec and H_0 = initial holding force in kg.

By eliminating q from Eqs. (4) and (5), the equation which determines the film thickness will be obtained as

Fig. 5

$$h^4 + \frac{H_0}{k_s} h^3 = \frac{3\mu Q}{k_s} R_2^2 \left[\left(\frac{R}{R_2} \right)^2 - 1 - 2 \ln \left(\frac{R}{R_2} \right) \right] \quad \dots\dots\dots (6)$$

When the experimental conditions are given, h will be calculated by Eq. (6), and the result thus obtained is as shown in Fig. 8.

The dashed line in the figure indicates the calculated values, and the experimental values

Fig. 6

Fig. 7

Fig. 8

joined by the full line correspond to the measured film thickness immediately after *A*. In this paper, the pressure at this stage will subsequently be referred to as the "flow-out pressure" and denoted by q_f .

The flow-out pressure q_f and the maximum pressure $q_{\max}$ measured from the diagrams in Fig.

Initial blank holding force H_0 kg

Fig. 9

$D_0=54$ mm, $r_p=4$ mm, $r_d=2.5$ mm, $t_0=0.316$ mm

Lubricant; Sulphurized oil & #30 Motorex oil

(b)
Fig. 10

6 are plotted against the initial holding force and shown in Fig. 9; the theoretical curve of q_f is a dashed line in the same figure. Though the theoretical and experimental values are somewhat different in their inclinations, it may at any rate be said that, when the other conditions are kept constant, the initially generated pressure is governed by the holding force considerably, and so we can control the feed pressure by changing the initial holding force.

4.4 Effect of the lubricant

To examine the effect of the kind of lubricant, a sort of rape oil and a #120 cylinder oil are applied and compared the cases with the #30 Motorex oil. The comparison diagrams are shown in Fig. 10 (a), in which the conditions other than the kind of the lubricant are common.

It may be shown in the figure that the higher the viscosity of the lubricant is, the thicker the formed film. This will be understood from Eq. (6). The pressure q becomes also relatively high in the case of a high viscous oil. In Fig. 10 (b), a comparison is made between the effective punch loads P_e for these cases. Though the curves coincide with each other approximately, they are somewhat lower for the relatively viscous lubricants. This indicates that even in the case of the pressure process a perfectly fluid lubrication in reality is not easily attainable and a somewhat mixed lubricating condition is likely to occur.

5. Possibility of the pressure process

The possibility of a deep drawing process is represented most explicitly by the attainable drawing ratio. To explain the possibility of this process, two examples of the drawn component by this method are shown in Fig. 11. In these, the blanks were annealed aluminium both 62 mm in diameter

Material; annealed aluminium

$D_0=62$ mm
 $t_0=0.301$ mm
 $r_p=12.0$ mm
 $r_d=2.5$ mm
 $\beta=2.58$

$D_0=62$ mm
 $t_0=0.224$ mm
 $r_p=4.0$ mm
 $r_d=2.5$ mm
 $\beta=2.58$

Lubricant: Sulphurized oil
#30 Motorex oil

Fig. 11

and 0.224 mm and 0.301 mm in thickness. The punch diameters were both 24 mm and the punch radii are 4 mm and 12 mm respectively.

The drawing ratio realized was both 2.58, whereas, that obtained in the ordinary process, was merely 2.08.

6. Conclusion for chapter I

It was stated that by a relatively simple mechanism, a force feed lubrication over the die surface in the deep drawing was realized.

The fundamental characteristics and the possibilities were ascertained by experiment with respect to aluminium blank.

The process brought about many an encouraging result and seemed satisfactory in the improvement of the drawing ratio.

Chapter II. Mechanism of the material deformation and the pressure generated

7. Thickness strain in the material lying around the punch head

In Figs. 12 and 13, a comparison is made, showing the thickness strains, for the deformations of the material in the neighbourhood of the punch head. In the case of the pressure process the material of this portion is so much strained from almost the first stage of the process that afterwards the strain is added very little in this portion and

the deformation proper is exclusively developed in the outer region of the material. Accordingly, the straining is successively stopped from the inner portion of the material. This means that the fluid pressure squeezes the material around the punch head and this action protects the material from overstraining caused by transmission of the tension necessary for the deformation of the flange part of the material. It is also shown in these figures that in the pressure process the so called "wall neck" in the ordinary process vanishes completely. This means that, in this process, the material being drawn into the die hole does not bear the total tension needed to deform the flange as in the ordinary process, but starting from the inner portion, it is squeezed successively against the punch surface by the fluid pressure, thus rather being drawn centripetally by the fluid than being stretched vertically by the solid punch in the ordinary process.

The difference of these mechanisms is shown in Fig. 14. This squeezing action in the pressure process shown in the right side of the figure seems very preferable for the improvement of the drawing ratio.

8. Ultimate thickness strain

In Figs. 15 and 16 the ultimate thickness strains for various punch profile radii are compared with one another, in which Fig. 15 refers to the

ordinary case and Fig. 16 to the pressure process.

