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A Sheet Metal Forming Process Employing Viscous Material as a Pressure-transmitting Medium (Examination into Mechanical Properties of the Medium)*

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Using a drop hammer apparatus, four kinds of impact compression and forming tests are carried out with nonmetallic materials (i.e., clay, plasticine, silicone polymer and rubber) which have various viscous/elastic /plastic characteristics, and their applicability to the new forming process previously proposed by the authors is discussed. It is concluded that a viscous medium with a high strain rate sensitivity m is advantageous for piercing and shallow stretch-forming. Some new applications (i.e., piercing of small holes and glass sheets) are presented.

Key Words : Forming, Viscous Materials, Strain-rate Sensitivity, Dynamic Contact Pressure, Stretch-forming, Piercing.

1. Introduction

Recently, flexible sheet-forming techniques that employ rubber or fluid as a pressure-transmitting medium have been recognized anew as an economical process suitable for multiple and small-lot production [1][2]. However, rubber involves the problem of recycling after aging or damage due to severe deformation. On the other hand, fluid requires special devices for sealing and generation of pressure. Thus, the utility of these media is limited to a certain extent.

To solve these problems, the authors previously proposed a new forming process which employs a viscous medium and does not require any punch and blank-holder [3]. The process is based on utilizing the high pressure generated by compressing impulsively a viscous medium with the drop hammer apparatus. A schematic drawing of stretch-forming by the free compression method is shown in Fig. 1. In the previous investigation using clay as a pressure medium [3], it was found that the proposed process is effective to improve formability as well as to avoid the aforementioned problems. In the present study, the preferable mechanical properties of a medium and a suitable method for pressure generation will be examined from the viewpoint of practical use. Some new applications of the process will also be presented.

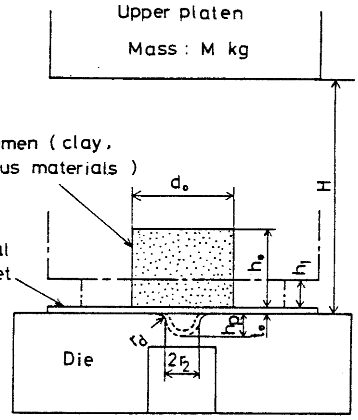

Fig. 1 Schematic drawing of stretch-forming by impulsive free compression of a viscous material.

2. Experimental Procedure

In order to clarify the preferable mechanical properties of the medium, the present investigation was undertaken to reexamine various properties, not only viscosity but also plasticity and elasticity. Thus, four nonmetallic model materials with the contrastive viscous/ elastic/plastic properties were chosen as pressure media for the following four tests: impact pressure tests (flat-platens and die-platen) and working tests (stretch-forming and piercing). Details are as

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follows.

2.1 Drop hammer apparatus

The drop hammer apparatus used is of free fall type and is the same one as used in the previous experiment[3]. The total mass of the hammer including the upper platen M is changeable from 39.6 kg to 85.2 kg in steps of about 9 kg and its fall height H is continuously changeable from zero to 172 cm. In this experiment, these were fixed (M = 39.6 kg and H = 70 cm).

2.2 Materials used as pressure media

The materials employed as pressure-transmitting media are clay (made by Takasaki Nendo Co., Ltd.; density ρ = 1.91 g/cm^3), plasticine (ρ = 1.8 g/cm^3 ; shear yield stress k = 0.083 MPa), silicone polymer (made by Shinetsu Kagaku Co., Ltd., KE-SAP1, ρ = 1.20 g/cm^3, coefficient of viscosity η = 5000 Pa·s at 25°C) and rubber (natural, hardness HS = 64, tensile strength = 2.45 MPa, total elongation = 260 %). The clay had been used in the previous experiment[3]. These materials were used in the as-received state.

2.3 Mechanical properties of media

In order to examine the mechanical properties of media, a compression test with varied compression speed as shown in Fig. 2 was carried out by the universal testing machine (Shimazu Autograph IS-5000). Cylinders 40 mm in diameter and height were made of the aforementioned materials. After these specimens were compressed to about half of the initial height at constant speed V (loading process $\overline{OA}$), they were held at V = 0 during the time interval t_h (relaxation process $\overline{AB}$) and then unloaded at constant speed(-V) (unloading process $\overline{BC}$), where V and t_h were 5, 50, 500 mm/min and 200, 20, 5 sec, respectively. Lubricants used were graphite grease for the rubber, and talc powder for the other materials. The test temperature was 20 ± 1 °C.

