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PRESSURE SENSITIVE PIN APPLICABLE TO THE SHEARING TEST OF SHEET METALS

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1. Introduction

In the shearing test of sheet metals, the contact pressure between the tool and the material is a matter of prime importance because it influences upon type of the deformation which takes place in the material during the testing.

A knowledge of the pressure facilitates to find the optimum condition of a blanking process and so to produce precision components by blanking operation alone as well as to attain an improvement of tool life.

Many investigators have tried to measure the contact pressure so far. But the method by photo-elasticity (Timmerbeil[1], Hojo[2]) could not be applied for the actual process, and the presumptive method having recource to hardness distribution in the material before and after the process (Saito[3]) could not be exact. Moreover, they seemed to be not compatible to a throughout measurement during the process.

The pressure sensitive pin, which is well known in the measuring technique, has generally been used in the deformation process for a long time. But, its technical skill is various. van Rooyen[4] measured the normal and tangential stresses at the same time in cold rolling by the aid of an obliquely located pin. Y. Kasuga *et al.*[5] got the pressure distribution in the kneading process of a cylinder between flat dies employing a pressure pin whose diameter was larger than the contact width. Recently, it was applied again for rolling by B. N. Chernyshev[6] and by P. F. Ivanushkin[7] for upset-forging. However, it has not been applied yet for a shearing process because the contact width in this process is so narrow that the possibility of measurement of the pressure distribution is strictly limited.

A pressure sensitive pin which was applicable to the measurement of contact pressure on the tool during a shearing process was newly designed by the authors and prepared for. This paper deals with the performance of this pin and the data concerning to the pressure distribution on the shearing tool face which was obtained successfully by means of this pin.

2. Constructions of the pressure sensitive pin and the tool equipped with it

2. 1. Pressure sensitive pin

In order that one can measure the contact pressure in such a limited zone as in a blanking process, the pressure sensitive pin must have a very small contact facet ($<0.2\,mm^2$) at its end, so the usual way employing a rigid pin for the sensor could not be applied in this case.

The scheme of newly designed and fabricated pin is shown in Fig. 1. Its feeler element consists of 0.48 mm dia. pin tip and 4 mm dia. stem whose root is press-fitted to diaphragm 2. The whole element was made of high-speed steel (SKH 9) and hardened, so as its hardness to be nearly equal to the general hardness of the tool. The cylindrical surface near the top of the pin was ground precisely so as to avoid the sticking to the fitting hole bored in the tool.

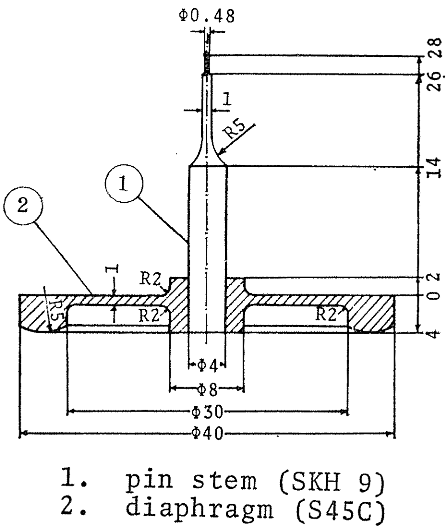


Fig. 1. Pressure sensitive pin.

The bottom rim of the diaphragm is shaped into a torus and located on the base of die and thus aimed at an even transmission of the load.

The pressure transducer are four strain gages which are bonded on the both surfaces of the diaphragm. Its output was amplified and recorded on a uni-corder together with other outputs.

By means of this special design, the pin has become enough sensitive and accurate to measure the pressure distribution in such a locarized place as cutting edge of blanking tools, though some space is needed for the bottom diaphragm.

