Journal of the European Ceramic Society **6** (1990) 9–14

Ultrasonic Testing for Flaw Detection in Ceramics

T. Nonaka, Y. Hayakawa, S. Takeda, H. Nishimori & S. Yamaguchi

Technical Research Laboratory, Hitachi Construction Machinery Co. Ltd,
650 Kandatsu, Tsuchiura, Ibaraki 300, Japan

(Received 16 October 1989; revised version received 20 December 1989; accepted 22 January 1990)

Abstract

An advanced high frequency ultrasonic imaging system has been developed for detecting fine flaws in ceramics. This system consists of a computer for data and image processing, a high precision xyz-scanner with an immersion transducer, a high frequency (5–150 MHz) pulser, a receiver, and a peak detector. By using the imaging system with high frequency from 50 to 100 MHz, a 10-μm tungsten wire embedded 1·5 mm under the surface in SiC ceramic is detected. Some image processing techniques are used to enhance the ultrasonic image and detect fine flaws with low reflection echo levels.

Zum Nachweis feiner Poren in Keramiken wurde ein fortschrittliches Hochfrequenzultraschallabbildungssystem entwickelt. Das System besteht aus einem Computer zur Daten- und Bildverarbeitung, einem hochpräzisen xyz-Scanner mit einem Eintauchwandler, einem Hochfrequenzsignalgeber (5–150 MHz), einem Empfänger und einem Signalspitzendetektor. Bei der Verwendung des Abbildungssystems mit einer Hochfrequenz von 50–100 MHz konnte ein 10 μm Wolframdraht detektiert werden, der sich 1·5 mm unter der Oberfläche einer SiC-Oberfläche befand. Einige Bildverarbeitungstechniken wurden angewendet, um das Ultraschallbild zu verbessern und um kleine Poren mit einem niedrigen Reflexionsechosignal erfassen zu können.

On a développé un système d'imagerie par ultrasons à haute fréquence pour détecter les défauts de petite taille dans les céramiques. Ce système est composé d'un ordinateur pour le traitement des données et des images, d'un scanner xyz de haute précision muni d'un transducteur d'immersion, d'un pulseur haute fréquence (5–150 MHz), d'un recepteur et d'un détecteur de pics. En utilisant ce système d'imagerie à une fréquence comprise entre 50 et 100 MHz, on a pu détecter dans une céramique de SiC un fil de tungstène de 10 μm situé à 1·5 mm de la surface. On utilise des techniques de traitement d'image pour améliorer l'image ultrasonique et pour détecter de petits défauts avec des échos de faible niveau.

1 Introduction

Ceramics are very attractive materials for various machine designs because they are excellent with respect to strength or heat resistivity, etc. Recently, they have been widely employed as key components of machines. In addition, many nondestructive tests have been studied to detect their defects, such as delaminations, cracks and voids for improving the reliability of machine components.[1,2] Ultrasonic testing is an effective method with ceramic materials. Ultrasound has been known to be sensitive to the existence of thin slits or cracks in solid materials because of a complete reflection of wave at these interfaces.

Generally, high strength materials are susceptible to small flaws when they are stressed excessively. In ceramics, small flaws of less than 50 μm must be detected to confirm the good quality of machine components. This paper describes several applications of ultrasonic testing by using ultrasonic imaging and data processing techniques.

2 Ultrasonic Imaging System

A schematic diagram of an ultrasonic imaging (C-scan) system is shown in Fig. 1.[3] The system consists of:

Journal of the European Ceramic Society 0955-2219/90/$3.50

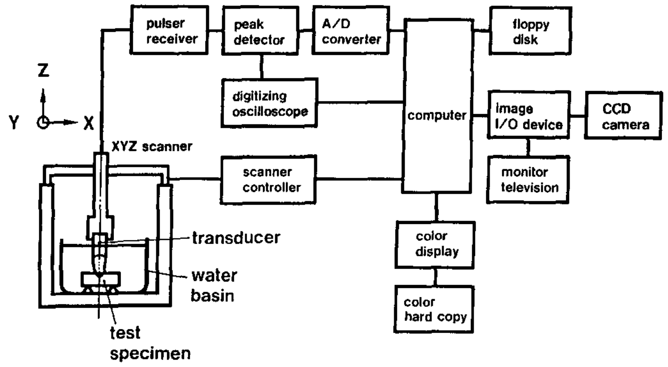


Fig. 1. Configuration of test equipment.

