A Piercing Technique for Glass Sheets by the Impact Compression of a Viscoplastic Pressure Medium*

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An improved method for piercing a circular hole in a glass sheet, difficult to achieve by conventional punching or drilling, is investigated by employing a manufacturing process using the impact compression of a viscoplastic pressure medium. Since the method previously proposed by the authors is not appropriate for a large ratio of hole diameter to workpiece thickness, an improvement is attempted in which two techniques are proposed: a method based on the delay phenomenon in the elastic response of workpieces and a differential pressurization method. Results show that both methods are useful. The latter method is also effective for improving the accuracy of the produced hole.

***Key Words*:** Nontraditional Processing, Special Piercing Technique, Glass Sheets, Viscoplastic Pressure Medium, Impact Pressure, Drop Hammer

1. Introduction

Recently, the remarkable development of new materials have presented a new manufacturing problem. Most of these materials have hard and brittle qualities and are difficult to work. Though there are a number of working processes available for such materials, e. g., grinding, machining with a diamond tool, water jet machining, electrodischarge machining and high-energy beam machining, they have the common disadvantage of low productivity and high equipment cost, and thus, limited applicability. If a high-productivity process, such as in punching, used for metal sheets and simple operations, such as in drilling, could be developed, it would increase the potential applications of these new materials.

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As the first step in pursuing such a possibility, the present research addresses the problem of piercing a circular hole in a glass sheet, and attempts to improve the piercing process by using the impact compression of a viscoplastic pressure medium. This method has been previously proposed[(1)~(3)]. This original method (hereinafter, O method) is schematically illustrated in Fig. 1. Its principle is the utilization of a high pressure field generated by impulsively compressing an amorphous, viscoplastic pressure medium with a drop hammer apparatus. The pressure is expected to produce a hole through the brittle fracture in the material region above the die hole (referred to as the die hole region, hereafter), while preventing cracks from penetrating the material region above the die face (referred to as the blank-holding region, hereafter). The concept of utilizing a high pressure field and a brittle fracture in a manufacturing process was also employed in the research on disking, by Satoh[(4)], and punching under high pressure, by Yamaguchi and his coworkers[(5)].

In previous research[(3)], it was pointed out that the O method is unable to pierce a material when there is a large hole diameter ratio (D/t, where D is the hole diameter and t is the thickness of the workpiece). In this paper, two countermeasures for this problem are presented, and their validity is confirmed experimentally.

2. Principles of the New Techniques

2.1 Line of improvement

Examples of success and failure in piercing soda lime glass by the O method are presented in Figs. 2 (a) and (b). In this process, cracks often penetrated the blank-holding region even in the case of a small hole diameter ratio ($D/t=5$), thus resulting in unsuccessful piercing, as shown in Fig. 2 (b). It was shown in a previous report[3] that the probability of this failure becomes higher with an increase in D/t, due to a decrease in the compressive stresses in the blank-holding region. Accordingly, it is regarded as a key point to enhance the pressure to apply thereto. Although various methods for this purpose may be devised, two procedures are proposed here from the viewpoint of simple operation. These principles are described in the following sections.