2. 2. Die

The die is shown in Fig. 2, and its cutting edge pieces in Fig. 3. The pin is set up in the back recess of the die body, its diaphragm being laid on the seat *l*. The distance from the die edge to the center of the pin (dimension a in Fig. 3) was varied in seven steps between 0.71 mm and 2.00 mm as shown in the appended table of

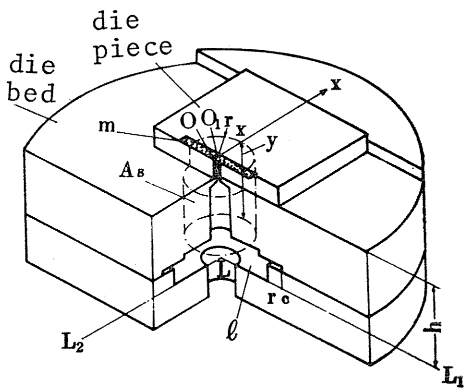
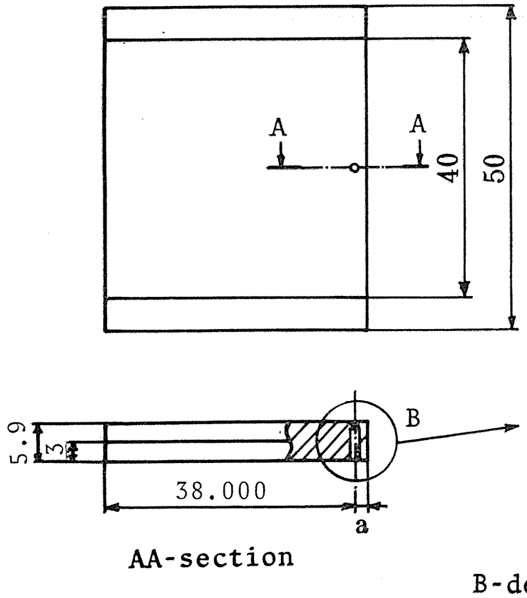


Fig. 2. Die (O : die edge, O_1: center of the pin, *l* : locating plane of the pin).



	a	d	d'	$\frac{d-d'}{2}$
1	0.712	0.503		0.012
2	0.796	0.505		0.013
3	1.198	0.501		0.011
4	1.398	0.512	0.480	0.016
5	1.602	0.504		0.012
6	1.799	0.494		0.007
7	1.999	0.498		0.009

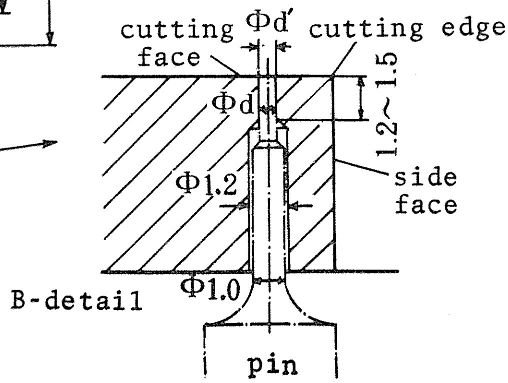


Fig. 3. Dimensions of the die. (in mm)

Fig. 3. A set of four tests for a common tool clearance was carried out in order to get the pressure at various measuring positions. However it was proved that the variance of maximum punch loads in a series of four tests came to within only 1 %.

3. Calibration of the output

To calibrate the output of the pin, the pin-diaphragm assembly was loaded on its shoulder (R5 in Fig.1) with the weight which was increased stepwise at a rate of 0.5 kg. The readings of the strainmeter were plotted against the load. The result is shown in Fig. 4. It was proved that the calibration curve showed not only a good linearity but little hysteresis of loading and unloading.

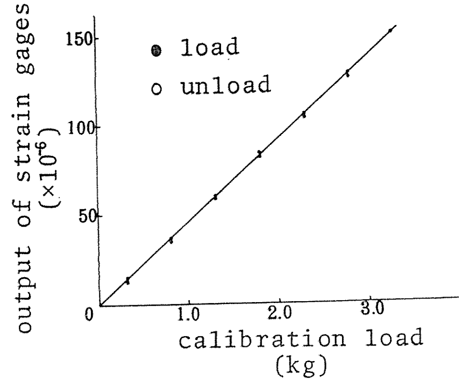


Fig. 4. Calibration curve.

4. Compatibility of the rigidities of the pin and the tool

The end face of the pin should form a part of the cutting face of the tool. Accordingly, it will be desired that this end face is always kept level with the cutting face of the tool throughout a working process. However, in general, as a difference in the rigidity between the pin and its surrounding part of the hole exists, under a pressure, their faces will form a step which is likely to lead to an error of the pressure measurement.