Examples of the compressive stress-compressive strain ($\sigma-\varepsilon$) curves obtained are shown in Fig. 3. Since no suitable constitutive equation which covers satisfactorily all the processes and materials could be found, the relation among σ, ε and $\dot{\varepsilon}$ at the loading process was approximated to the equation $\sigma = c\,\dot{\varepsilon}^m \varepsilon^n$, where $\dot{\varepsilon}$ is the strain rate. The material constants C, m and n were determined by applying the least-square method and given in Table 1. The ratio of the permanent strain left after unloading ε_c to the total strain ε_a is also given therein as γ-values, where ε_a and ε_c are the strains corresponding to the points A and C in Fig. 3, respectively. From Fig. 3 and Table 1, the following can be known. The viscous property is dominant in the silicone polymer, because it shows the most marked stress relaxation and has the highest m- and lower n-values. In contrast, the n-value in the rubber is the highest, whereas its m- and γ-values are very low. Thus, as might be expected, it is nearly elastic.

Table 1 Mechanical properties of media.

Materials	m	n	c MPa·s^m	γ %
Clay	0.11	0.23	0.100	99
Plasticine	0.01	0.21	0.173	99
Silicone polymer	0.45	0.39	0.122	100
Rubber	0.07	0.72	4.62	15

$\sigma = c\,\dot{\varepsilon}^m \varepsilon^n$, $\gamma = \varepsilon_c / \varepsilon_a \times 100$.

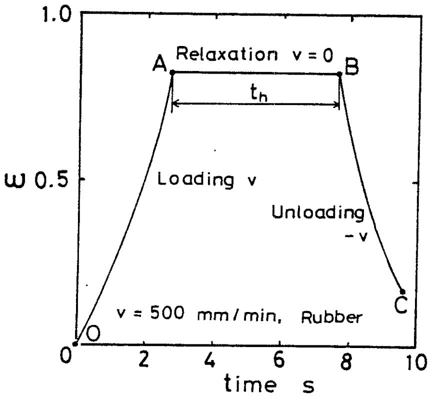


Fig. 2 Strain path in the low speed compression test.

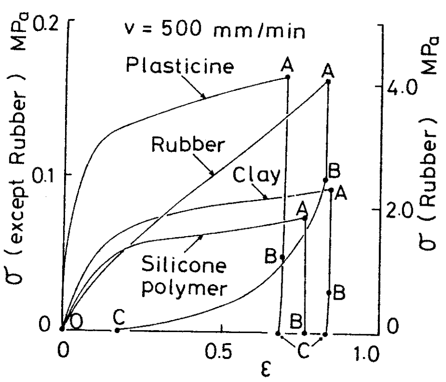


Fig. 3 Compressive stress-compressive strain ($\sigma-\varepsilon$) curves in the low speed compression test.

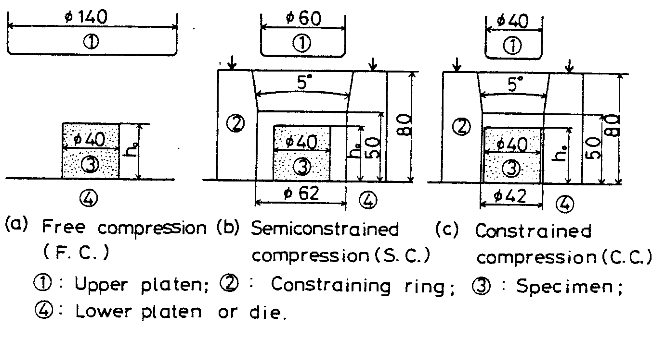


Fig. 4 Schematic drawing of compression methods.

It should be noted that the C-value of this material is more than forty times higher than others. The low n- and m-values in the plasticine indicate that it is nearly perfectly plastic. An intermediate property between the silicone polymer and the plasticine is seen in the clay. In this study the applicability of the media will be discussed in terms of the constants C, m and n.

2.4 Specimens for impact compression and working tests

Specimens used as pressure media in the impact compression and working tests were cylindrical; their nominal diameter d_o was fixed at 40 mm and the relative heights h_o/d_o were changed to 0.5, 1.0 and 1.5. Square blanks cut from rubber sheets of 10 mm in thickness were machined into disks 40 mm in diameter. Two, four or six disks were glued on their faces to each other and made into rubber specimens. For the other media specific forming tools were used. All the specimens thus manufactured were kept at room temperature at least for one night before testing.

