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Time-Frequency Analysis of Ultrasonic Echoes and its Application to Nondestructive Evaluation of Thermal Damage of Steel

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***Abstract*:** Recent trend to extend the original design life of pressure vessels and piping may increase the possibility of failure accident of these components caused by material degradation due to creep or creep-fatigue. Since sudden rupture of these components usually results in a serious industrial accident, such material damages must be detected using nondestructive evaluation technique to ensure the safety of workers at the industrial sites. Although there are a lot of different methods in nondestructive evaluation technique, ultrasonic pulse-echo technique is supposed to be one of the best methods to detect creep or creep-fatigue damage. In this method, reflected ultrasonic echoes by material internal defects and specimen interface often exhibit critical time and frequency information. However, it is difficult to determine creep or fatigue-creep damage using conventional signal processing technique. To conquer such a difficulty, the time-frequency analysis method is applied in this study. Because the time-frequency analysis method can provide an effective tool to represent a signal in a two-dimensional time and frequency plane, it is possible to obtain frequency dependent ultrasonic characteristics related to certain material properties in a time-frequency plane rather than only in a time domain or frequency, and these characteristics can be applied to identify internal defects or to assess creep damage of crucial structure material.

In this study, ultrasonic tests with high frequency contact transducers were carried out using thermally degraded steel in order to confirm the effectiveness of the time-frequency analysis method. Measured echo signals were analyzed by the Morlet function based wavelet transform, one of the methods for the time-frequency analysis. It is shown that with the increase of thermal degradation, both the ultrasonic attenuation and its change with frequency gradually increased within a significant frequency band but ultrasonic velocity was relatively unchanged. The effectiveness of the wavelet analysis to ultrasonic signals for the quantitative evaluation of material thermal damage is clarified.

***Keywords*;** Nondestructive evaluation, Ultrasonic echo, Time-frequency analysis, Wavelet transform, Ultrasonic attenuation, Ultrasonic velocity, Thermal damage, Heat treatment, Grain size

1. Introduction

In industrial application, a large number of components in vital areas of infrastructure and large-scale plants, such as a power plant, tubing pipelines, etc., are manufactured from various kinds of steel. These structural steels subjected to environments of high temperature and high pressure suffered from thermal degradation including creep or creep-fatigue damage during their service lives. It is strongly desired to detect and evaluate such a material phenomenon and a damage state with ultrasonic nondestructive test technique[1),2)]. However, the signal obtained in an

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actual ultrasonic measuring system is generally non-stationary and difficult to be analyzed due to frequency dependent scattering, attenuation and dispersion. Since the joint time-frequency analysis of a signal can provide its detailed time information at a concerned frequency and a detailed frequency distribution at any time indices, it should be an appropriate tool for ultrasonic signal processing. A lot of results about the application of time-frequency analysis to ultrasonic non-destructive tests have been reported in recent years[3),4)]. These studies indicated that it was possible to obtain frequency dependent ultrasonic characteris-tics in a time-frequency plane rather than only in a time domain or in a frequency domain, and these characteristics could be applied to identify internal defects or to assess creep damage of crucial structure material.

In this study, ultrasonic nondestructive evaluation for material damage was carried out using a measurement system we developed. This paper not only describes this system and discusses the performances of some typical time-frequency methods used to analyze the obtained ultrasonic echoes but also introduces the conducted ultrasonic testing on thermally degraded Cr-Mo steel specimens with a high frequency contact transducer. We also present the obtained results and discussions concerning the effect of growth in specimen's internal grain size due to thermal degradation on certain frequency dependent ultrasonic behaviors by using wavelet transform.

2. Basis of Time-Frequency Analysis

The time-frequency analysis aims to deal with signal possessing of non-stationary properties encountered in practice. It represents a signal in a time-frequency plane with a two-dimensional time-frequency distribution function in order to obtain the signal's time-varying spectra.

2.1 Basic Methods

A lot of time-frequency representation methods have been developed and improved[5)]. Although the behavior of these methods is quite different and each has peculiar properties, Wigner-Ville Distribution (WVD), Short Time Fourier Transform (STFT) and Continuous Wavelet Transform (CWT) are three elementary methods.

