

A Nondestructive Inspection System for the Inspection of Wear Surfaces in Tank Track Shoes

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ABSTRACT

In this paper we present a unique nondestructive inspection (NDI) system for inspection of Al/SiC metal matrix composite (MMC) inserts in cast aluminum tank track shoes (TTS). The system is based on two different nondestructive inspection methods, ultrasonics (UT) and eddy current (EC), which are capable of detecting and identifying defects in MMC, such as porosity, debonding, and cracking. This paper also discusses results obtained during inspections of Al/SiC MMC samples with different levels of porosity, and debonds using UT and EC inspection. The prototype version of the system is designed to perform an acceptance inspection after TTS manufacturing and before deployment. Other potential applications of this system are in the evaluation of complex MMC parts in the automotive industry.

Introduction

Light metallic alloys reinforced with ceramic materials such as SiC (Silicon Carbide), Si₃N₄ (Silicon Nitride), or Al₂O₃ (Aluminum Oxide) particulates and whiskers provide unique properties that are ideal for modifying existing designs. The resulting MMC can improve the high temperature performance and wear resistance while reducing the overall weight of a given part [1]. The total benefit of this combination is that the service life of the part is increased and significant weight reduction is realized when multiple parts are involved in the fabrication of a much larger piece of equipment. These advantages have contributed to the widespread use of MMCs in the past few years to the point where these materials have become the preferred materials for engineering components that operate in extreme conditions [2, 3]. Examples of such components are automotive drive shafts, high-speed train brake rotors, and aero-engine components.

Another important application of MMC is their use as wear inserts in selected areas of larger components, which are subjected to high stresses. An example of

such an application is the Army ground vehicles Vehicle Track Shoe (TTS), in which aluminum-silicon carbide (Al/SiC) MMC inserts are applied to a 356-T cast aluminum substrate [4].

When the TTS is fabricated, the quality of the manufacturing must be such that no further inspection is necessary after it has passed an initial production acceptance test. Ideally, the part is then placed in service where it will remain until it reaches a recommended service life and is then replaced. For this to happen, the Al/SiC MMC must be free of defects that impact its structural integrity (which in this case is primarily due to porosity) and must also adhere tightly to the aluminum substrate. Failure of the bond between the Al/SiC layer and the aluminum substrate will result in a significantly reduced service life [5, 6]. Therefore, an inspection technique and an instrument capable of detecting and identifying all of the defects that can potentially reduce the service life of the TTS are required. The inspection environment would have to be one where parts are easily inspected with a minimum of human intervention and data interpretation is free of subjective decision making.

Based on the results obtained in a Small Business Innovative Research (SBIR) Phase I project, Physical Acoustics Corporation (PAC) concluded that the best strategy for NDI of Al/SiC MMC wear inserts in cast Al TTS is a combination of the UT and EC techniques. The EC technique could be used to detect and evaluate the presence of porosity and cracks, and the ultrasonic technique could be used to detect the presence of debonds between the Al/SiC wear inserts and the cast Al base metal.

The results obtained in the SBIR Phase I were incorporated into a work plan for design and construction of a NDI system for the inspection of Al/SiC MMC wear inserts. Such a system is based on the application of UT and EC techniques and the fusion of data to provide a

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diagnosis of the inspected part. This system is currently being designed and built under a Phase II SBIR project.

EXPERIMENTAL WORK

SELECTION OF CONTROLLED-DEFECT MMC SPECIMENS

Eight controlled-defect MMC specimens, displaying properties and defects of interest; porosity, reinforcement, and debonds, were obtained from a manufacturer of MMC. The properties of the controlled-defect specimens were carefully selected in order to represent, as close as possible, the range of damage and property variation one might see in an actual TTS MMC insert.

The eight controlled-defect specimens consisted of 5mm thick Al/SiC reinforced MMC layers bonded to a thick cast Al substrate. The specimens are 10cm by 10cm squares with different degrees of porosity, amount of reinforcement, and debond, as shown in Table 1. The specimens were subjected to EC and UT inspections as described in the following subsections.

