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An Ultrasonic Testing Method for Detecting Delamination of Sprayed Ceramic Coating

D. Lian, Y. Suga, G. Shou, and S. Kurihara

The adhesion strength of thermal sprayed coatings is relatively low, and they sometimes tend to delaminate from the substrate during operation. In particular, sprayed ceramic coatings for thermal barriers, such as ZrO_2, often delaminate because of thermal shock; therefore, ceramic coatings are often submitted to thermal shock tests. A nondestructive inspection method using ultrasound to detect the delamination of sprayed coating was proposed. In this study, a coating model was made with acrylic plates, and an ultrasonic test was applied to investigate the precision of detecting delamination by the ultrasonic testing method. Results indicate that delamination more than 1mm in diameter can be detected by the ultrasonic testing method. Moreover, the delaminating process of sprayed coatings under thermal shock tests can be detected by this method.

Nomenclature

B_c	Bottom echo
C_T	Speed of ultrasound in substrate
C_W	Speed of ultrasound in water
d	Spot size of ultrasound
d_f	Focal distance
d_m	Masking diameter of thermal sprayed specimen
d_w	Water distance
D	Diameter of probe
n	Number of thermal shock test
P_m	Measuring pitch
P_s	Scanning pitch
S	Surface echo
t	Thickness of substrate
X, Y, Z	Coordinates of scanner
x_0	Critical distance of short sound field
λ	Ultrasound wave length

1. Introduction

CERAMICS such as ZrO_2 have superior thermal barrier or heat resistance properties, and thermal sprayed ceramic coatings are applied to machine parts or components that are used under severe conditions. These coatings may be subjected to thermal shock and have a tendency to delaminate from the substrate surface in operation. Delamination of coatings is prevented by subjecting them to thermal shock tests, and the soundness of the coatings is confirmed before practical use. The thermal shock test method authorized by industrial standards, such as the Japanese Industrial Standard (JIS), is used widely (Ref 1). In this test, the delamination of a coating is detected by a visual method because there is no suitable alternative. However, it is difficult to detect and evaluate objectively the delamination of coatings by such methods. As well, conventional technology does not allow direct observation of the coating condition; therefore, the initiation of delamination and growth for coatings under thermal shock testing has not yet been made clear.

A nondestructive inspection method using ultrasound to detect the delamination of sprayed coatings was proposed (Ref 2-8). In this study, a sprayed coating model was made by acrylic plates, and an ultrasonic test was applied to investigate the precision of detecting delamination. The investigation confirmed the application of the ultrasonic testing method to detect the delaminating process of sprayed ceramic coatings under thermal shock testing and to detect the accuracy of the delamination.

Keywords delamination, sprayed coating, thermal shock, thermal spraying, ultrasonic testing

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2. Experimental Equipment and Measuring Method

Figure 1 shows the equipment for the ultrasonic test. The equipment consists of an ultrasonic flaw detector, an ultrasonic probe, A/D converter, *X-Y-Z* axes scanner driven by pulse mo-

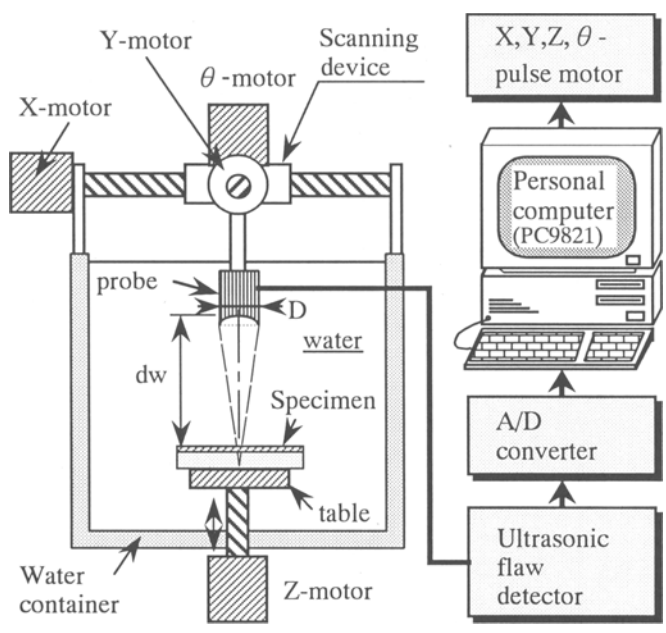

Fig. 1 Ultrasonic testing system

tors, and a personal computer. The computer acquires and analyzes the ultrasonic test data as well as controlling the pulse motors. The probe is an immersion type of 6 mm in diam and has a frequency of 5 MHz. The spot size of the ultrasonic beam at the focal point is about 1.8 mm in diam, and the focal distance is about 50 mm.