(i) equipment including a pulser, a receiver, a peak detector, and a transducer to send and receive ultrasonic waves;
(ii) a precision tri-axial scanner and its controller unit; and
(iii) a computer for data and image processing.

An example of the main hardware specifications used in the experiment is listed in Table 1. An immersed focusing transducer concentrates the ultrasonic power at the focal point of the ultrasonic beam to detect small defects. Reflected echo signals are detected, converted to digital data by an A/D converter and then stored in the computer, where they can be processed.

3 Detection of Delaminations

A delamination reflects back the ultrasound almost completely, so that it can be imaged easily. The ultrasonic testing therefore detects a thin slit in the material. An experimental test result for a narrow slit is shown in Fig. 2. A slit is formed between two glass plates, which contact at the center: one is flat and the other convex. The slit increases gradually from the center to the outside. The slit is filled with air. The top right picture shows an ultrasonic image measured by a 25-MHz transducer. Outside a 1 mm diameter the ultrasound is reflected back completely, but inside the diameter of 0·44 mm the ultrasound energy transmits into the lower plate. The lower right picture shows a Newton ring image, which is measured by green light with a 550 nm wavelength. The smallest dark ring diameter is 1·33 mm, and the thickness of the slit at the location is 0·13 µm. From these experimental results we conclude that the ultrasound is completely reflected back with an air slit wider than 0·13 µm.

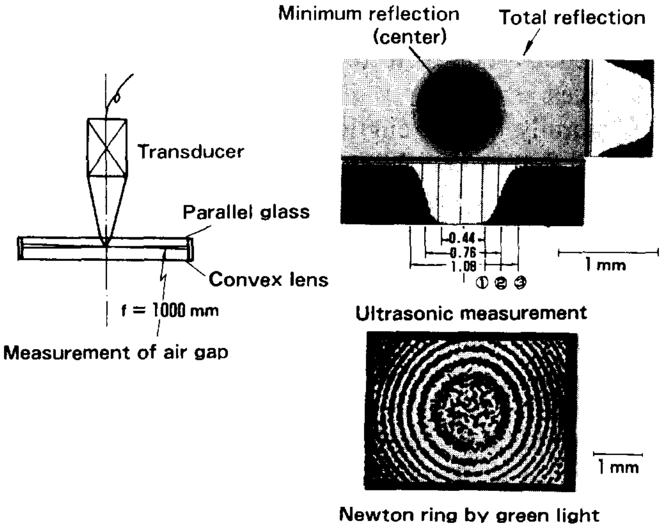


Fig. 2. Verification of gap detecting ability by ultrasonic testing.

High frequency ultrasonic testing is needed to measure very thin delaminations and small flaws in ceramics. A high frequency ultrasonic testing unit with a frequency range from 5 to 150 MHz has therefore been built. Figure 3(a) shows the frequency spectrum of the pulser output. Figure 3(b) shows the frequency characteristics of the receiver unit. The output voltage gain of the receiver unit is nearly flat with frequencies from 5 to 150 MHz. In the figure,