Really for instance, F. Dohmann[8] dealt with the above-mentioned problem with regard to three types of pressure pins. S. P. Gurov *et al.*[9] referred to also such effect in their research. H. Walter[10] measured the contact pressure between the tool and material in the compression test where the diameter of pins was altered and he compared the pressure distribution got from various rigidities of the pins.

In view of the above researches, the rigidity of the newly designed pin in this time should be compared with that of the tool, and it should be ascertained if a compatibility of them exists or not.

4. 1. Rigidity of the pin

When the load P acts on the pin (Fig. 1), the displacement δ_p at the pin's top in the direction of P will be the sum of the following components; the displacement δ_{p1} due to deformation of the pin itself; the displacement δ_{p2} which is caused by the diaphragm deflection; the access δ_{p3} of the torus-shaped bottom of the diaphragm to the basal plane (LL_1L_2 plane in Fig.2) which is caused by Hertzian contact.

When the diameters and lengths of the stepped stem of the pin, from the upper part, are denoted by d_1, l_1 ; d_2, l_2 ; d_3, l_3, the displacement δ_{p1} is expressed by

$$\delta_{p1}=\frac{P}{E}\left(l_1/\frac{\pi}{4}d_1^2+l_2/\frac{\pi}{4}d_2^2+l_3/\frac{\pi}{4}d_3^2\right) \tag{1}$$

When the inside and the outside diameter of the elastic diaphragm are $2r_i$ and $2r_o$, and its thickness is t, then δ_{p2} may be expressed by[11]

$$\delta_{p2}=\frac{3(1-\nu^2)\cdot P\cdot r_0^2}{4E\cdot t^3}\{1-r_1^2/r_0^2(2r_i\cdot 1nr_0/r_i)^2/(r_0^2-r_1^2)\} \tag{2}$$

If the perimeter of torus is l_t, and its contact width is b, then δ_{p3} will be expressed by Eq. (3) according to the Hertzian contact theory of a cylinder and a plane.[12]

$$\delta p_3=\frac{8P}{\pi El_t}1n\frac{f_1}{b}+\frac{4(1-\nu)\cdot P}{\pi El_t},\quad b=1.52\sqrt{\frac{P\cdot R}{El_t}} \tag{3}$$

where f_1 is the distance between the contact line and the point at which the sinking of the basal plane becomes virtually zero.

Substituting Young's modulus $E=2.1\times10^4$ (kg/mm^2), Poisson's ratio $\nu=0.3$ for steel and $d_1=0.48$, $d_2=1$, $d_3=4$, $l_1=2$, $l_2=12$, $l_3=14.5$, $r_0=15$, $r_i=4$, $t=1$, $l_t=35\pi$, $R=5$ for the dimensions in the above equations, the following expressions for the constituent displacements are obtained.

$\delta_{p1}=1.31\times10^{-3}P(\mathrm{mm}),\ \delta_{p2}=0.92\times10^{-3}P(\mathrm{mm}),\ \delta_{p3}=0.01\times10^{-3}P(\mathrm{mm})$ (4)

And after all, $\delta_p=\delta_{p1}+\delta_{p2}+\delta_{p3}=2.2\times10^{-3}P$ (mm)

Furthermore, it will be desirable for the sake of the rigidity proof that δ_p is being expressed in terms of the measuring position, a and the load, W in the present shearing tests. For this sake, the contact pressure p on the die was assumed to be expressed by a linear-approximation in terms of the distance ξ from the die edge on the basis of the experiment. As will be seen later, the pressure could be written as

$$p=(0.0098-0.00145\xi)W\ \ (\mathrm{kg/mm^2}) \qquad (5).$$

Integrating Eq. (5) on the tip face of the pin, the equation for load on the pin can be obtained as

$$P=(1.77-0.26a)\times10^{-3}W\ \ (\mathrm{kg}) \qquad (6).$$

Substituting (6) for Eq. (4), we finally obtain the expression for the displacement δ_p in terms of the measuring position a and W as

$$\delta_p=(3.96-0.58a)\times10^{-6}W\ \ (\mathrm{mm}) \qquad (7).$$

This equation was utilized for the purpose of the tool design as a basis.

4. 2. Rigidity of the tool

As shown in Fig. 2, whereas the die bed (lower tool) which provides the pin is formed almost axi-symmetrically, the area m on which the contact pressure distributes is nearly rectangular. So, a little difficulty in the calculation of the deflection of the die face arises.

