Variation of the strain waveform developed in strengthened porcelain upon impact

Akemi HAYASHI,† Hideaki TSUGE,* Kazumasa KURACHI, Masatoshi MIZUNO and Toshitaka OTA**

Gifu Prefectural Ceramics Research Institute, 3–11 Hoshigadai, Tajimi, Gifu 507–0811, Japan
***Research Institute for Machinery and Materials Gifu Prefectural Government, 1288 Oze, Seki, Gifu 501–3265, Japan**
****Ceramic Research Laboratory, Nagoya Institute of Technology, 10–6–29 Asahigaoka, Tajimi, Gifu 507–0071, Japan**

The impact strengths of strengthened porcelain bowls were evaluated using an impact examination machine based on JIS S 2402. A strain waveform developed upon impact was measured by a strain gauge adhered to the inside surface on the porcelain bowl. The deformation of the porcelain bowls was observed by high-speed camera. The strain waveforms showed two noteworthy peaks. The first peak was found to be caused by the initial impact, and the second peak was found to be caused by the restorative force generated by the deformation of bowl, which acted as a backstop. The high-speed camera also revealed that the bowl re-collided with the hammer or pushed the hammer again as the bowl returned to its original shape and position, resulting in the second peak. The variation of the strain waveform was found to be related to the size of bowl and the open angle of the backstop.

Key-words : Strengthened porcelain, Impact test, Strain waveform, High-speed camera

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1. Introduction

A porcelain strengthened by adding extra alumina to raw materials is two to three times as strong as ordinary porcelain.[1] The commercial strengthened porcelain used for a school meal has flexural strength of 200–300 MPa. The flexural strength of the general porcelain is about 70 MPa.[1] Such strengthened porcelain is often used for tableware for school lunches in Japan. Strengthened porcelain can be made more resistant to impact stress by rounding its rim. The strength of porcelain is generally evaluated by a flexure test or an impact test. Flexure tests are conventionally used to evaluating the strength of porcelain.[2)–4] However, impact tests are rarely used. Although an impact test can be usually performed as a pendulum-type impact test based on ASTM C368-88, the obtained data are widely scattered depending on the circumstances, and there have been few systematic investigations of the impact strength of porcelain.[5,6] In practice, porcelain generally cracks due to impact stress received as a result of dropping or during washing or transporting the porcelain. Therefore, the impact test is effective for evaluating the strength of real porcelain.

Recently, in conjunction with a number of public research laboratories in Japan, we were involved in the standardization of an impact test for strengthened porcelain.[7] Kamochi et al. performed a statistical and photographic analysis and clarified that the mathematical distribution of impact strength was expressed as a normal distribution[8] and that the initial failure in porcelain occurs as a result of tensile stress induced by the deformation of porcelain at the impact point.[9] Based on a stress–strain simulation, Akizuki reported that the origin of the failure was inside the impact point.[10] Furthermore, a round robin test conducted by a number of public laboratories revealed that, in impact testing, the impact strength was affected by parameters such as the hammer moment, the backstop, the porcelain shape, and the restraint weight.[7,8] Therefore, we considered the variation of the strain waveform developed in porcelain upon impact. As a result, we found that (1) the porcelain specimen deformed into an oval shape upon impact with the rim of the specimen, (2) larger tensile strain occurred in the horizontal direction on the inside surface of the specimen, (3) the maximum strains were observed at the impact point and at the contact point with the backstop, and (4) the strain waveform that varies according to sample size at the impact point exhibited two noteworthy peaks.[11] In the present study, we investigated following thing: (1) what does two peaks mean? and why does two peaks appear? (2) Why should we consider for measuring impact strength of porcelain?