The point to be noticed in these figures is that in spite of the different processes the minimum thicknesses of the material at the so called "profile neck" attainable in the optimum punch radius do not differ so seriously showing that even with the pressure process the necessary minimum deformation in this portion of the material could not be controlled freely. Consequently, if the total tensile load were wholly transmitted by that section of

the material, the drawing ratio would not be so improved even by the pressure process. This may lead one to think that in its effectiveness, the reduction of friction by the pressure lubrication will stand back and be replaced by the aforementioned squeezing action which is already recognized in the hydro-forming processes.

After all, it should be concluded that the reason why in the pressure process a relatively higher drawing ratio was attained was based rather on

Punch penetration 2.8 mm

Conventional process

Punch penetration 3.1 mm

Pressure process

Fig. 14

Initial blank position mm
Conventional process
Blank diameter $D_0 = 50$ mm
Blank thickness $t_0 = 0.280$ mm
Punch diameter $d = 24$ mm
Die radius $r_d = 2.5$ mm
Initial blank holding force $H_0 = 210$ kg
Lubricant; Sulphurized oil

Fig. 15

Initial blank position mm
Pressure process
Blank diameter $D_0 = 50$ mm
Blank thickness $t_0 = 0.280$ mm
Punch diameter $d = 24$ mm
Die radius $r_d = 2.5$ mm
Initial blank holding force $H_0 = 210$ kg
Lubricant; Sulphurized oil
#30 Motorex oil

Fig. 16

the hydroforming-like straining than on the reduction of the drawing load due to the pressure lubrication.

9. Effect of the die radius and the blank thickness (The flow-out pressure, the closing point and the representative pressure.)

To examine the effect of the die radius and the blank thickness on the generated pressure, the tools and the materials shown in Table 2 were prepared for the experiment. The pressure and holding force diagrams recorded in this case are presented in Fig. 17, where (a), (b) and (c) correspond to the cases where the die radius alone, the blank thickness alone and the holding force

alone are varied respectively, the other factors being fixed. The typical trends of curves in common with these all are represented in Fig. 18. In the figure there exist some specific points indicated by A and B. The former in the curve being the penetration point, and the latter the ultimate point. Point C in the curve represents the characteristic instant at which the pressure suddenly rises from a balanced flow-out pressure. As will be seen, point C appears in the various stages of the process according to the conditions indicated in Fig. 17, such that the smaller the blank thickness or the larger the die radius or the larger the holding force, the later the appearance of C in a process. At a

Conditions of experiment (unit mm)
 Blank; annealed aluminium, (specification class 3)
 diameter $D_0=50$, thickness t_0 =various
 Die; hole diameter $d'=25$, radius r_d =various
 Punch; diameter d_0 =about 24, radius $r_p=4.0$
 Lubricant; Tallow & #30 Motorex oil

Fig. 17

point of the holding force curve corresponding to C, the force also suddenly decreases and the decrement depends on the die radius and the blank thickness too. This change in the holding force, as already mentioned, represents that of a film thickness on the flat part of the die, so that the decrement corresponds to the thinning of the film. Under these circumstances, one cannot help thinking that C is a point representing the condition of deformation at which the material starts to adapt itself to the form of the die radius. That is to say, before C, the material may deform rather apart from the die radius due to the fluid pressure as shown in Fig. 14, right; but after C, the punch, having traveled to some degree, may force the material to overcome the pressure and make the material close the die chamber more tightly than before so that the pressure in it may naturally rise. Thus C is regarded as the critical point for that change. Hereafter, C will be referred to as "the closing point". As described previously, the flow-out pressure q_f which generally governs the pressure before the closing point could be calculated by Eqs. (4), (5) and (6). And originally, from Eq. (4), the theoretical value of q_f may, denoted by q_g for the sake of distinction, be written as

$$q_g = (6\mu Q / \pi h^3) \ln \left(\frac{R}{R_2} \right) \dots\dots\dots (7)$$

Fig. 18

where the notations are the same as in the preceding chapter. Whether this theoretical value q_g agrees with the experimental q_f or not will be discussed in the next section. From the significance of the closing point, the pressure after C will naturally be thought to be governed by the pressure exerted by the material on the radius which was given by Eqs. (2) and (3). If $2k \ln \beta$ in Eq. (3) were not changed, the value of q would depend on $1/\rho_d = t_0/r_d$ alone. The points in Fig. 19 belong to this kind of pressure measured in a comprehensive experiment. The pressures referred to are all corresponding to those at the maximum point of the effective punch load, and will be referred to as "the representative pressure" being denoted by q_x . The dashed line in the figure is an example of the theoretical curve taking $2k=10$ kg/mm² and $\beta=2.0$. In the region of a relatively

Fig. 19

Table 2

Die			Punch
Tools	Radius	$r_p=4.0$ mm	$r_d=1.0, 1.5, 2.5, 4.0, 6.0$ mm
	Diameter (mm)	24.25, 24.01, 23.81, 23.27	25.00
Blank	Thickness t_0 (mm)	0.225, 0.291, 0.402, 0.619	Diameter $D_0=50$ mm
	Material	Half hard, smooth finished Aluminium sheet (Specification class 3), annealed in a salt bath for an hour at 400°C $H_v=20\sim23$, Tensile strength=8.5~9.0 kg/mm ² 0.2 % proof stress=3 kg/mm ²	
Lubricants	For pressure lubrication	Tallow	
	For boundary lubrication	#30 Motorex oil, coefficient of viscosity about 450 cs (at 20°C)	

Drawing speed 1 mm/sec

large t_0/r_d , the representative pressure lies nearly on a straight line and this fact seems to show the approximate validity of Eq. (3).