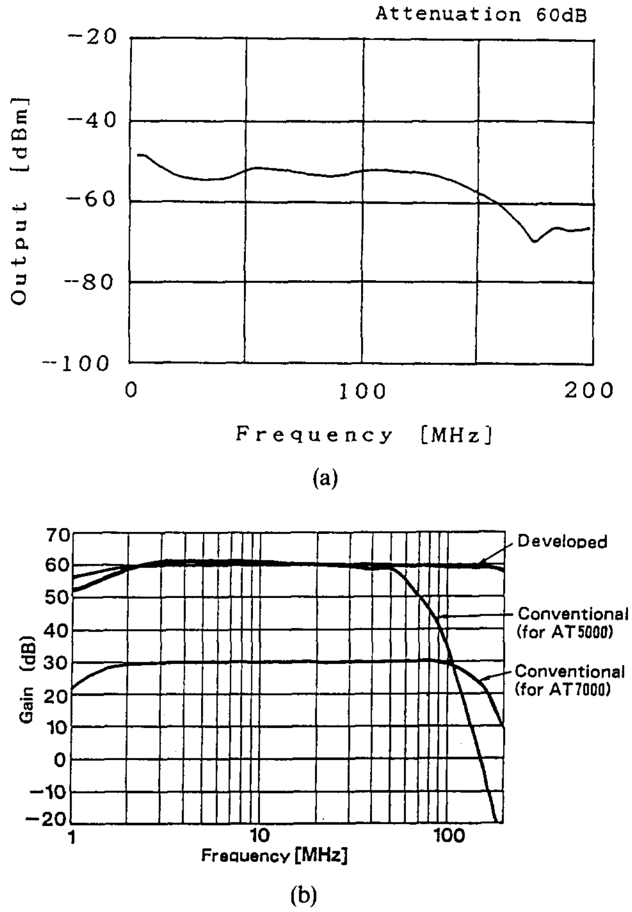


Fig. 3. Characteristics of (a) pulser and (b) receiver units.

Table 1. Main hardware specifications

Item	*Specifications*
Ultrasonic testing devices	
1. Probe	100 MHz
2. Pulser, receiver	Frequency band 1–100 MHz Gain 36 dB
3. Peak detector	Frequency band 10–130 MHz Gate delay 50 ns Gate width 30 ns +, − and absolute output
Scanner	
1. Standard	Scanning area 140 mm W × 140 mm D × 80 mm H
2. Optional	560 mm W × 450 mm D × 300 mm H with 360° rotating stage
Data processor	
1. Microcomputer	16 bit
2. Storage devices	Hard disk 10 Mbyte Floppy disk 640K × 2
3. Image input/output device	512 × 480 pixels 256 gradations
4. Digitizing device	Frequency band 1 GHz 1 024 points/wave

AT7000 and AT5000 are scanning acoustic imaging devices commercialized by Hitachi Construction Machinery Co. Ltd for ceramics, composites and semiconductors. The main hardware specifications, as shown in Table 1, are similar to those for AT7000. The frequency range in AT5000 is from 1 to 50 MHz, and the digitizing unit is not included.

4 Measurement of Defects in Ceramics

Ceramics are brittle in general, and their strengths are extremely sensitive to micro-cracks. Cracks less than 50 μm in length are required to be detected to ensure proper quality assurance of the materials. The following are several examples of ultrasonic testing in which the detectability of fine flaws in ceramics is discussed.

The images of ceramics 2 mm in thickness with nonthrough-drilled holes are shown in Fig. 4. Ultrasound is radiated from the top surface of the specimen, where the drilled holes are not open and focused on the bottom surface. The depths of the holes are measured from the bottom surface. The black dots are the acoustic shadow images of the drilled holes. Images in the window area of Fig. 4(b) are those enhanced by image processing, showing that the image enhancement technique is very effective. A drilled hole with a 40 μm diameter is clearly detected. The dark dots along the center line are of drilled holes; other dark dots are natural defects. Images in Fig. 4(c) are measured by the use of a 100-MHz transducer with delay time. The insertion loss of the transducer is −54 dB, and its focal diameter is 67 μm. All drilled holes are clearly detected without the enhancing technique. The signal–noise ratio of the signals back-reflected from the 40-μm hole is 31·6 dB.

