NON-CONTACT ULTRASONIC INSPECTION OF DIFFUSION BONDS IN TITANIUM

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ABSTRACT

A technique is described for the non-contact inspection of diffusion bonds in titanium, using a pulsed laser as an ultrasonic source and an electromagnetic acoustic transducer (EMAT) as a detector. The resultant waveforms have been analyzed using cepstral processing, with good results.

I. Introduction

The current Canadian concept for disposal of used fuel from CANDU nuclear reactors is to isolate the fuel in corrosion-resistant containers, which are then placed at a depth of up to 1 km in a stable rock mass. The objective is to develop a remote nondestructive evaluation (NDE) technique for the final closure weld of the container, which is to be fabricated from titanium and joined using diffusion bonding. The NDE method chosen should establish the mechanical integrity of the weld, and that a minimum corrosion barrier exists. Although a range of techniques exist for the inspection of diffusion bonds in titanium [1-3], ultrasonic testing has the advantage of simplicity [4]. In addition, recent research [5] has also indicated how the extent of porosity and cracking within the weld may be estimated.

The requirement for a non-contact approach comes from the radioactive environment that would be encountered by an operator. While a C-scan, using a water couplant, may be used to inspect such diffusion bonds [6], such a method would be more inconvenient than one in which a couplant is not necessary. A technique adaptable to robotics would also be an advantage. For these reasons, an ultrasonic method involving generation by a pulsed laser and detection by an electromagnetic acoustic transducer (EMAT) has been investigated, the adopted configuration being designed to operate in a similar fashion to a conventional pulse-echo system.

Pulsed lasers can be used to generate ultrasonic pulses via several mechanisms [7]. The most widely used of these are thermoelastic generation, where the substrate is heated in a transient fashion, and the evaporation of a coating applied to the surface prior to irradiation. The latter method gives higher amplitudes of longitudinal waves, whereas the former is a good source of shear energy. Various designs of EMAT are available for the detection of laser-generated waveforms [8-10]. All are based on a d.c. magnetic field and an r.f. coil. The mode sensitivity of the device depends on the magnetic field direction and the coil design.

II. Apparatus and Experiment

In the work to be reported here, it was decided to optimize the generation and detection of the longitudinal ultrasonic mode. This requires an EMAT for detection with a magnetic field parallel to the metal surface, and perpendicular to the coil windings. In addition, it was decided to have the EMAT coil either side of the generating laser pulse, to initiate conventional pulse-echo testing. The final EMAT design is shown in Fig. 1. The permanent magnets providing the magnetic field were fitted with pole pieces, to direct the field in a direction parallel to the titanium surface. Two coils were wound either side of the aperture, forming parallel line segments of 1.2 mm width, at a distance of ~ 5 mm from the centre. The EMAT contained a central aperture, through which the generating laser pulse was directed. The laser source was a pulsed Nd:YAG laser, with a 20 ns pulse duration at energies of ~ 200 mJ. The laser beam could be apertured or focused, to produce a 2 mm diameter irradiated area at the surface. To enhance longitudinal generation efficiencies, an oil coating was applied to the titanium surface prior to irradiation.

The laser/EMAT combination was scanned over a specially-prepared titanium sample containing diffusion bonds, where artificially induced defects were present along its length. The defect of concern here is that formed by non-operation of the diffusion bonding apparatus for a specified period, as it was scanned along the titanium plates to be joined. The transducer system was scanned along the bonded region, and over the area of defect caused by this process. Ultrasonic waveforms were recorded at 1 mm intervals, using a Data Precision Data 6000 Waveform Analyzer. Digitized data was processed on the oscilloscope, using Fast Fourier Transforms (FFT) and related functions. Waveforms and processed data could then be transferred to an IBM PS/2 microcomputer for further analysis. Triggering of the waveform was synchronized from the laser pulse itself, using a photodiode to detect scattered laser radiation.

III. Results and Signal Processing

The waveforms recorded over a region of disbond between two 3 mm thick titanium plates is shown in Fig. 2(a). As can be seen, it is relatively complex in nature, with a series of reflected signals being detected by the EMAT. This arises because the small diameter laser beam generates both longitudinal and shear waves. Although direct longitudinal radiation is the dominant factor, shear energy can mode

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convert on reflection to longitudinal waves. These are also detected by the EMAT, and a complicated waveform results. Hence, a form of signal processing is required, that can extract the required information, this being the amount of energy reflected at a certain depth into the material. For a good bond, where the two plates are joined, the ultrasound should reach the back wall of the sample. Conversely, for a complete disbond, all energy will be reflected from a depth of one plate thickness. Partial bonds would produce a signal with a partition of energy between these two extremes.

