Ultrasonic NDE of titanium diffusion bonds using signal phase

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Abstract

Diffusion bonding is a highly advantageous solid-state welding method. However, its full exploitation in titanium components is currently limited by a lack of robust NDE techniques capable of detecting anything but gross bond-line defects. A novel ultrasonic technique has been developed to address this lack of capability. This technique, based on the ultrasonic signal phase, has been demonstrated in a 'single-sided' scenario where only one side of the diffusion bond was accessible. Samples with differing degrees of bond quality were evaluated, and excellent agreement was found between the single-sided and double-sided experiments.

1. Introduction

The current use of titanium diffusion bonds in gas turbine engines is limited by a lack of robust NDE techniques. Safety-critical rotating components, such as compressor discs, cannot currently exploit Metal Matrix Composite (MMC) substructures and near-net manufacturing, since diffusion bonding is required for these and other advances. The potential weight and cost savings that could be achieved with this solid-state welding approach are significant: today's 'state-of-the-art' compressor discs could be made up to 30% lighter by the use of titanium MMCs (1), for example.

The shortcomings of current NDE techniques are a result of the anisotropic nature of Ti-6Al-4V, which is the most widely used titanium alloy in aviation gas turbine engines (2). This anisotropy is primarily due to the Hexagonal Close Packed (HCP) crystals that constitute the majority of the material structure (approximately 90% by volume). These crystals tend to form large colonies—up to millimetres in size—of preferred orientation within which sound propagation speed varies with propagation direction. However, the relative orientation of neighbouring colonies is random,
resulting in significant material texture and thus distortions of the propagating sound wave \(^{(3)}\).

At the diffusion-bond interface, this material texture manifests itself as a weak planar reflector orthogonal to the ultrasonic transducer axis, as illustrated in Fig. 1. This makes ultrasonic inspection difficult because benign signals from the 'natural' acoustic impedance mismatches at the interface can shroud signals from defects and voids. It is stressed that the presence of acoustic impedance mismatches at the interface is not itself an indicator of bond quality—it is possible to have an excellent diffusion bond yet still receive large signals from the interface.

**Figure 1.** Crystal colonies having preferred orientation and being misaligned at the diffusion-bond interface. Shades of grey represent different crystallographic orientations.

2. Ultrasonic Signal Phase

Discrimination between signals from 'texture mismatch' and those arising from defects/voids at the diffusion-bond interface was required. It was possible to obtain such discrimination by first using the Baik-Thompson quasi-static imperfect interface model to understand the effect of interfacial defects/voids on the reflection coefficient, \(R\). The reflection coefficient predicted by the model when the interface defect is an array of cracks is described by:

\[
R = \frac{Z_2 - Z_1 + i \omega Z}{Z_1 + Z_2 + \frac{i \omega Z}{2\kappa}}
\]

where \(Z_i\) is the acoustic impedance of the respective medium, \(Z\) is the harmonic average of the acoustic impedances, \(\omega\) is the angular frequency and \(\kappa\) is the interfacial stiffness \(^{(4)}\). This complex reflection coefficient becomes real for infinite \(\kappa\), as expected, but is dominated by the imaginary components if \(\kappa\) is small. The appearance of \(\kappa\) in only imaginary terms implied that it was possible to separate the \(\kappa\) and \(Z_i\)-mismatch contributions to the reflection coefficient. This separation was achieved by assuming
that $\omega Z < \kappa$ such that compliance effects dominate, as is the case for an array of cracks at the interface. It was then possible to express $\kappa$ in terms of the signal phase, $\Phi$, as shown by:

$$\kappa \approx \frac{\omega Z}{2 \eta \tan \Phi}$$  \hspace{1cm} (2)

where $\eta$ is the relative acoustic impedance mismatch; $(Z_2 - Z_1)/(Z_1 + Z_2)$.