The probe is moved along the scanning raster as shown in Fig. 2. The sampling distance of the ultrasonic echo data (measuring pitch, P_m) and the width of scanning line (scanning pitch, P_s) can be selected before measurement. The specimen is immersed in water under the scanning equipment.

3. Principle of Detection

3.1 *Principle of Ultrasonic Testing Method*

Figure 3 is a schematic illustration showing propagation of ultrasound and the result of ultrasonic testing of a plasma sprayed coating. Figure 3 shows (a) a sound coating, (b) a relatively sound coating obtained by employing a slightly lower plasma spray power setting, and (c) a comparatively poor coating obtained by a short blasting time and lower power. In Fig. 3(a), a high bottom echo, B_c, is indicated in the oscilloscope trace. However, the bottom echo has a tendency to decrease with a decreasing integrity of the coating. In particular, in the case where the coating has delaminated from the surface of the substrate as shown in Fig. 3(c), the bottom echo may not be detected because most of the ultrasound is reflected in irregular directions at the delamination. Consequently, the ultrasound returned from the bottom of the substrate is decreased considerably. As stated above, it is confirmed that the coating integrity in the vicinity of the substrate can be evaluated by detecting precisely the bottom echo, B_c.

3.2 *Measuring Condition*

Figure 4(a-c) show the schematic illustration of the ultrasound propagation, where the water distance (distance from probe to coating surface, d_w) is changed. When the water distance, d_w, is large as shown in (a), the bottom echo of the ultrasound wave diffuses and becomes damped. Consequently only a part of the echo returns to the probe as shown; therefore, it is disadvantageous to increase the water distance. Figure 4(c) shows the ultrasound propagation in the case of a short water distance. Although a relatively strong echo is obtainable, the precision of detection may decrease because the spot size, d, of the ultrasound at the surface of the substrate increases with a decreasing water distance. On the other hand, when the water distance decreases to less than a critical distance, x_0, then interference of the ultrasound wave occurs. Accordingly, it is difficult to perform stable ultrasonic testing in such short water distances. The distance x_0 is termed "the critical distance of short sound field" and is given by (Ref 9):

$$x_0 = D^2/4\lambda \quad \text{(Eq 1)}$$

where D is the probe diameter and λ is the ultrasound wave length. Generally, the distance between the probe and substrate should be $0.8x_0$ in the case of a single probe method. Accordingly, the water distance d_w should satisfy Eq 2:

$$d_w > 0.8x_0 - (C_T/C_W)t \quad \text{(Eq 2)}$$

where C_T is the speed of ultrasound in the substrate, C_W is the speed of ultrasound in water, and t is the thickness of the substrate.

Figure 4(b) shows a condition where the focal point of ultrasound just reaches the bottom surface of the substrate. In this case, a relatively strong echo can be obtained, and the spot size of ultrasound at the substrate surface is reasonably small. Under these conditions, the problems described above may not occur. As a result, when the ultrasonic testing

