A study of the effect of heat exposure on fiber reinforced aluminum matrix composites using non-destructive and destructive evaluation techniques

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Research Abstract

The effect of high temperature exposure on the interface and mechanical properties of an aluminum metal matrix composite (Al-MMC) was studied. After heat exposure the fiber-matrix interface was examined using optical microscopy to rule out any chemical interaction between the matrix and fiber. Non-destructive (ultrasound and laser Doppler vibrometry) and destructive techniques (tensile testing) were used to evaluate possible changes to the mechanical properties of the composite due to heat exposure. The non-destructive testing was compared to the destructive testing to determine any correlation between the results of the non-destructive testing and the maximum tensile strength of the composite. No reaction was observed between the fiber, ceramic, or matrix at the elevated temperatures. Non-destructive techniques showed specimens exposed to high heat showed no change to their mechanical properties relative to the specimens without exposure to heat. The tensile testing showed a slight decrease in tensile strength at longer heat exposure times. We have found no conclusive evidence that exposure to heat affects the mechanical properties of an Al-MMC.

Introduction

Various types of composite materials are used in a wide range of applications from bicycle parts, golf clubs, engine components, and electronics, to commercial airlines and space applications. In applications such as aerospace and engine design, the material is exposed to extremely high temperatures. In such cases, inexpensive polymer composites fail due to their low tolerance to heat exposure. Metal Matrix Composites (MMCs) however show a much greater resilience to extreme heat conditions. Unfortunately the matrix material can react with the fiber material under these conditions. The composite material can be coated in a ceramic to deter this reaction. The resulting matrix-ceramic-fiber composite material will exhibit improved performance at all temperatures.

In this work an Aluminum MMC was used. The Al-MMC was reinforced with unidirectional continuous graphite fibers coated in Al_2O_3. The overall makeup of the composite is 60% Aluminum matrix and 40% fiber by volume. Each sample consisted of an Aluminum matrix with a cross-section of 11.8 mm x 2.3 mm and a length of 152 mm. Twelve rows of 64 fibers (768 total fibers) aligned along the length occupied the matrix material to create the MMC. Each fiber consists of a 39.4 microns diameter graphite fiber coated with Al_2O_3 with a outside diameter of 132 microns. The purpose of this work was to expose Al-MMCs to varying degrees of heat and then analyze them both metallographically and mechanically.

Figure 1. Laser Doppler set-up

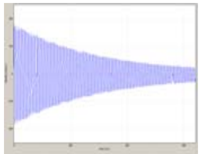


Figure 2. Laser Doppler output

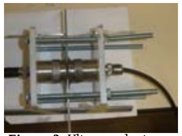


Figure 3. Ultrasound set-up with specimen

Figure 4. Ultrasound output

Figure 5. The Instron 5582

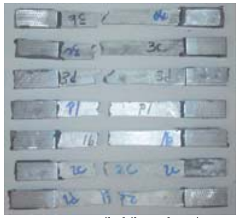


Figure 6. Tensile failure of specimens.

Methods

Heat Exposure:

Twenty samples were used total in this experiment. Samples were split into four groups used to determine duration of heat exposure. Samples were placed in an oven at constant temperature 500°C for 24 hours, 48 hours and 72 hours. After heat treatment samples were allowed to cool naturally to room temperature.

Metallographic Analysis:

One specimen from each group was used for the initial metallographic investigation. Two coupons were cut using a diamond saw from each specimen —one to expose the cross section [Fig. 7] and another to show an axial view [Fig. 8] of the fibers— then mounted and polished using various grits of paper and cloth until surface imperfections were eliminated. The resulting coupons were then examined using optical microscopy to determine the volume fraction and whether there was any chemical reaction at the interface.

Non-Destructive Evaluation Techniques:

A method used to determine the residual mechanical properties of damaged specimens is non-destructive evaluation (NDE). NDE techniques are used to predict the failure loads of damaged materials without performing traditional experiments that could destroy the structure or create more damage. Examples of NDE include acoustic emission monitoring, ultrasonic methods and laser-Doppler vibrometry. The output of these NDE experiments are used to characterize the damage of structures and predict the safe and reliable use of engineering structures.

Laser Doppler Vibrometry:

Specimens also underwent a vibration analysis utilizing Laser-Doppler techniques. The specimens were cantilevered in place in the path of a He-Ne laser and excited as shown in Figure 1. The velocity of the resultant motion was measured over time. From this, the natural frequency was determined using Fourier Transform calculations and the damping coefficient was found by measuring the amplitude of two peaks that are five periods apart then inserting them into the following equation:

$$\xi = \frac{1}{2\pi n}\left(\ln \frac{x_1}{x_{n+1}}\right)$$

Ultrasonic Analysis:

Ultrasonic testing was performed with a Tektronix TDS 5104 Digital Oscilloscope [Fig. 4]. A constant output signal with maximum amplitude of 5 V was used for all specimens. The two ultrasonic sensors were used and coupled to the specimen with an industrial ultrasound couplant. The sensors were attached to the specimens with the clamping system shown in Figure 3. The output of the signal sent through the specimens was measured in mV. Each specimen stood for 5 minutes to establish a steady state of the signal. Each specimen was tested three times and the average of these readings was used for all calculations.