3. True Phase

It was not possible to make conventional phase measurements to obtain $\Phi$ because these measurements—single-point phase-spectrum measurements at the transducer centre frequency—yield a phase, $\varphi$, that combines both phase information ($\Phi$) and delay information. This was undesirable because sound-wave propagation speeds depend on position through anisotropic media, meaning that the delay contribution to the phase measurement would randomly vary throughout an inspection, obscuring the desired $\Phi$ information.

The signal 'true phase' was sought in order to overcome this problem. Non-dispersive signals exhibit a linear region in their phase-spectrum around the transducer centre frequency, the slope of which is proportional to the time-difference between the centre of the observation window and the signal half-energy point. Extrapolation of this linear region to the zero-frequency axis allows a delay-free phase measurement to be made, as shown in Fig. 2. This was termed the true phase, $\Phi$, by Instanes et al. (6).

![Figure 2. Phase spectra for two identical 10 MHz signals having a difference in arrival times equivalent to 90°. $\Phi$ is the same for both signals because they are identical, whereas $\varphi$ is affected by the delay contribution.](image)

4. Reference Phase Measurement

A typical ultrasonic signal has a constant true phase as it propagates through non-dispersive isotropic media. However, textured materials such as the titanium alloy of
concern here distort the absolute phase significantly and unpredictably \(^{(7)}\). Corresponding distortions occur in the true phase, rendering individual true-phase measurements for the estimation of \(\kappa\) useless. Reference measurements of \(\Phi\) are required to eliminate the phase contribution from the material texture, thereby isolating the contribution to \(\Phi\) from the diffusion bond.

It has been shown that this could be achieved by inspecting the diffusion bond from both sides \(^{(8)}\), noting that the 'step change' in the acoustic impedance mismatch at the interface from either side is asymmetric (equal in magnitude but opposite in sign), while the contribution from interface imperfections is symmetric (approximately equal in both magnitude and sign from both sides) \(^{(9)}\). However, double-sided inspections are impossible for many components. It would not be possible to conduct a double-sided inspection on the compressor discs mentioned earlier, for example.

By inspecting the component both before and after diffusion bonding, it is possible to obtain the necessary reference phase measurement from just one side of the interface, as illustrated in Fig. 3. This constitutes a novel single-sided inspection that provides an estimate for the interfacial stiffness and is able to discriminate between benign signals originating from natural acoustic impedance mismatches at the diffusion bond and the signals resulting from defects.

5. Interfacial Stiffness Maps

The ability to produce high-resolution interfacial stiffness maps in an automated and computationally-efficient fashion was another novel development of this work. Figure 4 shows the results from a conventional ultrasonic inspection (where only signal amplitude information is used). The three samples shown have diffusion bonds of varying quality, but this is not immediately obvious from the C-scan results. Figure 5 shows the \(\kappa\) maps for the same three samples, obtained using the single-sided method. A distinction could readily be made between the three samples using the interfacial stiffness information.
Note that the black regions in Fig. 5 indicate positions at which the received diffusion-bond signals were of insufficient amplitude (< 12.5% Full Screen Height (FSH)) to make reliable phase measurements. This was taken to be indicative of good bonding at these positions, since voiding and/or defects were expected to have resulted in larger reflections of the ultrasonic pulse at the gain settings used. The assumption here was that low-amplitude signals could only be observed if there was an equally low-level response from both Z$_i$-mismatches and interfacial defects, since the mismatch response and that of the any defects are in quadrature and therefore could not simply cancel one another out.

Sample (a) was shown to be poorly-bonded by Scanning Electron Microscopy (SEM) of its diffusion bond after sectioning. Several instances of porosity and lack of bonding
were observed along the bond plane, as shown in Fig. 6. It is believed that this poor bonding was caused by a poor seal during the bonding process, resulting in a partial loss of vacuum at the interface. The interfacial stiffness measurements were in excellent agreement with these observed indicators of poor bonding.

