

Cold Work Quality Assessment and Fatigue Characterization Using Conformable MWM[®] Eddy-Current Sensors

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ABSTRACT

This paper presents four specific examples of single and multiple frequency MWM[®] (Meandering Winding Magnetometer) measurements for quality control of cold rolling (roller burnishing) and shot peening, as well as for crack detection. Cold rolling of the 54H60 propeller blade fillet results in anisotropic electrical conductivity in the fillet. A measure of this anisotropy such as the MWM-measured conductivity ratio has been correlated to acceptable cold work intensity in coupons with known residual stresses. A procedure with specified MWM conductivity ratio limits has been implemented on the 54H60 overhaul production line at WR-ALC for quality control of cold rolling integrity of propeller blades from original manufacture and from rework. Shot peened areas on the airfoil and taper bore on the 54H60 propeller blade frequently require corrosion removal which affects the shot peened layer. A multi-frequency MWM technique is being evaluated for use on the 54H60 overhaul production line to assess shot peening integrity after corrosion damage has been removed. A similar shot peening problem on the C-5 landing gear trunnions is also being investigated through the use of MWM sensors. Finally, cracks on the C-5 tie box fitting beams have resulted in 100% replacement of the fittings in the C-5A fleet. Crack detection using MWM sensors has been proven to be effective in identifying subsurface cracks long before they can be detected using traditional high frequency eddy current techniques. This capability is being considered for the C-5B fleet to enable inspectors to identify cracks early enough so that fittings can be replaced during scheduled maintenance. The conformable eddy current sensors called Meandering Winding Magnetometers (MWM sensors and MWM-Arrays) have been designed to match the response of computer models over a wide range of material under test properties and, when used with the measurement grids, allow measurements of absolute material properties. These sensors can be used in a scan mode to map corrosion or fatigue damage or can be permanently mounted in difficult-to-access locations with cables brought out to easy-access locations. This enables remote monitoring of crack initiation and growth to inspect such areas without disassembly and without sealant removal.

INTRODUCTION

This paper briefly describes four recent USAF applications of the Meandering Wandering Magnetometer (MWM™) sensors:

(1) inspection of cold rolling integrity on C-130 propeller blades; (2 and 3) assessment of residual shot peening integrity following damage removal on C-130 propeller blades and C-5 main landing gear trunnions; and (4) detection of subsurface cracks in C-5 Tie Box Beam Fittings. These applications are in various stages of development ranging from the C-130 cold rolling integrity inspection, which is fully implemented with trained technicians using the equipment on a daily basis, to the assessment of the C-5 main landing gear trunnion for which MWM has been proven to be an effective candidate inspection method but has not been implemented.

MWM sensors and MWM-Arrays with grid measurement methods have matured and have proven to be effective tools for a wide range of applications. The key advantage of the technology is the unique sensor geometry which matches the model and enables absolute material property measurements in real time using JENTEK grid methods. The conformable sensor geometry, with flat rectangular windings, provides a number of advantages including the following:

- Accurate modeling of sensor response.
- Ability to determine absolute properties such as electrical conductivity, magnetic permeability, and coating (or processed zone) thickness.
- Ability to perform bidirectional measurements to assess anisotropy.
- Accurate and independent determination of lift-off, i.e. proximity to a conductive surface, thickness of an insulating layer, or surface roughness.
- Ability to conform to curved surfaces including areas of slight double curvature.
- Additional control over the depth of penetration through the spatial winding wavelength.
- Ability to scan with and without direct contact with a component.
- Ability to be permanently mounted in difficult-to-access locations for fatigue monitoring.

C-130 Propeller Blade Cold Rolling Inspection

The 54H60 model propeller blades, used on all variants of the C-130 aircraft, experience high centripetal and aerodynamic loads in service. Several surface conditioning/treatment processes are used during manufacturing to extend the service life of the blade. The base of the blade is cold rolled which imposes deep compressive residual stresses near the surface making properly cold rolled blades unlikely to initiate cracks. In a series of catastrophic failures, a problem was identified in the cold rolling process used during manufacturing that resulted in a number of improperly cold rolled blades. These catastrophic events have resulted in the loss of one aircraft and near loss of several others.

Analysis and testing indicates that the fatigue life of a properly cold-rolled propeller blade is practically infinite, whereas a blade that has not been properly cold rolled would have a fatigue life of between 400 and 3,000 flight hours, depending on the load spectrum representing the mission design series of the aircraft. After two recalls of 840 propeller blades for suspected cold rolling deficiencies, the OEM has initiated a third recall under ASB 134 for 13,000 blades. The inspection strategy was to accomplish the inspection at a rate of 1% of the fleet per month. This rate of inspection was adopted because most of the propeller blades have already been operated beyond the fatigue life of an unrolled blade and are considered “service proofed”. At least half of the blades in this recall belong to the USAF.