2.5 Compression method of pressure media

The three compression methods shown in Fig. 4 were employed in the impact compression and working tests; the free compression method (F.C.) had been used in the previous investigation(3); in the other types the radial material flow during testing was constrained by a ring with $d_i \fallingdotseq d_o$ (C.C.) or partially constrained by a ring with $d_i = 1.55\ d_o$ (S.C.). Hereafter, they will be abbreviated and denoted as F.C., C.C. and S.C., respectively, where d_i is the internal diameter of the ring. The clearance between the upper platen and the constraining ring was 1 mm in both of the C.C. and S.C. methods. The tool ④ was changed according to the test items.

2.6 Impact pressure test with flat platens

In order to examine the pressure generating ability of the media, an impact compression test was carried out with a pair of flat platens, and the contact pressure on the specimen-platen interface was measured. For this purpose, the same pressure-sensitive pin apparatus as used in the previous experiment (see Fig. 5) was assembled into the lower platen. The pressure signal from the load cell was stored in a digital transient recorder (8 bits, 2048 words) and then transmitted to a pen recorder; thus the pressure versus time curves were obtained. The natural frequency of the apparatus 2.5 KHz was regarded as satisfactory for the present purpose. Each tool was degreased with acetone before every testing, but no lubricants were used. The test temperature was 20 ± 5 °C. These lubrication and temperature conditions were also employed in the other pressure and working tests.

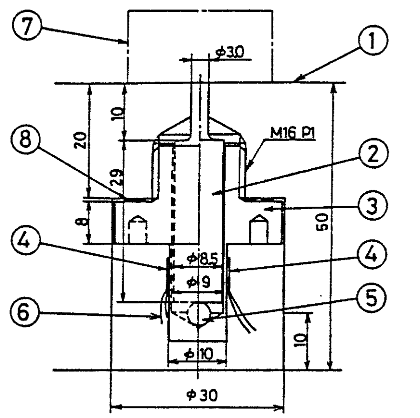


Fig. 5 Pressure-sensitive pin apparatus.

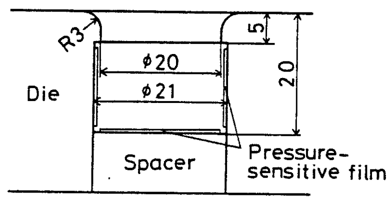


Fig. 6 Pressure measurement in the die cavity.

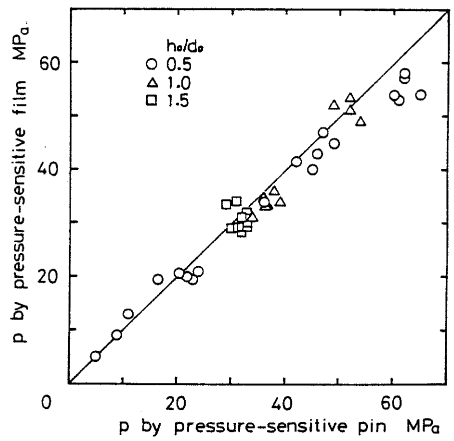


Fig. 7 Comparison of measured pressure between the pressure-sensitive pin and film methods.

2.7 Impact pressure test with die and flat platen

If any vessels with great depth to diameter ratios are to be formed, the pressure media will have to possess not only a pressure generating ability but also a sufficient fluidity to follow the plastic deformation of sheets and flow into the die cavity. As a simulation test for the

Table 2 Mechanical properties of metal sheets.

Materials	Direction	n-value	r-value	F-value MPa	Tensile strength MPa	Total elongation %
Commercially pure aluminum (A 1100-H24)	0°	0.13	0.50	170	116	22.5
	45°	0.10	1.55	144	104	20.0
	90°	0.12	0.77	166	114	21.0
	mean	0.11	1.09	156	109	20.9
Killed steel	0°	0.24	1.74	543	305	37.9
	45°	0.22	1.33	549	316	34.5
	90°	0.23	2.10	531	301	37.6
	mean	0.23	1.60	543	310	36.1
OFHC, soft	0°	0.44	0.90	513	221	44.4
	45°	0.44	0.98	501	218	47.6
	90°	0.45	1.00	509	219	48.3
	mean	0.44	0.97	506	219	47.0

