Session 2B (2) – Novel Techniques  
Chairman – Dr R A Smith

14.30  A new and novel inspection system for Titanium billets  
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Titanium is widely used in the manufacture of safety critical components for the aerospace industry. The difficulty related to the automated inspection of a Titanium billet is due to its coarse grain structure, which causes attenuation of the energy as ultrasonic waves are scattered by the grains during propagation. The flaws to be detected are typically less than 1mm in diameter and at depths of up to 150mm.

A new and novel automated phased-array ultrasonic system integrated with a multicoil eddy-current probe is being developed for the inspection of titanium billet at the raw material manufacturing stage. Ultrasonic inspection within 5mm of the surface is hampered by the ‘dead-zones’, where the interface signal from the surface can mask flaws. To address this, a multicoil eddy-current probe is being integrated in to the system to improve resolution in this area.

A novel phased-array ultrasonic probe has been designed and simulated with the objective of enabling electronic beam steering and focussing to compensate for misalignment of the probe due to variations in billet geometry and flaw orientation. The probe will consist of up to 256 elements and enable focal spot sizes of less than 2.5mm to be maintained at all depths.
A new and novel inspection system for Titanium billets

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Abstract

The titanium billet manufacturing process can produce sub-surface defects that are particularly difficult to detect due to the low SNR caused by the material grain structure and varying billet geometry and surface conditions. The aerospace industry demands higher quality, titanium billet to ensure safety against a background of increasing material performance needed to meet the requirements of modern engine design. To meet this challenge, a new and novel automated quality inspection system is presented in this paper, which integrates a multicoil eddy current inspection technique for detection of surface flaws within the ultrasonic dead zone, with a phased array ultrasonic inspection to detect defects within the volume of the billet. The system also incorporates a beam steering system to correct for variations in flaw response caused by misalignments due to variations in billet geometry, probe alignment and bar follower errors.

1. Introduction

The detection of defects in titanium billets present challenges that are considerably different from those encountered in traditional aerospace materials. This means that the proven Non-Destructive Testing (NDT) techniques that exist for inspection of defects in more traditional aircraft structures are not applicable for use in this application. Furthermore, existing NDT techniques currently applied have diminishing usefulness as increased production rates, operator subjectivity, and fatigue drastically decreases the probability of defect detection (POD). The crash of flight UA 232 at Sioux City, Iowa, USA in July 1989, with 111 fatalities, was directly attributable to a fatigue crack initiating from a hard alpha inclusion on the surface of a turbine disc that was not detected during manufacture\(^1\). Other reports \(^2,3\), of similar aircraft incidents involving fatalities have concluded that the current in service NDT inspections had failed to detect defects created during the manufacturing process that subsequently became responsible for the loss of life. This clearly illustrates an obvious and urgent need to develop advanced NDT technologies for application during the manufacture of titanium destined for aircraft components.
The QualiTi project is a collaborative research endeavour pursuing new techniques for reliable, comprehensive inspection of titanium billets. Two NDT technologies are being developed and deployed in parallel in order to achieve this. The inspection of the near surface of the billet is being undertaken using a new eddy current system, while the interior of the billet will be inspected using phased array ultrasound. This paper will present a detailed view of the ultrasonic system and the integrated eddy current inspection tool under development.

For the ultrasonic inspection to be both reliable and comprehensive, it must guarantee coverage of the entire billet with a consistent level of inspection sensitivity. In order to achieve the sensitivity requirement, the ultrasonic beam spot size must be consistent, at all inspection depths. In traditional ultrasonic inspection of billets, this is not the case. A single ultrasonic transducer cannot maintain a consistent beam spot at all penetration depths. This lead to the development of the multi-zone inspection technique\(^{(4)}\), whereby a billet is inspected with several transducers, each focused at a different depth within the material.

Multi-zone inspection, however, only guarantees full inspection coverage for an ideal billet in an ideal inspection environment. Due to imperfections in the radius of billets, imperfect initial alignment, and imperfect movement of the billet during inspection, misalignment of the ultrasonic probe with respect to the billet will occur. Therefore, a 100% effective ultrasonic inspection system must be able to correct for this misalignment. In the QualiTi project, this problem is solved by introducing a beam steering capability to ensure 100% inspection coverage. Thus, both the requirements for coverage and sensitivity are met\(^{(5,6)}\).

A similar project was previously undertaken in this area with partial success\(^{(7)}\). Due to limitations on the flaw detectors that can drive a phased array probe of 256 elements and limitations on phased array probe manufacturing technology, the inspection technique developed in that project was unable to fully meet the demanding inspection requirements. The results presented in this paper constitute a significant step forward from that research. All simulation results to date indicate that the technique proposed in this paper meet the inspection challenge raised by aerospace industry.