Previously, the only approved means for inspecting blades for proper cold rolling was a technique called blind hole drilling (BHD). BHD, a method for determination of residual stresses, is governed by ASTM E 837. It has become an industry standard for assessment of cold work quality when cold work processes are used to induce beneficial compressive residual stresses. Because the ASTM standard is limited to use on flat plates, the original equipment manufacturer developed a specification for application of BHD procedures for the propeller blade. Both the ASTM standard and the OEM specification require the following: application of a strain gage rosette at the base of the blade, precision milling of a hole in the center of the rosette at 0.001 inch intervals, and recording the strain relief from the rosette. The primary difference between the ASTM standard and the OEM standard is the interpretation of the strain data. This is a very expensive (\$360/blade), time-consuming (4 to 6 hours), and partially destructive process. Additionally, this inspection must be accomplished in a laboratory type environment and is highly disruptive to the propeller overhaul process. This process was described in more detail at the 1999 DoD/FAA/NASA Aging Aircraft Conference (Yentzer, 1999).

In the use of MWM as a tool to assess the cold work quality in the blade fillet, the material anisotropy is characterized by bidirectional MWM electrical conductivity measurements. Conductivity in unrolled Al 7076 is an isotropic property; it is, thus, independent of the direction in which conductivity is measured, i.e., the conductivity is the same in all directions. In the process of cold rolling, the near-surface layer is deformed plastically and initially equiaxed grains are stretched in the direction of the rolling. Once this occurs, the conductivity is higher in the rolling direction than across the rolling direction. This phenomenon was demonstrated by measuring the conductivity ratios of 20 propeller blades before and after cold rolling. The conductivity ratio is simply the conductivity in the radial direction (along the axis of the blade) divided by the conductivity in the circumferential direction:

$$\text{Conductivity Ratio} = \sigma_{\text{radial}} / \sigma_{\text{circumferential}}$$

where

σ_{radial} = absolute conductivity in the radial direction

$\sigma_{\text{circumferential}}$ = absolute conductivity in the circumferential direction

The effects of cold rolling on the conductivity ratio are illustrated in Figure 1, where the results are presented as blade fillet conductivity ratio vs. shank conductivity ratio.

Thresholds on the conductivity ratio for acceptable cold rolling in the fillet and shank were determined by the C-130 engineering staff using 30 coupons with known residual stress (from either BHD or x-ray diffraction) by determining the conductivity ratio of blades with acceptable and unacceptable cold rolling. These thresholds were used during a 12-month engineering evaluation period in which one of over 800 propeller blades inspected was removed from the overhaul production line for unacceptable cold rolling, as determined by using MWM. Subsequent measurements with BHD revealed that the propeller blade had borderline residual stress. Figure 2 depicts conductivity ratios from a sample of blades including two mishap blades and one coupon that was never cold rolled.

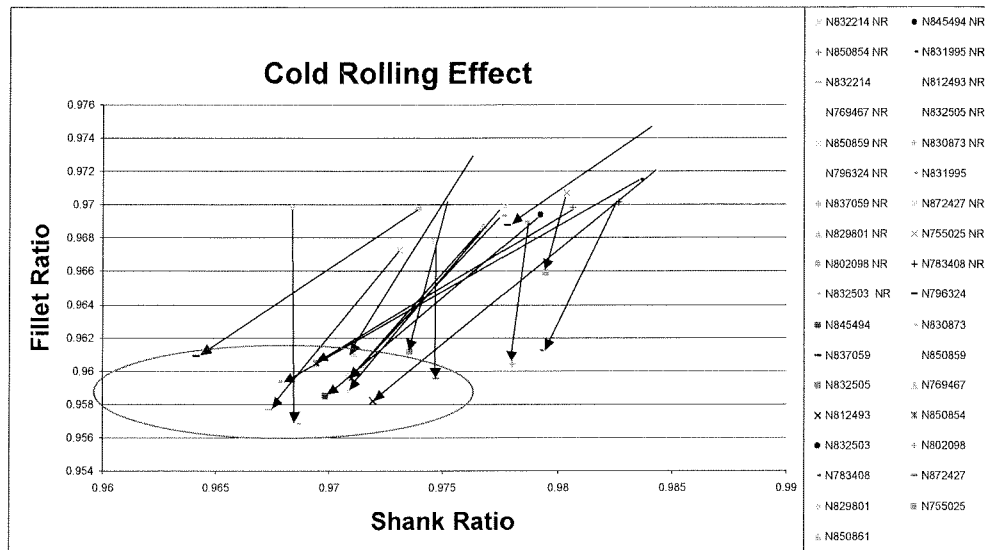


Figure 1. Change in Conductivity Ratio During Cold Rolling Operations.