t_o = 0.8 mm, $\sigma = F\,\varepsilon^n$

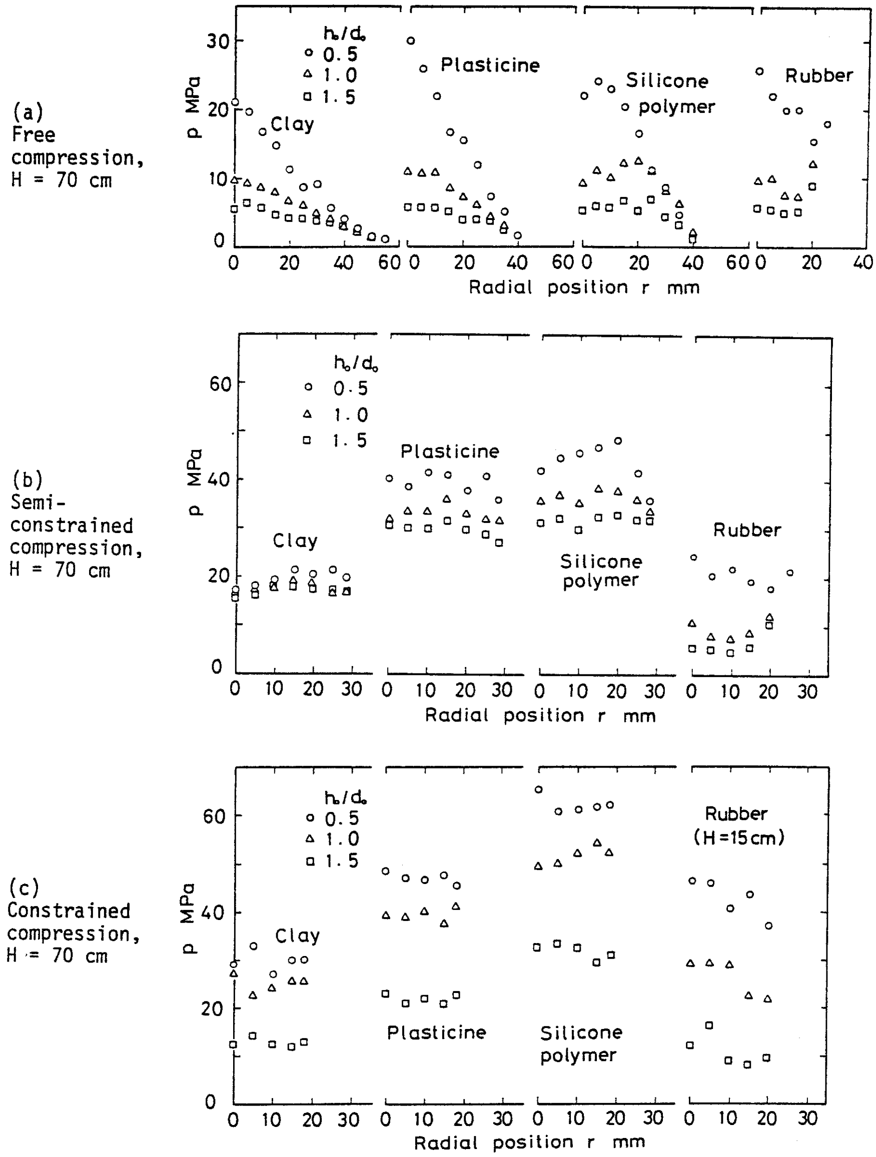


Fig. 8 Radial distribution of pressures in the flat-platen compression test.

assessment of such characteristics, an impact compression test which uses a combination of the die shown in Fig. 6 and the compression tools shown in Fig. 4 was carried out. The pressure was measured at the die wall and the bottom with pressure-sensitive films (Prescale for high pressure, made by Fuji Film Co., Ltd.), adhered thereto in advance. The pressure values by this method are compared with those by the pin method (C.C. and silicone polymer) in Fig. 7; the relative difference between them is within ± 10 percent.

2.8 Working tests

Using the aforementioned compression tools (Fig. 4), and putting a metal sheet and a pressure medium on the upper surface of the die, the following working tests were attempted. A piercing test was carried out with commercially pure aluminum sheets (A 1100-H24) and a die with a circular hole 10 mm in diameter. A stretch-forming test was carried out with killed steel or OFHC sheets and a forming die (aperture radius $2r_2$ = 20 mm, profile radius r_d = 3 mm). The nominal thickness of the sheets was 0.8 mm, and sheet blanks were square (42 mm × 42 mm). Their tensile properties are shown in Table 2.