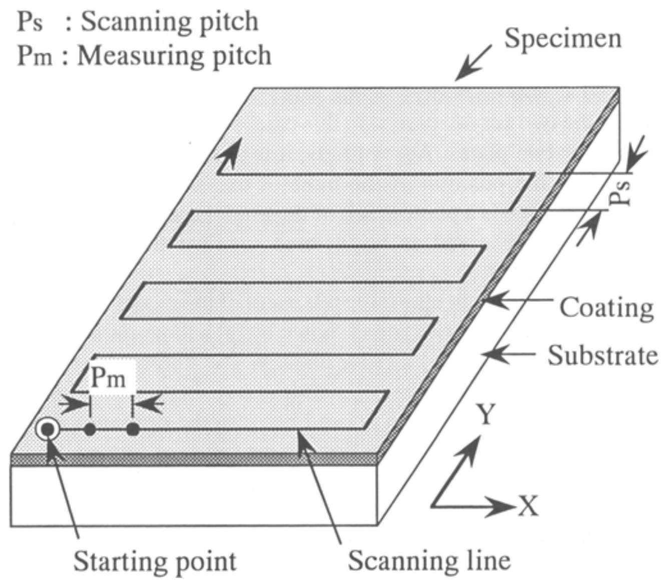

Fig. 2 Scanning method for ultrasonic testing of sprayed coating

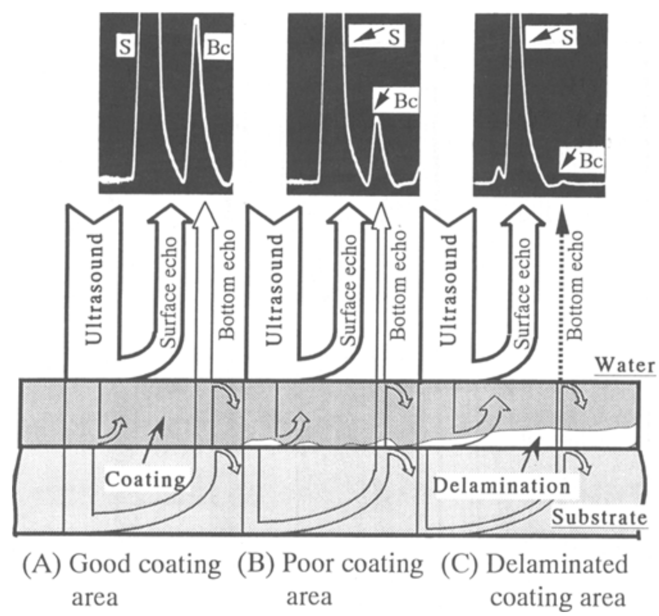

Fig. 3 Effect of integrity of sprayed coating on reflection and transmission of ultrasound The bottom point schematically indicates three coatings The relative behavior of ultrasound with respect to the coating/substrate integrity is indicated schematically in the form of echo response and the corresponding oscilloscope output.

method is used, the water distance, d_{wb}, which can be calculated by Eq 3 should be selected.

$$d_{wb} = d_f - (C_T/C_W)t \quad \text{(Eq 3)}$$

where d_f is the focal distance of the probe used.

4. Measurement of Detecting Precision

A model specimen was made by acrylic plates, and ultrasonic test was performed to measure quantitatively the precision of detecting delamination of thermal sprayed coatings, Fig. 5. The specimen is constructed with a thick acrylic plate (50 by 50 by 8 mm), a 0.2 mm thin spacer, and a 1.2 mm acrylic plate. They are stacked as shown in Fig. 5, and blue ink flows into the gap between the two acrylic plates. In this case, some bubbles exist between the two plates. Accordingly, it is possible to observe the shape and the position of the bubbles existing between these plates. Figure 6 is a photograph of the model specimen in which bubbles are observed as bright areas against the dark background of the ink.

Figure 7 shows an ultrasonic test result of the model specimen. The bottom echo distribution is shown by (a) a three-dimensional scanning graph and (b) a color display. The numbers 1 to 8 in Fig. 7(b) correspond to the color code above. In this experiment, a water distance of 30 mm is used because the optimum water distance, d_w, is calculated by Eq 3 as the speed of ultrasound in an acrylic plate (2730 m/s) and its thickness, 9.2 mm (i.e., 8 + 1.2 mm). Figure 7 clearly shows that the shape and the position of the low intensity area in the echo height distribution agree with those of bubbles in the specimen.

Figure 8 shows the ultrasonic test results that are obtained at water distances of 15 and 55 mm. The detection accuracy is lower than that at the optimum water distance of 30 mm as shown in Fig. 7. For example, when d_w is 30 mm, the shapes of the bubbles indicated by features (a) and (b) of Fig. 7, which have diameters of 1 and 1.5 mm, are distinct. However, although the existence of bubbles indicated by (a) and (b) can be confirmed, the shape cannot be recognized for the water distance of 15 mm, and at 55 mm the existence of bubble (a) cannot be confirmed. Consequently, if the optimum measuring conditions are adopted, then the detection of defects larger than 1 mm is possible by the ultrasonic testing method proposed.