### 2. Inspection System

The integrated inspection system will, when complete, deploy both the ultrasonic inspection system, and the eddy current inspection system in parallel. This has not yet been tested in full, as the manufacture of the phased array probe is still ongoing.

The combined system will eventually be deployed in an immersion tank with the billet on a set of rollers. The ultrasonic and eddy current probes will be mounted on a bar follower that aims to keep the probes positioned central to the billet axis. The ultrasonic probe will be 3” from the billet; the eddy current probe will be in direct contact with the billet surface. This mechanical setup has not yet been undertaken, and is not part of the results presented in this paper. It is outlined here only to clarify how the two inspection systems will eventually be deployed.
2.1 Eddy Current Inspection system

With ultrasonic inspection, the strong interface echo from the front face of the billet makes it impossible to reliably detect defects near the surface. The interface echo creates a blind zone of approximately 5 mm at the edge of the billet. In order to have complete inspection coverage, a complementary eddy current inspection system has been developed\(^8\). The eddy current system is able to inspect the titanium within 5 mm of the surface, ensuring complete inspection coverage.

The eddy current system has been developed at West Pomeranian University of Technology, Poland. A hybrid eddy current probe of 5 coils has been developed. Figure 1 shows both the arrangement of the coils and the electrical connections of the probe. The 4 coils situated at even spacing around outside of the probe induce eddy currents into the billet material. The central coil is a receiver, detecting the resulting eddy currents. Each pair of transmitting coils, on opposing sides of the centre, operate in differential mode. This favours detection of defects oriented perpendicular to a line drawn between them. Using both pairs of transmitting coils, defects in any orientation can be detected.

Two test samples have been manufactured to replicate the near edge of a 10” diameter titanium billet. At the thickest part of the sample (7 mm) flat bottom holes of diameter 0.8 mm and EDM slots have been introduced. These flat bottom holes and slots have depths of 100%, 80%, 60%, 40%, 20% and 10% of the through wall thickness. All the slots have been successfully detected. The flat bottom holes at depths of 100%, 80%, 60% and 40% of the through wall thickness have been successfully detected.

![Figure 1](image)

**Figure 1.** a) schematic diagram of the hybrid eddy current probe of 5 coils, b) simplified electrical scheme of the transducer; \(E_A\ldots E_D\) – excitation coils, \((S)\) – pickup coil, \((\phi_x, \phi_y)\) - magnetic fluxes, \(P\) – potentiometer that controls magnetic fluxes \(\phi_x\) and \(\phi_y\), \(n\) – number of turns in the pickup coil \(S\).

2.2 Ultrasonic inspection system

The ultrasonic inspection system is being developed at TWI Validation Centre, Wales. A phased array probe has been designed with the aid of the Probe Designer software by Acoustic Ideas Inc. and is currently being manufactured by Vermon SA, France. The probe uses a total of 255 elements and has an ultrasonic centre frequency of 5 MHz.
The design uses a customised contour represented by a 5th order set of cosine basis functions (Figure 2). The probe is an elliptic shape with a long axis of 98 mm and a short axis of 78 mm. The probe has been designed to deliver a 2.5 mm diameter beam spot at all inspection depths from just beyond the blind zone (5 mm) to half an inch past the centre of the 10” billet (139 mm from the surface). The optimisation of the surface shape was targeted at reducing the phase variation across any one phased array element. Phase variation is the maximum difference in the time of arrival for an ultrasonic wave received by an individual element, expressed as a phase angle of the ultrasonic wave. With low phase variation, the voltages induced by the wave arriving at different points on the element reinforce each other and produce a high output signal. As phase variation tends towards 180 degrees, the voltage induced by the arriving wave cancel out and little signal is produced. The results presented here are the simulation results for the developed probe design.

Furthermore, the probe was designed to support up to ±3 degrees of beam steering in the circumferential direction of the billet. This provides compensation for initial misalignment of the probe when it is positioned above the billet, and dynamic misalignment that occurs as the billet rotates. When the probe is tilted by just 3º in water the refraction at the boundary with the titanium creates an effective beam angle of approximately 12º inside the billet. Without correction, this means that there may be a significant area at the centre of the billet that is never inspected. It has also been shown by simulation that this design is able to steer in the axial direction of the billet too.

The contour and probe segmentation was designed to minimise the phase variation on any element, for the full range of inspection locations (the inspection locations being set by the full range of inspection depths and beam steering angles). Probe Designer iteratively re-calculated the shape of the probe face, determined the phase variation across the surface for all inspection locations, and finally assessed how the probe could be segmented to produce the minimum number of elements that were required to ensure the phase variation stayed below a specified limit. This loop was repeated, changing the surface contour, and seeking a minimum number of elements.