3. Results and Discussion

3.1 Pressure distribution in flat-platen compression

After the flat-platen compression test, peak pressure values were read from the pressure-time curves recorded for different radial positions r. They are denoted as p and plotted for r in Figs. 8 (a) ~ (c). It was forecast that p-values in case of the combination of the rubber and the C.C. method would considerably exceed the maximum capacity of the apparatus (60 MPa), and so the hammer fall height H was lowered to 15 cm only for this case. In Fig. 8 (a) showing the result in case of F.C. a notable increase in p with a decrease in the relative specimen height h_o/d_o is observed near the specimen center, resulting in a considerable non-uniformity in the p distribution. However, p tends to distribute more uniformly and to increase with the enhancement in constraint, i.e., with change of the compression methods from F.C. to S.C. and further to C.C., as seen in Figs. 8 (b) and (c). The case of the combination of the rubber and S.C. was exceptional. Since the deformation of the specimen in this case was relatively small, it was not constrained effectively with the ring; thus the result was nearly the same as that in the F.C. method. It can be concluded that the C.C. method is the most applicable from the viewpoint of the distribution state in p and its magnitude.

Here, we denote the maximum values of p as p_{fc} for F.C. and p_{cc} for C.C., respectively, and the flow stress at low speed compression as σ_s. Their mutual ratios are compared between the four materials in Table 3 (h_o/d_o = 0.5). The p_{cc} value of the rubber was measured at r = 0 mm (specimen center) and under H = 70 cm with pressure-sensitive films. The σ_s values were calculated from the equation $\sigma = C\,\dot{\varepsilon}^m \varepsilon^n$ with $\dot{\varepsilon}$ = 0.2 s^{-1} and ε = 0.5. From Table 3 it is seen that the values of p_{fc}/σ_s are on the whole considerably high in the materials except for rubber. It should be noted that p_{fc}/σ_s is highest for the silicone polymer with the highest m-value. In the previous report [3], the mechanism for the pressure generation in the F.C. method was explained in terms of friction-hill and strain-rate effects. It can be said here that these effects are enhanced with an increase of m-values. Concerning p_{cc}/p_{fc} values, they are higher for the silicone polymer and the rubber; this means that the constraining effect is more marked in these materials. The reason seems to be that a higher m- or n-value enhances the leak resistance at the clearance between the constraining ring and the upper platen and thus produces an excellent sealing action. Accordingly, one can expect to raise the pressure about three times by using the C.C. method and a pressure medium having a high n- or m-value. From these results it can be concluded that a high m-value is advantageous from the aspects of the strain-rate and constraining effects; in fact, the silicone polymer with the highest m-value possesses a surprisingly high p_{cc}/σ_s value (1460).

Table 3 Comparoson of p_{fc}/σ_s , p_{cc}/p_{fc} and p_{cc}/σ_s among four materials.

Materials	p_{fc}/σ_s	p_{cc}/p_{fc}	p_{cc}/σ_s
Clay	299	1.56	466
Plasticine	196	1.62	318
Silicone polymer	538	2.71	1460
Rubber	10	2.91	30

h_o/d_o = 0.5, H = 70 cm, $\sigma_s = c\,(0.2)^m(0.5)^n$

3.2 Pressure in die cavity

The pressure values measured at the wall and the bottom in the die cavity are presented in Table 4. In the case of the rubber specimens, they did not contact the pressure-sensitive films during testing because of their low fluidity; thus the pressure in this case was regarded as zero and was omitted in Table 4. Taking account of the measuring error involved in the pressure-sensitive film (± 10 %), the pressure at the wall nearly equals that at the bottom, and so it can be regarded as approximately isotropic. The tendency for the pressure to increase with a decrease of h_o/d_o and with an enhancement of the constraint coincides with that in the flat-platen test aforementioned. However, the effect of the media on the pressure is quite different here; for the pressure is higher in the plasticine as a whole. The reason seems to be that its low m- and n-values yield a low flowing resistance in the die cavity. In conclusion, since the perfectly plastic property produces an excellent fluidity, it may be preferable for forming vessels whose ratios of depth to diameter are larger than 1.0 or so, and large m- or n-values may be rather an impeding factor.