Table 1. Control MMC Samples Characteristics

Specimen	Reinforcement amount	Property
1	60%	Increased reinforcement
2	45%	Increased reinforcement
3	28%	Maximum porosity
4	28%	Medium porosity
5	28%	Minimum porosity
6	28%	Defect free
7	28%	Debonds in interface, high porosity
8	28%	Debonds in interface, low porosity

EDDY CURRENT ANALYSIS OF CONTROL-DEFECT SPECIMENS

The control-defect specimens were subjected to point by point EC measurements using a 15.7mm diameter EC probe operating at 2 kHz. The probe was held at a lift-off distance of approximately 1mm from the specimen surface. At this frequency, the penetration depth of the eddy current is approximately 3.6mm. The EC inspection of the MMC samples was carried out at the NDE laboratory in the Engineering Research Center at the University of Cincinnati.

ULTRASONIC ANALYSIS OF CONTROLLED-DEFECT SPECIMENS

Ultrasonic testing of the controlled-defect specimens was produced at the PAC research laboratory, in order to correlate the observed reflection magnitudes to the different properties indicated in Table 1. For this inspection, a 10 MHz, 37mm focal length transducer was used, and was focused midway between the front and back wall echoes of the MMC layer. In this way, the sensitivity of the transducer to damage throughout the volume of the specimen was maximized. At the same time the MMC layer back-wall reflection amplitude was monitored in order to detect the presence of debonds. C-scan images of both sections of the MMC were produced.

RESULTS

EC CONDUCTIVITY MEASUREMENTS

Point measurements were performed of the eight controlled-defect MMC specimens, and the results indicate the EC sensitivity to property variations as reinforcement and porosity content. Figure 1 shows the average conductivity of the specimens taken over 9 measurements on each specimen. Table 2 summarizes the results of the point EC measurements, and shows average conductivity and standard deviation, both in % IACS.

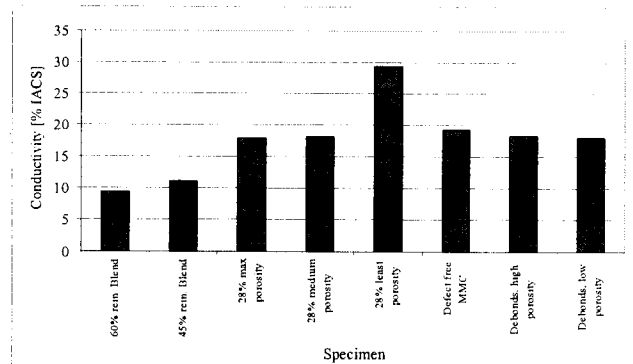


Figure 1. Conductivity measurements (point by point) on control defect specimens.

Effect of Porosity

The results shown in Figure 1 and Table 2 indicate that increasing the porosity decreases the average conductivity. The porosity changes from 29.45% IACS for the specimen with lowest porosity (specimen 5) to 17.92% IACS for the specimen with highest porosity (specimen 3). The medium porosity specimen (number 4) has a conductivity of 18.3% IACS.

Table 2. Conductivity variations in eight controlled-defect specimens received

Specimen	Characteristics	Conductivity [% IACS]	Std. Deviation [%IACS]
1	60% Reinforcement	9.42	0.57
2	45% Reinforcement	11.16	1.10
3	(28% reinforcement.) Max porosity	17.92	1.00
4	(28% reinforcement.) Medium porosity	18.28	0.54
5	(28% reinforc.) Least porosity	29.45	1.14
6	(28% reinforcements.) Defect free MMC	19.3	0.60
7	(28% reinforc.) Debonds, high porosity	18.42	0.67
8	(28% reinforcement.) Debonds, low porosity	18.12	1.04

Increasing the porosity effectively increases the number of 'air gaps' within the volume of the specimen, thereby reducing the overall conductivity. The specimens were engineered to show a certain amount of porosity, and from the measurements, assuming that the other parameters did not change between specimens, we see that specimens 3 and 4 have very close conductivity values. Whether this is because of variations in porosity or changes in reinforcement amount and distribution cannot be ascertained by this one measurement alone. Ultrasonic measurements in the same specimens are necessary to distinguish between the two properties. These measurements are discussed in the next section.