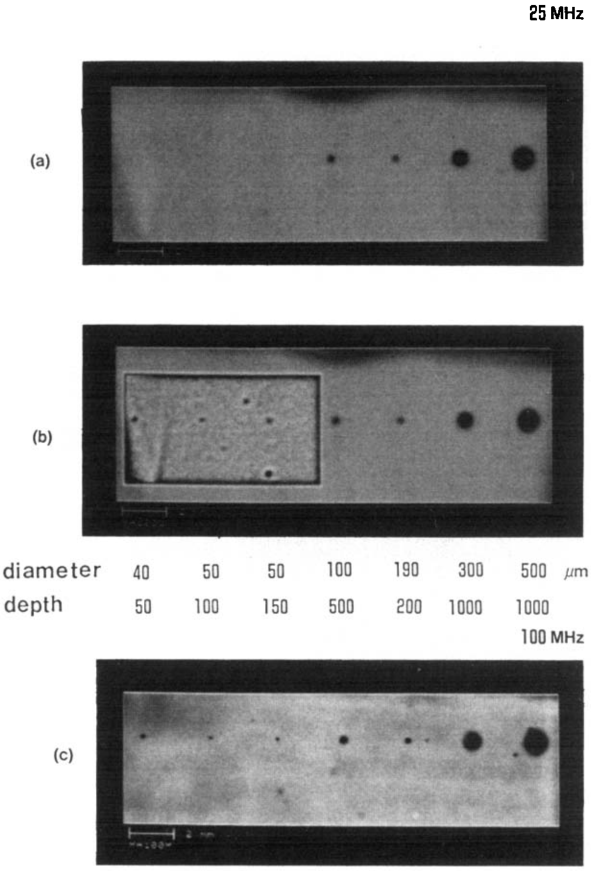
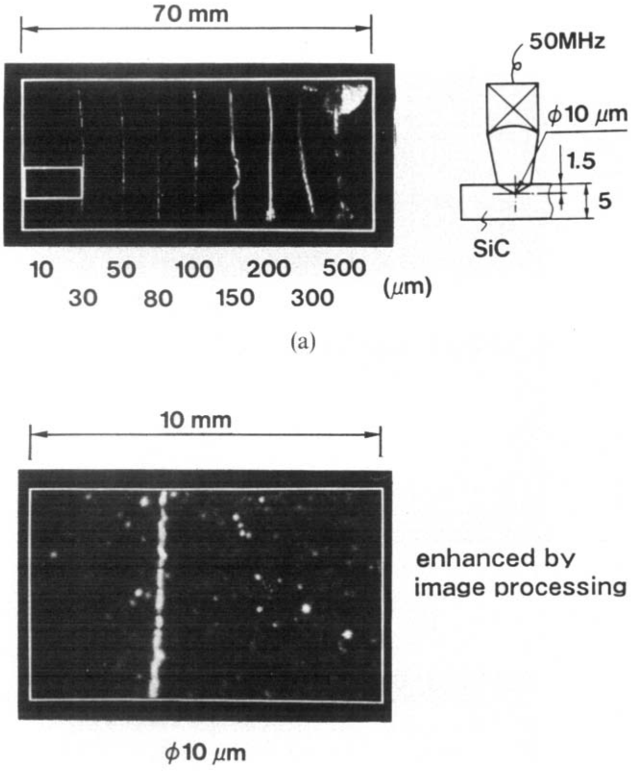


Fig. 4. Acoustic images of drilled holes in ceramic.

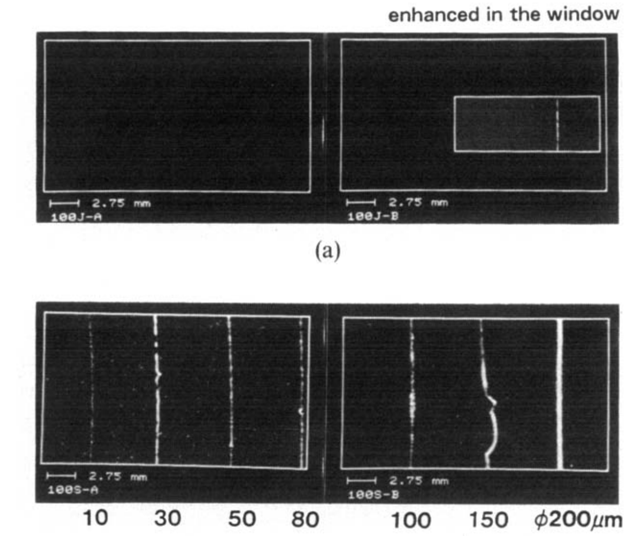
Images of tungsten wires which were embedded in the ceramic before sintering are shown in Fig. 5. These wires are at 1·5 mm under the surface of the silicon carbide plate. The diameters of the wires range from 10 to 500 μm. All wires can be imaged by the use of conventional testing units at a frequency of 50 MHz. The lower picture shows an enhanced image in the window area of the upper. A 10-μm-diameter wire and other very small natural defects are detected. As ultrasound exhibits steep attenuation at higher frequencies, these wires cannot be detected at a frequency of 100 MHz except for a 200-μm wire as shown in Fig. 6. The 200-μm-diameter wire is detected by the image enhancement. The lower picture is imaged by the newly developed ultrasonic testing instrument mentioned previously. This equipment has a high energy pulser and a high amplifier gain receiver, and all wires of 10 μm diameter or larger are detected clearly. The signal–noise ratio of the signals reflected from the 10-μm wire is 7·1 dB.