3.3 Piercing test results

Pierced samples are shown in Fig. 9. The test results are summarized in Table 5 with the following indications: o, successfully pierced; Δ, partially pierced; X, not pierced. Referring to Table 5 and Figs. 8 (a) ~ (c), the pressure p at r ≦ 5 mm is closely related to whether piercing is successful or not; the ranges in p, less than 23.6 MPa, 25.4 ~ 30.5 MPa and more than 30.6 MPa correspond to "not pierced," "partially pierced" and "pierced," respectively. Accordingly, the flat-platen pressure test can be utilized as a simulation test for estimating piercing success or failure.

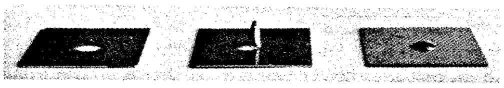
3.4 Stretch-forming test results

In Figs. 10 (a) ~ (c), the relative forming depths h_p/r_2 obtained by the stretch-forming test using killed steel sheets are plotted to the relative specimen heights h_o/d_o, where h_p and r_2 are the forming depth and the radius of the die aperture, respectively. Comparing these figures with Figs. 8 (a) ~ (c), h_p/r_2 has a positive correlation with p at r ≦ 10 mm and therefore the flat-platen pressure test is regarded as useful to estimate the forming depth in case of shallow vessels (h_p/r_2 ≦ 0.7 or so).

Table 4 Measured pressure in the die cavity.

Materials	h_o/d_o	F.C.		S.C.		C.C.	
		p_w	p_b	p_w	p_b	p_w	p_b
Clay	0.5	26	22	24	23	34	34
	1.0	15	10	25	26	34	37
	1.5	12	6	25	23	26	23
Plasticine	0.5	22	23	30	30	43	45
	1.0	13	9	26	29	45	49
	1.5	4	3	25	21	42	37
Silicone polymer	0.5	17	18	21	22	40	37
	1.0	8	9	19	19	40	39
	1.5	5	5	15	12	37	34

Unit : MPa, p_w and p_b : pressures at the wall and the bottom, respectively.



Pierced　Partially pierced　Not pierced

Fig. 9 Samples obtained in the piercing test.

Figure 10 (d) shows the result in the case of OFHC sheets and C.C., by which larger values of h_p/r_2 are obtained. In the figure it is found that h_p/r_2 in the silicone polymer is larger than that in the rubber, which is contrary to the result in Fig. 10 (c). This suggests that, in the range of h_p/r_2 which exceeds the aforementioned value, h_p/r_2 depends on the fluidity of media. From Figs. 10 (a) ~ (d) and Table 4, the following conclusions are drawn: the preferable property of the media for stretch-forming depends on h_p/r_2; in case of small h_p/r_2 (e.g., h_p/r_2 ≦ 0.7), a property which can generate a pressure as high as possible on the flat platen is preferable; in case of larger h_p/r_2, a high fluidity is advantageous.

3.5 Total estimation for media

Through four kinds of tests, the C.C. method was found to be the best of the three compression types. Based on the test results by this compression method, the applicabilities of the media are graded with the comparative ratings A ~ D in Table 6, where A and D indicate the highest and the lowest estimations, respectively.

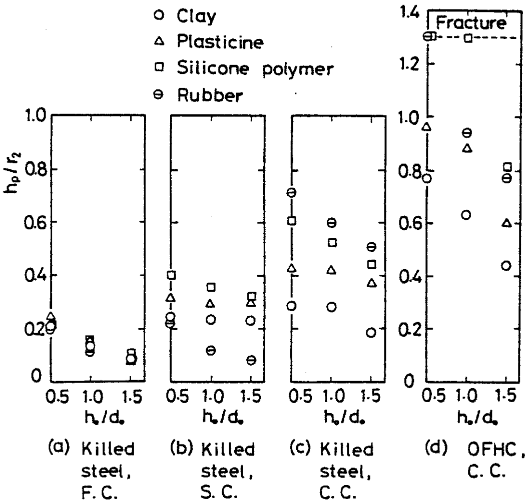


Fig. 10 Result of the stretch-forming test.

Table 5 Result of the piercing test.

Materials	h_o/d_o	F.C.	S.C.	C.C.
Clay	0.5	X	X	Δ
	1.0	X	X	Δ
	1.5	X	X	X
Plasticine	0.5	Δ	o	o
	1.0	X	o	o
	1.5	X	o	X
Silicone polymer	0.5	X	o	o
	1.0	X	o	o
	1.5	X	o	o
Rubber	0.5	X	X	o
	1.0	X	X	o
	1.5	X	X	o

o, pierced; Δ, partially pierced; X, not pierced; A 1100 H24, t_o = 0.8 mm, $2r_2$ = 10 mm.