The vertical displacement δ_t of the portion surrounding the pin with respect to the basal plane LL_1L_2 on which the bottm of the pin diaphragm is rested is thought to be the sum of the following component displacements δ_{t1}, δ_{t2}, δ_{t3}.

The signified components are

δ_{t1} : the compressive displacement of the die ring body in bulk which lies outside of radius r having height h and is subjected to the load W.

δ_{t2} : the shear displacement of the inside part which over-hangs within the circle of radius $\overline{Lr_c}$ (the displacement caused by the bending moment is trivial.)

δ_{t3} : the sinking displacement of the die edge due to the distributed pressure.

Now, δ_{t1} may be expressed easily as

$$\delta_{t1}=(W/A_r)\cdot(h/E) \qquad (8)$$

where A_r means the bearing area of the ring.

Whereas, δ_{t2} is considered as to be the mean of the following values, *i. e.* the axi-symmetrical displacement $\delta t_2'$ about $\overline{O_1L}$ axis and the two-dimensional displacement δ_{t2}'' in the longitudinal section containing the $\overline{Ox}$ axis, because the axi-symmetrical character of the die's geometry is incompatible with the two-dimensional character of the load.

If the mean pressure is assumed as p_m, which distributes over the rectangular area m whose width is r_c, and if the cylindrical area which is cut by a cylinder of radius r is assumed as As, then

$$\delta'_{t2}=\int_{r}^{r_c}\frac{l\cdot 2r\cdot p_m}{G\cdot A_s}dr \tag{9}$$

If in the vertical sectional plane LOx the height of the section at distance x from O is y, then

$$\delta''_{t2}=\int_{x}^{x_c=r_c}\frac{l\cdot p_m}{2y\cdot G}dx \tag{10}$$

As a result, through the sum of Eq.(9) and (10),

$$\delta_{t2}=\frac{1}{2}(\delta'_{t2}+\delta''_{t2})=\frac{1}{2}\int_{r}^{r_c}\frac{l\cdot p_m}{G}\left(\frac{2r}{A_s}+\frac{1}{2y}\right)dr \tag{11}$$

When the pressure p acts on the surface of the semi-infinite body over the width l, the displacement δ_{t3} at the position x will be expressed by[12]

$$\delta_{t3}=\frac{2}{\pi E}\int_{x-l}^{x}p\cdot\ln\frac{f}{r}dr-\int_{x-l}^{x}\frac{1+\nu}{\pi E}pdr \tag{12}$$

where f is the co-ordinate x at the point of $\delta_{t3}=0$. Putting Eq. (5) into Eq.(12), and integrating by x, we obtain

$$\delta_{t3}=\frac{2}{\pi E}\left\{\left(p_0-\frac{p_1}{2}x\right)x\ln\frac{f}{x}-\left(p_0-\frac{p_1}{2}x-\frac{p_1}{2}l\right)(x-l)\ln\left|\frac{f}{x-l}\right|\right\}+\frac{1-\nu}{\pi E}p_0 l-\frac{p_1 l}{\pi E}\left(x-\frac{\nu}{2}l\right) \tag{13}$$