2. Experimental procedure

Two types of strengthened porcelain, bowl (1) and bowl (2), were used for the impact test. The strengthened porcelains were manufactured in different sizes under the same sintering conditions using the same raw materials. **Table 1** shows the features and some properties of the porcelains. The flexural strength was performed according to Ceramic Society of Japan standard JCRS 203-1996:[Testing Method for Flexural Strength of Strengthened Porcelain Materials]. The specimen using flexural strength is made as follows. The tableware bottom plane is cut with a diamond cutter to 10 mm in width 40 mm in length. The flexural strength specimen was finished in 8.0 ± 0.5 mm width by ground cutting surface 1 mm with a diamond wheel (900 µm by #325, 100 µm by #800). The flexural strength tested by three point bending, and flexural strength is calculated from the following formula.

$$\sigma = 3PLs/2wt^2$$

[σ: flexural strength (MPa), P: maximum load (N), Ls: span of supporting point, w: width of specimen (mm), t: thickness of specimen (mm)]

† Corresponding author: A. Hayashi; E-mail: hayashi-akemi@pref.gifu.lg.jp

Table 1. Features and properties of the strengthened porcelain

	Diameter (mm)	Height (mm)	Weight (g)	Flexural strength (MPa)	Bulk density (g/cm^3)	Porosity (%)	Young's modulus (GPa)	Impact strength (J)
Bowl (1)	127	54	160	245	2.7	0.06	114	0.40
Bowl (2)	175	73	359	273	2.8	0.05	120	0.78

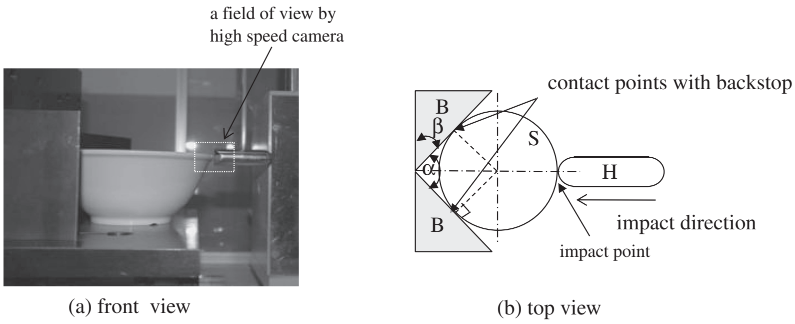

Fig. 1. Schematic diagram of the impact test: (a) front view; (b) top view (S: test specimen, B: backstop, H: hammer, α: open angle, β: apex angle).

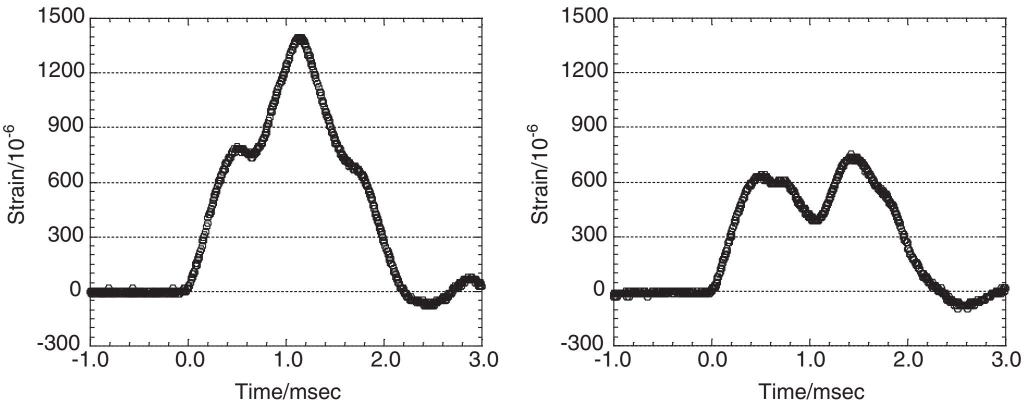

Fig. 2. Strain waveforms at the impact point with the backstop (a) for the small bowl (1) and (b) for the large bowl (2).

The porcelains had approximately the same density, porosity, flexural strength, and Young's modulus, but their impact strengths were noticeably different.