With the phase angle limited to 88 degrees, a solution to the surface contour and element segmentation was determined by Probe Designer, which uses only 132 elements However, the segmentation scheme means that many of the elements had a
much greater surface area than others; the largest element being 10 times larger than the smallest. An element’s surface area affects its electrical impedance, and hence its sensitivity. Therefore, the segmentation scheme was re-designed to minimise the variation between the element sizes. The probe was re-segmented into 255 elements (Figure 3) of approximately equal size, and the probe design was complete, the largest element being only 1.6 times larger than the smallest.

Figure 3. a) Schematic diagram of the 255 element probe design, b) plot of total area of each element.

At the greatest inspection depths all elements are active, but for shallower inspections this results in an increase in the phase variation across elements. The beam spot is defined at the region of inspection where a reflected signal will be within 6dB of peak amplitude. Therefore, in all design and simulation work only the required elements were included in the focal law for each inspection location. The required active elements were selected automatically by Continuum Ultrasonic Modeller’s focal law calculator by determining the inspection aperture required to achieve the beam spot size at a given location and selecting only the elements that fall within that aperture. Figure 4 shows the inspection aperture for an inspection point at the maximum inspection depth. Using only the selected elements, the beam spot is approximately constant across all inspection depths. This has been verified by simulation using both Continuum Ultrasonic Modeller and CIVA, the results of which are shown in Figure 5.
Figure 4. Required aperture for an inspection point at 5.5” below the surface of the titanium billet. The billet diameter is 10”; the water gap is 3”.

Figure 5. Simulated results of beam spot size as function of inspection depth. The points marked axial are the beam widths measured in the axial direction of the billet. The points marked circumferential are the beam widths measured perpendicular to the axis of the billet.

Figure 6 shows simulated 2D beam profiles in the plane of beam steering. The focal point is set at a depth of 125 mm, with no lateral translational. Tilt angles of 0°, 2°, and 3° have been applied to the probe, and the focal laws calculated with beam steering to compensate. Table 1 shows the amplitude of the sidelobe measured in dB with respect to that of the focused main beam. With 3° of tilt in the circumferential direction the sidelobe is at least 7.6 dB (2.4 times) smaller than the main beam at the focused point.
Figure 6. Beam profile with the phased array probe focused at 125 mm with the probe tiled at 0°, 2° and 3°. Left column: Beam steering compensating for tilt perpendicular to the longitudinal billet axis of the. Right column: Beam steering compensating for tilt along to the longitudinal axis of the billet

Table 1 Sidelobe amplitude relative to focused main beam at depth of 125 mm

<table>
<thead>
<tr>
<th>Beam steering along billet longitudinal axis</th>
<th>Tilt angle 0°</th>
<th>Tilt angle 2°</th>
<th>Tilt angle 3°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam steering perpendicular to billet longitudinal axis</td>
<td>$-\infty$</td>
<td>-13.7 dB</td>
<td>-8.6 dB</td>
</tr>
<tr>
<td></td>
<td>$-\infty$</td>
<td>-17.3 dB</td>
<td>-7.6 dB</td>
</tr>
</tbody>
</table>

Figure 7 shows the same beam profiles as those shown in Figure 6 but with the focus point set at a depth of 15 mm, rather than 125 mm depth demonstrated in Figure 6.
Figure 7. Beam profile with the phased array probe focused at 15 mm with the probe tilted at 0º, 2º and 3º. Left column: Beam steering compensating for tilt perpendicular to the longitudinal billet axis of the. Right column: Beam steering compensating for tilt along to the longitudinal axis of the billet

Figure 8 shows beam spot size as a function of beam steering. In this case, the probe remained normal to the billet, so the beam steering resulted in a lateral shift of the focal spot. It can be seen that the beam spot is approximately 2.5 mm in both the axial direction and the circumferential direction at low beam steering angles, but eventually diverges. As the beam steering passes 3º, which corresponds to around 29 mm of displacement, the beam spot size starts to expand rapidly.
3. Conclusions and future work

It can be seen that the results of the simulations using the new phased array probe design show that it meets the specification. A 2.5 mm beam spot size is achieved at all inspection depths and for all of the required steering angles. The probe achieves the ±3 degrees of beam steering requirement with a maximum sidelobe amplitude at least 7.6dB smaller than the main beam. The probe design should therefore deliver a consistent sensitivity level for all inspections, and be able to compensate for the misalignment of the probe.

Trial measurements using the eddy current system has demonstrated its capability to detect 0.8 mm flat bottom holes of 40% through wall thickness and 5 mm long slots of 10% through wall thickness. This should deliver reliable detection of flaws in the ultrasonic dead zone.

The next tasks within the project are to complete the manufacture of the phased array probe and integrate the two inspection systems into the mechanical mounting. Then the performance of the ultrasonic inspection system will be verified. Both systems will also be assessed for their ability to cope with the mechanical movement of the system when used on manufactured titanium billets.

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References and footnotes

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2. National Transportation Safety Board Aircraft Accident Report - NTSB AAR-98/01, Sioux City, Iowa.