Specimen 6 (the supposedly defect free specimen) has a value of 19.3% IACS. This relatively low value could be caused either by excessive reinforcement or higher porosity. Finally, specimens 7 and 8, which contain debonds in the MMC-aluminum interface, and supposedly differing amounts of porosity show essentially the same conductivity. This can occur because of one of two reasons: either the porosity amount is similar in both specimens, or because of changes in reinforcement volume fraction. This aspect is discussed in the following subsection.

Effect of Reinforcement Volume Fraction

The data reveal that increasing the reinforcement blend decreases the average conductivity. This is observed from the drop in conductivity from greater than 17% IACS for the 28% reinforcement blend specimens, to 9.6% IACS for the 60% reinforcement blend specimen.

In other words, all specimens that have a 28% reinforcement blend show a conductivity that does not drop below 17% IACS, whereas increasing this reinforcement amount to 45% and then to 60% decreases the average conductivity to 11% IACS and 9% IACS respectively. This result is not surprising, as it is the SiC reinforcement that reduces the conductivity of the specimen. Previous experimental results indicate that the measured conductivity dropped according to the distribution density of the reinforcement, decreasing from the center of the specimen to the rim [7]. SiC inherently has a lower conductivity than aluminum and the conductivity of the specimen will depend on the amount of SiC that is contained in the MMC.

Effect of Debonds

Another observation extracted from the results of table 2 is that the presence of debonds between the MMC and aluminum substrate does not affect the measured conductivity. The defect free MMC has a conductivity of 19.3% IACS, and the two specimens that contain debonds have a conductivity of around 18% IACS. EC are inherently insensitive to the presence of debonds, and will not show conductivity variations when such debonds are present. The conductivity of specimens 7 and 8 is close to the measured conductivity of the specimens with mild porosity and no debonds. This can be confirmed by examining the results of UT C-scans.

Combined Effect of Variation in Porosity and Reinforcement Distribution

The results obtained for the specimen with the least porosity (specimen 5) shows a conductivity of 29.45% IACS, whereas the presumed defect-free specimen (specimen 6) shows a much lower conductivity of 19.3% IACS. This difference can be explained by (a) the basis of possible changes in the amount and distribution of the SiC reinforcement and (b) possible variations in the amount of porosity, in spite of carefully controlled fabrication. As has been explained in earlier sections, measured conductivity is sensitive to changes in reinforcement as well as porosity. The $\approx 29\%$ IACS conductivity is very high for the MMC, and is closer to the conductivity of plain aluminum ($\approx 34\%$ IACS), than to that of MMC. In a case where relatively large reinforcement variations and mild porosity are acting simultaneously, the effect of the reinforcement change will be more pronounced than that of the mild porosity. This is not necessarily a negative result, as the sensitivity of the system to changes in reinforcement distribution and content make it an effective tool for quality control. Whether the change in conductivity is caused by porosity or reinforcement can be determined on a case-to-case basis by referring to the results obtained with UT. If UT C-scan images do not show the presence of porosity, then it can be concluded that the drop in conductivity is caused because of changes in reinforcement distribution and content.

RESULTS FROM UT MEASUREMENTS

Ultrasonic C-scan images of the volume of specimens as well as the MMC-Al interface were produced, in order to determine the presence of porosity and debonds, respectively.

Specimens with Different Porosity Levels and no Intended Debonds

Figure 2 shows C-Scan images of specimen number 5 with minimum porosity, specimen number 4 with medium porosity, and sample 3 with high porosity. The images shown represent data taken from the region between the front and back walls of the samples, and so represent the distribution of porosity in the specimen. As can be seen in Figure 2(a) (specimen # 5) there are no prominent defects seen (shades of color other than blue, especially green and red) in the specimen with low porosity. This indicates that there were no features in the interior of the specimen that gave reflections between the front and back wall, which is expected from low porosity in the volume of the specimen.

