

# A Manufacturing Process Using the Impact Compression of a Viscoplastic Pressure Medium (Application to the Piercing of Fine Holes)\*

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Recent developments in the electronics industry require a piercing technique for making fine holes at a high production rate. The present research attempts to apply to such piercing a new manufacturing process utilizing the impact compression of a viscoplastic pressure medium recently proposed by the authors. As a result, the process is shown to be successful in piercing various fine holes, unobtainable by the conventional shearing process: for example, circular holes of 0.05 mm and 0.1 mm in diameter and a slit of 0.05 mm in width. The piercing pressure is examined theoretically and experimentally.

**Key Words:** Nontraditional Processing, Fine Hole Piercing, Viscoplastic Pressure Medium, Drop Hammer, Dynamic Contact Pressure

## 1. Introduction

Recent, remarkable developments in the field of electronics and other allied industries require a new technique for piercing very small or fine holes. Though there are a number of processes for this purpose, e. g., drilling, chemical etching, electro-discharge machining and high-energy beam machining by means of an electron beam or a laser beam, they have the common disadvantage of low productivity and, thus, limited applicability. Only from the viewpoint of productivity do some mechanical processes such as punching seem advantageous. However, with the decrease of hole diameter, the rigidity of a punch diminishes and difficulties arise both in manufacturing the punch and in giving an accurate clearance between the

punch and the die hole. Thus, the practical diameter of holes in the punching process is limited to 1 mm for the conventional method, and 0.4 mm for a special device<sup>(1)</sup>. Since these problems are related to the punch, they may be avoided by using a new, punchless process.

The present research attempts to apply to fine hole piercing a simple mechanical process employing the impact compression of a viscoplastic pressure medium recently proposed by the authors<sup>(2)-(4)</sup>. It is schematically illustrated in Fig. 1. The principle of this process is based on utilizing high pressures generated by compressing impulsively an amorphous material which has a high sensitivity to flow stress. It requires neither punch nor blank-holder, and piercing is expected in a zero-clearance state without the aforementioned problems. In this paper, circular holes of 0.05~0.3 mm diameter, much smaller than the diameters attainable by conventional punching, will be considered. The piercing pressure will also be examined, theoretically and experimentally.

## 2. Experimental Procedure

### 2.1 Drop hammer apparatus

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A drop hammer apparatus of the free-fall type was manufactured for the impulsive tests. Two kinds of compression methods were employed, as illustrated in Fig. 1. The pressure medium ④ is partially or fully constrained with the plate ③ during impacting; hereafter, they will be abbreviated as P.C. and C.C., respectively. The diameter  $d_o$  of the pressure room ④ was 10 mm for both methods, and the thickness of the constraining plate ③ was 5 mm in the P.C. method and 15 mm in the C.C. method. The height of the piston ⑥ in the C.C. method was 10 mm and the clearance between the piston and the wall of the pressure room was 0.04 mm. The total mass of the hammer, including the upper platen  $M$ , was fixed at 39.6 kg, while the vertical height of the fall of the hammer  $H$  was varied from 2 cm to 50 cm, where  $H$  was measured from the upper surface of the piercing die or the lower platen.

## 2.2 Material for pressure medium and specimens

The following are required for the pressure medium used in the present process: high pressure-generating potential, excellent releasability from a die face and ease repetition (recycling). From the previous investigation<sup>(4)</sup>, a commercial silicone polymer was employed as a pressure medium satisfying these requisites. Its coefficient of viscosity measured by a flow tester was 5 000 Pa·s at 25°C and its density was 1.20 g/cm<sup>3</sup>. Its constitutive equation at a low strain rate was measured by means of a universal testing machine, and was approximated to the expression  $\sigma =$

$0.122\epsilon^{0.45}\dot{\epsilon}^{0.39}$  in the range of  $\epsilon=0\sim 1.0$  and  $\dot{\epsilon}=0.21\sim 0.42\text{s}^{-1}$ , where  $\sigma$  is the compressive stress (MPa),  $\epsilon$  is the compressive strain and  $\dot{\epsilon}$  is the strain rate. On the other hand, the dynamic relation measured by the drop hammer apparatus was expressed as  $\sigma = 0.032\epsilon^{0.59}\dot{\epsilon}^{2.0}$  in the range of  $\epsilon=0\sim 2.0$  and  $\dot{\epsilon}=90\sim 420\text{s}^{-1}$ . In the pressure tests and the piercing tests mentioned in sections 2.3 and 2.4, cylinders made of silicone polymer, 10 mm in height  $h_o$  and diameter  $d_o$ , were employed as pressure medium specimens. They were manufactured with special forming tools and were kept at room temperature for at least one night.