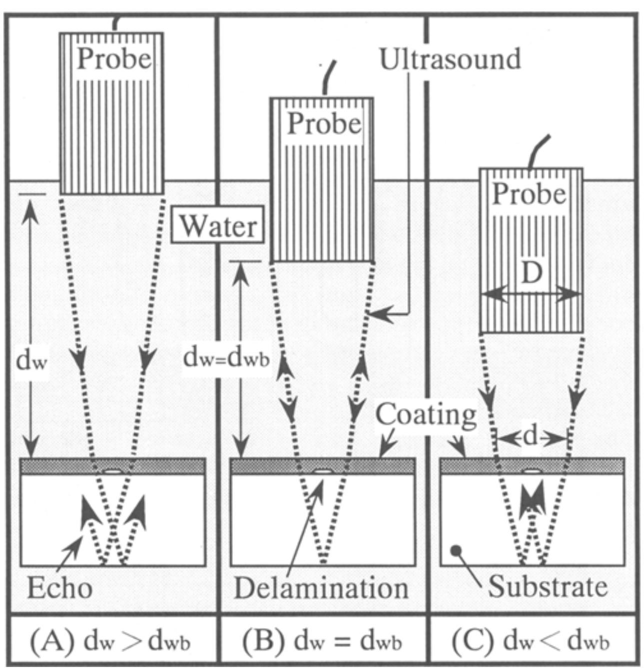

Fig. 4 Effect of water distance on propagation of ultrasound

5. Delamination Process of Coating

5.1 *Detection of Delamination of Sprayed Ceramic Coating*

Figure 9 shows the test results for ceramic coatings, which are obtained by plasma spraying ZrO_2 particles onto a mild steel coupon of 50 by 50 by 6 mm. The plasma spraying conditions used are shown in Table 1. The ultrasonic test results are shown

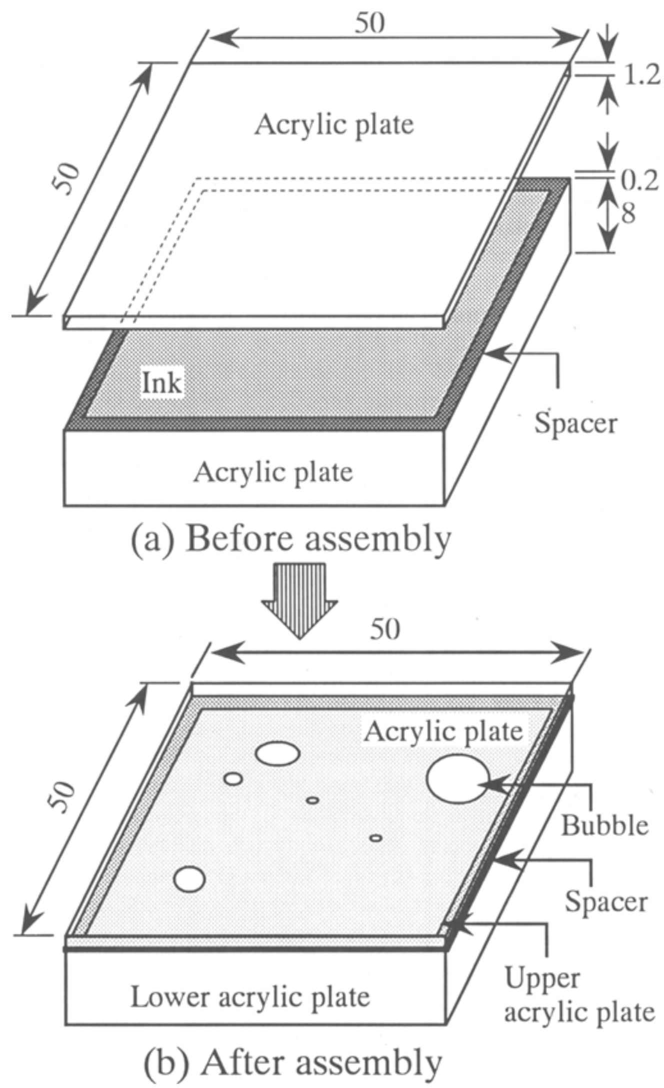

Fig. 5 Acrylic model for ultrasonic test

by a three-dimensional scanning graph and color display (as a two-tone representation). In this case, since the speed of ultrasound in mild steel is 5900 m/s and the thickness is 6 mm, the approximate water distance of 30 mm is adopted.