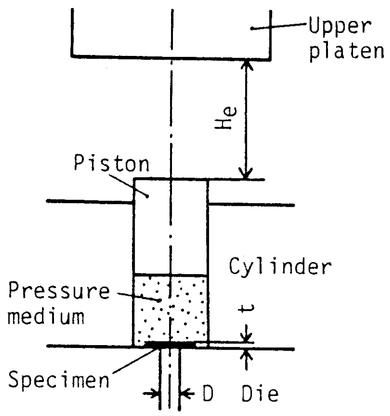


Fig. 1 Schematic drawing of hole piercing of a glass sheet by the O method

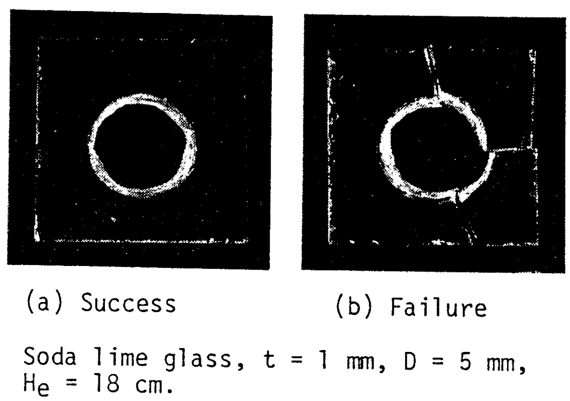


Fig. 2 Samples of successful and failed piercing by the O method

2.2 C method, utilizing the delay of elastic response

Here, we regard as the blank-holding pressure the dynamic compressive stress in the medium at the instant when the fracture is initiated in the die hole region. If an elastic response therein is delayed by any means during pressurizing, and the timing of the fracture is retarded, the blank-holding pressure will be enhanced. As measures for delaying the response, a cushioning metiod is employed. First, the cushioning effect is examined in the following sections through a dynamic analysis of a simple impact model and a simulative test.

2.2.1 Cushioning effect in logitudinal impact of elastic bars Let us consider an elastic bar B with a uniform cross section fixed at one end, as shown in Fig. 3. An elastic cushion, A, and a rigid body are attached to the other. Let the body be struck with a velocity (v_o). The materials of A and B are assumed to be aluminum and mild steel, respectively, and both adhere to one another at their interface. The stress (σ) at the fixed end, calculated according to a procedure mentioned in the appendix, is shown in Fig. 4, where σ_o is an initial stress, and T and τ are a time lapse after impact and a time interval (time interval $=2\times10^{-8}$ S), respectively. The initial velocity (v_o) is specified so as to satisfy the relation $\sigma_o=-\rho_b C_b v_o=-1$ MPa, where ρ_b and C_b are the density and the velocity of the elastic wave of the bar B, respectively. The bar length (l_b) was fixed at 1.04 mm, while the

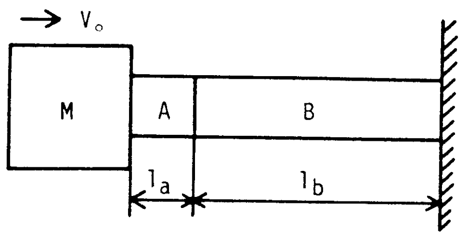


Fig. 3 Calculation model of longitudinal impact of elastic bars

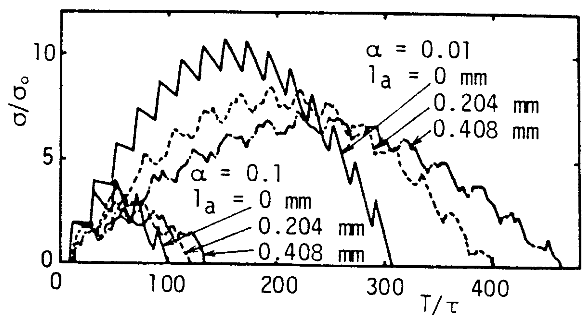


Fig. 4 Cushioning effect calculated for the longitudinal impact of elastic bars

cushion thickness (l_a) was changed (l_a=0, 0.204, 0.408 mm). The parameter, $\alpha = A_o l_b \rho_b / M$, is a measure of the response rate, and a small value indicates a load system with a slow response, where A_o is the cross-sectional area of the bar and M is the mass of the rigid body.

It is seen from Fig. 4 that with an increase in l_a, the response is delayed and σ/σ_o decreases. This effect is more marked in the slow response system. It was found that a decrease in the Young modulus of the cushion enhances the delay effect, although not presented here. In conclusion, within the model calculation, the cushion is effective in delaying the elastic response. However, it is wondered whether this holds true for such a loading system as in the piercing equipment which involves different boundary conditions. It is difficult to verify the cushion effect directly for an actual piercing condition. Therefore, it must be examined qualitatively by using the following simulative test.