## 2.3 Pressure tests

In order to examine the pressure level attainable by the present apparatus, impact compression tests were carried out with a pair of flat platens, and the contact pressures on the specimen-platen interface were measured. For this purpose, a pressure-sensitive pin apparatus was assembled in the lower platen ①, as shown in Fig. 2. When the pressure was to be measured at a specified radial position, the pressure-sensitive pin ② was located there eccentrically to the specimen ⑦. Both the P.C. and the C.C. methods were tested. A pressure signal from the quartz load washer (piezoelectric force transducer, maximum force 118 KN, natural frequency 55 KHz) was stored in the digital transient recorder (8 bits, 2048 words) and was then transmitted to a pen recorder. Pressure values were calibrated through sudden unloading with a universal testing machine, and good linearity was

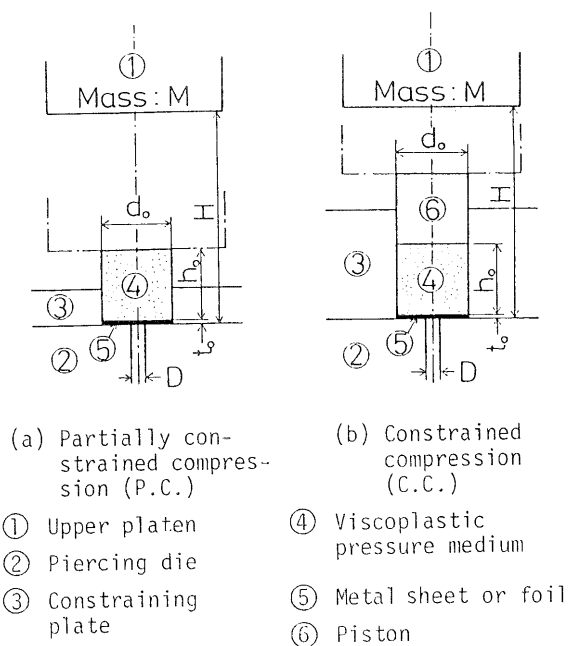


Fig. 1 Schematic drawing of a piercing process using impact compression of a viscoplastic pressure medium.

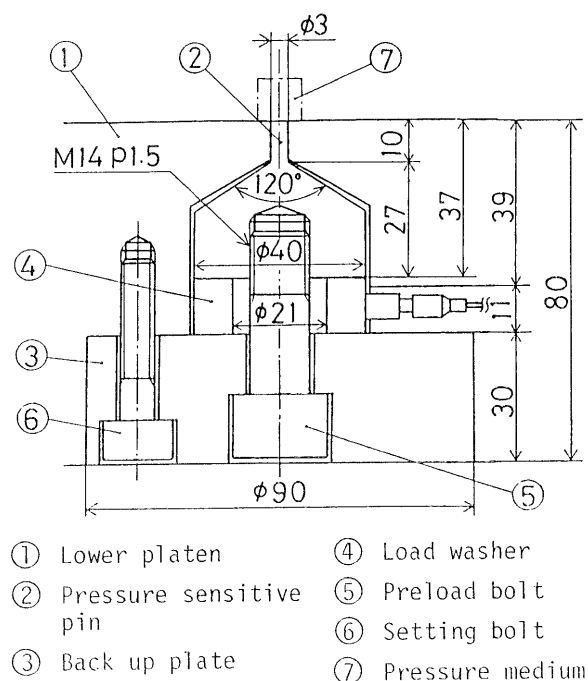


Fig. 2 Pressure-sensitive pin apparatus.

obtained. Examples of the recorded pressure-time curves are presented in Fig. 3. Hereafter, the pressure peak will be noted and denoted as  $p$ . The response of the whole measurement system was examined by dropping a steel ball from various heights on the end face of the pressure-sensitive pin, and the natural frequency obtained was 16.1 KHz, regarded as being satisfactory for the present purpose. The surface of the lower platen was lap-finished to produce the roughness  $R_{max}=0.5\ \mu\text{m}$ . The tool surfaces were degreased with acetone before each testing, but no lubricants were used. The test temperature was  $25\pm 5^\circ\text{C}$ .