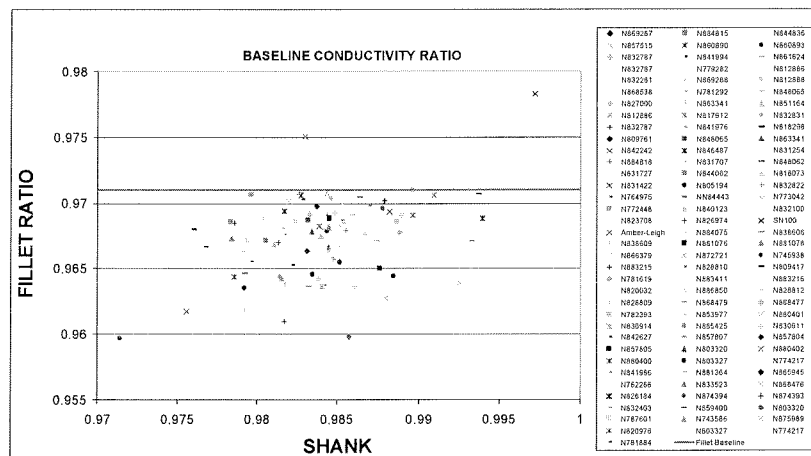
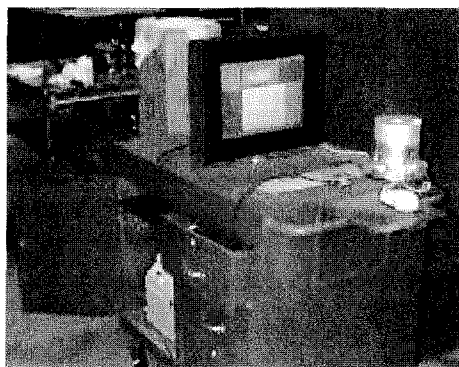


Figure 2. Quality Control Chart for Cold Rolling Integrity.

MWM inspection has been transitioned to the 54H60 propeller overhaul production line at Warner Robins Air Logistics Center (WR-ALC) for 100% inspection of all propeller blades. The inspection was published in T.O. 3H1-18-3 which includes set up, inspection procedures, and acceptable limits in terms of conductivity ratios. WR-ALC has procured a production hardened GridStation system and two laptop based GridStation systems (Figure 3). The latter are used both as back ups for the production unit and to support deployed operations.



(a)



(b)

Figure 3. (a) Production and (b) Laptop MWM GridStation Units.

C-130 Propeller Blade Shot Peening Inspection

In addition to the cold working in the fillet area previously discussed, the inside of the propeller blade (referred to as the taper bore) and the lower section of the airfoil are shot peened to enhance the fatigue performance of the propeller blades. These areas are depicted in Figure 4. During overhaul, thorough inspections are made of all the surfaces on the C-130 propeller blade to identify damage. Corrosion, often found in the taper bore and on the leading edge of the airfoil, must be removed either by localized grind out (both locations) or reaming (taper bore location only). Maintaining the residual stresses originally imparted by the shot peening is critical, however, process controls for localized rework of these areas is difficult. As with most shot peening operations, Almen strips are used by the operator to establish the proper shot peening parameters for the size of shot being used. Localized shot peening of the airfoil is difficult because the proximity to the edge of the airfoil makes it difficult to duplicate the incident angle and coverage used on the Almen strip. Similarly, localized shot peening of the taper bore is also difficult because it is a fairly narrow internal area and it is difficult to duplicate the incident angle and coverage used on the Almen strip. These areas are shot peened in original production using automated booths using process controls that are not cost effective for overhaul applications.

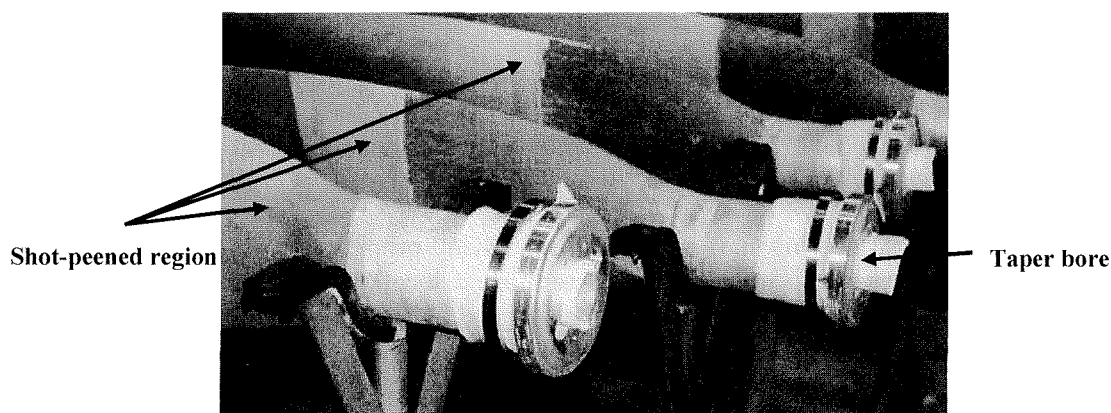


Figure 4. Shot-Peened Areas on C-130 Propeller Blades.

Electrical conductivity changes due to shot peening are caused by the severe plastic deformation resulting in a distinct drop in conductivity. Shot peening only affects the near surface

layer of the material. The underlying material not affected by shot peening retains the initial higher conductivity. A module was designed and developed by JENTEK Sensors, Inc. to take conductivity measurements at 19 different frequencies ranging from 63 kHz to 3 MHz. Each of the measurements at these frequencies represents effective conductivity of the various layers from the surface to a specific depth into the material. Components with little or no shot peening will have little or no change in conductivity at any frequency whereas components with high levels of shot peening will have a significant decrease in conductivity at higher frequencies. This module was tested on an airfoil with regions of known shot peening intensity ranging from unpeened to 0.015A – 0.017A as shown in the Table 1. Figure 5 shows the results of multi-frequency MWM measurements in these regions.

