ACOUSTOELASTIC RESPONSE OF TUNGSTEN FIBER-REINFORCED KANTHAL METAL MATRIX COMPOSITES DUE TO THERMAL LOADING

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INTRODUCTION

Metal Matrix Composites (MMCs) can have many attractive properties including high specific modulus and strength, high temperature performance, and the ability to be tailored to specific applications. However, due to the mismatch in the coefficients of thermal expansion between the reinforcement and matrix, residual stresses can develop due to processing or in-service conditions.

Acoustoelasticity is an ultrasonic technique that relates a stress state to the speed at which ultrasonic waves propagate within a material. Third-order elastic constants can be calculated based on normalized changes in ultrasonic wave speed. These constants along with the second-order (Hooke's Law) constants can be related to micro- and macroscopic behavior of materials, including the state of thermal residual stresses [1-3].

In this study, preliminary acoustoelastic tests are performed on tungsten fiber-reinforced Kanthal MMCs containing 0 and 70% reinforcement, by volume. Wave speed measurements of longitudinal ultrasonic waves propagating in the MMCs in a pulse-echo configuration are made as a function of applied thermal loading. Due to the inhomogeneous nature of fiber-reinforced composites, wave speed measurements are performed as C-scans over a relatively large area of each MMC. In order to replicate the development of thermal residual stresses in the MMCs during processing, the thermal stress state within the MMCs is modified by increasing the temperature.

BACKGROUND

The Advanced Composites Fabrication Group at NASA-Lewis Research Center uses an arc-spray process for primary fabrication of W/Kanthal MMCs. A schematic of the arc-spray process is shown in Figure 1. There are three components: a rotating drum for fiber lay-up, an arc-spray head with a vacuum chamber for making plies of tungsten fibers arc-sprayed with Kanthal, and a Hot Isostatic Press (HIP) for consolidating the plies. The

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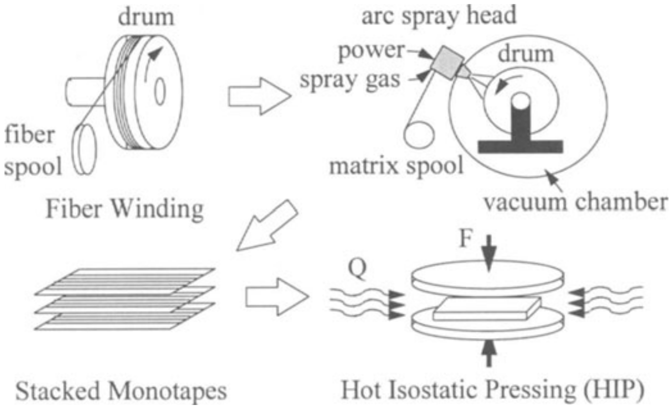

Figure 1. Schematic of arc-spray processing.

unreinforced W/Kanthal MMC was fabricated using the same arc-spray process as for the 70% fiber-reinforced MMC.

Fiber Lay-up

A backing material is placed around a drum mounted to a lathe. A spool of 0.008" diameter GE 218 tungsten fiber is wound onto the drum by rotating the lathe and translating the spool laterally. The rotational speed of the lathe and the feed rate of the fiber spool are carefully controlled to achieve proper fiber spacing, and thus the desired volume percentage of reinforcement in the resulting MMC.

Arc-Spray

The drum containing the laid-up tungsten fiber is placed in a vacuum chamber. After aligning an arc-spray head with the drum, a vacuum is drawn. A spool of Kanthal material is fed into the arc-spray head. The Kanthal composition is (wt %): 73.2% Fe, 21% Cr, 5.8% Al and 0.04% C. An inert gas is supplied under pressure to the head as an arc atomizes the Kanthal and propels the spray onto the fiber lay-up. The drum is rotated and the arc-spray head translated laterally to coat the fibers evenly. The rotational speed of the drum and the feed rate of the arc-spray head are also carefully controlled to achieve the desired volume percentage of fiber reinforcement.

