STUDY OF INTERFACIAL STRESS IN METAL MATRIX COMPOSITES USING ULTRASONIC VELOCITY MEASUREMENTS

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INTRODUCTION

The numerous potential applications of metal matrix composites (MMCs) in the military and aerospace industries have resulted in the widespread study of their mechanical properties to determine optimum fabrication techniques for improved composite strength. Due to the difference in the thermal expansion coefficients of the matrix material and its reinforcement, thermally-induced residual stresses exist in the composite as a direct result of cooling from the MMC fabrication temperature. Several nondestructive techniques have been used to determine the residual stress present in various engineering materials. Radiographic techniques have been used extensively, but are somewhat limited in penetration depth and spatial resolution. However, ultrasonic techniques have proven to be a useful nondestructive means of determining bulk mechanical properties of a material. To determine the influence of internal stresses in MMCs on ultrasonic velocities, specimens of various second-phase silicon carbide content were subjected to a change in temperature. As the specimen temperature was raised, interfacial stresses between the aluminum matrix and silicon carbide reinforcement were relaxed, resulting in an overall change in the stress state of the material. Longitudinal ultrasonic waves were used to measure the acoustoelastic effect due to this change in the internal stress of the MMC. Longitudinal waves have been successfully used to determine internal stresses due to the influence of temperature on railroad rails [1] and prestrained aluminum and copper specimens [2]. The ultrasonic velocities in this investigation were measured with a computer automated time-of-flight acquisition system accurate to better than 1 part in 10,000.

EXPERIMENTAL

Two aluminum alloys, Al-7064 and Al-8091 have been studied in this investigation. For each alloy three specimens with various silicon carbide (SiC) content were tested ultrasonically. The three Al-7064 alloy specimens contain 0, 15, and 20% SiC, the Al-8091 specimens contain 0, 10, and 15% SiC. Furthermore, a pure silicon carbide specimen was tested to study wave propagation behavior in monolithic silicon carbide. The aluminum specimens were fabricated as 1 inch diameter extruded rods, then machined flat for ultrasonic testing to dimensions 0.6 x 0.6 x 0.9 inch, the long dimension corresponding to the extrusion direction. The matrix composition of each alloy is presented in Table 1.

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Tab.1. Composition for the Al-7064 and Al-8091 matrix alloys.

Alloy	Si	Fe	Cu	Mg	Zn	Cr	Zr	Co	Li
7064	0.05	0.10	2.0	2.3	7.1	0.12	0.20	0.22	---
8091	0.02	0.01	1.9	0.8	---	---	0.11	---	2.7

One of the most common techniques used to evaluate the ultrasonic time-of-flight for laboratory specimens is the pulse-echo-overlap system, described by Papadakis [3]. However, an automated time-of-flight acquisition system has been developed for the measurement of the change in time-of-flight as a function of temperature and applied stress. In this method, the received 5.0MHz signal is sent to a 10-bit 60 MSample/s digitizer which samples analog voltages every 16.7ns and assigns discrete output levels according to the signal amplitude. The waveform data are read by a computer via an IEEE-488 GPIB connector and analyzed to determine the time-of-flight using a BASIC computer program. Since small changes in the time-of-flight due to a change in temperature are expected during testing, a method is proposed to interpolate between two points on either side of a known reference point, significantly decreasing the time resolution error.

Consider Figure 1 where a peak value in a typical received echo has been determined and two digitized points P_i and P_{i+1} are considered about the neutral axis corresponding to the zero-crossing in the first echo. It can be seen that a line drawn joining P_i to P_{i+1} intercepts the zero-crossing at a point $P_i + \Delta p_i$. The determination of Δp_i lies in the method of similar triangles. Knowing P_i, P_{i+1}, $\Delta p_i + \Delta p_{i+1} = 1$, h_1, and h_2, Δp_i can be determined as

$$\Delta p_i = \frac{h_2}{h_1 + h_2}, \tag{1}$$

where Δp_i is a value between 0 and 1. Therefore, the zero-crossing corresponds to a point equal to $P_i + \Delta p_i$. This same technique can be used to determine the zero-crossing in the next echo, say $P_j + \Delta p_j$. The time-of-flight is then determined as the difference in the number of digitized points between P_i and P_j, as

$$\text{TOF} = \frac{P_j + \Delta p_j - \left(P_i + \Delta p_i\right)}{60\text{x}10^6} \text{ seconds}, \tag{2}$$

where $60\text{x}10^6$ is the sampling rate. Experimental results show that after 200 individual measurements, the maximum deviation (difference between the highest and lowest reading) from a constant time-of-flight value is approximately 1ns out of 9.8μs, a 0.01% error in an absolute measurement, corresponding to approximately an 8-bit ideal digitizing rate. However, if multiple samples are evaluated, this accuracy can be significantly enhanced through averaging. The deviation from the digitizer's ideal 10-bit resolution can be attributed to electrical noise, jitter, and the tendency for the signal to occupy "preferred states" at high slew rates. These aspects have been addressed by Elsley [4] in an ultrasonic application using a 10MHz transducer for signal generation and an 8-bit 100 MSa/s digitizer for data acquisition.