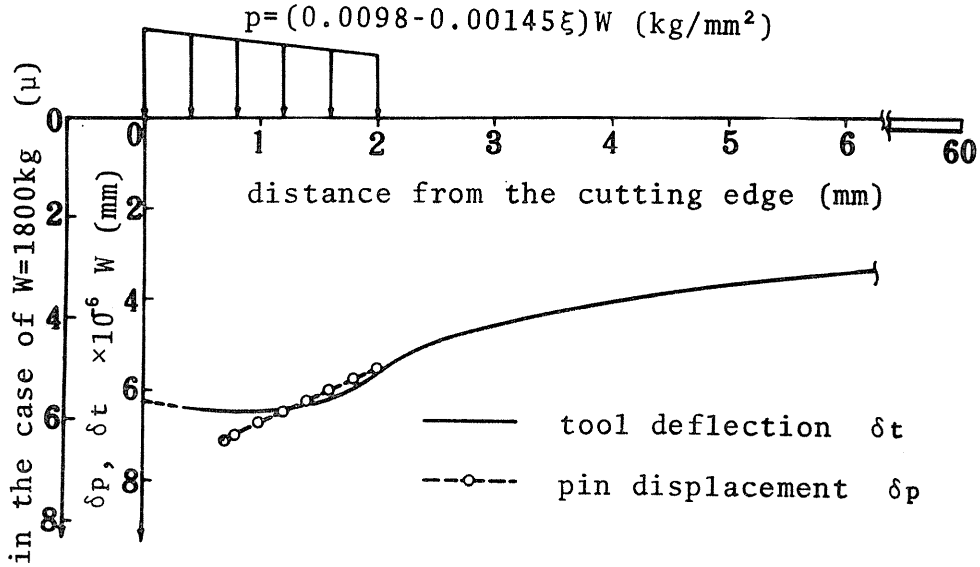


Fig. 5. Comparison of tool deflection δt and the pin displacement δp.

In leading to this equation, Eq. (5) was represented by $p=p_0-p_1\xi$.
By means of putting the material constants for the steel and the dimensions of the tool into Eq. (8), (11) and (13), δ_t can be calculated as a function of x and W.

Fig. 5 shows the probable deflection δ_t-curve of the tool surface thus estimated from the above calculation. In the same figure, the displacement of the pin δ_p which has been obtained in the preceding section is shown by a broken line, comparing with the deflection of the tool surface δ_t. Since the measuring position is near to the cutting edge, the rigidity of the pin seems somewhat smaller than that of the tool. Indeed, it was realized that in experiment a part of the sheared component sank into the hole at some measuring positions. But, it was ascertained that such a small difference in rigidities, could not affect seriously the pressure measurement. (See next section.)

5. Influence of the pin protrusion above the tool face on the pressure measurement

Besides the difference in rigidities of the pin and of the tool, as many researchers[10)13)] ever suggested, the measurement is influenced by the amount of protrusion of the pin from the tool face at its initial adjustment. Fig. 6 shows an experimental result in regard to this problem. A copper anvil was pressed on the top end face of the pin and/or the tool face, protrusions being 5μ and 0μ lubricated with the Johnson-wax No. 151. A massive supported shape of the anvil facilitated concentration of the load, and in this way the accuracy of calibration was secured. It can be seen that the characteristic of the pin sensitivity dose not alter by a change in protrusion. However, with anxiety to a simple linearity of calibration the experiment was conducted for a zero protrusion.

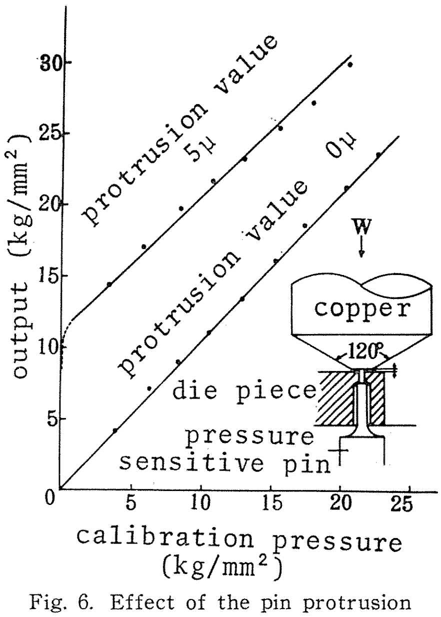


Fig. 6. Effect of the pin protrusion above tool face.

6. The experimental method and condition

In order to get the pressure distribution in a basic shearing process, tests were carried out on cutting band strip with a pair of die edges in a plane strain condition. The specimens were 4 mm thick, 20 mm wide and 120 mm long half-hardened aluminium and were sheared at opposed two positions, 60 mm apart. The experiment was conducted for various vertical clearances (explained in the latter part of this section), with the lubricant of Johnson-wax No. 151. The mechanical properties of the material used and the other experimental conditions are enumerated in Table 1.

Fig. 7 shows the tool set which includes the said special dies. The specimen 4 is cut by a set of the double shearing edges, the punch edge 3 and the die edge 6.

Table 1. Mechanical properties of material and Experimental conditions.