Estimations for recycling and releasability from the die face are also included.

The rubber has the A marks for the flat-platen compression, piercing, shallow stretch-forming (killed steel sheets) and releasability, but it has the D mark for fluidity (die and platen compression). In addition, it is inadequate for repeated use and recycling, because an extruded region is formed in the specimen during piercing, as seen in Fig. 11; it is difficult to recover the specimen shape by some mechanical treatment. In contrast with the rubber, the plasticine is excellent in fluidity and repeated use (recycling), but it is inferior in the other items. The silicone polymer is rather universal; it is relatively good in all the test items and is superior at least to the clay used in the previous investigation [3]. Accordingly, the combination of the C.C. method and the silicone polymer is recommended at present.

The preferable mechanical properties of a medium may be summarized as follows. The elastic or strain-hardening plastic materials with high n-values can generate a very high pressure under the flat-platen or shallow-die condition, but the problem exemplified with the rubber is not avoidable; thus they are not applicable to the proposed manufacturing process. Accordingly, the selection is narrowed to perfectly plastic and viscoplastic materials, which are expressed with the constitutive equations $\sigma = C$ and $\sigma = C\dot{\varepsilon}^m$, respectively. As seen in Table 3, the pressure-generating potential can be markedly enhanced by the strain-rate and

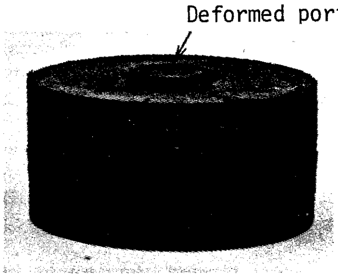


Fig. 11 Appearance of the rubber specimen after piercing.

constraining effects with an increase of m-value. Therefore, the latter type media with high C- and m-values are preferable for forming of shallow vessels with $h_p/r_2 \leq 0.7$ and for piercing. The development of such materials seems to be a key point in putting the proposed process to practical use. On the other hand, in the forming of deeper vessels attention should be paid to the fact that the applicability of media depends on h_p/r_2. Further investigation is necessary to clarify the optimum combination among h_p/r_2, working speed, m- and n-values.

4. Some New Applications

The presented process is characterized by high speed working, high compressive atmosphere, small working area, punch-less tooling and simple operation. Taking account of these features, the following applications were attempted by using the C.C. method and silicone polymer.

A slit 0.1 mm in width and 4.8 mm in length was made in carbon steel foil (SK3, 0.01 mm thick). A sample is shown in Fig. 12 (a). A droop and some irregular regions observed near the slit portion indicate that slitting was caused by the combined action of extrusion and bending under tension at the die edge. However, it was confirmed that the slit width deviation was very small (0.005 mm or so).

An example of piercing of small circular holes (0.3 mm in diameter) is presented in Fig. 12 (b). In piercing small holes, the usual shearing process has been used for circular holes greater than 1 mm in diameter and a special method (stripper-guide type) has been applied to 0.4 mm [4]. These smaller limits are due to difficulties in manufacturing the punch and in arranging an accurate clearance, fracture in the punch and so on. However, since the present process does not employ a punch, it is applicable to piercing of smaller holes, which would be impossible by the conventional process.

A circular hole 1 mm in diameter was made in glass sheets (cover glass for microscopy observation, 0.15 mm thick). The result is shown in Fig. 12 (c). The conventional process using a punch and a die was found inapplicable. The reason the

Table 6 Comparison of applicability among four materials.

Materials	Fundamental test *		Stretch-forming *		Piercing *	Re-cycling	Releasa-bility
	Flat-platen	Die and platen	Killed steel	OFHC	A 1100-H24		
Clay	D	C	D	D	D	A	D
Plasticine	C	A	C	C	B	A	D
Silicone polymer	B	B	B	A	A	A	B
Rubber	A	D	A	B	A	D	A

A~D : comparative ratings, with A indicating the highest estimation, D the lowest. * : constrained compression.