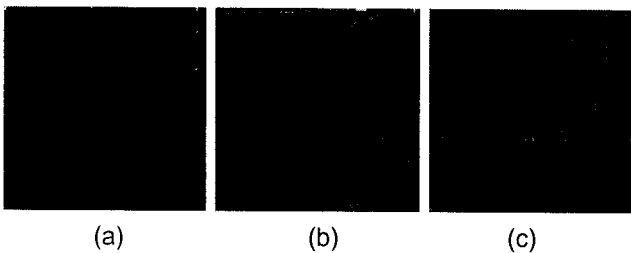


Figure 2. Ultrasonic C-scan images of controlled-defect specimens bulk reflections: (a) Specimen 5 (low porosity), (b) Specimen 4 (medium porosity), (c) Specimen 3 (high porosity).

As can be seen from Figure 2(b) (specimen #4), there is a rather uniform distribution of damage throughout the specimen with medium porosity. It is important to note that the damage here is representative of the entire volume of the insert, and the different damage spots correspond to varying depths. There is a clear distinction from Figure 2(a) (specimen # 5), which produced a very clean image.

Figure 2(c) (specimen #3) shows an ultrasonic C-scan image of the specimen with the maximum amount of porosity. Again, there is a relatively large amount of damage visible in this picture. As mentioned before, it is important to keep in mind that this damage is representative of the entire volume of the specimen.

The critical point to note here is the similar amounts of porosity visible in both specimens 3 and 4, although they had been thought to contain different amounts of

porosity. This result corroborates the eddy current measurements discussed earlier. Visual inspection of the ultrasonic image provides no indication of any such distinction. From the EC measurements, we observed that specimens 3 and 4 had conductivity values of 17.92% IACS and 18.28% IACS, and the difference is less than the standard deviation of the measurement as indicated in Table 2. This very similar value of the measured conductivity is reflected in the similar amount of porosity seen in the ultrasonic images. A quantitative analysis of the images is needed to establish a precise correlation between EC and UT.

Figure 3 shows the images obtained by mapping the amplitude of the back wall echo from specimens 5, 4 and 3.

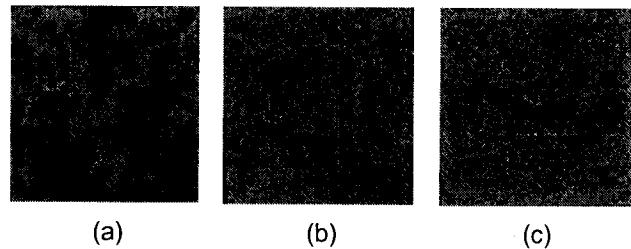


Figure 3. Ultrasonic C-scan images of controlled-defect specimens back-wall reflection: (a) Specimen 5 (low porosity), (b) Specimen 4 (medium porosity), (c) Specimen 3 (high porosity).

The red areas are the regions where the system detects a large reflection from the interface between the MMC and the aluminum substrate, indicating that there exists a region of high acoustic impedance mismatch, or in other words, debonds. Under good bonding conditions, the MMC-Al interface produces a relatively small reflection since the acoustic impedances of MMC and Al have very similar values. On the other hand, the presence of air in this interface results in a larger reflection. As can be seen, all three specimens have some debonds in the interface region, and specimen 5 in particular displays a large number of debonds. Again, specimen 5 showed the largest conductivity measurement (29% IACS), indicating the insensitivity of eddy current measurements to debonds.

Specimens with Debonds and Different Porosity Levels

Figure 4 shows the ultrasonic C-scan images taken of specimens 7 and 8, the specimens with debonds, but containing different amounts of porosity. These images are from the interior of the specimen, and thus represent porosity damage. As can be seen from the images, the two specimens contain essentially the same amount of porosity, and there is little distinction between the 'high porosity' and 'low porosity' specimens. The main difference is that the high porosity specimen has larger spots of porous regions, distributed over a smaller area, whereas the low porosity specimen has smaller spots of

porosity, but distributed over the right hand side volume of the specimen. This almost identical amount of porosity indicated by the ultrasonic measurements explains why the EC measurements gave almost identical conductivity values for the two specimens, further corroborating those results. As in the case of specimens 3 and 4, a quantitative analysis of the UT C-scan images is necessary to establish a precise correlation with the EC measurements.