10. Effect of the spring constant k_s of the holder

As Eq. (6) contains the spring constant k_s

Fig. 20

..... Raw rubber 8mm thick insertion; $k_s=484$ kg/mm
 ----- Vulcanized rubber 8mm thick insertion; $k_s=866$ kg/mm
 - · - · - Vulcanized rubber 4mm thick insertion; $k_s=1119$ kg/mm
 ——— Steel diaphragm; $k_s=1936$ kg/mm
 Conditions of experiment (Unit mm)
 Blank; annealed aluminium (specification class 3) diameter $D_0=50$, thickness $t_0=0.395$
 Die; hole diameter $d'=25$, radius $r_d=2.5$
 Punch; diameter $d_0=23.81$, radius $r=4.0$
 Lubricant; Tallow & #30 Motorex oil

Fig. 21

of the holder plate, the film thickness and the generated pressure will naturally be affected by it. To ascertain this, experiments were made changing the pressure medium of the holding device by inserting various kinds of rubber ring between the holder plate and the hitherto used steel diaphragm. In Fig. 20, two examples of the load deflection characteristics in this case are shown. The curves presented in Fig. 21 are the pressure and the holding force recorded in this case. As will be seen, when k_s is diminished, the closing point in the pressure curve appears in the earlier stage of

Fig. 22

Fig. 23

the process. The flow-out pressures q_f in the cases of a rather rigid holder and a rather flexible holder were measured and plotted against the initial holding force. A result obtained is as shown in Fig. 22. In this figure, curve *A* corresponds to the rather rigid steel diaphragm and *B* to the rather flexible raw rubber. The dashed lines *a* and *b* in the same figure are the corresponding theoretical curves obtained from Eqs. (6) and (7).

As easily recognized in the pressure, whereas in the case of a rigid holder the experimental and the theoretical curves differ considerably, in the case of a flexible holder they agree moderately with each other. On the other hand, in the film thickness, the experimental values of the flexible holder show extremely higher values than the theory in the region of the low holding force. This fact makes one think that the deformation modes of the material should be changed according to combinations of k_s and H_0 as shown in Fig. 23. If k_s is relatively small, the flange part of the material will at any rate be beveled as shown in the left side of the figure. On the contrary, if k_s is relatively large, the flange will contact with the holder face from R_x to R as in the right side lower figure. Generally, it should be expected that $R_2 \geq R_x \geq R_1$, and so, if this will be the case, Eq. (6) must be modified as follows:

$$h^4 + \frac{H_0}{k_s} h^3 = \frac{3\mu Q}{k_s} R_2^2 \left\{ \left(\frac{R}{R_2} \right)^2 - 1 - 2 \left(\frac{R_2}{R_x} \right)^2 \ln \left(\frac{R}{R_2} \right) \right\} \dots\dots\dots (8)$$

Using this equation in which $R_x = R_1$ was assumed, the theoretical pressure and the film thickness were calculated. The results are represented

in Fig. 22 as the chain lines *a'* and *b'*. As will be seen, *a'* curve of the pressure for the case of the rigid holder is very near to the experimental curve *A*. In the film thickness of Fig. 22, the experimental *A* and the theoretical *a'* also fairly coincide with each other. The difference between *B* and *b* in the film thickness may result from the material inclination shown in the left side lower of Fig. 23.

In order to make the flow-out pressure as high as possible as desired in practice, the value of k_s should be determined according to the allowable initial holding force H_0 as follows: If a relatively high value of H_0 can be taken, k_s may be a low value, and if H_0 must be low, k_s must be high accordingly.

11. Conclusion as regards the generated pressure

The factors having influence upon the generated pressure were examined fairly exhaustively. The validity of the pressure formulae previously proposed was ascertained. It was clarified that according to the holding force and the spring constant of the holder, a modification of the formulae was necessary. By assuming some deformation models of the material, and by means of this modification, the pressure phenomena encountered in this process were clarified consistently. A notice was made qualitatively as regards the correlation between the allowable holding force and the spring constant.

References

- (1) B.F. Eary: *Tool Engr.*, Vol. 43, No. 2 (1959), p. 83.
- (2) H. Wiegand: *Werkstatt u. Betrieb*, Jg. 93, Heft 3, (1960), S. 147.
- (3) Y. Kasuga: *Trans. Japan Soc. Mech. Engrs.*, Vol. 19, No. 86 (1953), p. 1.