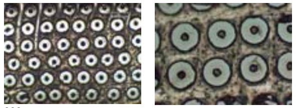
Tensile Stress Testing:

Tensile analysis was performed by stressing the specimens axially in the direction of the fibers using an Instron 5582 to determine any change in maximum stress the material could withstand. In order to ensure failure in the middle of the specimen, the samples were milled to a dog-bone shape. Aluminum tabs were placed on the ends of the samples to decrease the chance of failure at the points of attachment. The samples were then attached vertically into the Instron [Fig. 5] and loaded at a constant load rate of 0.026 mm/s until catastrophic failure occurred. The data was then analyzed and averaged to determine the maximum failure stress of each group.

Results

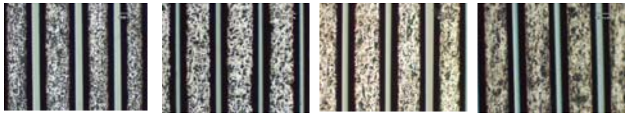
Optical Microscopy showed no interaction between the ceramic and the matrix.

Figure 7. Cross-sectional view of specimen showing fiber, ceramic coating, and aluminum matrix.



200µm 60µm

Figure 8. Axial view of ceramic-coated fibers with varying degrees of heat exposure (60µm).



No Heat Exposure 24 Hour Heat Exposure 36 Hour Heat Exposure 72 Hour Heat Exposure

Laser-Doppler: An example of the output of the laser Doppler testing is displayed in Figure 2 which shows the vibration of a sample after excitation. The damping coefficient was calculated from these outputs, averaged and displayed in Figure 9 for all samples, showing a slight decrease in damping coefficient as exposure time increases. Fourier Transform analysis was also performed based on these outputs to determine the natural frequency of the sample, the results of which are displayed in Figure 10.

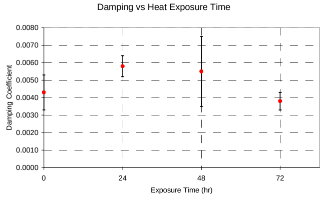


Figure 9. Damping Coefficients

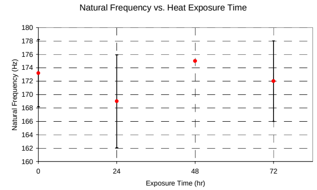


Figure 10. Natural Frequencies

Ultrasonic Analysis: A sample of the output of the ultrasonic testing is displayed in Figure 4. The peak amplitudes were measured, averaged and the results are displayed in Figure 11, showing a slight decrease in peak amplitude as exposure time increases.

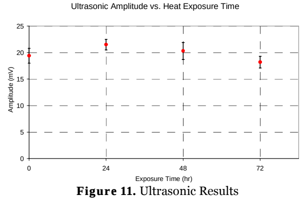


Figure 11. Ultrasonic Results

Tensile Testing: Samples after tensile failure are displayed in Figure 6, showing failure at the tapered section of the sample. From the tensile data the maximum stress at failure was calculated and displayed in Figure 12, showing a slight decrease in maximum stress as exposure time increases.

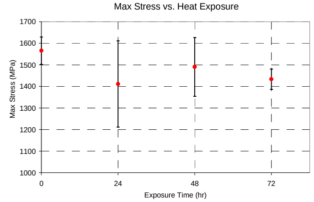


Figure 12. Maximum Stress

Conclusions & Further Research

Prior to testing, we had expected that longer heat exposure would result in greater composite stiffness and therefore lower composite strength. Results from both non-destructive evaluation techniques (ultrasound and laser Doppler) show no conclusive evidence of change to the mechanical properties of the MMC as a result of heat exposure. Results in Figure 10 show no correlation and low precision. This could be due to imprecise placement of the samples, inconsistent clamping force and unaccounted for effects of air damping. Figures 9, 11 and 12 do show some trends, mainly the values at 72 hours are all lower than all other values including those not exposed to heat. Although this is not conclusive, it does support further investigation with more precise measurement techniques, longer heat exposure times and SEM analysis to better determine any changes to the microstructure of the MMC. Further testing may show that as the damping coefficient and/or the ultrasonic transmission amplitude of a Al-MMC decreases due to heat exposure, the maximum failure stress of the MMC will also decrease by a predictable amount. This supports the view that NDE techniques have some validity as a means to predict failure stress in Al-MMCs.

Classroom Connection

Our research in an engineering lab this summer can be implemented in the class in multiple ways. In a unit on the EM Spectrum students will understand that some phenomena cannot be "seen" in the literal sense, but must be indirectly observed—similar to our attempts this summer to indirectly observe internal damage through non-destructive methods. Students will use indirect observation to "see" different regions of the EM Spectrum.

In another lesson, students will physically damage materials (MMCs, metals, wood, etc) in a fashion similar to the experiments the Young Scholars did in parallel with our research. The Young Scholars looked at impact damages while we looked at heat damage. In the classroom students will create a setup and damage their own samples. They will then be able to look at and measure the damage and determine the force of impact based on its depth and shape.

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