Region	Peening Intensity
1	Unpeened
2	0.005A - 0.008A
3	0.008A - 0.010A
4	0.010A - 0.012A
5	0.012A - 0.015A
6	0.015A - 0.017A

Table 1. Shot Peening Intensity.

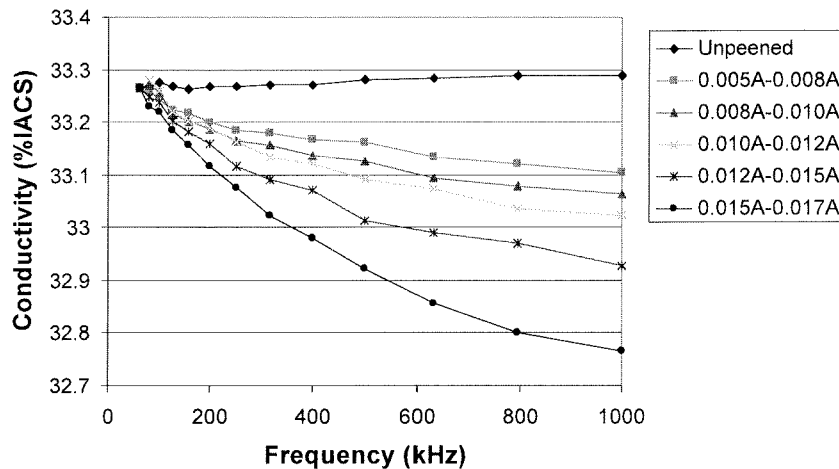


Figure 5. MWM Measurements on Shot Peened Propeller Coupon.

The WR-ALC engineering staff supporting the 54H60 propeller overhaul production line is now using MWM sensors with GridStation to determine if localized shot peening is required for those instances where the corrosion removal is shallow and as an additional process control when localized shot peening is required. The equipment used is shown in Figure 3b, configured with a software module to support shot peening assessment.

C-5 Tie Box Beam Fitting Inspection

The C-5 Tie Box Beam Fitting has been identified as a target application in JENTEK's Small Business and Innovative Research (SBIR) Phase II project sponsored by WR-ALC/TIE to

assess advanced nondestructive inspection techniques. This fitting is on the horizontal stabilizer and ties the left and right horizontal stabilizer aft spars together as well as providing the support structure for attaching the aft of the horizontal stabilizer to the vertical stabilizer (Figure 6). Although the design stresses throughout this fitting are quite low, cracks have been identified across the upper flange and in the spar cap attachment arms, which have required extensive repairs. The damage was sufficiently severe on the C-5A fleet that the fittings are being 100% replaced during programmed depot maintenance (PDM). The same fittings on the C-5B have not been replaced because cracks have not been detected on these aircraft. Several explanations for this phenomenon have been suggested but no conclusions have been made as to why the C-5A fittings crack and the C-5B fittings do not. One of the most likely explanations is that the C-5B fittings are 17 years newer and the fasteners appear to have been installed with more sealant, reducing their susceptibility to stress corrosion cracking.

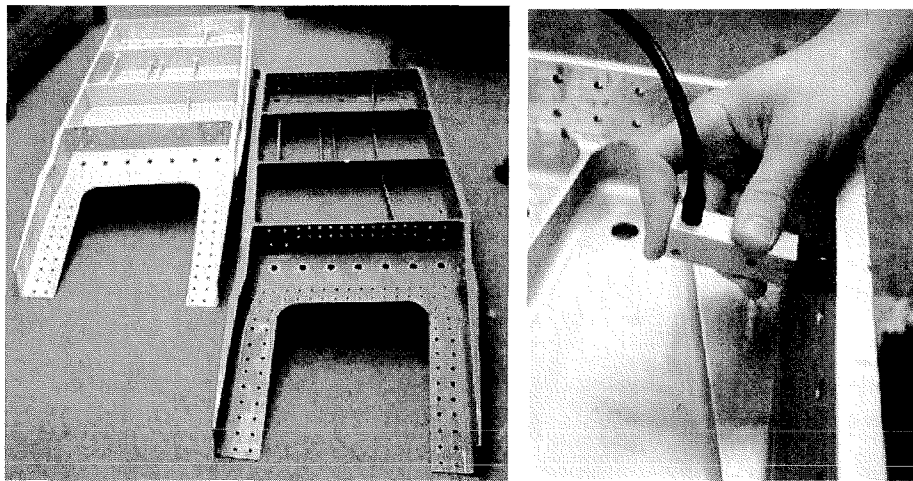


Figure 6. Left: C-5 Tie Box Fittings, and Right: MWM Scanning Bolt Hole Locations.