Specimen	Material: aluminium (A1100) Dimension : 4mm×30mm×120mm Hardness (Hv) : 45. 7kg/mm^2 0.2% proof stress: 14.2kg/mm^2 Ultimae strength: 14.9kg/mm^2 Strain hardening exponent: 0.03
Tool (Punch & Die)	Tool angle: 90° Material: SKD 11 Hardness (HRc) : 54～57
Clerance (Lateral) (Vertical)	 5%, 10%, 15% of thickness 0mm, 1mm, 2mm, 2.5mm, 3mm, 3.8mm, 5mm
Lubricant Punch speed	Johnson-wax No. 151 0.25mm/sec

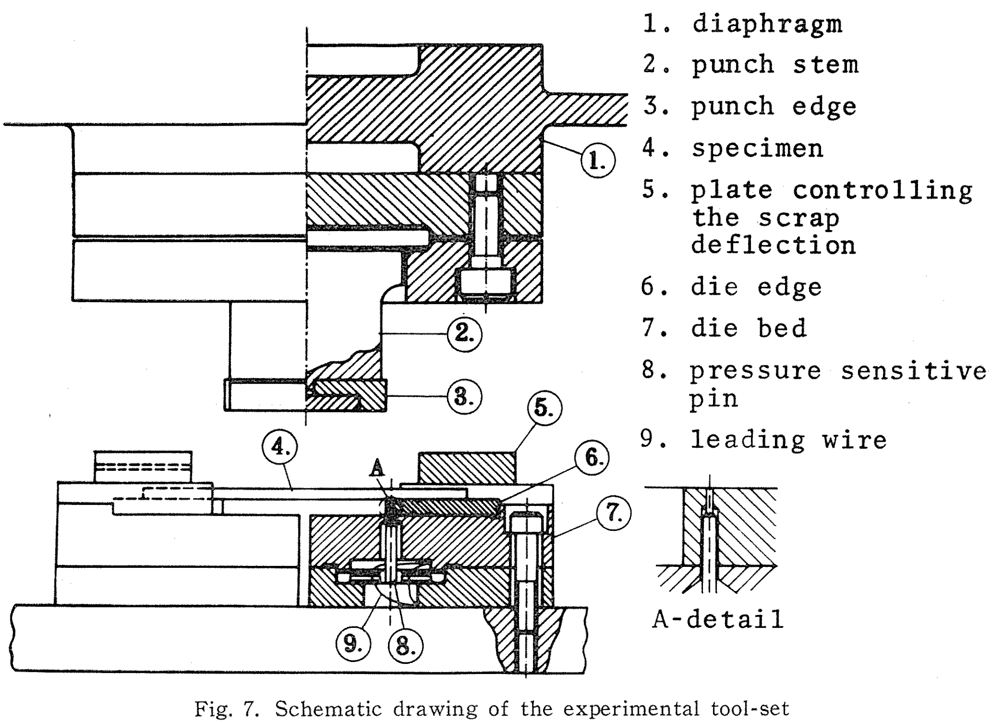


Fig. 7. Schematic drawing of the experimental tool-set

A plate which could limit the scrap deflection was attached to the die as indicated by 5. When this actuates, a sudden change in the contact pressure on the die edge occurs. Thus we can control the pressure distribution by means of changing the set position of this plate. A capability to control the pressure must facilitate to clarify the shearing mechanism. The clearance between the scrap material and the plate, which determines the stage when the scrap stops its arising movement, may be said to be "the vertical clearance".

Three quantities in regard to the acting force were measured in a test; the punch load, by means of the strain gages bonded on the diaphragm surface, the constraining force of the scrap's arising movement, by means of the strain gages similar to the punch load and the pressure on the die, by means of the mentioned way. The punch travel was measured by means of the potentiometer mounted on the side of the punch stem.

7. The experimental result and discussion

Fig. 8 shows stereographically the contact pressure distribution against the punch stroke in case of lateral (or horizontal) clearance of 5% and vertical clearance of 5mm.

At the beginning of the process when the sinking of the free surface near the edges dominates, the contact between the tool and material near its border appears to be governed by an elastic behaviour. See the tail end zones of the pressure hills. It is probable that the larger the lateral clearance the broader the spread of the elastic zone with a due lowering of the amount of pressure in this zone. Indeed, Timmerbeil has ever pointed out this fact when a mild steel was pierced with a round punch.