The impact strength was measured using an impact examination machine (Research Assist Company, RA-112) based on JIS S 2402 (set a standard based on ASTM368-88). Place the test specimen in the apparatus as the **Fig. 1** so that rests in Backstop. Repeatedly strike rim by hammer with blows of increasing energy until failure occurs, beginning with an initial blow of 0.04 J and increasing the energy of each succeeding blow in the increments of 0.02 J. The impact strength is the energy when the specimen is failure. Backstop open angle in measurement is 120°. A porcelain test specimen (S) was placed in the machine as shown in Fig. 1. The specimen was kept in contact with the backstop (B), which consisted of two triangular prisms with apex angles (β) of 15, 30, and 45°. Thus, the open angle (α) between the two prisms became 150, 120, and 90°, respectively. An impact was applied by striking the specimen with a 180-g hammer (H) having an energy of 0.2 J, the magnitude of which was smaller than the impact strengths of both bowls, as shown in Table 1. Therefore, these specimens did not crack during the impact test to measure the strain waveform.

The strain developed in the specimen was measured by a strain gauge (Kyowa Electronics Instruments Corporation, KFG-3-120) connected a dynamic strain amplifier (Kyowa Electronics Instruments Corporation DPM713B) and a digital oscilloscope (LeCroy Japan Company, WaveSurfer 422). Measurement parameter is following: measurement range was 1k-$\mu\varepsilon$ Low-pass Filter was 1k Hz. Low-pass Filter is a filter that passes low-frequency signals with frequencies higher than the cutoff frequency. Time/division was 5 ms/div, Max Sample Point was 2MS. The strain gauge was adhered horizontally to the inside surface of the bowl specimen at the impact point and at the contact point with the backstop, where the maximum tensile strains occurred.[11]

During the impact test, the deformation of the specimen and the movement of the hammer were observed using a high-speed camera with a frame rate of 10,000 fps (photron FASTCAM SA MRPG Model 120k-3M), which was able to take a snapshot every millisecond.

3. Results and discussion

Figure 2 shows the strain waveforms at the impact point for the small bowl (1) and the large bowl (2) with backstop (α = 120°) on impact. The beginning of impact (0 ms) was regarded as

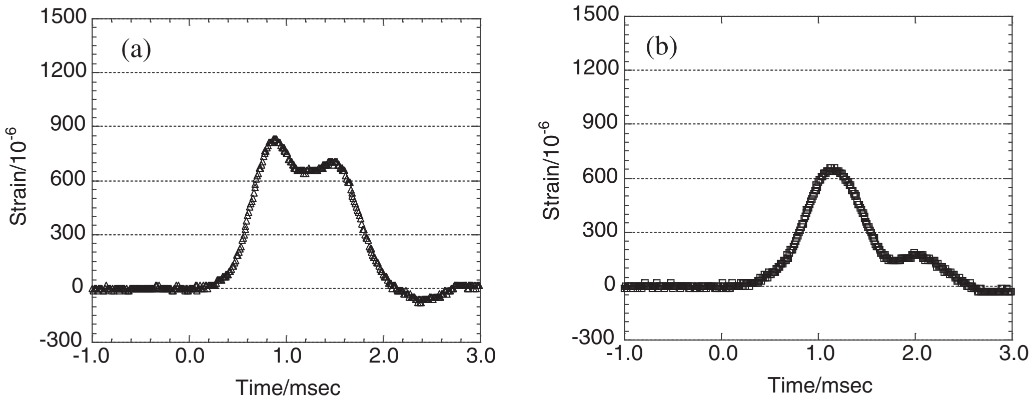

Fig. 3. Strain waveforms at the contact point with the backstop (a) for the small bowl (1) and (b) for the large bowl (2).

the point in time at which strain was first detected. Two noteworthy peaks were observed in the strain waveform. The first peak had approximately the same magnitude at 0.5 ms for each specimen, regardless of bowl size. On the other hand, the second peak appeared at different times, depending on bowl size. The second peak appeared at 1.2 ms for the small bowl (1) and 1.5 ms for the large bowl (2). The time lag between the first peak and the second peak was 0.7 ms for the small bowl (1) and 1.0 ms for the large bowl (2). The magnitude of the second peak for the small bowl (1) was larger than that for the large bowl (2). The above results revealed that a larger second peak occurred sooner in the smaller specimen. This behavior was also observed in an impact test conducted on plate-shaped porcelain specimens.[11)]