Hot Isostatic Pressing

The arc-sprayed fibers are detached from the drum to produce a monotape. Depending on the volume percentage of reinforcement to be produced, a number of monotapes are stacked and placed into a Hot Isostatic Press (HIP). The stacked monotapes are consolidated under 15 ksi of pressure at 1950°F for one hour before cooling to room temperature.

Secondary Fabrication

After arc-spray processing, the edges of the as-fabricated plate are very rough, resembling a stack of cards. Composite specimens are machined from the consolidated plates at NASA-Lewis using a wire EDM machine. The final composite dimensions are 1.0" x 0.1" x 8".

THEORY

Ultrasonic Wave Propagation

Normal-incidence ultrasonic transducers propagate waveforms through materials in a pulse-echo configuration as shown in Figure 2 [4]. An ultrasonic waveform is transmitted through the transducer's wear plate into the couplant gap. The pulser/receiver receives reflected echoes as the wave reverberates within the specimen. The full scale, front surface, first, and second back echoes (FS, F1, B1, and B2, respectively) are shown in the oscilloscope trace in Figure 2. In this study, immersion tests were performed to measure longitudinal wave speeds using the first and second back echoes (B1 and B2) for analysis.

Transfer Function

In general, a transfer function is defined as the ratio of the output of a system to the input. In this study, the Fourier transform of the first back echo (B1) is defined as the system input, and the Fourier transform of the second back echo (B2) is defined as the system output [5]. The transfer function H(ω) is the ratio of these two signals, as shown in Equation (1):

$$H(\omega) = \frac{\bar{Y}(\omega)}{\bar{X}(\omega)} = e^{-[\alpha + i\cdot(\omega/\mathrm{v})\cdot 2\cdot d]} \tag{1}$$

where ω is the frequency (rad/s); v is the wave speed (in/s); d is the specimen thickness (in); $\bar{Y}(\omega)$ is the Fourier transform of the second back echo (B2); and $\bar{X}(\omega)$ is the Fourier transform of the first back echo (B1). The slope of the linear portion of the phase spectrum is used to calculate the phase shift (θ(ω)) between the system input and output. The wave speed is calculated using Equation (2):

$$\mathrm{v} = \frac{-2\cdot d}{\left(\frac{\theta(\omega)}{\omega}\right)} \tag{2}$$

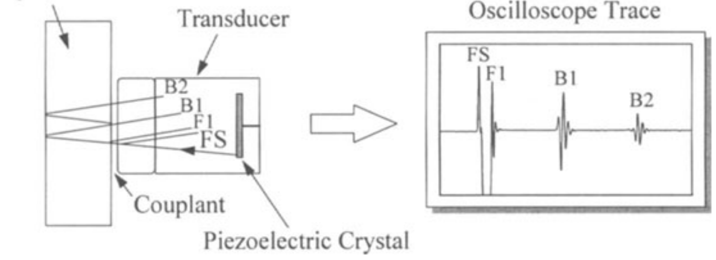

Figure 2. Pulse-echo technique using longitudinal ultrasonic waveforms.

Table 1. MMC constituent properties

	W	Kanthal
ν	0.28	0.30
E	395 GPa	200 GPa
CTE	4.5e-6 K^{-1}	9.5e-6 K^{-1}

Residual Stresses

The pertinent properties of tungsten and Kanthal are shown in Table 1. Due to the CTE mismatch between the matrix material and the fiber reinforcement, thermal residual stresses develop in W/Kanthal MMCs due to the large temperature changes during processing. Additionally, such stresses can develop during in-service conditions. Residual stresses can lead to matrix cracking, resulting in inferior mechanical properties of the composites. Figure 3 shows an idealized stress-strain curve for the constituent materials in an MMC [6]. The typical MMC reinforcement is fairly brittle and fails before any plastic deformation develops. The matrix, on the other hand, is ductile and has an elasto-plastic behavior. As can be seen by the highlighted locations on the stress-strain curves, thermal residual stresses are tensile in the matrix and compressive in the reinforcement. Using a modified rule-of-mixtures, the composite strength (S_c) is given by Equation (3):