Figure 5 shows the ultrasonic C-scan images taken of the back wall echo of the MMC, showing the presence of

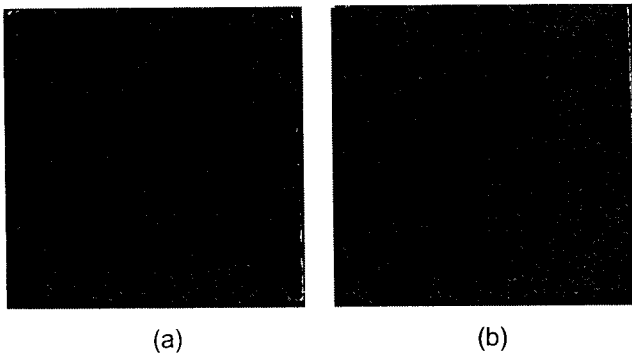


Figure 4. C-scan images of specimens with debonds, bulk reflections: (a) Specimen 7 with high porosity, (b) Specimen 8 with low porosity.

numerous debonds. There is clearly much more damage in this interface region compared to specimens 3, 4 and 5. Again, The presence of debonds does not affect the eddy current measurement, as eddy currents are inherently insensitive to their presence.

Specimens with Different Reinforcement Volume

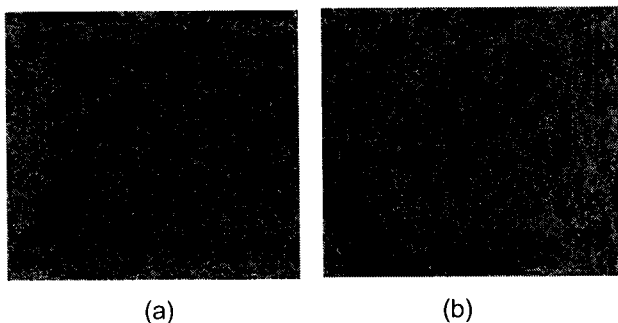


Figure 5. C-scan images of specimens with debonds, back wall reflection: (a) Specimen 7 with high porosity, (b) Specimen 8 with low porosity.

Fraction

Specimens 1 and 2 were engineered to contain a higher percentage of reinforcement in the MMC insert. Figure 6 shows the ultrasonic images taken of the interior of the specimens. As can be seen from these images, specimen 2 has a high degree of porosity in the interior, whereas specimen 1 is relatively porosity free.

The eddy current measurements had indicated low conductivity values for both of the specimens in Figure

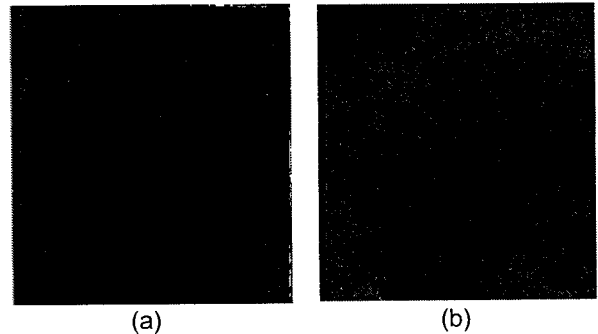


Figure 6. Ultrasonic C-scan of interior of specimens with different reinforcement volume fraction: (a) Specimen 1, with 60% reinforcement, (b) Specimen 2, with 45% reinforcement.

6, and there was some doubt as to the actual origin of this drop in conductivity. This can now be resolved by analyzing the results of the ultrasonic scans. The higher degree of porosity in specimen 2, coupled with a higher degree of reinforcement most likely gave the low value of conductivity in the eddy current measurement. Specimen 1, on the other hand, contains very little porosity, and the low conductivity value obtained arises solely due to the increased reinforcement content. Thus, the tandem inspection technique utilizing both EC and UT makes a comprehensive analysis of the specimen possible. A low value of conductivity measured with EC need not necessarily indicate porosity induced damage, but could mean a different reinforcement concentration and distribution. This can be verified by performing an ultrasonic C-scan, and correlating the damage found with the two techniques.

Defect-Free Specimen

The supposedly defect-free specimen had an average conductivity of 19.3% IACS. This would mean that this specimen has either greater amounts of reinforcement or porosity (or both), that is pushing the effective conductivity down. The ultrasonic image helps in making a conclusion about the actual source of the lower conductivity. Figure 7 shows the ultrasonic image of this "defect-free" specimen.