As shown in **Fig. 3**, there were two peaks in the strain waveform at the contact point with the backstop. The first and second peaks appeared at 0.85 and 1.55 ms for the small bowl (1) and at 1.0 and 2.0 ms for the large bowl (2), respectively. These peaks appeared later as compared with the peaks at the impact point. The delay time was 0.35 ms for the small bowl (1) and 0.5 ms for the large bowl (2). The time lag between the first peak and the second peak at the contact point was 0.7 ms for the small bowl (1) and 1.0 ms for the large bowl (2). These time lags also correspond with the time lag at the impact point. Therefore, the strain waveform at the impact point was deduced to have propagated to the contact point after a delay of 0.35 ms for the small bowl (1) and 0.5 ms for the large bowl (2). Assuming the strain waveform at the contact point returned to the impact point after the same delay, the delay time was equal to one half of the time lag between the first peak and the second peak.

Figure 4 shows photographs of the bowl and the hammer during impact as captured by the high-speed camera. Figures 4(a) and 4(a′) show photographs of the moment that bowl came into contact with the hammer. This moment was fixed at 0 ms as the beginning of impact, and this position was fixed as the origin of the abscissa. The force of the moving hammer moved the rim of bowl slightly to the left, as shown in Figs. 4(a) through 4(d) and Figs. 4(a′) through 4(d′), and the hammer then rebounded from the bowl to the right, as shown in Figs. 4(d) through 4(h) and Figs. 4(d′) through 4(h′). Simultaneously, the bowl deformed to the left and then returned to its original shape (from an oval to a circle) and position by the restitutive force. The displacement of the bowl (1) was synchronized with the displacement of the hammer. However, since the displacement of the large bowl (2) was greater than that of the hammer at approximately 1.0 ms, there was a clear space between the bowl and the hammer, as shown in Fig. 4(e′). The bowl (2) then collided with the hammer again, as shown in Fig. 4(f′). The situations shown in Figs. 4(e′) and 4(f′) corresponded to the minimum strain waveform and the start of the second peak, respectively.

Based on the results shown in Figs. 2 through 4, the behavior of the bowl (2) upon impact is illustrated in **Fig. 5**. Figure 5(a) shows the beginning of impact, as the hammer comes into in contact with the bowl, before which there was no strain in the bowl. After the hammer struck the bowl, a strain occurred locally at the impact point, as shown in Fig. 5(b). Simultaneously, the bowl began to deform, as shown in Fig. 5(c). The strain at the impact point then gradually increased as a result of both the local stress and the deformation of the bowl and reached a maximum corresponding to the first peak. The deformation propagated toward the backstop, and the shape of the bowl changed from circular to oval, as shown in Fig. 5(d). Then, stress generated by the reaction between the backstop and the bowl generated a local strain in the bowl, as indicated by the first peak in the strain waveform at the contact point with the backstop, as shown in Fig. 3. On the other hand, the hammer stopped and began moving in the opposite direction upon rebounding from the collision. As a result, the hammer separated from the bowl. Since the stress generated by the impact of the hammer was partly released, the strain waveform at the impact point decreased to a minimum. After the bowl deformed a certain amount, the bowl began to return to its original state. Since the backstop restrained the bowl from moving forward, the bowl was moved backward by the restorative force, i.e., toward the right. When the bowl re-collided with the hammer as the bowl returns to its original shape, the strain should increase, as shown in Fig. 5(e), resulting in a second peak in the strain waveform at the impact point. Furthermore, this collision forced the bowl to deform again, resulting in a second peak in the stain waveform at the contact point with the backstop. This strain must generate a third peak in the strain waveform at the impact point. Thus, since this phenomenon was repeated while the hammer remained at the left side of the origin, as shown in Fig. 4, various peaks appeared in the strain waveform. However, these peaks were attenuated. Actually, since the strain would propagate back and forth in the bowl as a wave, the strain waveform should become more complicated. Eventually, the bowl returned to its original shape and position, whereas the hammer moved away from the bowl, as shown in Fig. 5(f).