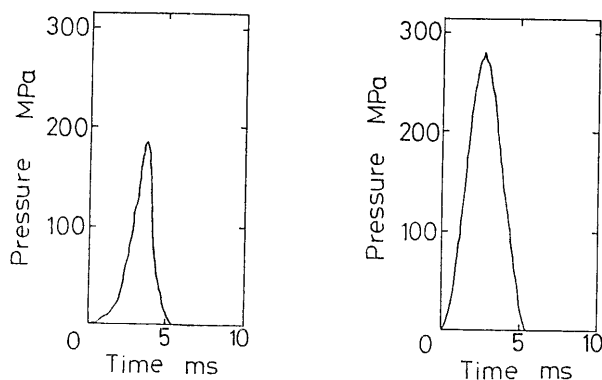
#### 2.4 Piercing tests

Circular straight holes were provided to the piercing dies by electro-discharge machining. Six kinds of hole diameters were employed; their nominal diameters  $D$  were 0.05, 0.1, 0.3, 0.5, 0.8 and 1.0 mm and the corresponding actual diameters were 0.056, 0.135, 0.314, 0.487, 0.808 and 1.127 mm, respectively. Regarding the die materials, carbon tool steel sheets (JIS SK3, 0.2 mm thick, quenched,  $Hv=910$ ) were used in the cases of  $D=0.05$  and 0.1 mm, and alloyed tool steel bars (JIS SKS3,  $15\times 15\times 85\ \text{mm}^3$ , quenched,  $Hv=780$ ) in the others. The die surfaces were lap-finished to produce the roughness  $R_{max}=0.5\ \mu\text{m}$ . Small workpieces of  $7\times 7\ \text{mm}^2$  were cut from the foils of high-strength carbon tool steel (SK3) of 0.01 mm and 0.05 mm nominal thicknesses. Their mechanical properties are shown in Table 1. The lubrication and tempera-

Table 1 Mechanical properties of SK3 foils.

Thickness $t_0$ mm	0.05	0.01
Tensile strength MPa	1891	1793
Total elongation %	2.4	1.3
n-value	0.026	0.015
F-value MPa	1932	2128
Vickers hardness $H_v$	593	-

$$\sigma = F (\epsilon_\gamma + \epsilon)^n, \quad \epsilon_\gamma = 0.002$$



(a) P.C.,  $H = 8\ \text{cm}$

(b) C.C.,  $H = 8\ \text{cm}$

Fig. 3 Examples of recorded pressure-time curves.

ture conditions in the piercing tests were the same as those in the aforementioned pressure test.

### 3. Results and Discussion

#### 3.1 Impact pressure

Peaks of pressure were measured at the radial positions of  $r=0\ \text{mm}$  (specimen center) and  $r=3\ \text{mm}$ . The relation between  $p$  and the hammer height  $H$  is shown in Fig. 4. The variation in  $p$  with  $r$  is very little and, therefore, the distribution of  $p$  can be approximately regarded as being uniform. Under a specified  $H$ , the value of  $P$  in the C. C. method is at least 1.5 times larger than that in the P. C. method, but either of these methods serves for producing very high pressure levels, such as 450 MPa, which amounts to a factor of about ten thousand times the quasi-static compressive stress of the pressure medium.

#### 3.2 Factors influencing piercing

Piercing was tested for various combinations of working factors, i. e., the hammer height  $H$ , the hole diameter  $D$ , the thickness of workpieces  $t_0$  and the constraining methods. The results are summarized in Fig. 5, where the actual diameters are used for  $D$ . The circle and cross marks indicate a successful hole formation and a failure in piercing (partial or no hole formation), respectively. The critical hammer height  $H_{cr}$ , meaning the boundary between them, is given with solid lines. It is observed in the figure that  $H_{cr}$  tends to increase markedly with a decrease of  $D$ . Under a specified foil thickness, e. g.,  $t_0=0.05\ \text{mm}$ ,  $H_{cr}$  in the C. C. method is much less than that in the P. C. method, indicating that the former method has a better energy efficiency. This result corresponds to the fact in Fig. 4 that the C. C. method can produce higher pressures than the P. C. method. The present experiment succeeded in piercing through SK3 foils with holes of  $D=0.1\ \text{mm}$  in the case of  $t_0=0.01\ \text{mm}$  and  $D=0.3\ \text{mm}$  in the case of  $t_0=0.05\ \text{mm}$ . The lower limits were found due to the pressure capacity of the appara-

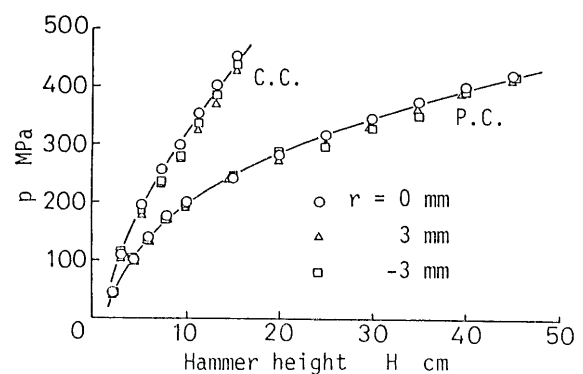


Fig. 4 Relation between the generated pressure  $p$  and the hammer height  $H$ .