2. 2. 2 Examination of the cushioning effect by simulative testing As a simulative test of the die hole region, a lateral impact was imposed on a beam fixed at both ends, as shown in Fig. 5 (a). A cylindrical weight (made of carbon tool steel SK3, 19.3 mm in diameter, 38 mm in length, 87 g in mass) was dropped onto a square pressure medium (made of silicone polymer, 30×30 mm, 2 mm thick) from a height of 10 cm. Thus, an impact force was applied to the beam through the cushioning plate. The response of the beam was measured by a strain gauge located on the lower surface of the beam. The output signal was stored in a digital transient recorder (8 bits, 2 048 words) and was then transmitted to a pen recorder. The beam, measuring 50 mm in length between the fixed ends, 30 mm in width, and 4 mm in thickness, was made of carbon steel S55C. The natural frequency of the whole system was 1.7 KHz. A 30×30 mm aluminum sheet, 0.4, 0.8 or 1.5 mm thick, was employed as a cushion.

As a simulative test for the blank-holding region, an impact was imposed on a plate in the thickness direction, as shown in Fig. 5 (b). The plate, 30×30 mm and 4 mm thick, was made of carbon steel S55C. Since the measurement of the response in the plate was difficult, a quartz load washer (piezoelectric force transducer, maximum force 118 KN, natural frequency 55 KHz) was assembled under the plate. The natural frequency of the whole system was 10 KHz. The impact condition was the same as that in the aforementioned beam test.

Test results are presented in Figs. 6 and 7. In the case of the beam with the slower response system (Fig. 6), the response time decreased with an increase in the cushion thickness. This was accompanied by the lower output, thereby agreeing with the theoretical results mentioned in section 2. 2. 1. In the case of the plate with the rapid response, however, the cushioning effect was hardly observed, contrary to the calculated result. This is presumably due to a different boundary condition. In this case, an elastic wave is apt to dissipate through the bed on which the apparatus is placed, thus it is deduced that the effect of the reflection of waves is weak. (Actual piercing seems to take place under similar circumstances). It should be noted that the delay phenomenon occurs through repeated reflections of the waves.

2. 2. 3 Proposition of the C method Noting that from the viewpoint of dynamic mechanics, the elastic response is slower in the die hole region than in

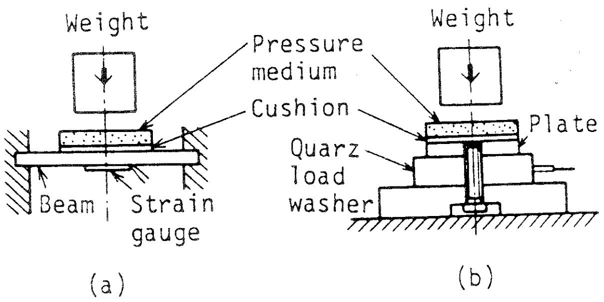


Fig. 5 Illustration of simulative impact tests

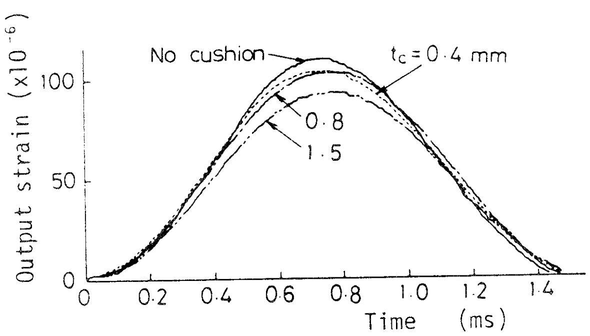


Fig. 6 Experimental result of lateral impact on a beam

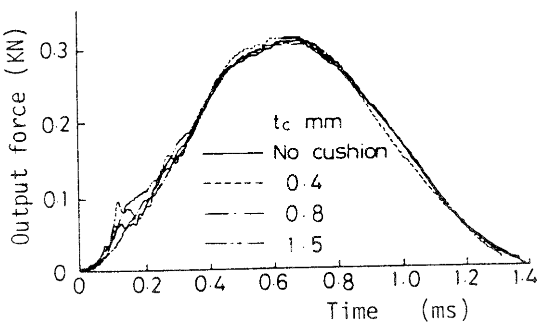


Fig. 7 Experimental result of through-thickness impact on a plate

the blank-holding region, and considering the results mentioned in sections 2. 1. 1 and 2. 1. 2, one can expect to delay the elastic response in the former region by placing a cushion on the specimen, as shown in Fig. 8. Hereafter, it will be referred to as the C method.