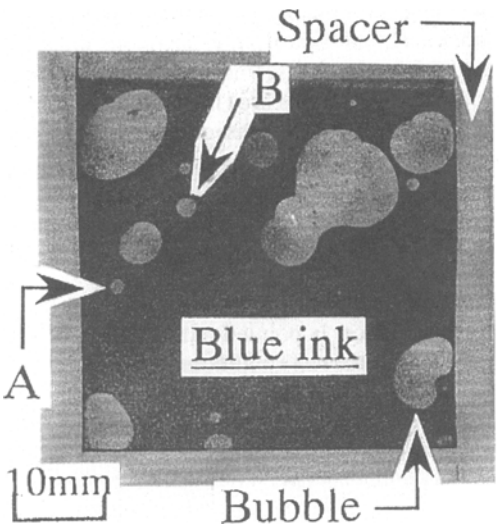

Fig. 6 Appearance of sprayed coating model specimen

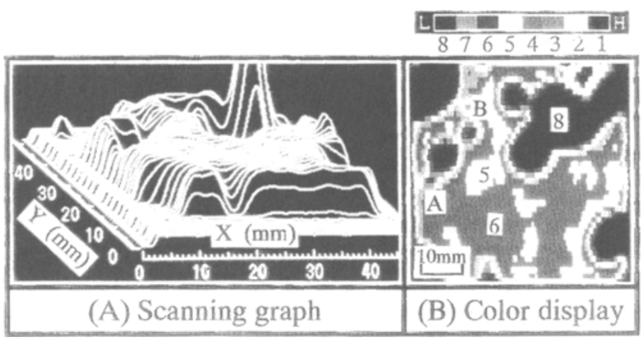

Fig. 7 Ultrasonic testing result of the model specimen

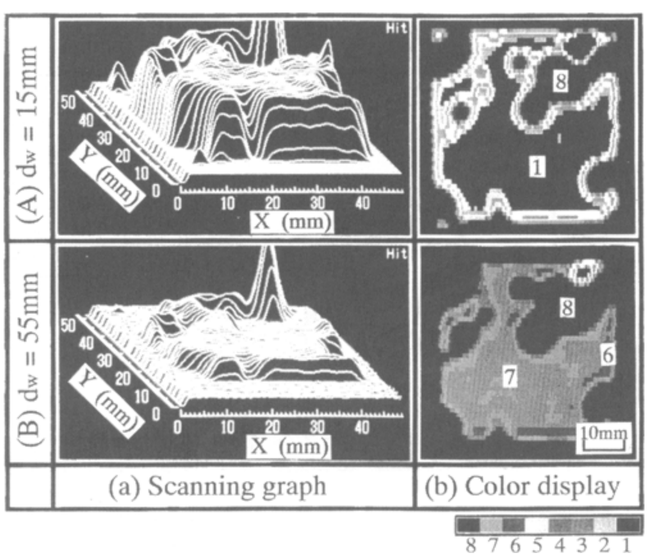

Fig. 8 Effect of water distance on ultrasonic testing results

Figure 9(a) shows a test result on the coating sprayed after grit blasting the complete substrate surface. On the other hand, Fig. 9(b) shows a test result on the coating after grit blasting a substrate, which had been masked in a small area with adhesive tape. In the nonblasted area, the coating adhesion to the substrate may be lower than that of the other area. In Fig. 9(a), the echo distribution is relatively even, and accordingly, it is surmised that the adhesion of the coating is even. However, in Fig. 9(b), the echo height at the masked area (nonblasted area) is much lower than that of the other area, which means the coating adhesion at this location is much lower. The color display readily confirms the shape and position of this area. Furthermore, by judging the echo height, it is surmised that the coating in this area delaminates from the substrate surface. Therefore, the ultrasonic testing method and the display method of results are effective to detect and recognize the delamination within thermal sprayed coatings.

5.2 *Thermal Shock Test*

Thermal shock tests were performed to observe the delamination process of sprayed coatings using the ultrasonic testing method. Sound specimens and delaminated specimens, which were made as stated in Fig. 9, were used. At first, the specimen is put into a furnace heated at 773 K (500 °C). It is held in the furnace for 12 min, taken out, and cooled in air. The ultrasonic test is performed after cooling to room temperature. The sample is then placed in the furnace, and the same treatment is repeated.

