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Nondestructive evaluation of SiC/SiC composites by wavelet analysis of an elastic wave signal

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We studied the nondestructive evaluation of the elastic wave signal of SiC ceramics and SiC/SiC composite ceramics under monotonic tensile loading. The elastic wave signal of cross and unidirectional SiC/SiC composite ceramics were obtained by the pencil lead method and a bending test. This was applied for the time-frequency method which used the discrete wavelet analysis algorithm. The time-frequency analysis provides the time variation of each frequency component involved in a waveform, which makes it possible to evaluate the contribution of the SiC fiber frequency. The results were compared with the characteristic of the frequency group from SiC slurry and fibers. Based on the results, if it is possible to shift up and design a higher frequency group, we can then make a superior material better than those of exiting SiC/SiC composites.

Key words: SiC/SiC composites ceramics, Wave propagation, Elastic wave, Wavelet analysis, Dominant frequency.

Introduction

Since silicon carbide has many advantages in terms of thermal and mechanical properties, it is a necessary material especially in aerospace and advanced energy systems [1]. Although SiC/SiC composites have superior characteristics as structural materials, these are very brittle and have a complex structure. Referencing previous works [2, 3], for example, when it is sintered with 3 wt.% Y_2O_3 additive, which was most suitable, its properties were demonstrated as mechanical superiority and concentrated relatively on the highest frequency group. In brittle materials like ceramics, if we could make the strength high, with a similar density of the composites, we should make the stiffness high. The high stiffness presents a high frequency performance of the microstructure on the whole. In order to give a high stiffness to a structural material under a similar density of the composites, if it would be possible to control the matrix formation with certain amount of sintering additives or SiC fibers, it can obtain the high frequency performance. So it is necessary to investigate the characteristic of frequency of SiC/SiC composites ceramics.

In this research, we analyzed the frequency of the elastic wave of the SiC/SiC composites ceramics by a bending test and pencil lead method. From these results, the frequency of SiC/SiC composites ceramics can be classified as the specific frequency of the different frequency groups. Therefore, after analyzing the elastic wave frequency when structural composites are fractured by some load, we can understand that every frequency can be classified into some frequency group. Using the information of the specific frequency group, it will be possible to feed-back into an improvement of the process for the sintering additives and reinforcement of the SiC/SiC composites ceramics.

Materials and Test Method

The SiC/SiC composite ceramics were prepared on the NITE (Nano-Infiltration Transient Eutectic Phase Sintering) process [4]. Tyranno-SA SiC fibers (Φ7.5 μm, thickness of pyrolytic carbon : 500 nm) as a reinforcement material. Fig. 1 shows the cross section of a Tyranno SA fiber. After mixing 90 wt.% β-SiC nano powder (average particle size 100 nm) of a base powder, 6 wt.% Al_2O_3 (average particle size 0.3 μm) and 4 wt.% Y_2O_3 (average particle size 0.4 μm) as sintering additives at a ratio of 90 : 10, the slurry was impregnated into the SiC fiber preform which was made of about 40~50% by volume. The mixtures were subsequently hot-pressed in an Ar gas atmosphere for one hour via hot-pressing conducted under a pressure of 20 MPa at 2123 K. Two types of specimen were prepared, UCS (unidirectional composite specimen) in Fig. 2(a) and CCS (cross direction composite specimen) in Fig. 2(b), according to the orientation of the SiC fibers to investigate the relationship with the elastic wave characteristics. After the two types of specimens had been cut into 3.0 × 4.0 × 20 mm sizes from the sintered material, all fracture tests were performed on a three-point loading

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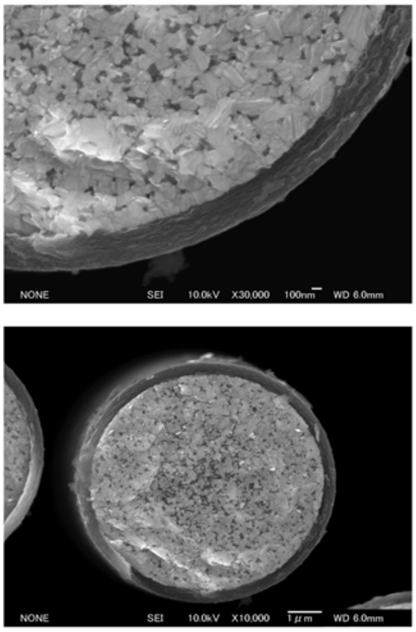


Fig. 1. Cross section of a Tyranno-SA SiC/SiC fiber.

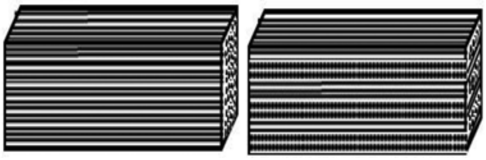


Fig. 2. Specimen figure according to fiber orientation. (a) Unidirectional composite specimen (UCS), (b) Cross directional composite specimen (CCS).