2. 3 FR method, utilizing differential pressurizing

Another piercing principle is proposed here. This is based on the concept of controlling the pressure distribution so that a higher pressure may then be achieved in the blank-holding region than in the die hole region. As schematically illustrated in Fig. 9, two pressure rooms, a large and a small one, are bounded by a ring having a hole whose diameter is equal to that of the die hole. Metal foils are placed both on and under the ring. The lower foil is employed to reduce the pressure in the pressure-medium region beneath the ring hole by being stretched upward. The upper foil is used to control the level of the blank-holding pressure by changing its thickness. Piercing is expected to be accomplished through the following sequence:

(1) Pressurization in the upper pressure room.
(2) Generation of nonuniform pressure distribution in the lower pressure room.
(3) Piercing of the upper foil.
(4) Flow of the pressure medium into the ring hole.
(5) Piercing of the lower foil.
(6) Piercing of the glass specimen through the brittle fracture at the die hole region.

This process will be referred to as the FR method, hereafter.

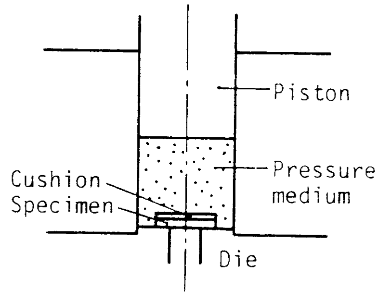


Fig. 8 Illustration of piercing by the C metiod

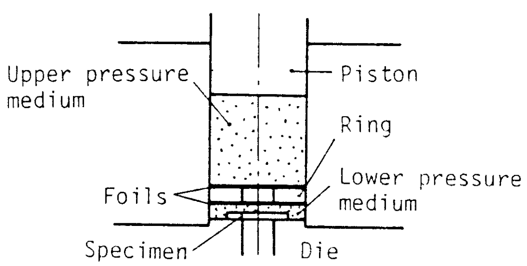


Fig. 9 Illustration of piercing by the FR method

3. Experimental Procedure

A free-fall drop hammer apparatus was manufactured for the impact piercing test. The mass of the hammer including the upper platen (M) was fixed at 39.6 kg, while the vertical drop of the hammer (H_e) was varied in the range of $H_e \leqq 40$ cm. The pressure capacity of the apparatus was about 450 MPa. The same commercial silicone polymer as employed in previous research[3] (made by Shinetsu Kagaku Co., Ltd., KE-SAP) was used here as a pressure medium. Its coefficient of viscosity, measured by a flow tester, was 5 000 Pa·S at 25°C, and its density (ρ) was 1.1 g/cm^3. The size of the pressure room in the O and C methods, and of the upper room in the FR method, was 15 mm, both in diameter and height. The length of the piston was 20 mm, and the clearance between the piston and the hole wall of the cylinder was 0.01 mm. The piston and the cylinder were made of carbon tool steel SK3 (quenched, $H_v=780$). Commercial dies, with a circular hole of 5 mm in diameter (made of die steel SKD11, $H_{RC}=60\sim62$), were used for the piercing test.

As a cushion for the C method, reasonably priced polyethylene sheets (thickness $t_c=18$, 81 and 280 μm) and aluminum foils ($t_c=6$, 17 and 40 μm) were selected for a small Young modulus. In the FR method, a ring made of die steel SKD11 ($H_{RC}=60$, hole diameter 5 mm, thickness 2 mm) and carbon tool steel foils (upper foil thickness $t_u=50$ μm, lower foil thickness $t_l=10$ or 50 μm) were employed.