In the case of the small bowl (1), even if the bowl remained in contact with the hammer, the immanent restorative force in the deformed bowl should act on the hammer for an instant. This reaction caused a local strain in the bowl, resulting in a considerable second peak in the strain waveform. In this case, the

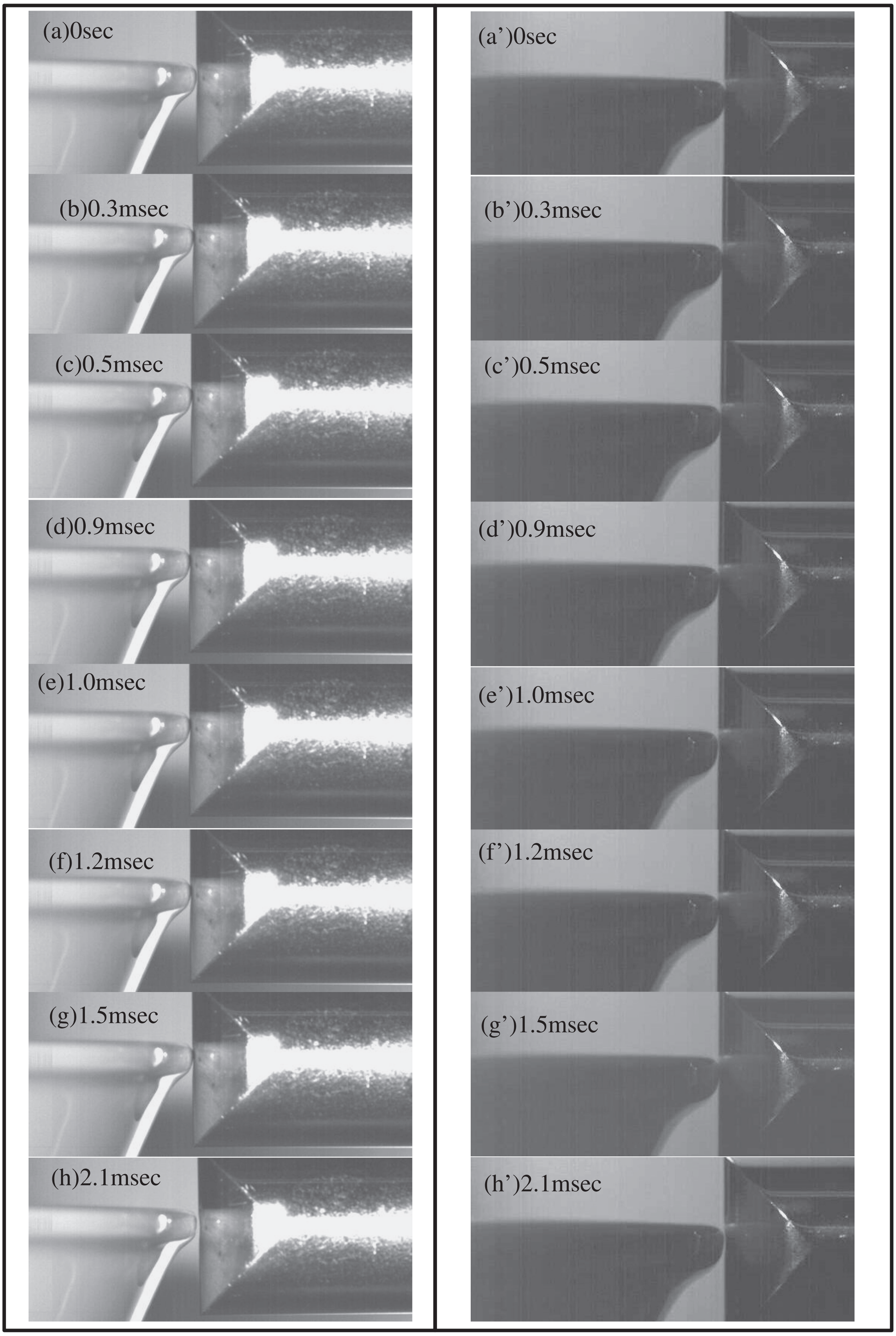

Fig. 4. Photographs of the bowl and hammer during impact captured by the high-speed camera: (a) through (h) small bowl (1); (a′) through (h′) large bowl (2).