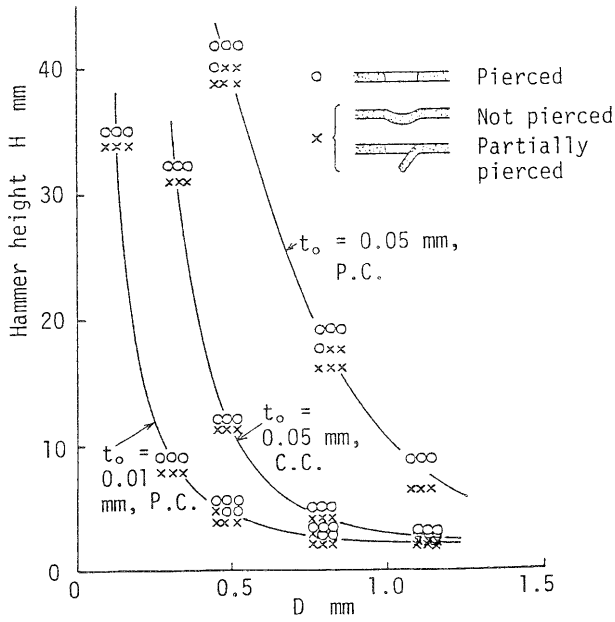


Fig. 5 Relation of success and failure in piercing with the hammer height  $H$ .

tus.

3.3 Observation of pierced holes

The SEM or microscopy pictures of pierced samples are shown in Figs. 6 (a) and (b), which are the side views of the pressure medium; and the appearances of die holes are also presented for comparison. From the figures, it is seen that the shape of the die hole is well-transcribed into the workpiece. According to Fig. 7, which shows a cross section of a pierced sample, an irregular region including shear droop and burr extends from the hole wall to a distance of about  $1/2t_0$ . The fractograph of the hole wall by SEM is presented in Fig. 8; material flow into the die hole and many dimples are observed. The traces of the surface profile of samples obtained by changing the hammer height within  $H_{cr}$  ( $=32$  cm) is illustrated in Fig. 9, showing that the workpiece is stretched to an extent in the order of  $t_0$  before hole formation. Combining the facts presented in Figs. 7~9 leads to the deduction that a hole may have been formed in the workpiece through ductile fracture caused at the die edge by the