(a)

(b)

Fig. 5. Acoustic images of tungsten wires in silicon nitride. (a) Total image; (b) close-up image.



(a)

(b)

Fig. 6. C-scan images of tungsten wires in ceramic. (a) Conventional images; (b) tungsten wire images by developed units.

5 Image Processing

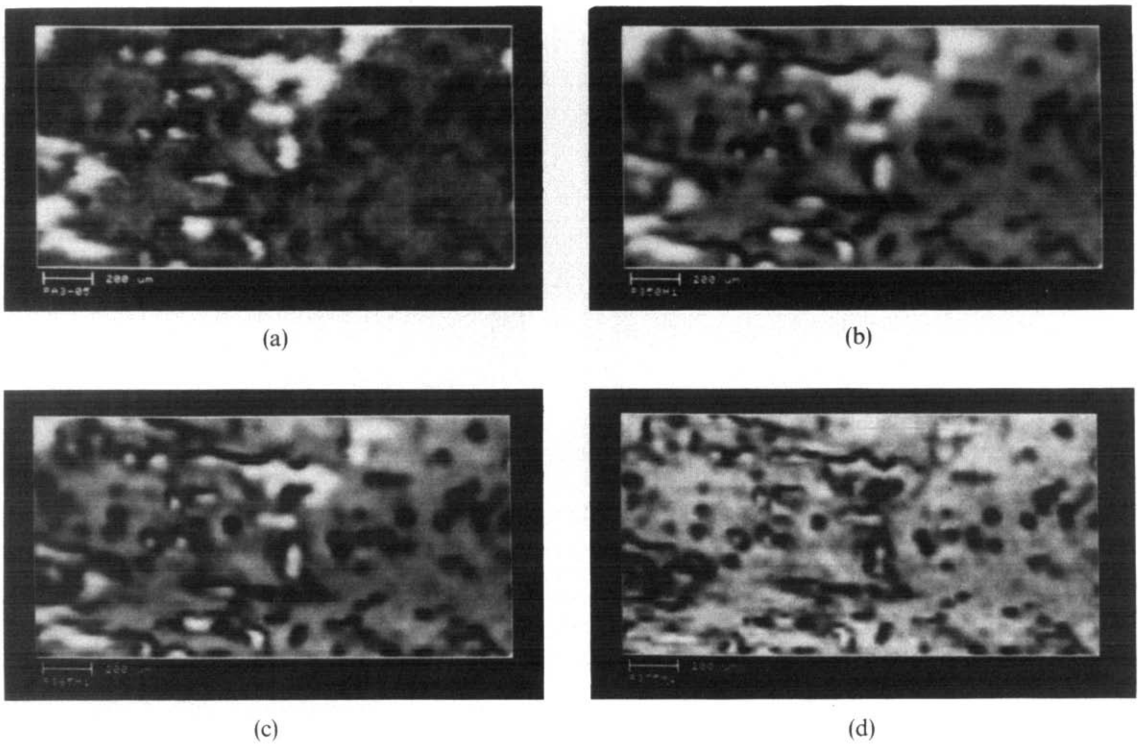
The detectability of defects by ultrasonic images is improved by an image enhancement technique. The image of drilled holes in Fig. 4(b) is an example. In the picture, a contrast stretching of the image is applied in addition to smoothing and subtraction processing. This is a very useful technique for detecting fine flaws with low echo levels.