For a given signal $f(t)$, its WVD is defined as the Fourier transform of its bilinear product at each time, that is:

$$WVD_f(t,\omega)=\int f^*(t-0.5\tau)f(t+0.5\tau)e^{-j\tau\omega}d\tau \qquad (1)$$

where t is time, ω is angular velocity, τ is time lag, and * represents complex conjugate.

The STFT of a signal $f(t)$ is defined as:

$$STFT_f(t,\omega)=\int f(\tau)w^*(\tau-t)e^{-j\tau\omega}d\tau \qquad (2)$$

where w is a selected window function used for observing the signal's local spectrum by translating it along time.

The CWT of a signal $f(t)$ is defined as its convolution with a serial of scaled and translated wavelet base function $\psi(t)$, that is:

$$CWT_f(t,s)=\frac{1}{\sqrt{s}}\int_{-\infty}^{\infty} f(\tau)\psi^*\left(\frac{\tau-t}{s}\right)d\tau \qquad (3)$$

where scale $s>0$. The key of wavelet analyses is to choose a suitable wavelet function for actual applications. A commonly used wavelet function is Morlet wavelet, consisting of a plane wave modulated by a Gaussian function:

$$\psi(t)=\pi^{-0.25}e^{j\omega_0 t}e^{-0.5t^2} \qquad (4)$$

where ω_0 is non-dimensional frequency, here taken to be 6 to satisfy the admissibility condition[6)].

The time-frequency methods mentioned above can be easily implemented by fast algorithm, taking advantage of fast Fourier transform. This makes it possible to use them in various actual applications of signal processing.

2.2 Performance Comparison

As is shown in **Fig. 1**, it is usually known that an ultrasonic echo is a broadband pulse modulated near the center frequency of the transducer used, and is very similar to a Gaussian pulse in nature. **Fig. 2** plots the contours of WVD, STFT and CWT for the actually obtained echoes given in **Fig. 1**. It gives an intuitive performance comparison of these methods used for analyzing ultrasonic echoes.

Theoretically, a high time resolution and a high

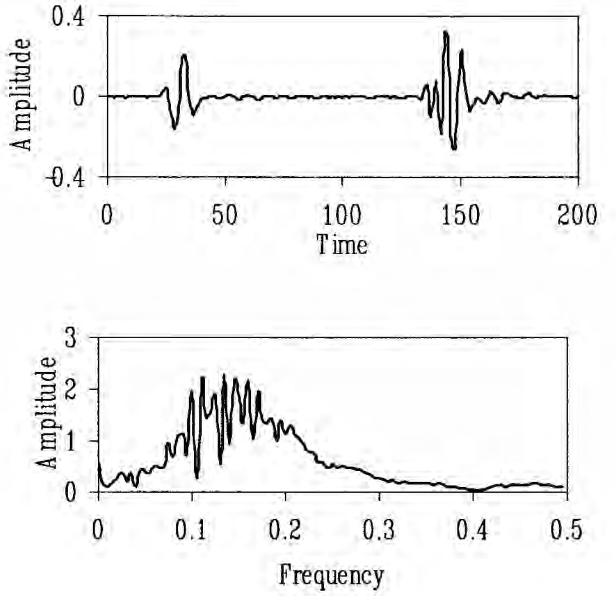

Fig. 1 Waveform of two tested ultrasonic echoes and their amplitude spectrum.