This system has been successfully used in the study of ultrasonic velocity as a function of temperature from -30 to 60°C. In this system, a temperature controller is used to ramp the temperature over this range in eight hours. Approximately every six seconds, the temperature is read and a new waveform analyzed. This corresponds to an average of 50 measurements per Celsius degree. Process temperature is read by the computer through the serial port via an RS-232 connector. Set points, alarms, ramps, soaks, and process times can be controlled at the computer for ease in operation. The acquired velocity is printed to a line printer and saved as a text file to disk to be used for further evaluation. Furthermore, the

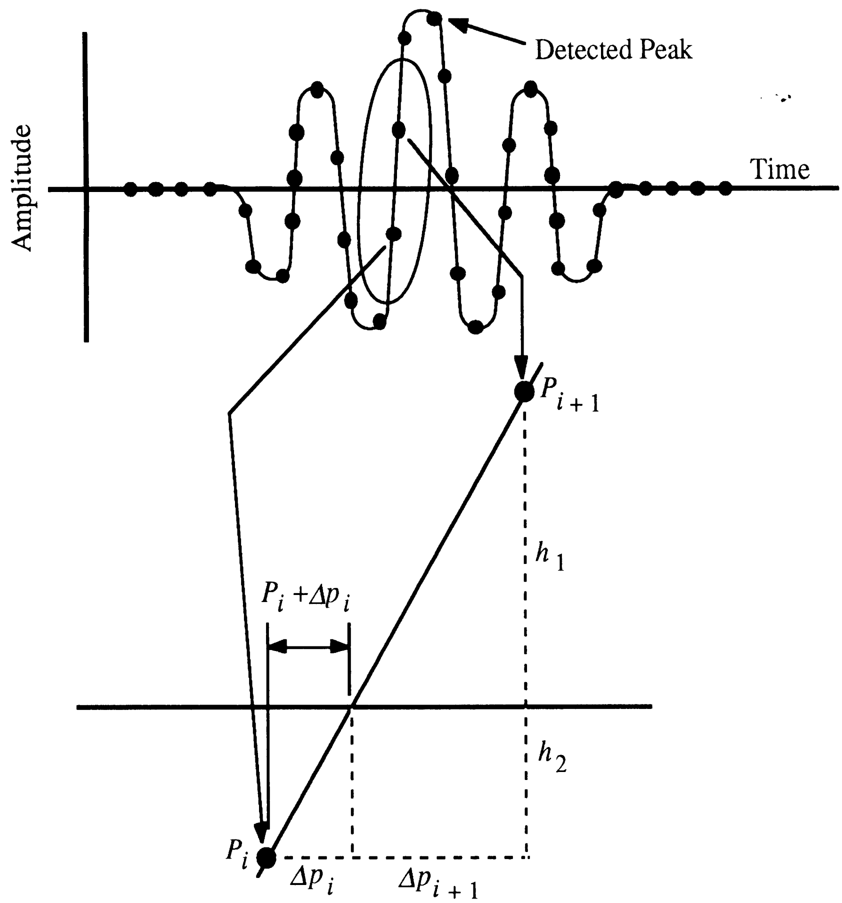

Fig.1. Schematic for zero-crossing determination.

computer system can also be used to monitor the changes of ultrasonic velocity as a function of stress. A -5 to +5 volt output from an Instron corresponding to zero and full-scale load, respectively, is read by a voltmeter and transferred to the computer via the IEEE-488 GPIB connector.

RESULTS AND DISCUSSION

Typical results of the longitudinal wave velocity propagated perpendicular to the extrusion direction as a function of temperature are shown in Figures 2 and 3 for Al-7064 and Al-8091, respectively. For both alloys at a given temperature, the absolute velocities increase with silicon carbide addition. Further, it can be seen that there is a linear relationship between velocity and temperature over the temperature range tested. However, it is more interesting to note how the slopes (dV/dT) change with silicon carbide addition. The averaged values for several measurements of dV/dT are reported in Figures 2 and 3 for the various amounts of silicon carbide addition. In the Al-7064 alloy, the smallest velocity dependency on temperature occurs in the unreinforced specimen. This dependence increases for 15% silicon carbide addition, but decreases in the 20% silicon carbide specimen. From Figure 3, the unreinforced Al-8091 alloy has the smallest velocity dependency on temperature, but dV/dT for both the 10 and 15% SiC specimens are about equal.