Ultrasound is absorbed and attenuated in proportion to the square of the frequency during the time in which it propagates through the medium. The peak frequency of the reflected echo signals therefore shifts to a lower frequency. This causes a reduction in the image resolution. Acoustic images of die-attach of a semiconductor chip measured by a 100-MHz transducer are shown in Fig. 7. The upper right picture is an image as measured. Because of the attenuation of echo intensity at higher frequencies, the resolution of the upper right image reduces to almost the same extent as the upper left, which is processed by fast Fourier transform (FFT) and is imaged by 50-MHz-frequency components of the signals. An image with higher resolution can be obtained by processing the echo signals with FFT analysis and imaging by using higher frequency components as shown in Figs 7(c) and (d). In the figure, the lower right image, processed at 75 MHz, has the highest resolution.

It is very difficult to detect fine pores on the surface of a ceramic specimen that is finished by grinding. The pores are masked by grinding grooves, as shown in Fig. 8. In this case, two-dimensional FFT processing is effective to separate horizontal parallel grinding stripes from the pores in the spatial frequency domain. The right-hand picture shows an image of the pores. The grinding stripes are eliminated in the spatial frequency domain, and the image is transformed again into the spatial domain by inverse FFT analysis.

6 Velocity Measurement

The transit time of ultrasound from the top surface to the bottom of the specimen is inversely proportional to the sound velocity of the material. The velocity reflects the change in material characteristics, such as residual stress, hardness, bulk density, etc. Figure 9(a) is an acoustic image of a ceramic specimen surface with uniform thickness. The intensity of the reflected echo is nearly flat all over the surface. Figures 9(b) and (c) show the intensity of the reflected echoes from the bottom surface. The white area shows the high intensity of reflected bottom echoes; the absorption of ultrasound through the beam path is low in the area. Figure 9(d) is an image of the transit time from the top surface to the bottom. The thickness of the specimen is uniform, so the transit time coincides



(a) (b)

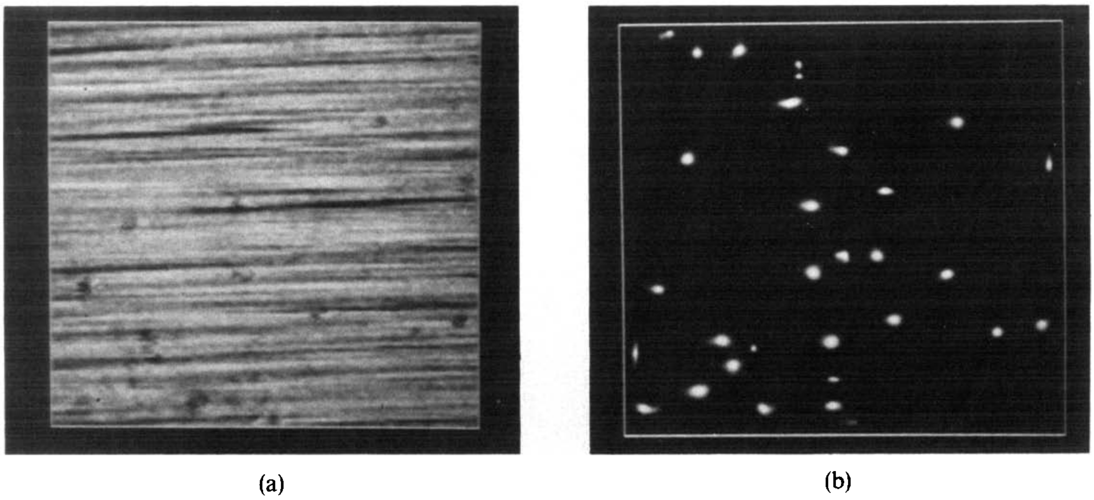
(c) (d)

Fig. 7. Resolution improvement by fast Fourier transform processing. (a) Conventional image; (b) 50-MHz component; (c) 65-MHz component; (d) 75-MHz component. All 2·0 × 1·2 mm samples.

with the variation in the velocity. The contrast in these two images shows the characteristics of the ceramic, such as its bulk density.