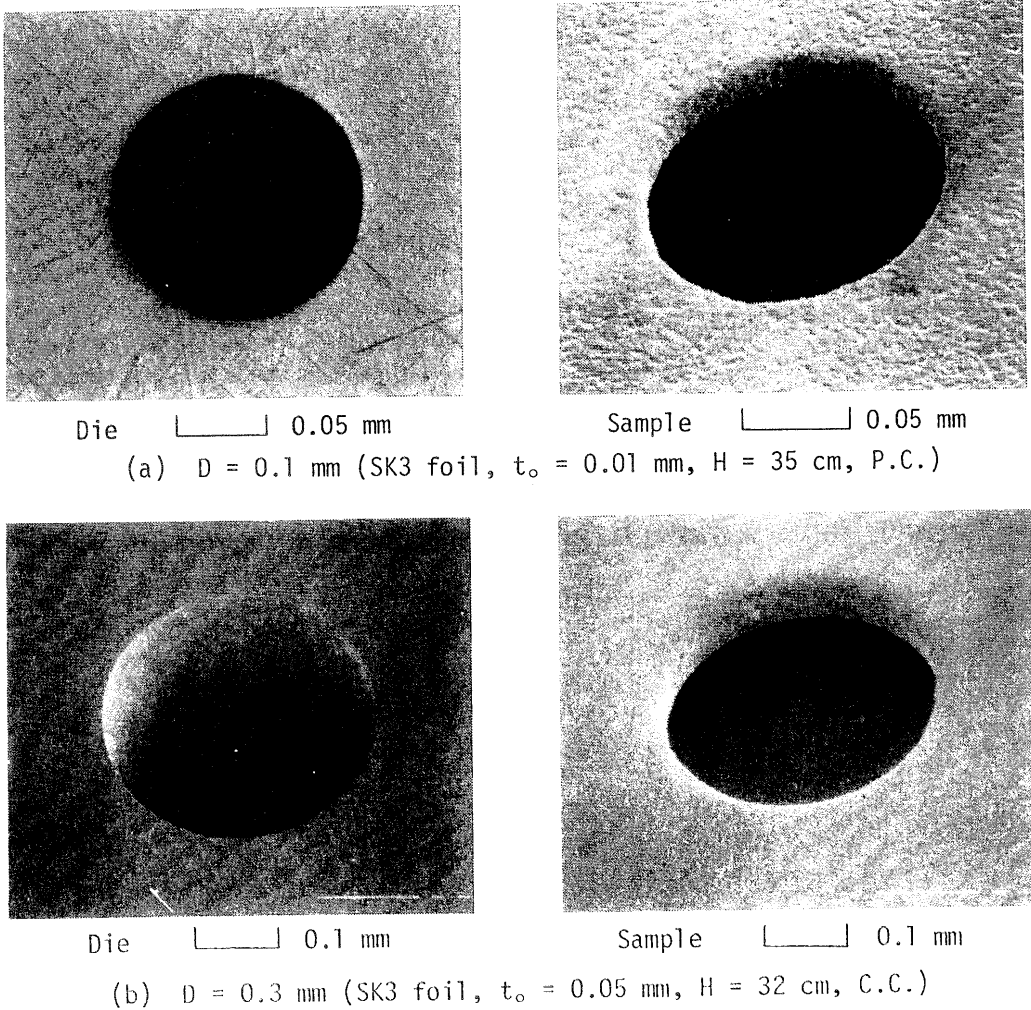


Fig. 6 Examples of circular small holes pierced.

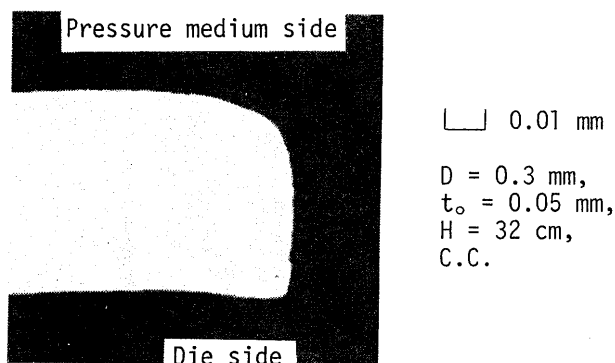


Fig. 7 Cross section of a pierced sample.

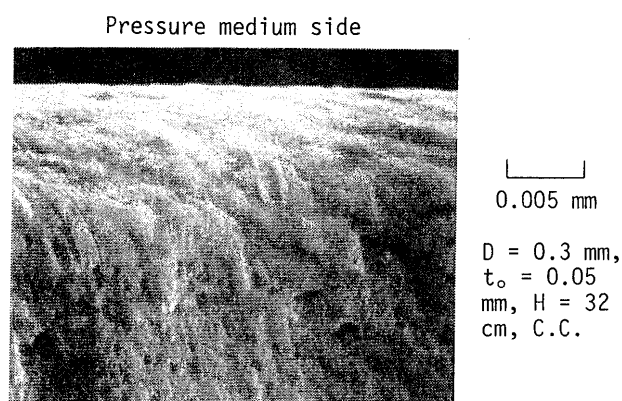


Fig. 8 Fractograph of a hole wall.

action of bending under tension during stretching. Under the present experimental conditions, the moving velocity of the stretched part was estimated as being several millimeters per second, the same order as that in conventional hydraulic bulging.

### 3.4 Accuracy of pierced holes

For every  $D$ , ten samples were picked out and their diameters were measured along the directions parallel and perpendicular to the rolling direction of the workpiece by means of a tool microscope calibrated to 0.001 mm. The difference  $\Delta d = \bar{d} - D$ , its relative value  $\delta = \Delta d / D \times 100$  (%) and standard deviation  $S_d$  are plotted against  $D$  in Fig. 10, where  $\bar{d}$  is the mean hole diameter, and  $0^\circ$  and  $90^\circ$  indicate the angles to the rolling direction. The following were found:  $\Delta d$  is always negative, that is, the formed holes are less than the die holediameters;  $\Delta d$  depends only on the thickness and  $|\Delta d| \approx 0.5 \sim 1.0 t_o$  holds irrespective of  $D$ ;  $|\delta|$  decreases with an increase of  $D$ ;  $S_d$  is less than 0.01 mm and, thus, the reproducibility of hole formation is regarded as generally good. From these observations, it can be concluded that the accuracy of the pierced holes improves with a decrease in the thickness of the workpieces, and accordingly, the present piercing process is suitable for thinner objects. No significant differences in the accuracy between the P. C. and the

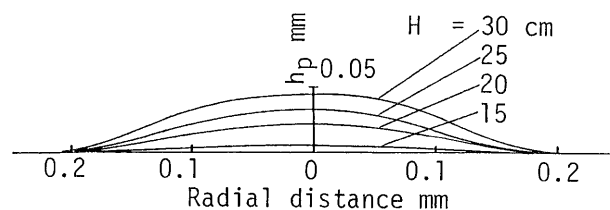


Fig. 9 Variation of surface profiles in samples with the hammer height  $H$ .