The materials prepared for the piercing test were two commercial glass sheets, i. e., soda lime glass (nominal thickness $t=1$ mm, $D/t=5$, bending strength $\sigma_b=92$ MPa) and borosilicate glass ($t=0.15$ mm, $D/t=33.3$, $\sigma_b=122$ MPa). These were selected as materials difficult or impossible to pierce by means of the O method. Square specimens of 10×10 mm were cut from the original sheets by a microcutting machine. The tool surfaces were degreased with acetone before each testing, and no lubricants were used. The test temperature was 25±5°C.

4. Results and Discussion

4. 1 Result by the C method

Piercing was tested with various conbinations of hammer height (H_e) and cushion materials. The results are summarized in Figs. 10(a)～(d), where γ (%) is the ratio of the number of successful piercings to the number of tests (number of tests=10). It is shown by these figures that on the whole, γ was greater in the C method than in the O method. It should be noted, especially in Fig. 10 (c), that in the case of the borosilicate glass, with the large ratio of D/t, piercing was impossible ($\gamma=0$) by the O method;

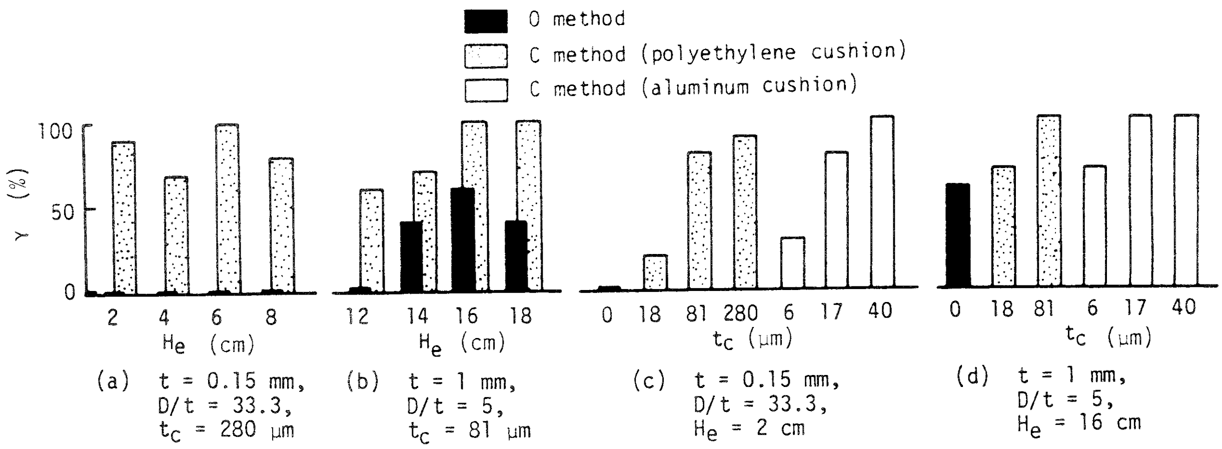


Fig. 10 Experimental result of piercing by the C metiod

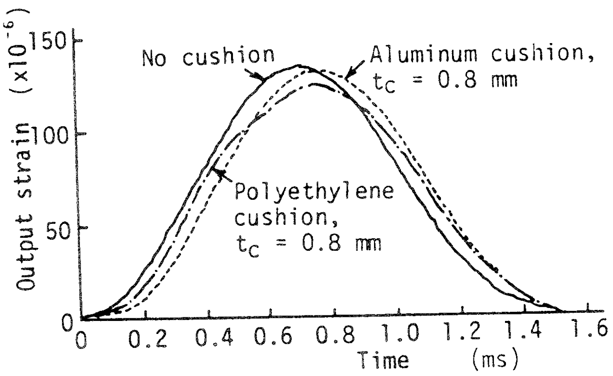
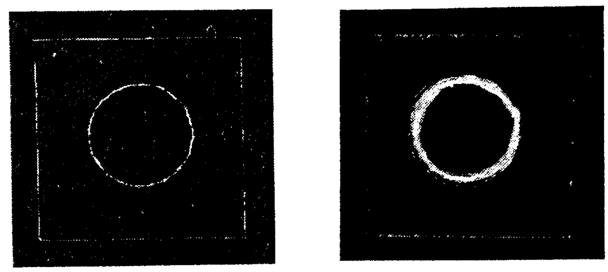


Fig. 11 Effect of cushions on the elastic response of beams



(a) Borosilicate glass, $t = 0.15$ mm, D/t 33.3, $H_e = 2$ cm.