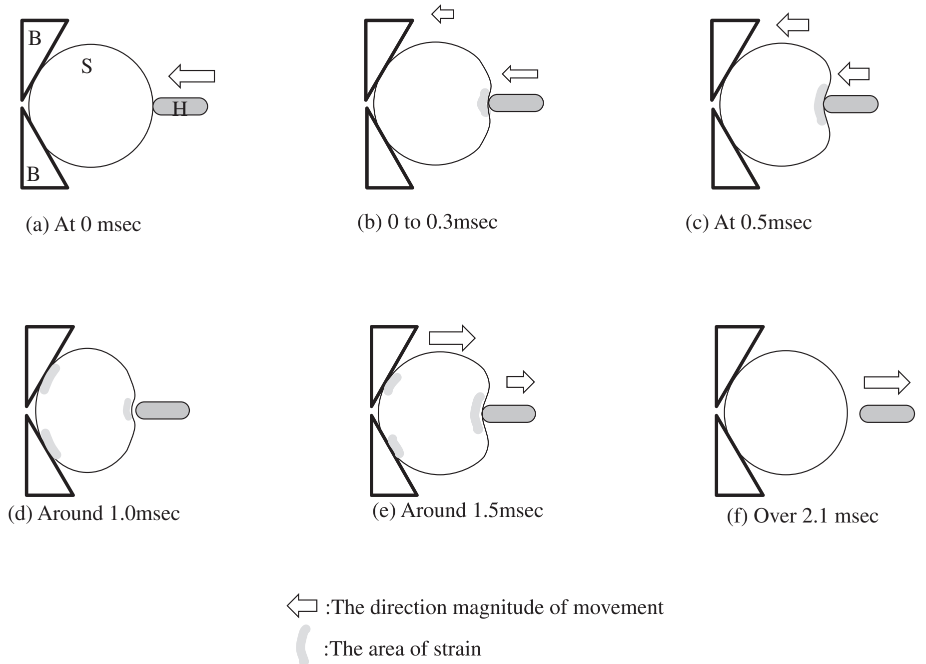

Fig. 5. Exaggerated illustration of the deformation of the large bowl (2) upon impact.

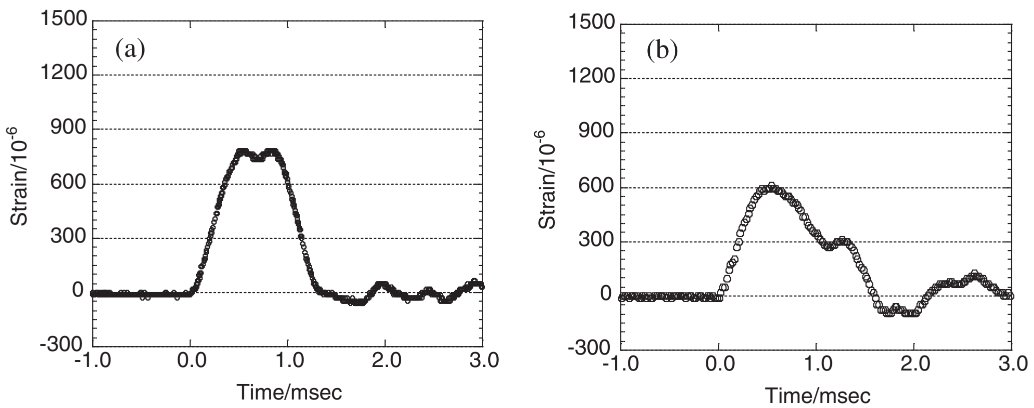

Fig. 6. Strain waveforms at the impact point without the backstop (a) for the small bowl (1) and (b) for the large bowl (2).

second peak appeared sooner and was higher than that in the case of the large bowl (2). For the small bowl (1), the contact points with the backstop were much closer to the position of the hammer than in the case of the large bowl (2). As such, in the case of the small bowl (1), the restorative force quickly acted on the hammer. Then, since the first peak should remain at the impact point, the new strain generated by the restorative force should overlap the remaining strain of the first peak. As a result, the second peak would become much higher, and the magnitude of the second peak might exceed that of the first peak. However, the maximum magnitude of the second peak was twice the magnitude of the first peak.