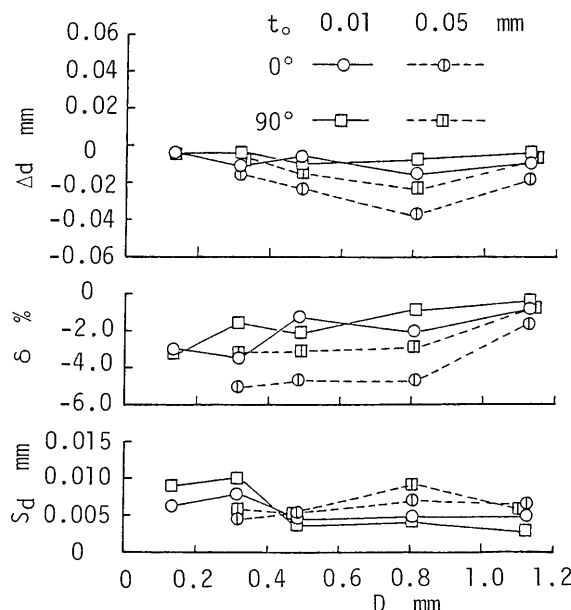


Fig. 10 Accuracy of pierced holes.

C. C. methods were found, although they are not presented here.

## 4. Examination of Piercing Pressure

The following, simplified calculation models were employed to estimate the pressure necessary for small hole piercing.

### 4.1 Simple shear model

Let us consider a sheet subjected to a uniform normal pressure over a circular area  $D$  in diameter, on one face, as shown in Fig. 11 (a). Assuming that a hole is formed through a simple shear fracture caused at the radial position  $D/2$ , and neglecting any deflection of the sheet, an equilibrium equation in the thickness direction is expressed as

$$p_{cr} = 4 t_o \tau_{cr} / D \tag{1}$$

where  $\tau_{cr}$  is shear fracture strength. Approximating the relation between  $\tau_{cr}$  and tensile strength  $S_r$  as  $\tau_{cr} \approx (1/\sqrt{3}) S_r$ , Eq. (1) is written as

$$p_{cr} / S_r = (4 / \sqrt{3}) / (D / t_o) \tag{2}$$

### 4.2 Combined model of stretching and bending under tension

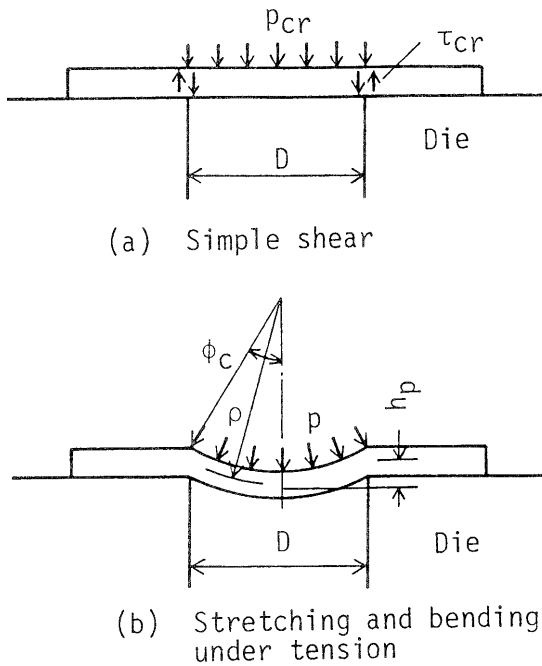


Fig. 11 Calculation models used for estimation of piercing pressure.