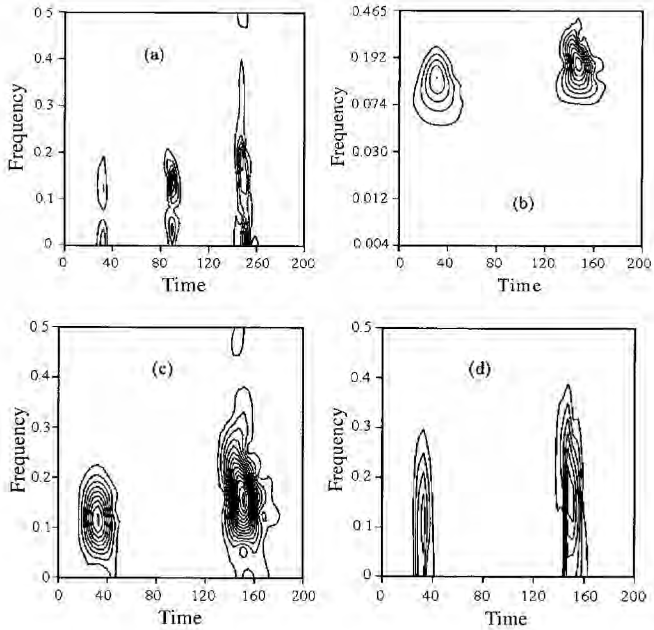

Fig. 2 Time-frequency distribution of two tested echoes: (a) WVD; (b) CWT based on Morlet wavelet; (c) STFT with 31-Hamming window; (d) STFT with 9-Hamming window.

frequency resolution can be achieved by WVD. However, in the case of multi-component signals, it can also introduce unwanted cross-term interference due to the bilinear product in the definition of WVD.

The STFT is free of cross-term interference, but its behavior greatly depends on the window function used. Although most of the commonly used window functions can be applied to it, it is difficult to make a tradeoff between time resolution and frequency resolution by STFT due to the length-fixed window.

The scale-varying structure of CWT makes it possible to have finer frequency resolution for low frequency components than high frequency components, and a finer time resolution for high frequency contents than low frequency contents. This is quite useful for most of the actual applications.

From theory and performance comparison, it is clear that the wavelet transform based on Morlet function is suitable for analyzing ultrasonic echoes since it can achieve excellent time and frequency concentration and can track the frequency trend at local time better than other methods. The presented results in the following parts of this paper are based on this kind of wavelet transform.

3. Ultrasonic Measurement System Developed

The developed ultrasonic measurement system in this study is shown in **Photo 1**. A pulsar/receiver, Imaging Supersonic Lab. Inc., BLP-12R, which is capable of high frequency application up to 150MHz, was employed to generate, receive and pre-amplify ultrasonic pulses and echoes. Through a NBC connector, the received waves were acquired with a digital oscilloscope LeCroy 9354C whose maximum sampling rate is 2GHz in a single channel or 500MHz in quad channels. Thus, the system is capable of accurate measurement for time of flight (TOF) with resolution up to 0.5ns. Each of the scope's channels has an 8-bit A/D converter to digitize the acquired analog signal. The digital oscilloscope was connected to a personal computer with GPIB bus to make it easier to store and analytically process ultrasonic wave data by a computer.

A single transducer was used to conduct ultrasonic measurement in this system. It received all of the echoes reflected from the surface and the bottom of the tested specimen. The system can operate with a wide range of transducers with

Photo 1　Photograph of the system developed to undertake ultrasonic measurement.

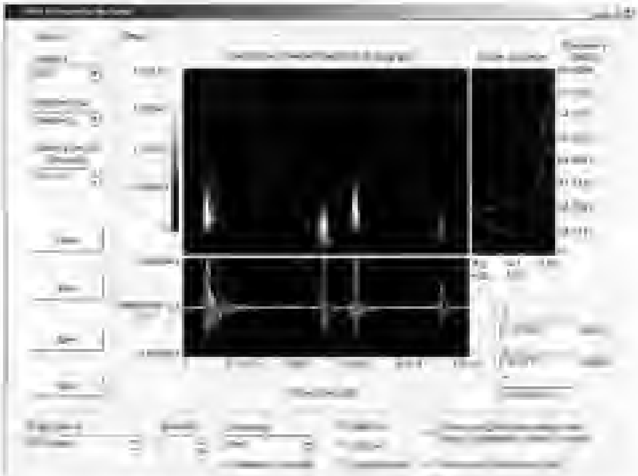

Photo 2　An example of the time-frequency analysis window.

different types of acoustic couple.