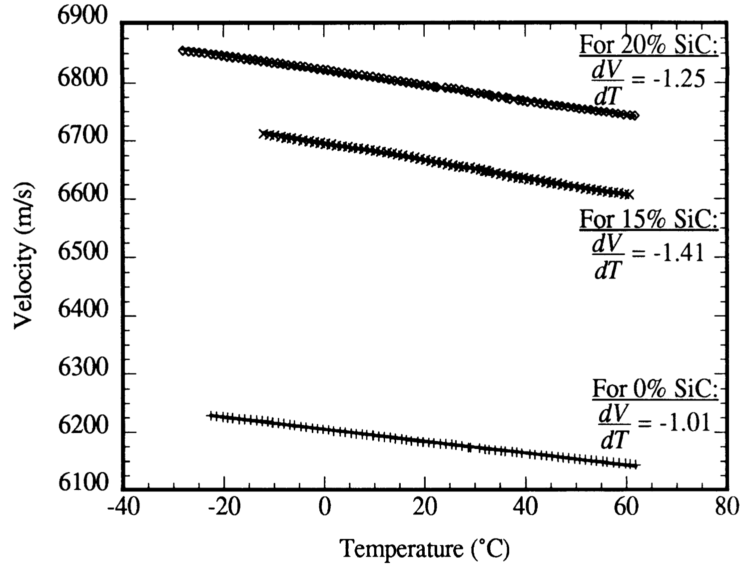

Fig.2. Longitudinal ultrasonic velocity as a function of temperature - Al-7064.

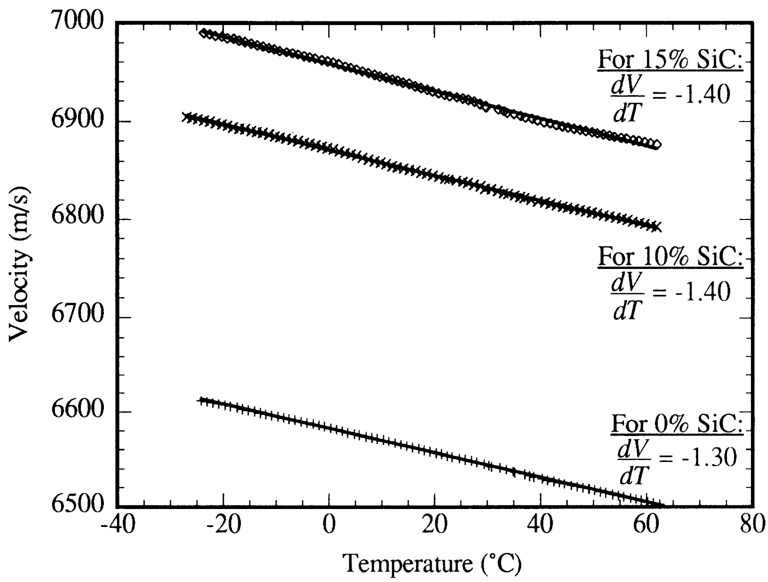

Fig.3. Longitudinal ultrasonic velocity as a function of temperature - Al-8091.

To better reflect the velocity dependency on temperature as a function of second-phase addition, Figures 4 and 5 plot the magnitude of dV/dT as a function of silicon carbide addition for Al-7064 and Al-8091, respectively. Also plotted are the results for the velocity dependency on temperature for monolithic silicon carbide ($dV/dT = 0.17$). It can be noted in Figure 4 that the velocity dependency perpendicular to the extrusion direction initially increases for second-phase addition to 15%. However, this dependence decreases upon further addition of silicon carbide. Ultimately, the temperature dependency decreases to a minimum value for pure silicon carbide. This trend is also displayed when velocities are evaluated in the extrusion direction, but the dependency is significantly decreased.

The same trend can also be seen when velocities are evaluated in Al-8091, shown in Figure 5. There is an initial increase in the magnitude of dV/dT, a peak value is obtained, followed by a decrease to its minimum value for 100% SiC.