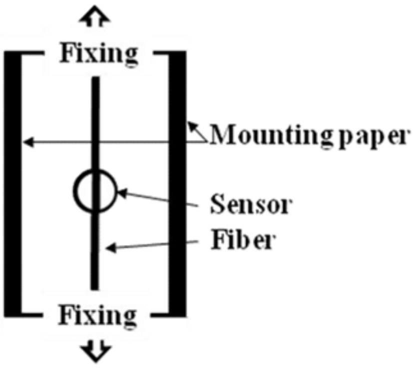


Fig. 3. AE sensor attachment method for the signal sensing of SiC single fiber.

system with a span of 16 mm and a cross head speed of 0.5 mm/minute. The elastic wave signal of a SiC fiber was obtained from the tensile test of a single fiber. The SiC single fiber was a tensile loaded to a speed of 0.5 mm/minute, fixed to paper cut by scissors. The elastic wave signal obtained by the sensor attached to the fiber rear side as shown in Fig. 3.

A fracture wave detector (FWD; Model FM-1, Digital Wave Corp., Englewood, co.) was used to detect the elastic wave. It was carried out using a threshold of 10 mV and a digitization rate of 12.5 MHz with a 1024 point gate length for each channel. The sensor (DWC B1025) was a broadband sensor with a reasonably flat response from 1 kHz to 1.5 MHz. The detected signals were pre-amplified by 40 dB with a FWD. The trigger and event duration time were considered, selected and observed at about 10 μsec and 102.4 μsec, respectively. And the frequency of the elastic wave signal was analyzed using the discrete wavelet analysis method.

Results and Discussion

Frequency characteristics of SiC single fibers by tensile load

Fig. 4 shows the results of the time-frequency analysis from fracture of two types of SiC single fiber. In the case of a SiC single fiber of diameter 7.5 μm, the frequency group was concentrated in the about 488 kHz range and additionally, found at frequencies of 322 kHz and 585 kHz. On the other hand, the output from a SiC single fiber of diameter 10 μm was concentrated between 468 kHz and 478 kHz. When the SiC single fiber was fractured, specific frequencies of elastic waves were slightly different according to the diameter of the fibers. It was judged that the frequency difference arose from gravitation depending on the fiber diameter.

Frequency characteristics of SiC/SiC composites ceramics by the pencil lead break method

The elastic wave signals depending on the stacking direction of SiC/SiC composites ceramics were detected by the pencil lead break method. Fig. 5(a) shows a typical signal of CCS. It is very interesting that the wave signal has a semi-beat phenomenon during the duration time. This can be confirmed by the frequency and wavelet analysis. It be can understood that the semi-beat is repetitive at time responses of about 50 μsec and 80 μsec in Fig. 5(a) and Fig. 5(c), respectively. In Fig. 5(b), the frequency shows two components 146 and 166 kHz which are relatively near

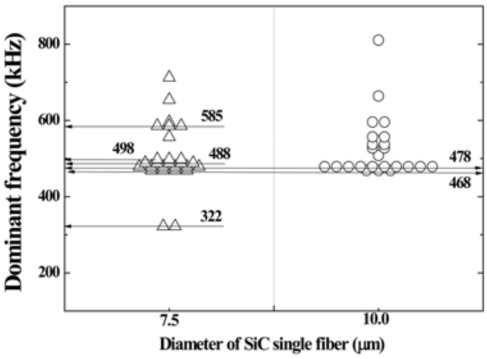
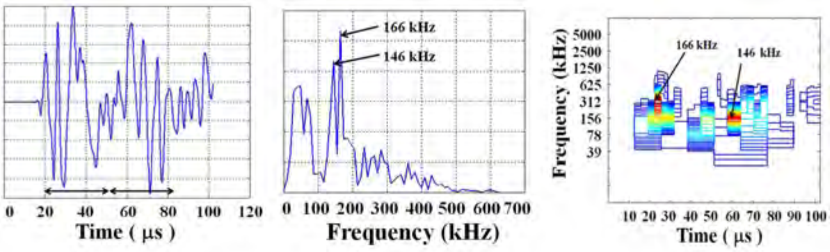


Fig. 4. Distribution of dominant frequency according to diameter of SiC single fibers.



(a) (b) (c)

Fig. 5. (a) Time response of AE signal, (b) Frequency spectrum and (c) Contour map of WT analysis for CCS.

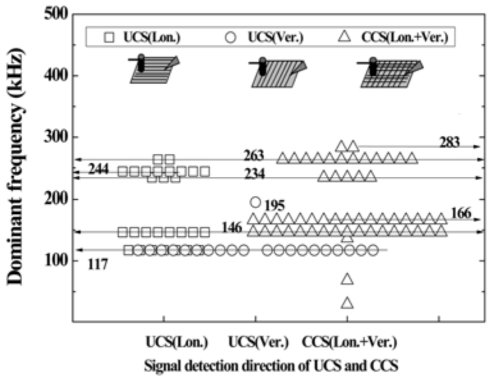


Fig. 6. Distribution of dominant frequency according to signal detection direction of UCS and CCS samples.

and a large amplitude in the range of 100 and 200 kHz. In the elastic wave with respect to the microstructural feature of the regular reinforcement by SiC fibers of diameter 7.5 μm, these semi-beat phenomena occurred in the CCS only, but it did not occur in the UCS samples. It is remarkable that the beat frequency exists in the burst elastic wave signal, and it is considered as one of the rare and unique features occurring when the SiC/SiC composites were have a regularity of cross directional type by the same diameter fibers.