System software was developed using Microsoft Visual C++ and MathCAD. It is able to control the oscilloscope's activity, transmit and store a large amount of data, and perform time-frequency transform including WVD, STFT, CWT, spectrum analysis, graph displaying and zooming, parameter measurement, etc. **Photo 2** gives an example of the time-frequency analysis window.

4. Ultrasonic Testing for Thermally Degraded Steel

4.1 Specimen and Transducer

Tested specimens for present work were made of 2-1/4Cr-1Mo steel, mainly used for power boiler heating tubes and high pressure piping. To simulate thermal degradation, they were processed by four different types of heat treatment followed by air-cooling. As shown in **Table 1**, the grain size, measured according to JIS G0551, increased with the increase of heated temperature and holding time. **Photo 3** gives grain structures of specimens.

Table 1　Heat treat condition and grain size of 2-1/4Cr-1Mo specimens.

Specimen	Temperature (°C)	Time (hours)	Average Grain Diameter (μm)
S1	As received		11
S2	950	1	38
S3	1050	20	119
S4	1100	100	186

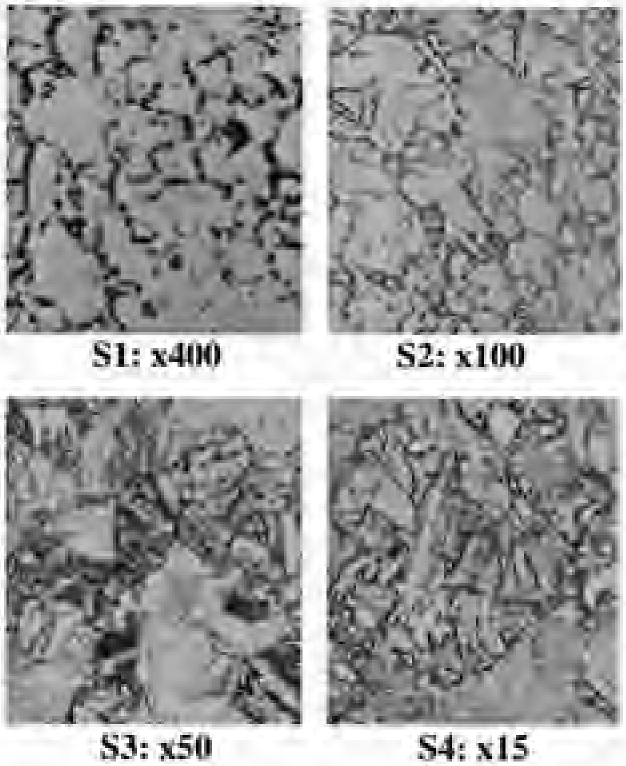

Photo 3　Grain structures of specimens.

Each specimen was machined to a plate of the unified dimensions, 80mm long, 12mm wide and 6mm thick, which has smooth and parallel faces to ensure precise measurement.

For a given specimen, statistical results presented were based on multiple tests at different locations on its surface. Furthermore, one hundred results were averaged at each location so as to reduce random noise.

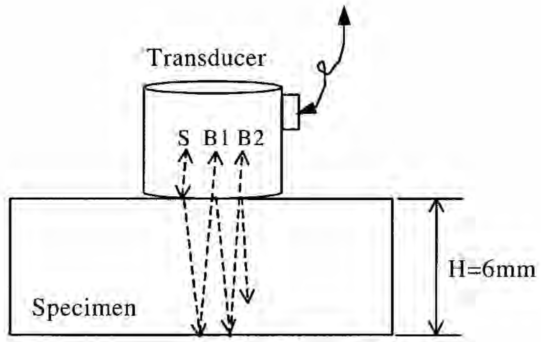

Fig. 3 Method of measurement.

Ultrasonic tests were conducted using a commercial longitudinal wave high frequency contact transducer, PANAMETRICS V214-BC whose nominal frequency is 50MHz, element size is 6.34mm and delay is 2.5 μs. See **Fig. 3**, the method of measurement, in which the surface echo (S) appeared immediately behind the delay line echo of a transducer. The first bottom echo is B1 and the second one is B2.