Table 1 Plasma spraying conditions

Spraying method	Plasma spraying
Electrical power	100 kW
Spraying powder	ZrO_2
Diameter of powder	10 - 30 μm
Substrate	SS41 mild steel
Thickness	6 mm

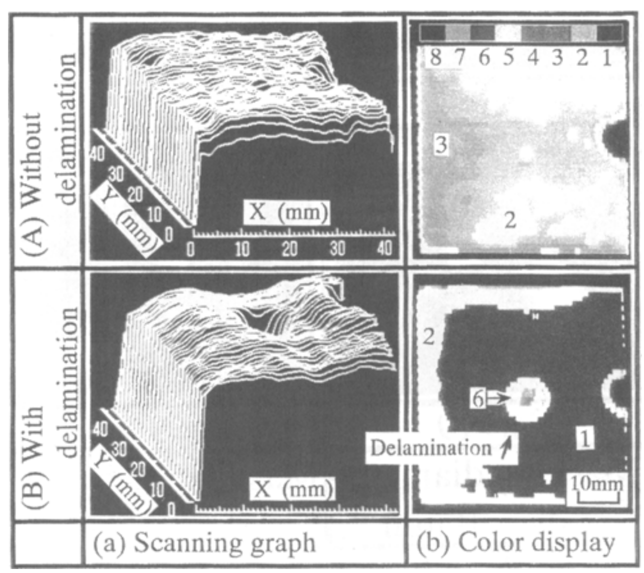

Fig. 9 Ultrasonic testing result of adhesion of thermal sprayed coating

Any changes in coating/substrate integrity are detected by performing the ultrasonic test.

Figure 10 shows two examples of the change of ultrasonic test results with respect to the thermal shock tests. The test results are indicated by a color display of three steps (as a two-tone representation). The photographs on the left-hand side show the results for a specimen with a good coating (masking diameter is 0 mm), but those on the right-hand side are the results for a specimen with poor adhesion in the central area (masking diameter is 5 mm). The echo height decreases with an increasing number of thermal shock tests, and the change in this phenomenon is more significant for the specimen with a delamination area than for the specimen with a good coating. Furthermore, the delamination tends to propagate from a peripheral region of the specimen into its center. However, in the specimen with a centered delaminating area, the delamination also propagates from the center to the peripheral regions of the coupon.

Figures 11 and 12 show the change of echo height with respect to the thermal shock test. Figure 11 is for a specimen with an integral coating, and Fig. 12 is for a specimen with a delaminating area of 5 mm diam. In each figure, the change of echo height at three sampling regions of the specimen are indicated. The ordinate in the figure shows the relative echo height, which corresponds to the coating integrity with respect to the substrate. The coating integrity is maintained in the initial 3 or 4 cycles of thermal shock test, but thereafter, it decreases drastically. The propagation of delamination seems to accelerate the preexisting delaminated area. Even if this area is small, the delaminated region tends to spread rapidly; consequently, the coating failure occurs within a short time.

6. Conclusions

- The importance of test conditions, such as focal distance and water distance, is pointed out. Furthermore, a simple method to select the test conditions is shown.
- The shape and position of coating delamination can be detected by the ultrasonic testing method, especially by detecting the bottom echo.