Fig. 6 presents the results of the dominant frequency after using the pencil lead break method for creating the elastic wave signal and analyzing the signal detected. Here, UCS (Lon.) and UCS (Ver.) are horizontal and perpendicular for the alignment direction of SiC fibers, respectively. CCS (Lon.+Ver.) is arranged to cross the SiC fibers. In the case of UCS (Lon.), these are that the relatively low frequency group distributed over about 117 kHz to 263 kHz, but the frequency group of UCS (Ver.) is almost concentrated at 117 kHz. From experimental results of the authors' research [2, 3], it was suggested that the component of frequency, 117 kHz, could be seen as the characteristic frequency of the SiC slurry. Because it penetrated between the SiC fiber and slurry, it was eliminated from the microstructural space. And also, it is impossible to detect the signal of a SiC fiber by the pencil lead method, which the pencil lead has a limitation with the size for the SiC fiber diameter. That is, the SiC fiber cannot be stimulated by the pencil lead force because it has the very low frequency comparatively. In the case of CCS (Lon.+Ver.), there is no the component of a low frequency, 117 kHz. This shows that the dominant frequency has not only the high frequency group, 234 kHz up to 283 kHz, but also the semi-beat frequencies, 146 kHz and 166 kHz.

Frequency characteristics of SiC/SiC composites ceramics by the bending load method

Fig. 7 shows the dominant frequency distribution from bending tests using the two types of specimen. This was determined as the highest power spectrum density of the contour map by wavelet analysis from the elastic wave signal. The elastic waves were continuously detected from the UCS and CCS specimens. The dominant frequency components of a UCS (Lon.) specimen are 322, 498, 527 and 703 kHz. These are confirmed as the same or slightly high frequencies with the result of the SiC fiber of diameter 7.5 from Fig. 4. In Fig. 4 and Fig. 7, it seems that the frequency of the SiC fiber fracture is implied on the whole to the central frequency of the burst elastic wave signal. The dominant frequency components of the CCS (Lon.+Ver.) specimen are 244, 283, 361 and 605 kHz. It can be found that the frequencies are concentrated at the slightly low frequency group between 244 kHz and 283 kHz, relatively. And there is many frequencies obtained from the fracture of a single fiber. It is assumed that the

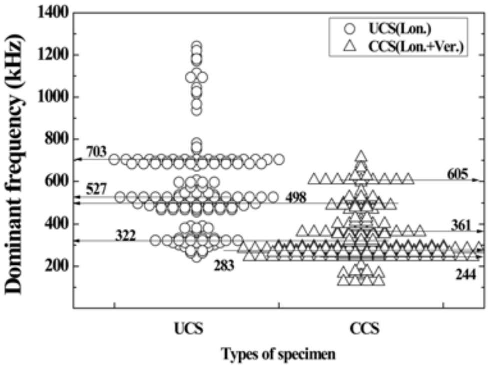


Fig. 7. Distribution of dominant frequency from the two types of specimen.

frequency group between 244 kHz and 283 kHz occurred due to the regular uniformity of the microstructural slurry to the cross directional and unidirectional reinforcement by the SiC fibers.

The microstructural space infiltrated by the slurry must geometrically be larger than that of the UCS (Lon.) specimen because the SiC fiber bundle is perpendicularly reinforced. The physical characteristics of the SiC fibers are more dominant than that of the SiC slurry in the UCS (Lon.) specimen of a dense structure and relatively in the CCS specimen of a less dense structure. The frequency group beyond the 244 kHz is considered as the characteristic frequency of the SiC slurry to the space between the reinforced SiC fiber bundles [2, 3]. In Fig. 7, the characteristic frequency of SiC fibers is found strongly in the UCS (Lon.) specimen. That of the SiC slurry in the CCS specimen is considerably more dominant and also provided to the frequency of the SiC fibers.

Conclusions

This study was carried out to compare the characteristic frequency of the elastic wave signal detected from the pencil lead break method and the bending test using SiC/SiC composite ceramic specimens. The results obtained were as follows: From the result of tension test of a SiC single fiber, the frequencies of the fiber fracture were commonly concentrated at the frequency band of about 478 kHz. By the pencil lead break method, it can be confirm that a semi-beat frequency exist the burst elastic wave signal to the microstructural features of the regular reinforcement of SiC fibers, these semi-beat phenomena occurred only in the CCS specimen. The characteristic frequency of SiC fibers is found strongly in the UCS specimen. That of the SiC slurry in the CCS specimen is considerably more dominant and also detected in the frequency of the SiC fiber. Through improvement of the sintering additives and/or the microstructural properties for the SiC slurry, we could made a structural material with the superior mechanical properties if we can shift up to a higher frequency group than the characteristic frequency of the SiC slurry.

Acknowledgments

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