$$S_c = (S_f - \sigma_f^r)V_f + (S_m - \sigma_m^r)(1 - V_f) \tag{3}$$

where V_f is the volume fraction of reinforcement; σ_f^r and σ_m^r are the residual stresses in the fiber and the matrix, respectively; and S_f and S_m are the fiber and matrix strength. To develop composites with reliable and enhanced properties, it is necessary to understand the nature and the magnitude of these residual stresses and its effect on the acoustoelastic response.

Acoustoelasticity

It is well known that the elastic behavior of solids has nonlinear as well as linear components. Hooke's law relates stress and strain through the use of second order elastic constants. For characterization of micro- and macroscopic behavior of materials and residual stresses, higher order elastic constants are required. Ultrasonic techniques, such as acoustoelasticity, may be sensitive to these nonlinear components [1].

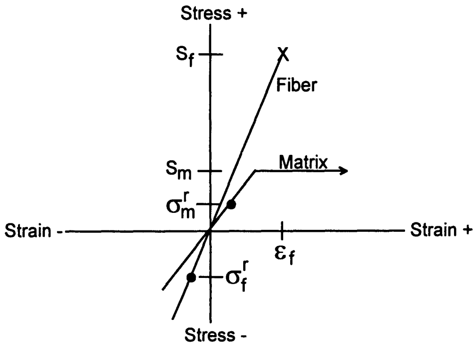

Figure 3. Typical MMC stress-strain curve.

Acoustoelasticity is modeled as the propagation of an ultrasonic waveform superimposed on a state of finite elastic deformation that is homogeneous in the direction of wave propagation. The ultrasonic waveform is described by a plane wave that propagates in the direction of deformation homogeneity [7]. A set of simultaneous equations are derived which yield the third-order elastic constants of a test material through the measurement of normalized ultrasonic wave speed as a function of applied stress, as given in Equation (4).

$$\begin{aligned}
\frac{\Delta V_{22}}{V_{22}} &= \frac{1}{2(\lambda + 2\mu)}\left[(m_1 + 2m_2)\frac{(1-2\nu)}{E} - \frac{\nu}{E}(4\lambda + 8\mu + 4m_2 + 8m_3)\right]\sigma_{11} \\
\frac{\Delta V_{23}}{V_{23}} &= \frac{1}{2\mu}\left[m_2\frac{(1-2\nu)}{E} - \frac{4\nu}{E}(\mu + m_3)\right]\sigma_{11} \\
\frac{\Delta V_{21}}{V_{21}} &= \frac{1}{2\mu}\left[m_2\frac{(1-2\nu)}{E} + 2(\mu + m_3)\frac{(1-\nu)}{E}\right]\sigma_{11}
\end{aligned} \tag{4}$$

where v_{22} is longitudinal wave speed (in/s), v_{23} is shear wave speed for oscillation normal to loading direction (in/s), v_{21} is shear wave speed for oscillation parallel to loading direction (in/s), σ_{11} is the applied stress (psi), ν is Poisson's ratio, E is the modulus of elasticity (psi), λ and μ are second-order elastic [Lamé] constants (psi), and m_1, m_2 and m_3 are third-order elastic constants (psi) [8].

EXPERIMENTAL SETUP

There are three main components in the C-scan setup: the normal-incidence transducer used for ultrasound propagation; the equipment used for positioning the specimen; and the equipment used to control, acquire, and analyze the ultrasonic waveforms. To measure longitudinal wave speed, immersion tests were performed. A Panametrics V312, 10 MHz, 1/4"-diameter normal-incidence longitudinal transducer is oriented so that wave propagation and oscillation are in the specimen thickness direction.