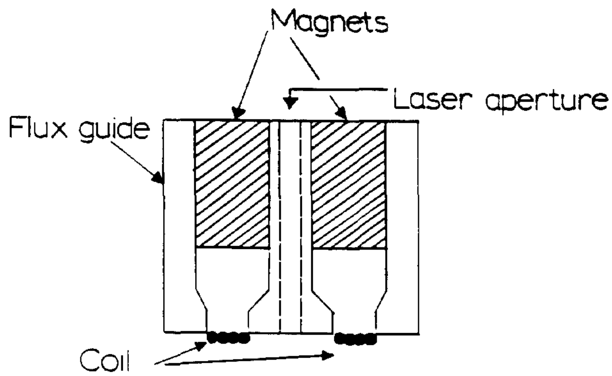

Fig. 1. The EMAT configuration used for detection of laser-generated longitudinal waves.

Ceptral analysis is a method of obtaining such information [11], as it was formulated to detect periodicity within time waveforms. In the example of Fig. 2(a), the energy multiply-reflected at the bond interface would have a certain time periodicity, whereas that passing through to the back wall would have approximately twice the transit time. Mode conversion effects would lead to the same periodicities, and hence would not be a complicating factor. A cepstrum $C(\tau)$ of a time waveform $x(t)$ may be defined as

$$C(\tau) = F[\log(S(f))] \qquad (1)$$

where F is the Fourier transform operator and $S(f)$ is the frequency spectrum of $x(t)$. In a digital system, a simple method of implementing the above is to perform an FFT on a time waveform to obtain a power spectrum, and then to execute a second forward FFT. If desired, the logarithm step may be omitted if it introduces too much noise into the resulting cepstrum.

The cepstrum of the waveform shown in Fig. 2(a) is shown in Fig. 2(b). Note the strong peak at ~ 1.15 μs, this being the transit time for a multiply-reflected longitudinal wave from the top surface to the bonded area. This method clearly demonstrated that the waveform of Fig. 2(a) is that taken over an area of complete disbond.

Results obtained over a bonded area are shown in Fig. 3(a). The waveform contains a series of transients, separated by 2.3 μs, the time period expected over a competent bond. Note that smaller additional signals are also present, which again arise from mode conversion of shear to longitudinal energy on reflection. (A close inspection of these smaller signals indicates that they are also separated by 2.3 μs, and hence confirms that mode conversion leads to a second set of multiply-reflecting longitudinal transients). The cepstrum of

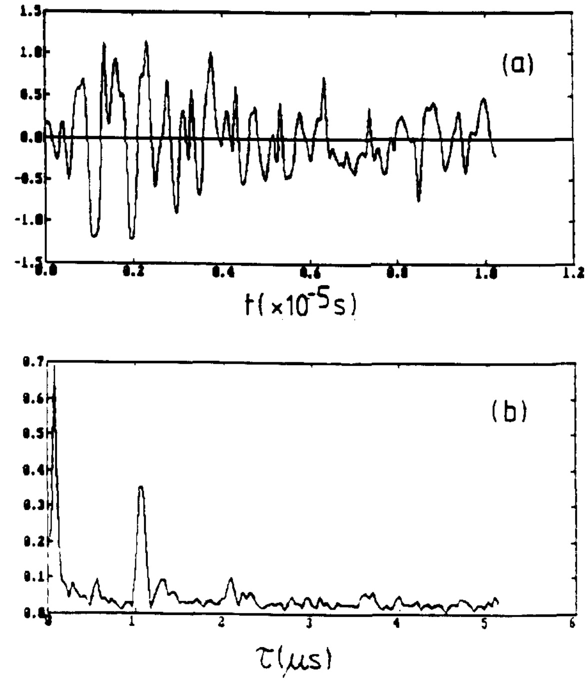

Fig. 2. (a) Waveform recorded over a disbond region between two 3 mm thick titanium plates.
(b) Cepstrum of waveform in (a).