7 Conclusions

A novel ultrasonic imaging system has been applied to studying the detection of ceramic defects. This system includes an xyz-scanner with a transducer, ultrasonic testing units, a computer for controlling the system, and data processing equipment. A thin slit, wider than 0·13 μm, is detectable by using this system with a 25-MHz transducer. In ceramics, a tungsten wire of 10 μm diameter can be detected easily. It is also found that a measurement of sound velocity is very useful in evaluating the material properties of ceramics.



(a) (b)

Fig. 8. Detection of pores by two-dimensional fast Fourier transform processing. Si_3N_4 surface, 100 MHz. (a) Original; (b) after processing.

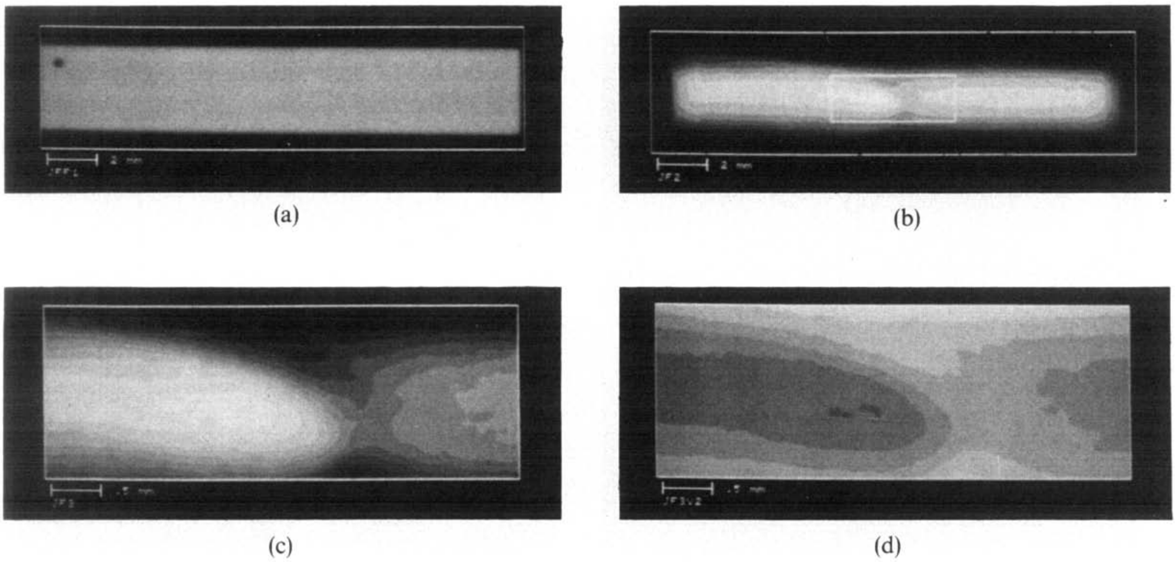


Fig. 9. Measurement of characteristics in ceramic. (a) Surface and (b) bottom of 20 × 5 mm sample of Si_3N_4 at 50 MHz; (c) magnified (5 × 0·9 mm) acoustic image; (d) magnified (5 × 0·9 mm) velocity image.

References

1. Roth, D. J., Klima, S. J., Kiser, J. D. & Baaklini, G. Y., Reliability of void detection in structural ceramics by use of scanning laser acoustic microscopy. *Materials Evaluation*, **44** (1986) 762–9.
2. Rogovsky, A. J. & Buchanan, R. A., Statistical data analysis for quantitative NDE of composites in the real-time acoustic imaging system. SME technical paper, IQ83-930, Oct. 1983, pp. 1–17.
3. Nonaka, T., Hayakawa, Y., Takeda, S., Igarashi, T., Takishita, Y., Miyata, T., Yamamoto, H., Yamaguchi, S. & Nishimori, H., Ultrasonic imaging and data processing techniques for semi-conductor and new materials. In *Proceedings of the 12th World Conference on Non-destructive Testing, Amsterdam, April 1989*, pp. 784–9.