Let us consider a sheet plastically stretched by applying a uniform pressure to the aforementioned area, as shown in Fig. 11 (b). Assumptions made here are that during stretch deformation, bending under tension is loaded to the material on the die edge; and that when the meridian strain  $\epsilon_\phi$  at its upper surface reaches a certain limit, a hole is formed by a tension-type ductile fracture. The pressure  $p$  necessary to stretch a sheet was calculated from the spherical equation for the hydraulic bulging process by Takahashi<sup>(5)</sup>. With the additional assumptions of isotropic materials and power-law hardening  $\sigma_{eq} = F(\epsilon_V + \epsilon_{eq})^n$ , and neglecting the edge radius of the die, the stretching pressure is expressed as

$$p = 2t_0 F(\epsilon_V + \ln a)^n / \rho \alpha \quad (3)$$

where

$$\begin{aligned} \alpha &= 8\rho^2(1 - \cos \phi_c) / D^2, \\ \phi_c &= \sin^{-1}\{D / (2\rho)\} \quad \text{and} \\ \rho &= (D^2 + 4h_p^2) / (8h_p). \end{aligned}$$

Notations  $\phi_c$  and  $\rho$  are illustrated in Fig. 11 (b). In the beginning, the polar height  $h_p$  of the stretched dome was specified and  $p$  was determined from Eq. (3), and then the meridian tension  $t\sigma_\phi$  per unit length was calculated from the equilibrium equation  $t\sigma_\phi = p\rho/2$ . Here, it was assumed that plane-strain bending was loaded to the die edge region under this tension, and the meridian strain  $\epsilon_\phi$  at the outer plane of bending was estimated using the theory of Chung and Swift<sup>(6)</sup>. Increasing, stepwise, the polar height  $h_p$ , these calculations were carried out. The piercing pressure  $p_{cr}$  was

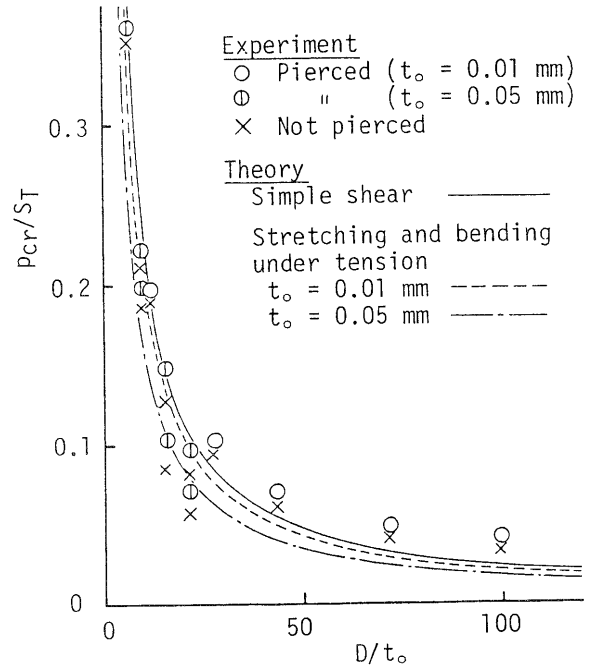


Fig. 12 Relation between piercing pressure  $p_{cr}$  and hole diameter  $D$ .

defined as the pressure on the stage just when  $\epsilon_\phi$  attains the critical value  $\epsilon_{\phi cr}$ . The radius of curvature  $\rho_d$  during bending was determined from the experimental relation  $\rho_d = 0.29 / \phi_c$ , where the unit of  $\rho_d$  is mm. Since an accurate estimation of  $\epsilon_{\phi cr}$  was difficult, it was quoted from the limit strain measured in the hydraulic bulge tests, and was taken as being 0.09 for  $t_0 = 0.05$  mm or 0.06 for  $t_0 = 0.01$  mm.

### 4.3 Calculated results and discussion

The theoretical relations between  $p_{cr}/S_T$  and  $D/t_0$ , calculated on the basis of the aforementioned models, are shown in Fig. 12, along with the experimental. These were obtained by combining the  $p$ - $H$  relation (Fig. 4) and the relation of the piercing result with  $H$  (Fig. 5). The pressures  $p$  in the case of the C.C. method and  $H > 16$  cm, not given in Fig. 4, were measured by supplementary tests. In the previous research<sup>(4)</sup> it was clarified that when hole formation energy is far lower compared with the supplied potential energy to the pressure medium, the pressure test with the flat platens is effective for estimating the piercing pressure.

According to Fig. 12, a slight difference between the theoretical curves is found, but either provides a good fit to the experimental results, as a whole. Even a simple expression such as Eq. (2) is useful for the estimation of piercing pressure. These facts seem to be due to the low ductility in the foils used in the present experiment. It can be concluded here that  $p_{cr}$ , in other words, the difficulty in piercing, depends not