Based on the above discussion, the restraint due to the backstop was concluded to cause the second peak in the strain waveform. This is also demonstrated in **Fig. 6**. For the case in which there was no backstop, a noteworthy second peak did not appear. The strain waveform coincided approximately with only the first peak in Fig. 2. In other words, the strain waveform at the impact point was considered to be composed of a local strain generated by the initial impact and a secondary strain generated by the deformation of the bowl by the backstop. The stress developed at the impact point by the initial impact generated the strain waveform at the contact point with the backstop, as shown in Fig. 3. Moreover, a new stress developed at the contact points with the backstop must generate a certain strain waveform at the impact point. Assuming the strain caused by the backstop resembles the strain waveform, as shown in Fig. 3, the strain caused by the backstop can be obtained by delaying the strain waveform, as shown in Fig. 3, until a certain time. As mentioned in Figs. 2 and 3, the delay time was estimated to be 0.35 ms for the small bowl (1) and 0.5 ms for the large bowl (2). Therefore, the strain waveforms returned from the backstop would be similar to the strain waveforms developed at the contact point with the backstop in Fig. 3, provided that the waveforms were delayed 0.35 ms for the small bowl (1) and 0.5 ms for the large bowl (2). These delayed strain waveforms (△) and the strain waveforms shown in Fig. 6 (○) could be combined to obtain the estimated strain waveforms (□), as shown in **Fig. 7**. Then, the estimated strain waveforms were approximately the same as the measured strain waveforms, as shown in Fig. 2.

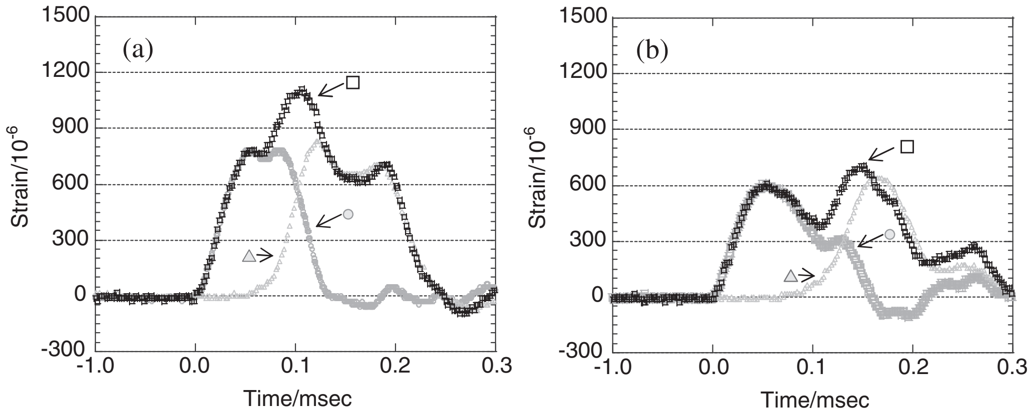

Fig. 7. Mechanism of two maximum peaks that appeared in the strain waveform: (a) small bowl (1); (b) large bowl (2). ●: strain waveforms caused by the initial impact, which are identical to the strain waveforms in Fig. 6. ▲: strain waveforms that returned from the backstop, which are equivalent to the strain waveforms in Fig. 3 after a delay of 0.35 ms for the small bowl (1) and 0.5 ms for the large bowl (2). □: strain waveforms estimated by the combination of ● and ▲.