4.2 Obtained Waveforms and Their CWT

Fig. 4 gives the signal waveforms obtained from four specimens.

The CWT based on the Morlet function was applied to analyze these received signals. The CWT of above waves is plotted in **Fig. 5**. The differences between echoes are clearly depicted in the time-frequency plane. Thus, it is possible to calculate frequency dependent ultrasonic parameters according to the value and location of the peak around each echo.

5. Results and Discussions

Generally, ultrasonic measurement involves comparing the time of flight and the change of amplitude between a surface echo and a bottom echo. However, in the situation of contact measurement, it was difficult to distinguish surface echo from the delay line echo of a transducer. Therefore, the difference between the first bottom echo B1 and the second one B2 was usually compared since they are directly related to time of sound flight and loss of sound energy.

Because an ultrasonic echo is generally band-

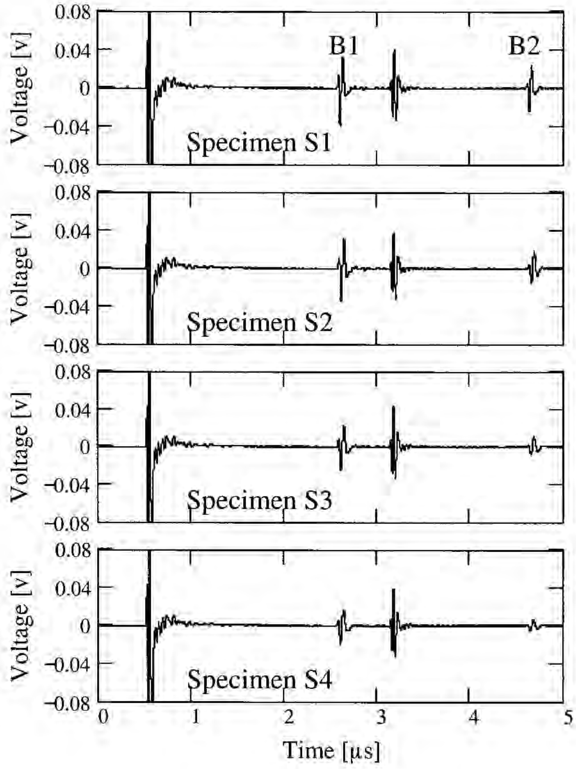

Fig. 4 Ultrasonic echoes measured from tested Cr-Mo steel specimens.

limited, it is important to determine a significant frequency band in advance, so as to obtain meaningful results. Below this band, accurate time of the echo was obscured due to wavelet transform. Above this band, the transducer was unable to effectively receive those high frequency components from the reflected wave.

5.1 Group velocity

Velocity is one of the basic ultrasonic properties. Its change is related to the alteration of elastic modulus and the density of a material as the sound wave travels through it.

The group velocity means the velocity at each frequency. In a time-frequency plane, it was calculated as the time of flight between the local peak around B1 and that of around B2 at each frequency, divided by transmitted distance (twice the specimen thickness).

Fig. 6 gives the results of group velocity obtained. **Fig. 7** shows the change of velocity with the grain size, in which error bars show the range