(b) Soda lime glass, $t = 1$ mm, $D/t = 5$, $H_e = 18$ cm.

Cushion: Polyethylene, $t_c = 81$ μm.

Fig. 12 Pierced samples by the C method

whereas, the C method improved γ up to 100%. Concerning the applicability of the cushion, the aluminum foils were better than the polyethylene sheets, as shown in Fig. 10 (c). This result is in agreement with the result of the simulative impact test of the beam, as presented in Fig. 11. The delay of the response is greater in the aluminum cushion than in the polyethylene cushion. However, these results are contrary to the aforementioned theoretical prediction that the cushion effect would be enhanced by a decrease in the Young modulus of the cushion. The reason for this is not fully understood at present, but the viscosity of the polyethylene might have influenced the dynamic response. Although further investigation is necessary to search for an optimum cushion, it can be concluded, within the limits of the present experiment, that by using an aluminum cushion with a thickness of $t_c \geqq 40$ μm, 100% successful piercing is expected, irrespective of D/t.

Photographs of the successfully pierced samples by the C method are shown in Figs. 12 (a) and (b), which are views from the die side. The appearance of the formed hole in the case of the soda lime glass (Fig. 12 (b)) is similar to that obtained by the O method (Fig. 2 (a)).

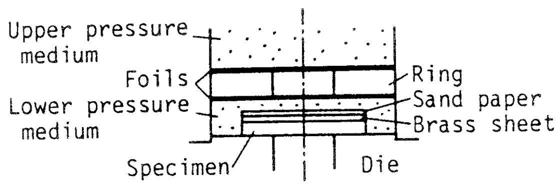


Fig. 13 Method for measuring pressure distributions in the FR process

4.2 Result by the FR method

4.2.1 Pressure distribution Prior to the piercing test, the pressure distribution in the FR method was examined. A method for measuring the pressure is illustrated in Fig. 13. A 60/40 brass sheet, 0.2 mm thick, and a # 240 sand paper were employed in the pressure sensor. The pressure was estimated from the roughness transcribed onto the surface of the brass sheet. The center-line average roughness (R_a) was measured by a Talysurf 10. In order to calibrate the pressure value, a compression test of the pressure sensor was carried out by using a universal testing machine, and the relationship between the pressure (p) and the roughness (R_a) was determined. The traversing distance in the measurement of R_a was 8 mm. Three specimens were tested for a specified pressure, and the R_a measurement was taken three times for each specimen; then, the nine measurements of R_a were averaged. The calibration result, shown in Fig. 14, indicates a good linear relation.

The traversing distance for the piercing condition was 2 mm. Ten specimens were prepared for the specified condition, and R_a was measured three times at the specified position in each specimen. Hence, thirty R_a measurements were averaged and converted into the pressure values found in Fig. 14. Examples of the pressure distribution, obtained under a condition of no cracking in the glass specimens, are shown in Fig. 15, wherein the results using the O method are also presented for comparison. With the FR method, using soda lime glass, a marked pressure gradient was produced, and the pressure increased with an increase in the distance from the specimen conter, as expected.

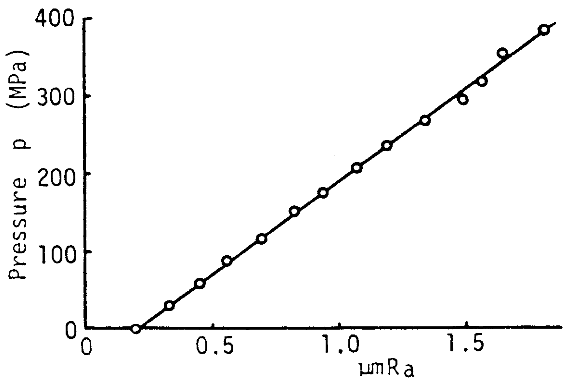


Fig. 14 Calibrated result for pressure

It was found from the test using borosilicate glass that a too thick lower foil fails to cause differential pressurizing.