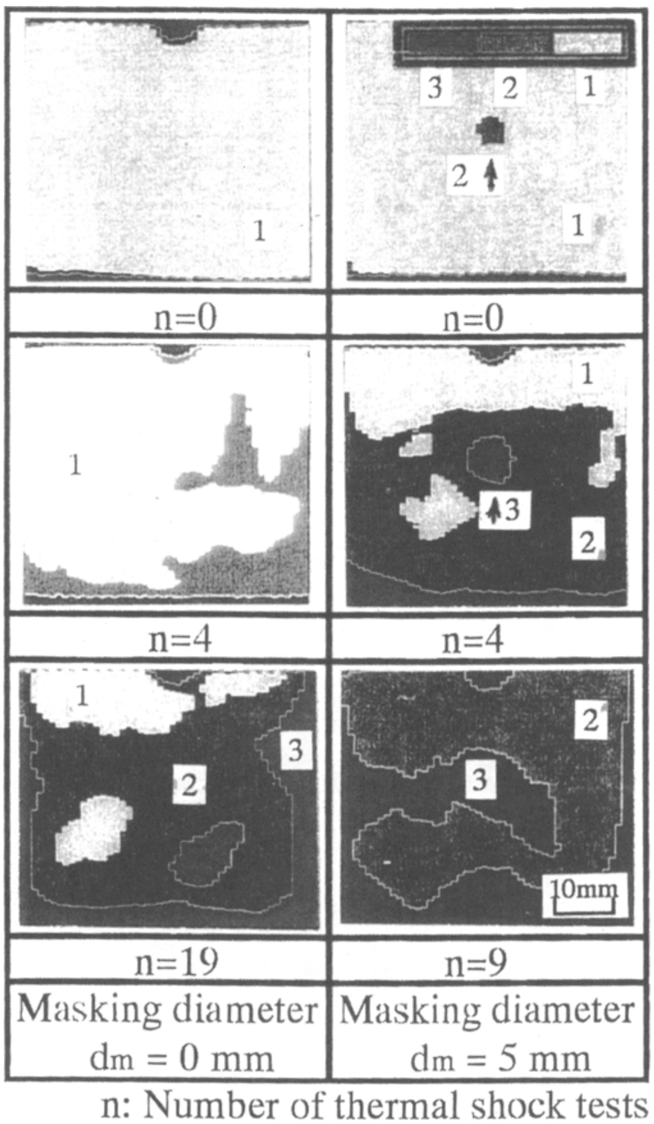

Fig. 10 Examples of thermal shock test results

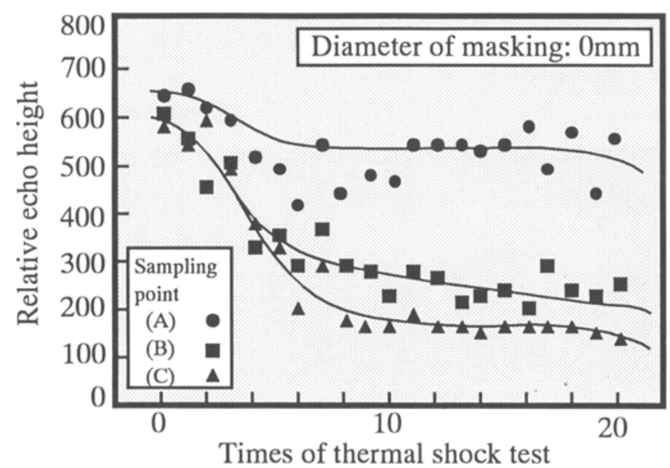

Fig. 11 Effect of thermal shock test on adhesion of sprayed coating (d_m = 0 mm)

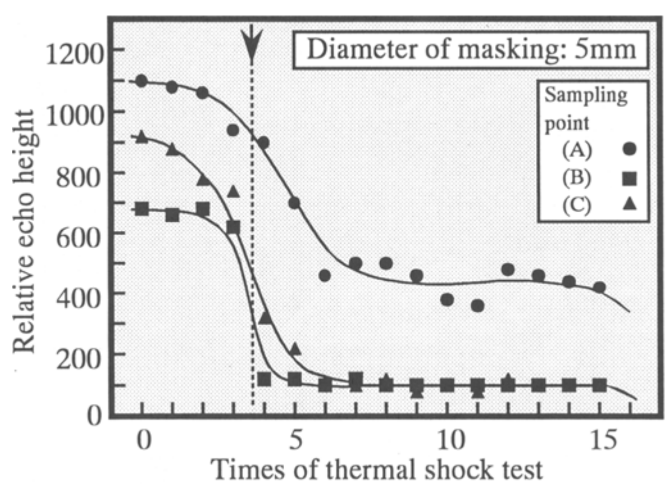

Fig. 12 Effect of thermal shock test on adhesion of sprayed coating (d_m = 5 mm)

- The detection accuracy of delamination by the ultrasonic testing method is confirmed by an acrylic model specimen. If proper test conditions are selected, a delamination of 1 mm diam can be detected.
- The delamination process of coatings under thermal shock conditions can be observed nondestructively by the ultrasonic test method.

Acknowledgments

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