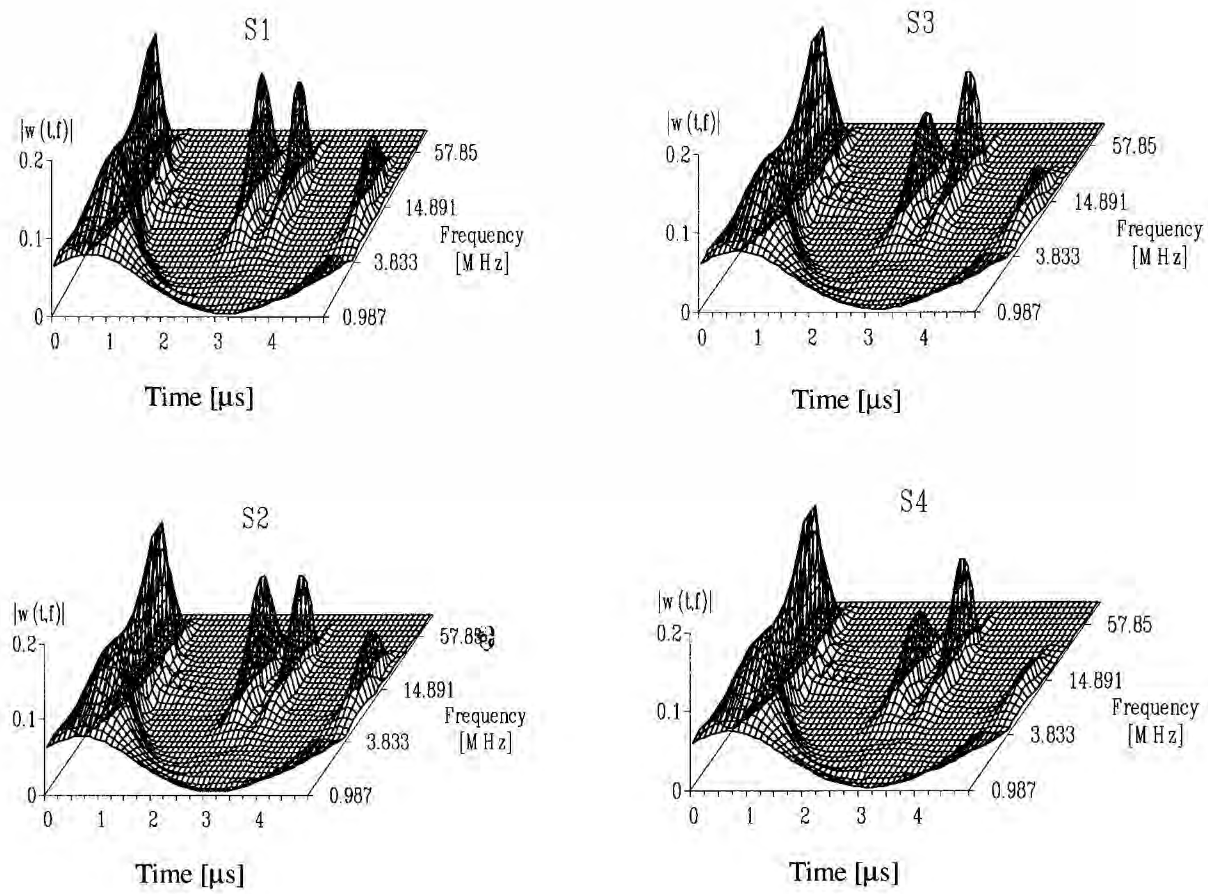

Fig. 5　CWT of echoes measured from tested Cr-Mo steel specimens.

of change at different frequencies within a significant frequency band of 10MHz~50MHz. It was observed from these results that the relatively low levels of change in ultrasonic velocity appear to be due to small differences in the phase present rather than the direct consequence of any increasing in grain size caused by thermal degradation in Cr-Mo steel.

5.2 Attenuation coefficient

Attenuation is principally caused by the heat condition and scattering as the sound wave travels through material.

The attenuation coefficient at each frequency obtained in a time-frequency plane was the ratio of the local maximum value near B1 to that of B2 at that frequency, divided by the transmitted distance.

From the results shown in **Fig. 8** , it was observed that ultrasonic attenuation gradually increased with the increase of thermal degradation within a significant frequency band of 10MHz to 50MHz. **Fig. 9** gives the dependence of the attenuation on grain size, in which error bars indicate the range of the attenuation's change with frequency within this frequency band. It was found that the grain size greatly affected the ultrasonic attenuation and the change of attenuation in terms of frequency.