4.2.2 Result of piercing test The success probability in piercing γ was examined in the same way as in the C method. The results are summarized in Figs. 16 (a)~(b). Figure 16 (a), showing the relation between γ and the volume of the lower pressure medium (V_l), indicates the existence of an optimum V_l value. All the other data about the FR method presented in this paper are based on this optimum value (V_l=0.27 cm^3, mass=3 g). From Figs. (b) and (c), showing the case of the borosilicate glass, it is found that γ is enhanced with a thinner lower foil, which is in accordance with the aforementioned pressure distribution. Thus, it can be said that only the working condition causing differential pressurization improves the piercing. It is concluded from Figs. (c) and (d) that a γ value of 100 % is

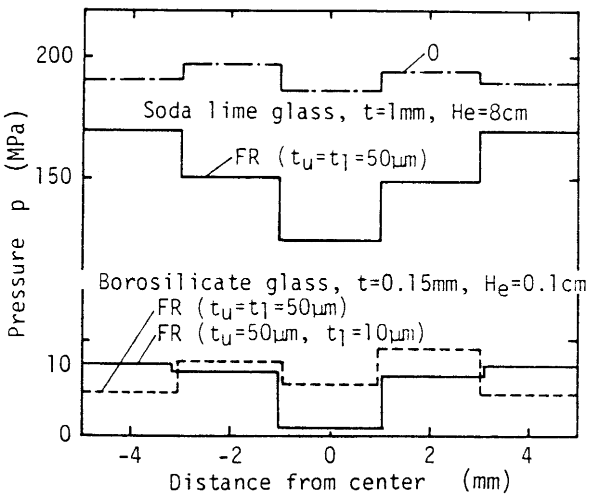


Fig. 15 Pressure distributions measured in the FR process

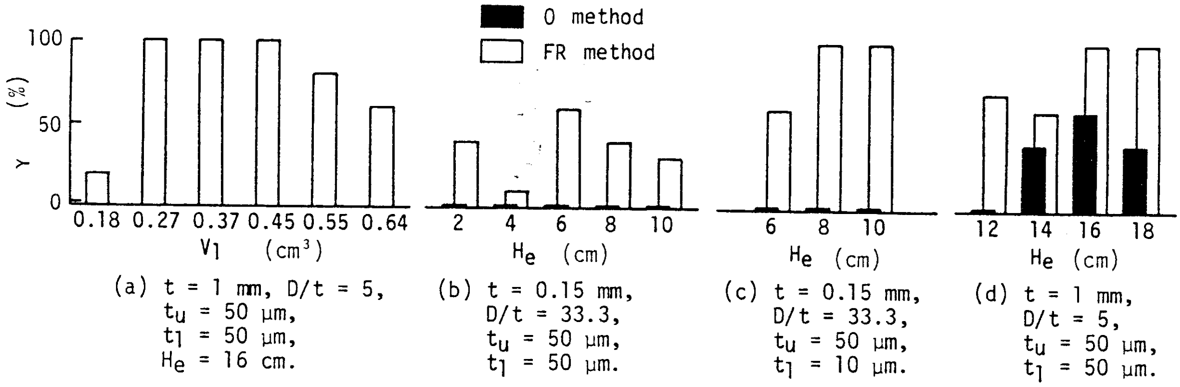
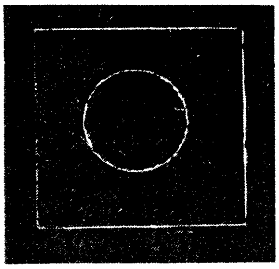
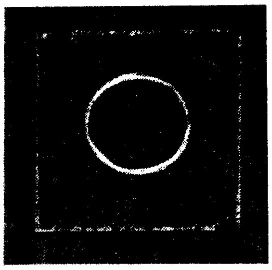


Fig. 16 Experimental result of piercing by the FR method



(a) Borosilicate glass, t = 0.15 mm, D/t = 33.3, t_u = 50 μm, t_l = 10 μm, H_e = 6 cm.