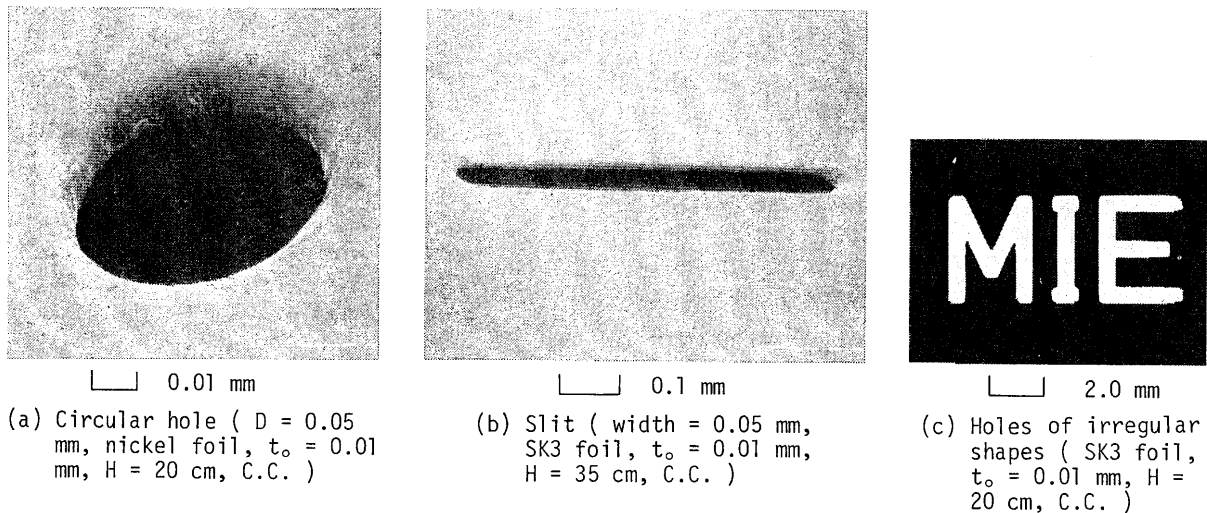


Fig. 13 Various examples of fine hole piercing by the proposed process.

on the absolute dimension of a hole  $D$ , but on its relative value  $D/t_0$  and  $S_T$ . Besides, it should be noted that a pressure higher than  $0.1 S_T$  is required for a small value of  $D/t_0$ . As stated in Section 3.2, the minimum hole diameter attained in the present experiment was 0.1 mm ( $D/t_0=7$ ) for SK3 foils. However, this limitation is merely due to a shortage in the pressure capacity of the apparatus, and does not indicate any problem regarding the principle of the process.

### 5. Some Applications

An additional experiment was carried out to examine various possibilities involved in the present process. A circular hole of 0.05 mm in diameter, smaller than the aforementioned holes, could be pierced through a nickel foil of 0.01 mm in thickness. Its appearance is shown in Fig. 13(a). A slit of 0.05 mm in width was also pierced through a SK3 foil of 0.01 mm in thickness, as shown in Fig. 13(b). As an example of small holes of irregular shape, the holes of English characters are presented in Fig. 13(c). These were photographed from the pressure medium side, and their aspects are good, on the whole. A further precise observation indicated that such a small hole is sensitively affected by the sharpness of the die edge, the geometrical error in a die hole and the surface roughness of a die and a workpiece. Finally, such piercing as achieved by the present process may also be expected by means of electro-discharge forming. This process is characterized by a much higher working speed (15~20m/s) and a shorter duration of applied pressure (an order of  $10^{-6}$  s)<sup>(7)</sup>; thus, a higher  $p_{cr}$  will be required. Besides, fracture initiation due to intensive strain concentration at the pole region<sup>(8)</sup> may impose some restrictions on the workable range

of  $D/t_0$  and materials. On the other hand, the authors' process is characterized by a simplicity of operation and an economy of apparatus.

### 6. Conclusions

Results obtained from the present investigation may be summarized as follows.

(1) The proposed process succeeded in piercing circular fine holes 0.05 mm and 0.1 mm in diameter and a slit of 0.05 mm in width, which are unobtainable by conventional punching methods.

(2) It was found that the accuracy of a pierced hole depends on the thickness of the workpiece, irrespective of the hole diameter; it improves for thinner workpieces.

(3) Methods for estimating a piercing pressure  $p_{cr}$  were presented using two simplified calculation models and were found to be useful. It was confirmed through an experiment and a theoretical calculation that  $p_{cr}$  depends on the ratio of the hole diameter to the thickness of the workpiece  $D/t_0$  and its tensile strength  $S_T$ , irrespective of the hole diameter  $D$ . Within the tested range of the hole diameter, it was concluded that the difficulty in piercing increases with a decrease of  $D/t_0$  and an increase of  $S_T$ .

(4) Taking into account the aforementioned characteristics and the advantage of requiring neither punch nor blank-holder, the present process will serve to pierce many fine holes or small irregular holes through very thin sheets with one shot.

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