Positioning Equipment

A 3-axis Bridgeport Interact 412 CNC (Computer Numeric Control) machine was used for positioning the specimen. A Heidenhain TNC151 control was used for programming the CNC bed position. The transducer was attached to the CNC spindle using a fixture installed in a CNC collet. A water bath of distilled water was mounted on a hot plate, which was used to thermally load the MMCs. A constant water-gap between the transducer and specimen of 0.375" was used. A support fixture suspended the specimen in the water bath and provided alignment between the transducer and specimen. An electronic height gage was used to accurately initialize the distance between the top surface of the specimen and the CNC-mounted transducer.

The Heidenhain controller was programmed to move to each C-scan position in a 13 x 7 grid with 0.050" step spacing as shown in Figure 4. All positions were maintained at least one transducer's radius away from each edge. A relatively slow feed rate of 15 in/min

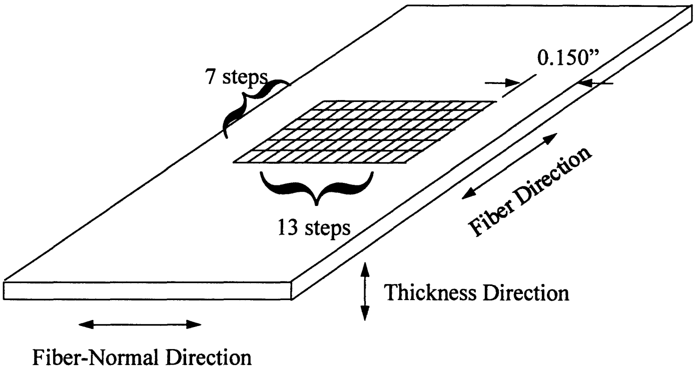

Figure 4. C-Scan positioning on W/Kanthal MMCs.

was used to avoid excessive disturbance of the water bath. At each position, a pause (approximately 27 s) allowed time for the experimental setup to take data.

Ultrasonic Control, Acquisition, and Analysis

The ultrasonic transducer is excited by a Krautkramer-Branson USIP 12 pulser/receiver. The ultrasonic echoes from the test specimen are sent as analog waveforms to a Philips PM3323 500 MS/s digital oscilloscope. Individual ultrasonic echoes are windowed on the oscilloscope. A Gateway2000 486/66 MHz computer running National Instruments' LabVIEW software is connected to the oscilloscope using an internal National Instruments IEEE card (GPIB). Using GPIB commands, the echoes on the oscilloscope are transferred digitally to the computer. After the download, a transfer function analysis algorithm is employed to calculate the ultrasonic wave speed.

RESULTS AND DISCUSSION

A three-dimensional contour plot of the longitudinal wave speed at room temperature in the unreinforced MMC is shown in Figure 5. C-scans of longitudinal wave speed measured as a function of temperature in the unreinforced Kanthal MMCs are shown in

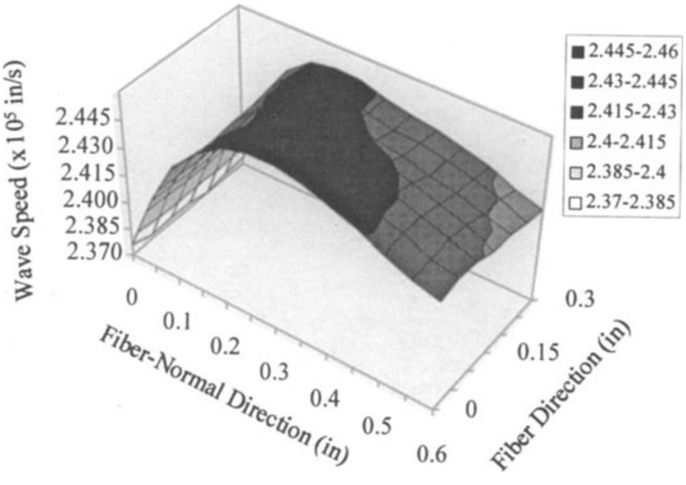

Figure 5. Longitudinal wave speed C-Scan of 0% W/Kanthal MMC (80°F).