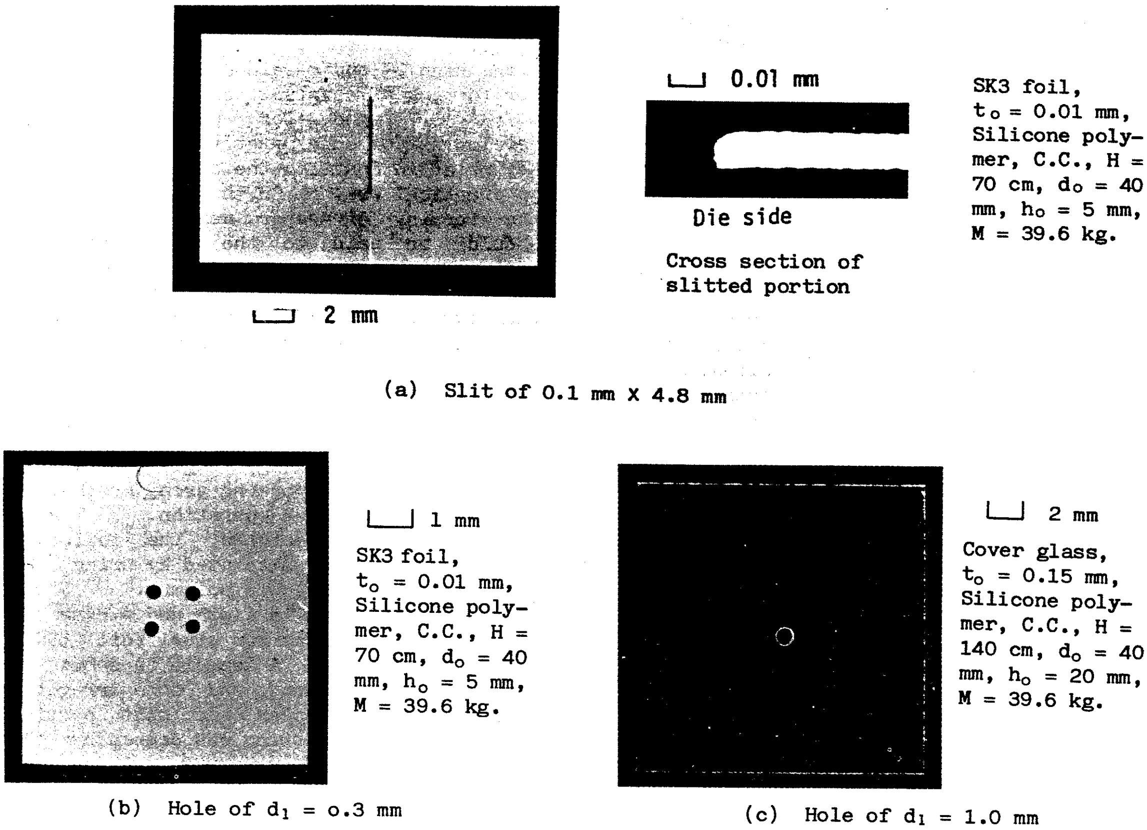


Fig. 12 Piercing of small holes and glass sheet.

hole could be made seems to be that both the initiation and the propagation of cracks were localized immediately near the die hole by virtue of the high compressive atmosphere. No examples of piercing of glass sheets by means of the shearing process have been reported to date.

5. Conclusions

Results obtained from the present investigation may be summarized as follows:
(1) Among the compression methods, constrained compression (C.C.) type is the most effective, because it generates the highest and the most uniform pressure.
(2) The flat-platen compression test can be utilized as an esitimation test for piercing and for stretch-forming of shallow vessels with the relative forming depth $h_p/r_2 \leqq 0.7$, where h_p is the forming depth and r_2 is the die aperture radius.
(3) Concerning the applicability of media, the following can be said in terms of the constitutive equation $\sigma = C\,\dot{\varepsilon}^m\,\varepsilon^n$.
The viscoplastic media with high C- and m-values are preferable for stretch-forming of aforementioned shallow vessels and for piercing. However, plastic media with low m- and n-values (i.e., almost perfectly plastic property) are advantageous for forming deep vessels (h_p/r_2 = 2 or so).
(4) In practice, silicone polymer with a high m-value is the most recommendable of the four media, because it possesses the highest p_{cc}/σ_s value ($p_{cc}/\sigma_s \fallingdotseq 1500$); thus, it has the highest potential to enhance the pressure by utilizing the strain-rate and constraining effects, where p_{cc} is the maximum pressure in the C.C. method and σ_s is the flow stress in the low speed compression test.
(5) It was found that the proposed process can serve as a special technique for piercing of small holes and brittle materials such as glass sheets.

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