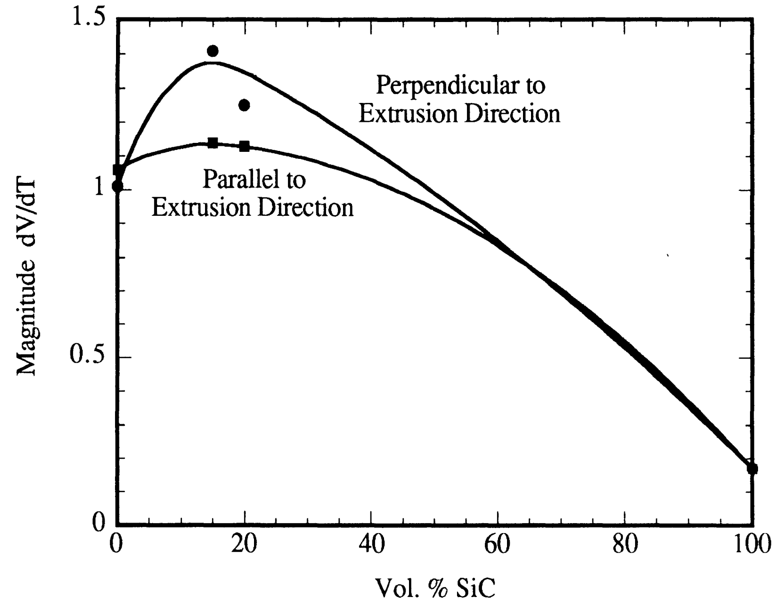

Fig.4. Velocity dependency on temperature as a function of volume percent of silicon carbide addition - Al-7064.

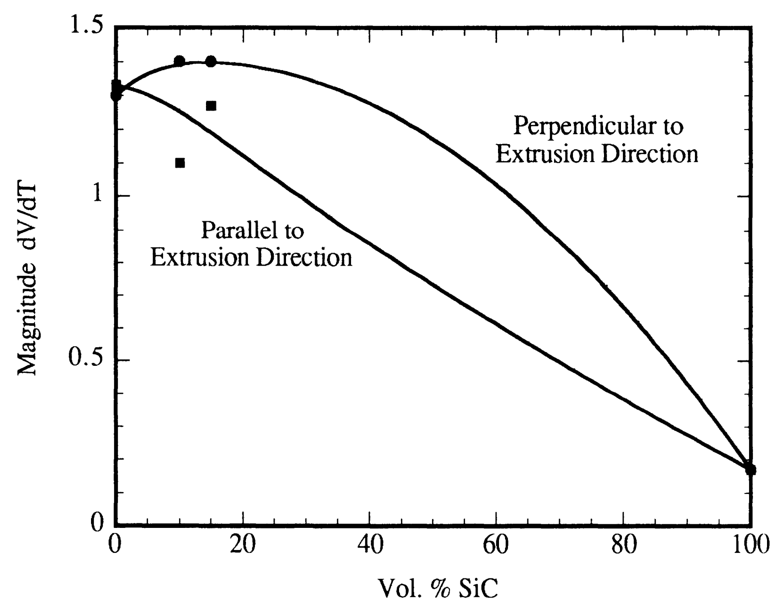

Fig.5. Velocity dependency on temperature as a function of volume percent of silicon carbide addition - Al-8091.

In the extrusion direction, the changes in *dV/dT* are not as prominent. From Figure 4, there is only approximately an 8% increase in the magnitude of *dV/dT* before decreasing to its minimum value. In Figure 5, there is no detected increase in *dV/dT*, only a decrease to the minimum value at 100% SiC.

From these results, it can be seen that small amounts of silicon carbide addition lead to an increase in the velocity dependency on temperature. Silicon carbide is a material with an extremely small velocity dependency on temperature. If the aluminum matrix material and silicon carbide reinforcement acted independently, *dV/dT* would decrease for an addition of the SiC second-phase material. In other words, an addition of silicon carbide would result in a proportional decrease in *dV/dT*. However, in this study, *dV/dT* has been measured to initially increase with silicon carbide addition. This change in the velocity dependency on temperature may be the result of two competing phenomenon in the matrix: anisotropy in the matrix due to the extrusion process and the presence of thermal residual stresses. Extrusion imposes directional anisotropy on the matrix material, while the spherical second-phase silicon carbide inclusions are not influenced by this process; the matrix is composed of elongated grains in the extrusion direction, but the silicon carbide inclusions remain spherical. Therefore, the composite is a combination of an isotropic reinforcing material embedded in an anisotropic matrix. This directional anisotropy is detected when evaluating wave velocities either parallel or perpendicular to the extrusion direction. Besides directional anisotropy, there is also the difference in the coefficients of thermal expansion for the matrix and the reinforcement. This mismatch is expected to impose interfacial residual stresses in the matrix, indicating that there is an interaction at the aluminum-silicon carbide interface. The residual stresses from the fabrication process have been shown to be tensile in the matrix [5]. Therefore, an increase in temperature relaxes these tensile loads by placing the matrix under compression. Since compressive loads decrease the longitudinal ultrasonic velocity in metals, the initial increase in the magnitude of *dV/dT* can be attributed to the relief of the tensile matrix stresses. However, at large second-phase volume fractions, the change in the stress state of the material can no longer be detected due to the large amounts of second-phase material with very small *dV/dT*. The change in *dV/dT* due to the change in stress when evaluated parallel to the extrusion direction cannot be detected due to the influence of texture. Preferential grain alignment due to the extrusion process masks any stress changes at the matrix-particle interface. Therefore, these results show a promise of evaluating interfacial stresses in metal matrix composites using measurements of the temperature dependency of longitudinal ultrasonic velocities.

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