The diffusion-bond quality of samples (b) and (c) was assessed by subjecting these samples to low-cycle fatigue tests. The C-scans and κ maps of samples (b) and (c) were representative of a set of eight samples, four of which were well-bonded (represented by (b)) and the other four of which were less well-bonded (represented by (c)). The typical crystal colony size of the samples in these two sets was different. A significant drop in the average fatigue lives of sample set (c) was observed, and this was corroborated by a reduction in the interfacial stiffness of 67% on average, as illustrated qualitatively in Fig. 5.

Figure 6. SEM and κ map of sample (a) showing that low interfacial stiffness was observed in the vicinity of porosity and lack of bonding at the diffusion-bond interface.
However, it was not possible to directly relate the reduction in fatigue life with the difference in $\kappa$ for these two sample sets because it was not possible to fully separate the contribution to the lower fatigue life from the microstructure variation and that of the poorer diffusion bonding. There was insufficient data to prove the extent to which the microstructure inhibited the diffusion bonding process, but it is believed that the reduction in fatigue life was greater than would have been expected had no diffusion bond been present. Further work is clearly needed to provide more conclusive evidence in this regard.

Despite this, the results across all three samples indicated an ability to distinguish between different quality diffusion bonds using a single-sided phase-based interfacial stiffness measurement technique. Importantly, this novel method did not require additional equipment or excessive acquisition or computational time, and the results required very little interpretation, making the technique attractive for industrial implementation.

6. Comparison of Single-sided and Double-sided Methods

It was mentioned previously that there exist two branches to the phase-based $\kappa$-measurement technique: single- and double-sided methods. The results discussed above were acquired using the single-sided method, but it was not highlighted that the two methods produced equivalent results. A point-by-point cross-correlation procedure was employed in order to quantify their equivalence. Interfacial stiffness maps were created using both methods for a set of 25 samples, generating 50 images (25 image pairs) similar to those shown in Fig. 5. Each image pair was subjected to a normalised two-dimensional cross-correlation algorithm that generated correlation coefficients ranging from zero to unity. An image pair were said to be correlated when their correlation coefficient was greater than $1/e$ (approximately 0.37), where $e$ is the natural number $^\text{(10)}$. It was observed that all of the image pairs were correlated, with the average correlation coefficient being $0.61 \pm 0.17$ for all 25 samples. Importantly, the lower correlation coefficient observed with some image pairs was not a result of disparity between the two methods, but rather a result of the point-by-point nature of the correlation algorithm combined with the speckled appearance of some of the images, which had the effect of increasing the algorithm's sensitivity to small misalignments. This is illustrated in Fig. 7, where only three samples are shown in the interest of brevity. These three image pairs were selected to show the lowest, median and highest correlation coefficients observed in the study, and it is clear that each constituent in a pair was in excellent agreement with its counterpart.
7. Conclusions

NDE of titanium diffusion bonds has been investigated. Conventional ultrasonic techniques have been shown to be inadequate for the robust inspection of these solid-state welds as a result of the anisotropy observed in Ti-6Al-4V, which is the most widely used titanium alloy in aviation gas turbine engines. A solution to this lack in NDE capability has been proposed in the form of a phase-based inspection technique that delivers an estimate of the interfacial stiffness by analysis of the signals received from the diffusion bond. Novel algorithms have been developed to produce a map of a component's interfacial stiffness in an automated and computationally-efficient fashion. The technique has been shown to distinguish between diffusion bonds of varying quality, and equivalence has been demonstrated between single-sided and double-sided inspection methodologies.

Future work will focus on understanding the limitations of this phase-based technique in order to fully quantify the advantages that it may bring over conventional inspection methods. This will be achieved by generating diffusion bonds of more carefully-controlled quality in one type of material only, thereby facilitating direct comparisons. In addition, the technique will be evaluated against the more exotic non-collinear wave mixing technique that is the subject of ongoing research \(^{(11)}\). It is hoped that industrial evaluation will follow naturally from this, with implementation as appropriate.

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Figure 7. Interfacial stiffness maps obtained by single-sided (s-s) and double-sided (d-s) phase measurements on three different samples. Each sample pair has a different Correlation Coefficient (CC).
References