This Section provides results of MWM eddy current examinations that demonstrate the capability to detect subsurface cracks at C-5 tie box beam fitting bolt holes. The findings were later confirmed by examinations, from the ID surface of the bolt hole, with high-frequency eddy-current and visual inspections. This Section also describes possible use of a new surface mountable MWM eddy current inspection without requiring disassembly for difficult-to-access locations.

Measurements on C-5A and C-5B Fittings. Four fittings were identified for this project, all of which were original structure on aircraft. These fittings were removed from aircraft for various reasons. The identification and condition (based on prior inspections) of these four fittings was as follows:

- Fitting 1. S/N 69-0007 (extensive cracks).
- Fitting 2. S/N 69-0025 (moderate cracks).
- Fitting 3. S/N 70-0456 (no cracks detected).
- Fitting 4. S/N 84-0059 (C-5B, no cracks detected).

Fittings 1 and 4 were shipped to JENTEK Sensors in Watertown, MA for evaluation using multi-frequency scans with the MWM eddy current sensor. Fittings 2 and 3 were inspected at WR-ALC/TI using dual frequency MWM scans.

Fittings 1 and 4. MWM measurements were performed in the upper flange of the structural “box” and the horizontal flanges of the upper and lower spar cap attachment arms, at defined 0.25 inch increments between adjacent fastener locations and in the fillets. At each location, measurements with the JENTEK MWM eddy current sensor were performed at the following 19 frequencies: 25 kHz, 31 kHz, 40 kHz, 50 kHz, 79 kHz, 100 kHz, 126 kHz, 158 kHz, 200 kHz, 251 kHz, 316 kHz, 398 kHz, 501 kHz, 631 kHz, 794 kHz, 1 MHz, 1.26 MHz, 1.58 MHz, and 2 MHz. The findings from these measurements were as follows:

Fitting 1. In addition to finding crack indications in all of the previously identified locations, there was an additional indication of an anomaly between two of the fasteners. This anomaly was detected by a local drop in conductivity at frequencies below 794 kHz (see Figure 7). Conductivity measured at higher frequencies remained uniform along the scans. Visual inspections of the areas including the ID surface of each bolt hole failed to reveal the source of the anomaly in conductivity. While the fitting was at JENTEK, no clean up or any additional NDI was accomplished in this area.

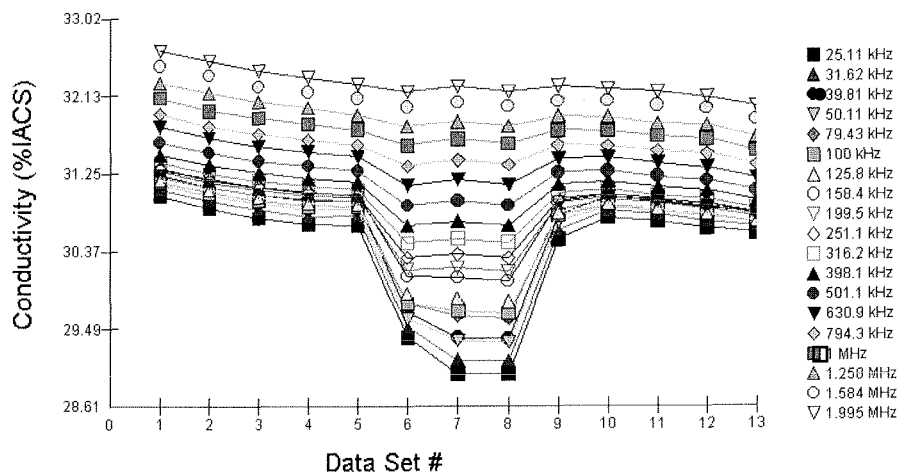


Figure 7. MWM Eddy Current Sensor Multi-Frequency Scan of Subsurface Anomaly in Fitting 1.

Fitting 4. No crack indications had been reported for this fitting based on previous inspections, and no anomalies were identified in any of the MWM measurements.

Fittings 2 and 3. Dual frequency (100 kHz and 1MHz) MWM eddy current scans were made in the upper flange of the structural “box” and in the horizontal flanges of the upper and lower spar cap attachment arms. Because the initial anomaly on Fitting 1 was detected at low frequencies, the number of frequencies was reduced to two, 100 kHz and 1 MHz. Fittings 2 and 3 were inspected in a continuous scanning mode as opposed to taking data in incremental scanning mode at distinct 0.25 inch increments.

Fitting 2. In addition to finding crack indications in all of the previously identified locations, there were additional indications of anomalies between pairs of adjacent fasteners at three different locations. These anomalies were detected by a drop in conductivity at 100 kHz (Figure 8).