(b) Soda lime glass, t = 1 mm, D/t = 5, t_u = 50 μm, t_l = 50 μm, H_e = 18 cm.

Fig. 17 Samples pierced by the FR method

expected beyond a certain limit of H_e, irrespective of the kind of glass or the D/t ratio. A blank-holding pressure for successful piercing was measured for reference, and 143 MPa (H_e=8 cm) and 214 MPa (H_e=16 cm) were obtained for borosilicate and soda lime glass, respectively.

Photographs of the samples obtained by the FR method are shown in Figs. 17 (a) and (b). The appearance of the pierced hole in the borosilicate glass (Fig. 17 (a)) is similar to that obtained by the C method (Fig. 12 (a)); good holes are produced by both methods. On the oter hand, comparing the holes of the soda lime glasses between the FR, O, and C methods (Figs. 17 (b), 2 (a) and 12 (b), respectively), the width of the white annular band near the hole is markedly decreased in the FR method, and accordingly, the FR process serves to improve the accuracy of the pierced hole as well as the success probability. This band corresponds to a tapered hole wall; the hole diameter decreases from the die side to the pressure-medium side[3]. It is presumed that the blanked tips from the upper and lower foils have machined the hole wall during the FR process.

5. Conclusions

As new techniques for piercing a hole in a glass sheet, two working principles were proposed: a method utilizing the delay phenomenon in the elastic response (C method) and a differential pressurization method (FR method). By experimentally examining their validity, it was found that both methods served to facilitate the piercing of a hole with a large hole diameter ratio, an operation difficult to undertake by the original method previously proposed. Thus, nearly 100 % successful piercing was accomplished in the range of the diameter ratio 5～33 by means of either the C or FR methods. The latter method was found to be effective in improving the accuracy of the produced hole. Since the main purpose of the present research was to confirm the validity of the proposed principles, neither the abvantages and disadvantages of the two processes nor the optimum working conditions were thoroughly examined; thereby, problems to be solved by further study.

Appendix

A procedure for the analysis of the one-dimensional impact of the elastic bar, illustrated in Fig. 3, is described here. The following are assumed:

(1) At any time, the elastic pulse wave with the stress $\sigma=-\rho_a C_a v$ starts from the left end of the cushion A.

(2) The motion of the rigid body is governed by the equation $(M/A_0)dV/dt-\sigma=0$.

(3) At the interface between the cushion A and the body or between A and the bar B, waves are reflected or transmitted according to the Hugoniot theorem[6].

(4) Density changes in the A and B materials are neglected.

Symbols ρ_a and C_a are the density and the velocity of the elastic wave related to the cushion A, respectively, and v and M are the velocity of the body and its mass, respectively, while A_0 is the cross-sectional area of the bar. Due to assumption (1), an elastic pulse wave was sent into the cushion A at a time interval of τ ($\tau=2\times10^{-8}$ s), and the variation in the position of each wave and the stress with the time lapse were calculated. Cushion A and bar B were divided into the small elements so that all the waves might proceed by a distance equal to the length of the elements during the time interval. The stress at each element was determined by superposing the stresses due to all the waves involved at each instant. The calculation was carried out with a personal computer. The number of waves was reduced by summing all the waves which proceeded in the identical direction at the respective elements and creating one equivalent wave. The validity of the present numerical calculation was confirmed for a single beam without the cushion by referring to the sulution presented by Timoshenko and Goodier[7]. The material of cushion A was assumed to be aluminum, and thus its Young modulus (E_a) and density (ρ_a) were taken as 7×10^4 MPa and 2.7g/cm^3, respectively. On the other hand, the material of bar B was assumed to be mild steel, and thus its Young modulus (E_b) and density (ρ_b) were taken as 2.1×10^5 MPa and 7.9 g/cm^3, respectively. The length of the bar (l_b) was fixed at 1.04 mm (number of elements $N=10$), and the thickness of the cushion (l_a) was varied in three ways: $l_a=0$ mm ($N=0$), 0.204 mm ($N=2$), and 0.408 mm ($N=4$).

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