As can be seen, there is only a hint of porosity, and it is reasonable to make the conclusion that this specimen, while "damage" free, is still different from an ideal MMC reinforcement. This difference is most likely caused by

an increased reinforcement content that will not be detected in the ultrasonic C-scan image.

PROTOTYPE INSPECTION SYSTEM

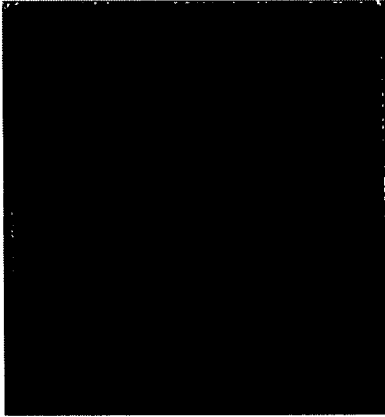


Figure 7 Defect-free Specimen 6.

As part of the Phase II of the SBIR project, PAC will design and build a prototype system for the inspection of the MMC inserts in the TTS. The main components of this prototype system are a waveform generation board (ARB 14101), an analog to digital converter board (IPR 1210), and an EC board that is currently under development at PAC. The two existing PAC boards (ARB 14101 and IPR 1210) are of the PCI type. The ultrasonic sensors and EC probes are commercially available and will be acquired from well-known manufacturers. The only components that need to be developed are the EC board, which will be of the PCI type (PCI-EC), and the mechanical subsystem that will hold the ultrasonic and EC probes in position over the TTS and will move these probes into position during the inspection process.

The most important requirements that the mechanical subsystem has to satisfy are:

- The scanning speed must be a minimum of 2" per sec.
- During the EC/UT inspections measurement must be taken at an interval of 0.0625" (1/16") as a minimum.
- The step distance (distance between neighboring scan lines) must also be

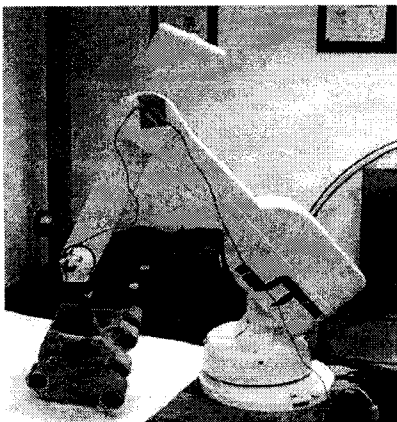


Figure 8. Robotic arm undergoing test at PAC.

0.0625" as a minimum.

- The total scan area (4 contour panes and 2 flat panes) of the TTS will be 46 square maximum, and will contain a minimum of 12500 measurement points.

The most likely approach to satisfy the mechanical requirements of the inspection system is a robotic arm with 5 degrees of freedom and probe changing capabilities.

An inspection system based on a robotic arm will offer great flexibility in terms of application of the UT/EC inspection technique to pieces of different geometries, therefore it would have great potential for its application in the automotive industry. Currently, a series of tests are being performed at PAC using the robotic arm shown in Figure 8.

CONCLUSION

Conductivity measurements using EC are sensitive to two primary property variations in MMC inserts: porosity in the specimen and reinforcement content. Both of these tend to reduce the measured conductivity value. It is difficult to separate these effects by the EC measurement alone. Ultrasonic analysis is needed to better understand the condition of the MMC insert, and draw a comprehensive conclusion about the degree of damage by correlating the results from these two independent measurements.

The information obtained from the ultrasonic C-scans images of the controlled-damaged specimens indicated that porosity and debonds can be easily detected. Ultrasonic images are not sensitive to factors such as amount and distribution of reinforcement, which makes the EC-UT technique an effective way to discriminate between different material conditions. Further work is required to image the specimens using EC, to determine a precise correlation between UT and EC data.

PAC is currently investigating the possibility of using a robotic arm as a mechanical subsystem to perform the EC-UT inspection of TTS. An EC-UT prototype system based on a robotic arm will have the potential to be applied in inspection of complicated geometries as commonly found in the automotive industry.

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