6. Conclusions

This study concerned the application of time-frequency analyses in the field of ultrasonic nondestructive material evaluation. It is concluded that the wavelet transform provides an effective tool to obtain frequency dependent ultrasonic characteristics, such as group velocity and attenuation coefficient related to certain material properties. Present results indicated that, with the increase of thermal degradation of Cr-Mo steel, both the attenuation and its change with frequency gradually increased within a significant frequency

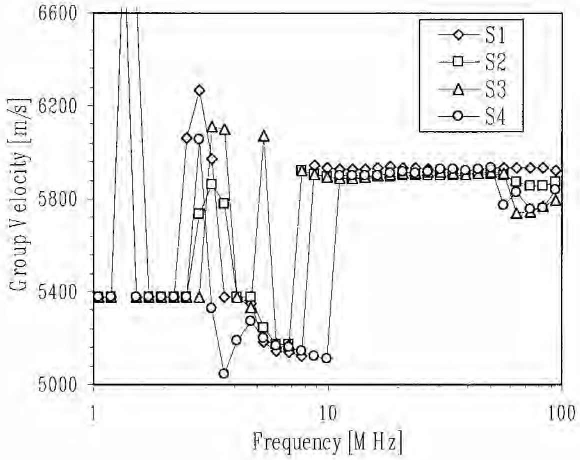

Fig. 6 Group velocity vs. frequency

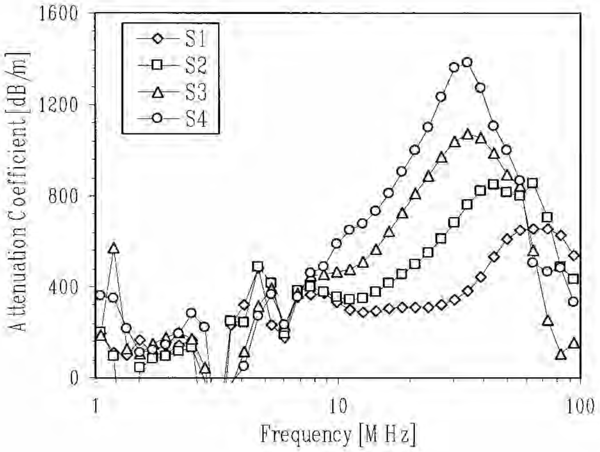

Fig. 8 Attenuation coefficient vs. frequency.

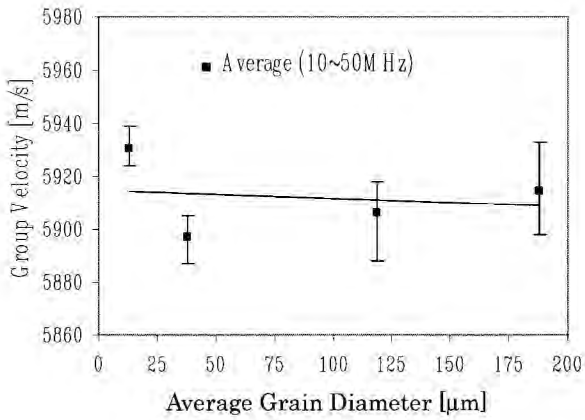

Fig. 7 Relationship of group velocity and grain size.

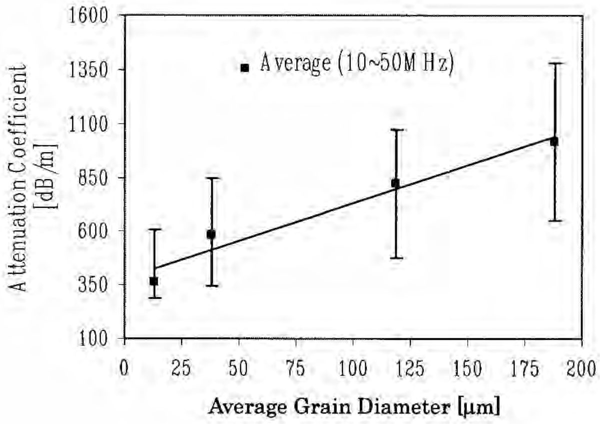

Fig. 9 Relationship of attenuation coefficient and grain size.

band although velocity was observed relatively unchanged. These results obtained in a time-frequency plane are certainly useful for quantitative evaluation of material damage.

Acknowledgement

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