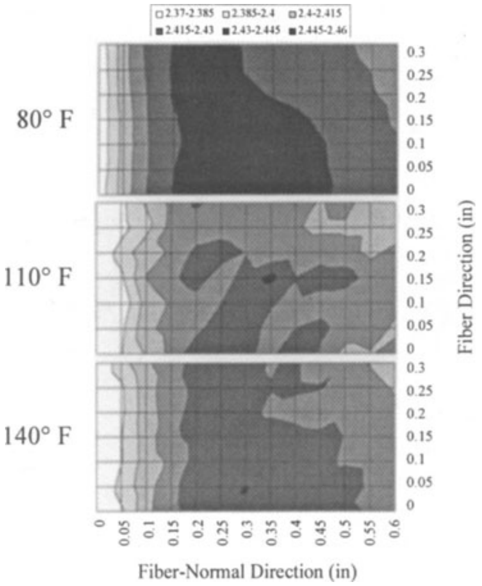

Figure 6. Longitudinal wave speed C-Scan of 0% W/Kanthal MMC.

Figure 6. Longitudinal wave speed is fairly constant along the fiber direction, while there is a Gaussian-like distribution normal to the fibers. The highest wave speeds are located along a band oriented axially near the centerline of the MMC. In general, as the temperature increases, wave speed decreases. Figure 7 shows C-scans of longitudinal wave speed as a function of temperature in the 70% MMC. The maps are much more complicated, in that the wave speed isn't constant along the fiber direction. As in the unreinforced MMC, the wave speed in the 70% MMC decreases with increasing temperature. Figure 8 shows a comparison of the C-scans for each MMC as a function of testing temperature.

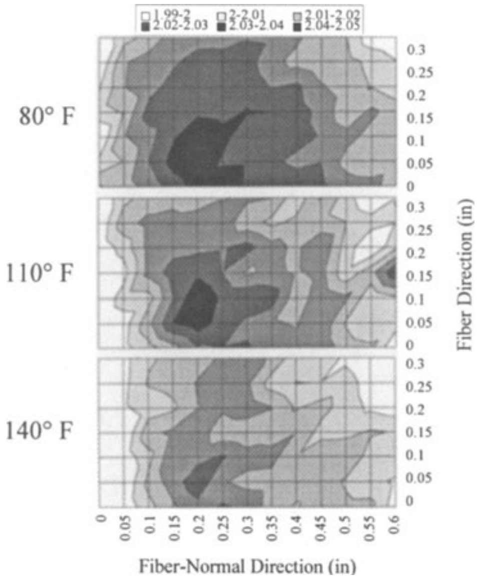

Figure 7. Longitudinal wave speed C-Scan of 70% W/Kanthal MMC.

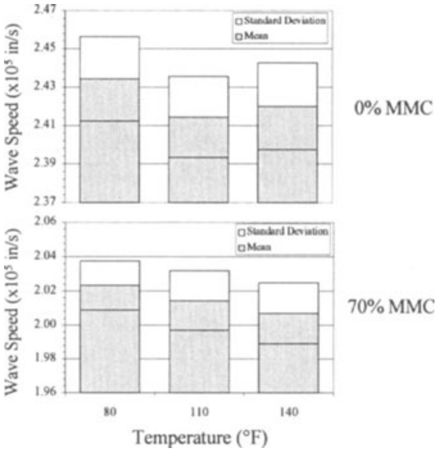

Figure 8. Longitudinal wave speed of W/Kanthal MMCs as a function of temperature.

CONCLUSIONS

Based on these preliminary acoustoelastic tests of thermally loaded W/Kanthal MMCs, several conclusions are drawn:

- C-scanning can be used to track changes in ultrasonic wave speed as a function of temperature.
- Longitudinal C-scans of reinforced W/Kanthal MMCs are much more complicated than the unreinforced MMC.
- Longitudinal wave speed is significantly lower in the 70% MMC than in the unreinforced MMC.
- Longitudinal wave speed in the 70% MMC decreases linearly with increasing temperature.

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