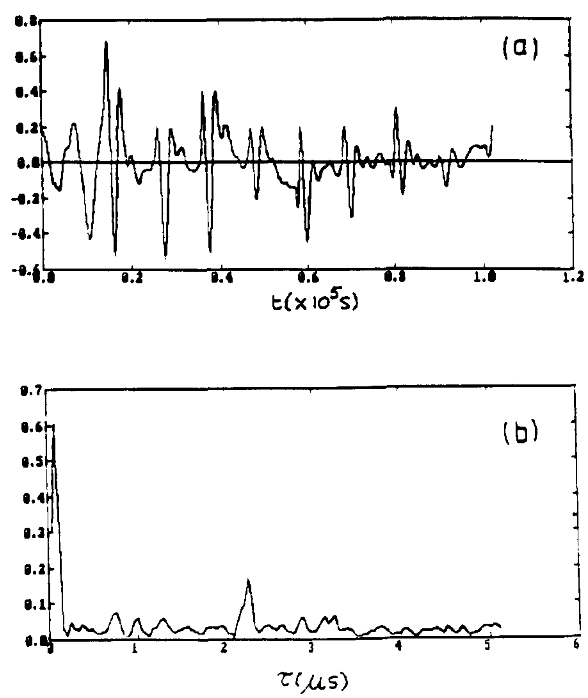

Fig. 3. As Fig. 2, but over a bonded region.

this waveform is shown in Fig. 3(b), and contains the expected peak at 2.3 μs. Note that on this and the cepstrum of Fig. 2(b), a large d.c. cepstral peak is present. This is commonly observed following such processing, and can be reduced in size by suitable further processing.

It is evident from Figs. 2 and 3 that cepstral processing has been successful in extracting the required information from the time waveforms. In addition, it should be noted that a conventional C-scan approach could not be used in this situation. This is because mode conversion at a disbond leads to the presence of a signal in a similar time window to that expected from conventional reflection in a bonded sample. Other methods would also be difficult to apply, because of mode conversion signals. Cepstral processing removes this ambiguity, in that it extracts periodicities throughout the whole waveform.

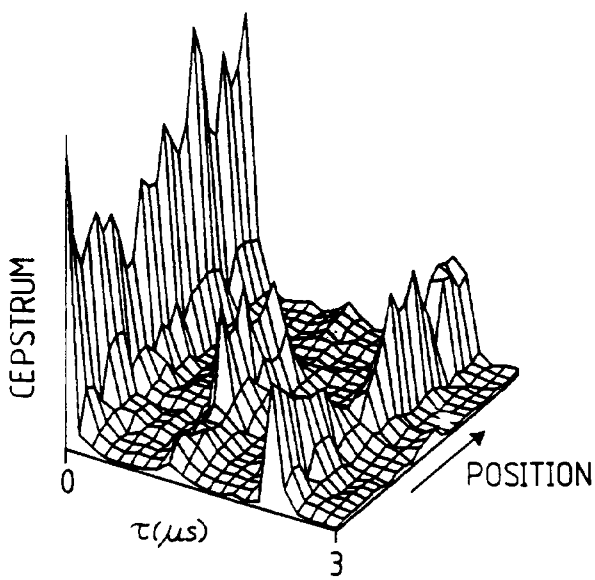

Fig. 4. Variations in the cepstrum as the transducer system was scanned over a defect.

The laser/EMAT system of Fig. 1 has also been used to record a series of waveforms, as it was scanned over a defect region where the diffusion bonding apparatus was switched off for a period of 10s during the joining operation. This produced a defect of approximately 1 cm in width. Data was taken at 1 mm intervals, and the cepstrum of each waveform recorded. The result may be plotted as a 3D graph, as shown in Fig. 4. As the transducer system passes over the defect, the cepstral peak at 1.15 μs goes through a maximum, whereas that at 2.3 μs becomes a minimum. The relative heights of these two peaks correspond to the partition of energy reflected at the bond line and back wall.

IV. Conclusions

A method has been presented for the remote ultrasonic inspection of diffusion bonds in titanium. Analysis using cepstral processing has shown that it is possible to obtain information concerning the state of bonding. The method shows promise for the inspection of nuclear used fuel containers.

V. Acknowledgements

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VI. References

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