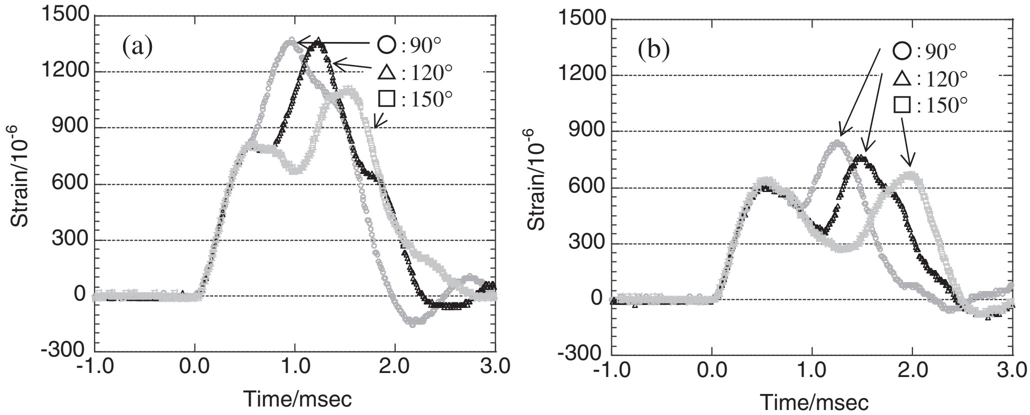

Fig. 8. Variation of the strain waveforms at the impact point with the open angle of the backstop (α): (a) small bowl (1); (b) large bowl (2).

The open angle of the backstop (α) also had a significant influence on the strain waveform.[11] **Figure 8** shows the variation of the strain waveform with α. The first peak appeared at the same time and had the same magnitude for every specimen, regardless of α. On the other hand, the second peak appeared at different times and had different magnitudes, depending on α. With increasing α, the time at which second peak appeared became later and the magnitude of the second peak decreased. Since the second peak was generated by the backstop, a larger second peak was expected to appear sooner in the case of small α, where the contact points were close to the impact point. In addition, for the case of the small bowl (1), where the contact points were closer to the impact point, a larger second peak appeared sooner, as compared to the large bowl (2).

The above results suggested two failure modes for porcelain impacted by a hammer, i.e., failure in the first peak and failure in the second peak. In the case of failure in the first peak, cracking must be simultaneous upon initial impact. In this case, the stress generated by the initial impact surpasses the flexural strength of the porcelain. In the case of failure in the second peak, cracking was delayed slightly. In this case, the stress generated by the backstop surpassed the flexural strength of the porcelain by overlapping the remaining stress generated by the initial impact, although the stress generated by the initial impact did not surpass the flexural strength of the porcelain. In such a case, the impact strength of the porcelain would be significantly affected by the size of the porcelain and the position of the backstop. Therefore, under certain conditions, the smaller porcelain bowl may crack as a result of a smaller stress, as compared with the larger porcelain bowl. For example, the impact strength for the small bowl (1) was approximately half that for the large bowl (2), as shown in Table 1.

In practice, a porcelain specimen generally cracks due to an impact stress caused by dropping, washing, or transporting the specimen. The dropping of a porcelain specimen can be regarded as an impact that occurs without a backstop. On the other hand, a porcelain specimen subjected to washing or transportation is consider to be restrained from moving as a result of contact with other porcelain specimens or a container. In which case, various types of strain will overlap, leading to cracking.

4. Conclusion

The impact test was carried out for strengthened porcelain bowls, and the strain waveform and the deformation of the bowls were examined using a strain gauge and a high-speed camera, respectively. Upon impact, the bowl deformed from a circle to an oval and then returned to its original shape due to a restorative force generated by the backstop. As the bowl returned to its original shape and position, the bowl re-collided with the hammer or pushed the hammer again, resulting in the second peak.

The smaller bowl had a larger second peak that occurred sooner. Since in the case of small bowl, the contact points with the backstop were much closer to the position of the hammer, as compared to the case for the larger bowl, the restorative force quickly acted on the hammer. The magnitude of the second peak occasionally exceeded that of the first peak, and was at most twice that of the first peak. Furthermore, the larger second peak appeared sooner in the case of a smaller open angle (a), where the contact point was close to the impact point. Therefore, when we use the impact examination machine based on JIS S2402, we should consider that impact strength considerably varies with sample size, the existence of backstops and their angle.

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