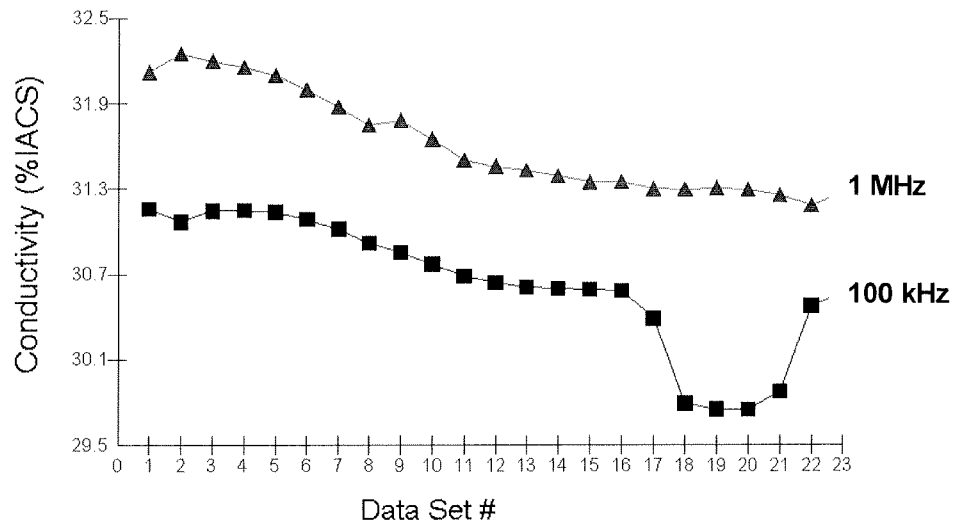


Figure 8. Dual Frequency MWM Eddy Current Scan of Fitting 2, Showing a Subsurface Anomaly.

Initial visual inspections of the areas including the inside diameter surface of each bolt hole failed to reveal the source of the anomalies. However, after the bolt holes were cleaned up using a mild abrasive and visually inspected, distinct subsurface cracks were visually identified inside the bolt holes (these “tunneling” cracks did not reach the exposed surface outside the bolt hole). These indications were later verified using traditional high frequency eddy current inspection inside the bolt hole with a bolt hole probe. The cracks appeared to be small radial cracks oriented along the bolt hole axis. The depth of the crack (as measured radially from inside the bolt hole) has not been determined but it appeared to be quite small.

Fitting 3. No crack indications had been reported for this fitting and no anomalies were identified in any of the MWM measurements.

Conclusions from MWM Inspections on C-5 Tie Box Fittings

1. MWM was able to detect all crack indications detected with conventional NDI techniques.
2. At a total of four locations on two different fittings, MWM was also able to detect anomalies that were previously undetected using conventional NDI. These anomalies were determined to be subsurface cracks using conventional means (visual inspection and bolt hole eddy current). **These latter conventional inspections required removal of fasteners, while the MWM inspection could be performed without removal of the fasteners.**
3. For inaccessible bolt hole locations, surface mountable MWM-Rosettes might be used to inspect these locations without requiring disassembly (see Figure 9).

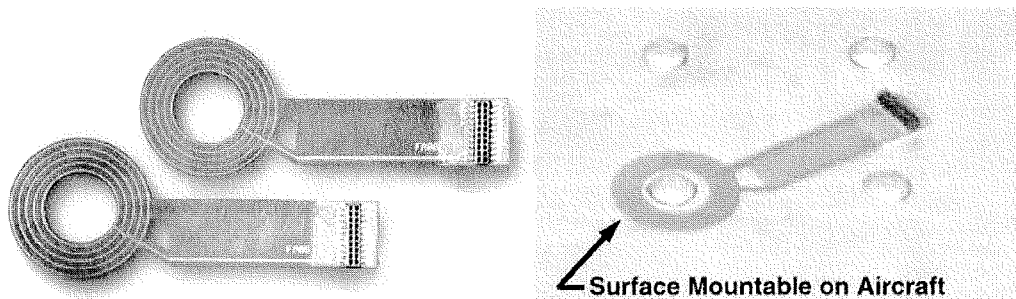


Figure 9. Surface Mountable MWM Rosettes for In-Service Detection of Cracks in difficult-to-access locations around fasteners.

MWM has been used to demonstrate the capability of finding all cracks detectable with traditional eddy current as well as cracks that traditional eddy current failed to identify. Although the C-5A fittings are being replaced 100%, there appears to be an application for MWM on C-5B fittings to identify cracks during PDM instead of potential wholesale replacement of the fittings. The two-frequency MWM scanning appears to be as effective at identifying cracks as the 19-frequency MWM measurements and should be considered for future applications. The technology could be implemented for inspections in a scanning mode as well as with sensors permanently mounted at selected critical locations, as required.

C-5 Main Landing Gear Trunnion Shot Peening Assessment

The C-5 main landing gear system has large trunnion fittings to support the strut assemblies which are virtually impossible to remove from the aircraft (Figure 10). During programmed depot maintenance, thorough inspections are made of all the surfaces on the trunnions to identify damage. Corrosion often found in the bore area must be removed either by localized grind out or reaming. Maintaining the integrity of the residual stress originally imparted by shot peening is critical; however, process controls for localized rework of these areas is difficult. As with most shot peening operations, Almen strips are used by the operator to establish the proper pressure and incident angle for the size of shot being used. Unlike the C-130 propeller blade taper bore, the internal area of the bore is relatively large. However, as all operations must be accomplished on the aircraft, the use of an automated booth is impossible.