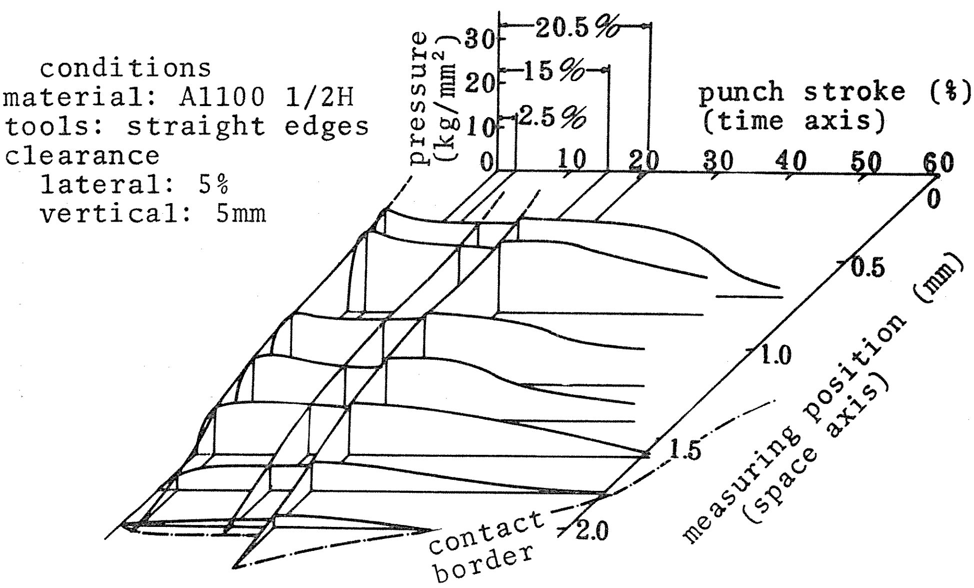


Fig. 8. Contact pressure between tool and material during blanking.

The plastic zone in the contact area shows a somewhat plateau distribution of the pressure hills. At a punch penetration of 20.5%, the pressure over the whole contact zone rises suddenly by 1~2 kg/mm². This stage coincides with the time when the scrap end touches the limiting plate. After crack initiation at about 25% of the penetration, the spread of the contact begins to decrease and the contact border zone becomes again to an elastic state.

By integrating the measured pressure over the contact zone and comparing the result with the punch load, one can estimate the pressure at the die edge extremity. Fig. 9 shows the pressure distribution when the vertical clearance is varied keeping the lateral clearance at 5% of the material thickness.

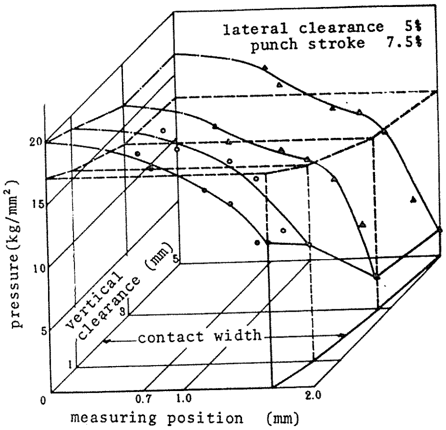


Fig. 9. Pressure distribution vs. the vertical clearance.

8. Conclusion

A special pressure sensitive pin which can measure accurately the contact pressure distribution in such a locarized region as cutting edge of blanking tools was newly designed and prepared for the shearing experiment. According to this, the following new stages in our research have been attained.

(1) Since the acting force on the pin becomes small due to very small measuring contact facet and the pin body must ever have a robustness, a diaphragm could be employed to sense the force.

(2) The torus-shaped bottom of the diaphragm rested on the basal plane of the die-recess instead of fixing it to the die, can exclude well the disturbances which will be detected by the calibration work.

(3) By means of employing this construction, the pin and the tool can be so designed as the difference of their rigidities to be small, and so a reliable measurement have been accomplished.

(4) The experiment on the two-dimensional shearing proves that at the beginning of the process, the end zone of the contact between the tool and material is almost under an elastic state.

By utilizing the result of the further pressure measurement the authors are intend to estimate the hydrostatic-pressure prevailing in the material around the cutting edge and so to clarify the crack initiation mechanism.

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