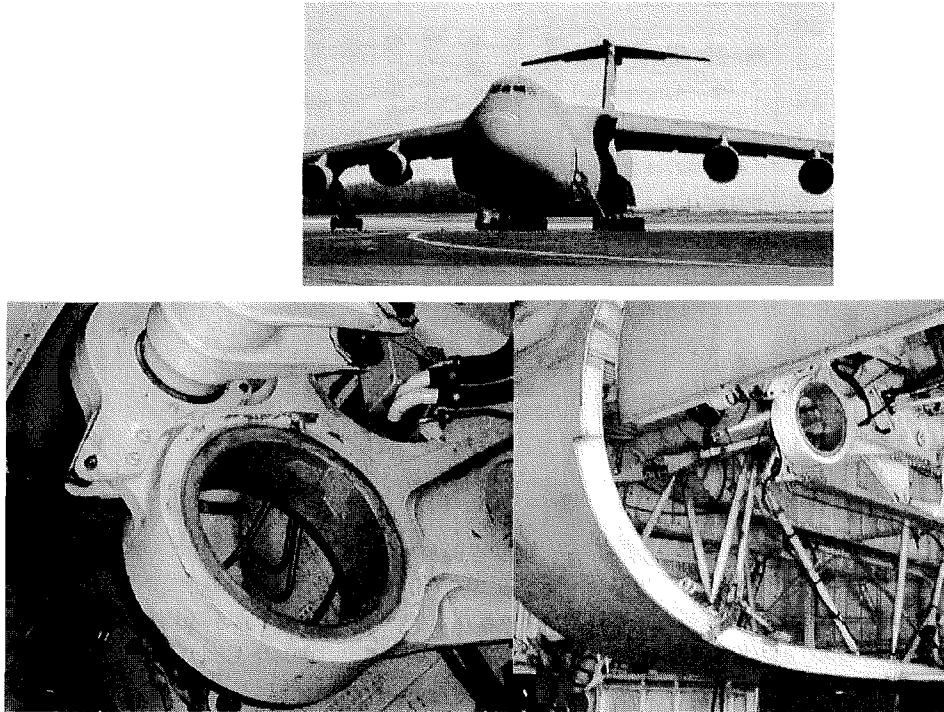


Figure 10. C-5 Landing Gear Trunnions.

The WR-ALC engineering staff supporting the C-5 aircraft has completed proof of concept to begin the implementation of MWM with grid methods to determine if localized shot peening is required for those instances where the corrosion or damage removal is shallow and, as an additional process control, when localized shot peening is required. Shot peening on an aircraft is a very time consuming and messy process. Each area that must be peened must be sealed off to restrict contamination of the surrounding structure from the shot and dust from disintegration of the shot. Even when the area is sealed off, clean up is very time consuming because even thorough sealing is marginally effective. Additionally, process control can be difficult because the shot peening must be accomplished in areas that are difficult to access.

Two trunnions were used in this analysis. Trunnion #1 was found to have significant corrosion on the inner surface. It was determined that the surface needed to be bored out approximately 0.026 inches and repaired by installing a large bushing. MWM was used to assess process control for the shot peening on Trunnion #1. Trunnion #2 was found to be out of round (egg-shaped) requiring reaming that only affected the upper and lower surfaces which were bored out to approximately 0.009 inches at the center of the bored area. MWM multi-frequency conductivity profiles were obtained for the areas that were and were not reamed on Trunnion #2. Figures 11 and 12 depict the MWM measured conductivity profiles after reaming only (Figure 11) and after reaming and shot peening (Figure 12) on Trunnion #1. Figure 13 depicts the conductivity profile for Trunnion #2.

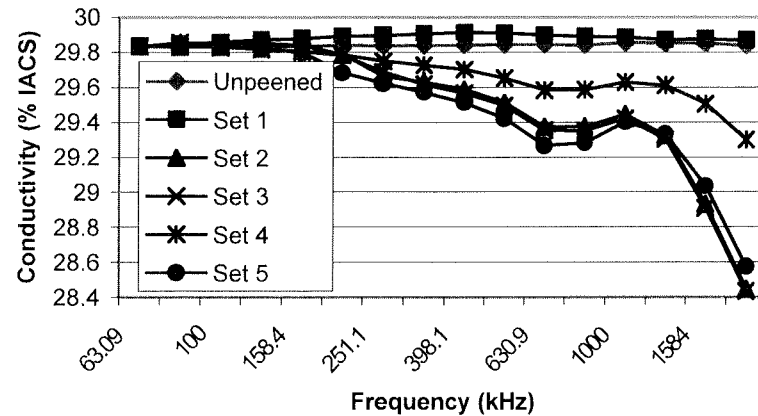


Figure 11. Multifrequency MWM Measurements of Conductivity inside Trunnion #1 after Machining (Prior to Shot Peening).

In Figure 11, the conductivity was essentially unchanged throughout the thickness in some of the areas measured (represented by sets 1 and 2) indicating that all of the shot peening effects have been removed. Other areas (represented by sets 3 through 5) were also essentially unchanged from 63 kHz to 199.5 kHz but had a significant change in conductivity between 199.5 kHz and 2MHz. This relatively large conductivity gradient could be attributed to the effects of aggressive machining, or remaining shallow shot peening.

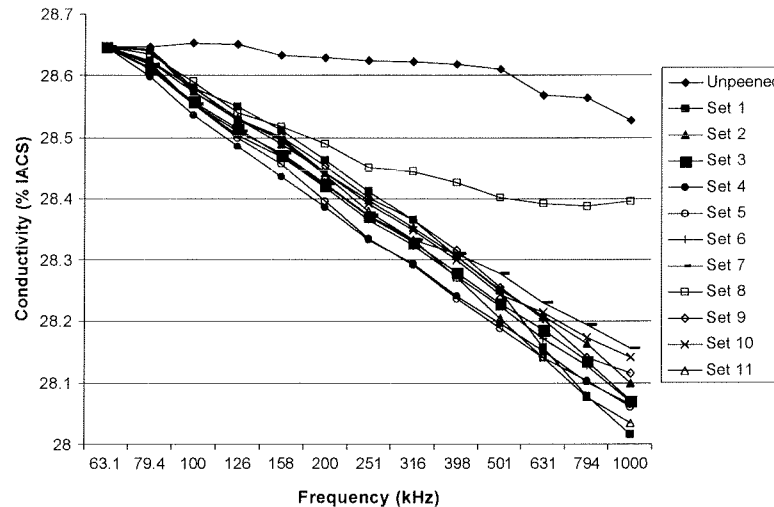


Figure 12. Multifrequency Conductivity of Trunnion #1 after Shot Peening.

In Figure 11, Set 1 was taken on an unpeened surface adjacent to the peened surface as a reference. Sets 2 through 5 represent areas from approximately 6 o'clock to 2 o'clock. Sets 6 through 12 represent areas from 2 o'clock to 6 o'clock, an area which is somewhat awkward for the shot peening equipment to reach. The following observations were made from assessing the data depicted in Figure 11:

- The large conductivity gradient, due to aggressive machining effects, virtually disappears after shot peening probably due to the stress redistribution that occurs as part of the shot peening process (it could also occur due to the removal of very near surface defects).

- Although the conductivity gradient is not as pronounced on the trunnion after shot peening, the conductivity continues to change with frequency throughout the measured spectrum.
- Finally, there is a distinct difference in the conductivity profile represented by measurements in easy-to-access areas and difficult-to-access areas, indicating potential for improving the process controls currently being used.

On Trunnion #2, the only set of MWM measurements made was after the partial reaming. As depicted in Figure 12, Set 1 represents the unshot peened lip of the trunnion, which was used as a reference. Sets 2 and 3 represent the conductivity profiles on the side of the trunnion that was not reamed. Sets 4 through 6 represent conductivity profiles of areas that were reamed. Although all but the reference (Set 1) indicates conductivity gradients throughout the profile, Sets 5 and 6 appear to be affected by the machining. When the conclusion might be that reshot peening is not required, it is critical to assess uniformity of preserved shot peening.

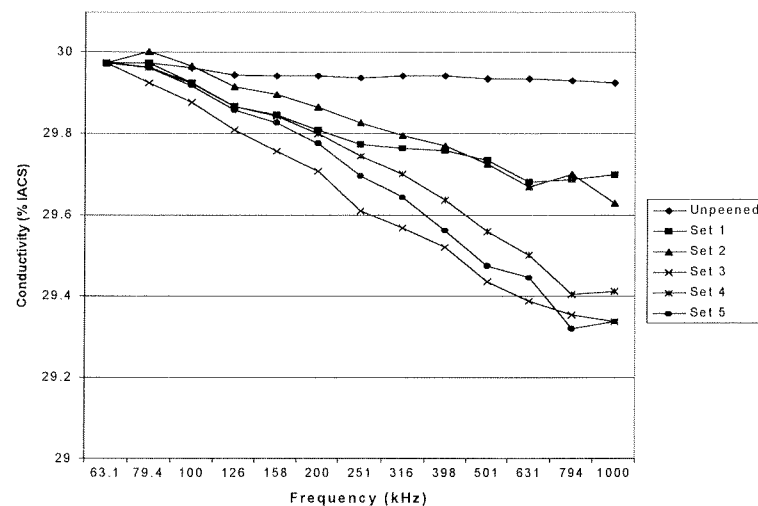


Figure 13. Conductivity Profiles of Trunnion #2

The conclusions from the testing accomplished on these trunnions are that MWM sensors with grid methods can effectively be used as both a process control for shot peening in this difficult-to-access area and to determine if partially reamed or ground out areas require shot peening to restore residual stresses. The effects on conductivity due to aggressive machining can be differentiated from shot peening because only a thin surface layer is affected during machining operations and the conductivity is not affected at lower frequencies. Shot peening, at these shot peen intensities, affects the conductivity throughout the majority of the measured frequency spectrum.

References

Yentzer, T., et al. (2000), "Fatigue Life and Residual Stresses in Cold Rolled Propeller Blades", in Proc. of the Third Joint NASA/FAA/DoD Conference on Aging Aircraft, September 21-23, 1999, Albuquerque, NM.