DEVELOPMENT OF ULTRASONIC INSPECTION FOR A BONDED SUPERALLOY BLADE

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INTRODUCTION

Directionally solidified multigrain and single crystal airfoils have been used in aircraft gas turbines for over ten years and are currently found in aircraft engine-derivative gas turbines used for land-based power generation. However, the adoption of this technology for large land-based gas turbines is just underway and is not a simple scale-up. One approach to produce the large blades required for this application involves casting the blade in two separate halves and then bonding these halves together using the transient liquid phase bonding (TLPB) process [1]. This process results in a number of internal bond surfaces at the ribs. The condition of these bond surfaces must be determined prior to the blade entering service.

This paper reports the feasibility of using ultrasonic techniques to evaluate the bond surface between two half-blade sections cast from the nickel based superalloy CMSX-4 [2-4] joined by the transient liquid phase bonding technique. The results presented here are a follow-on to previous work in which ultrasonic measurements were used for the flaw detection and quality assessment on bonded specimens with simpler geometries [5]. The approach of the study was to first measure the longitudinal wave velocities of the material along the crystal growth direction and in a plane perpendicular to the crystal growth direction. Next the sensitivity of ultrasonic scanning and imaging for detecting flaws was evaluated using an "I-beam" which simulated the geometry of a rib in the airfoil and contained machined defects. Finally measurements were made on an actual bonded blade.

LONGITUDINAL VELOCITY MEASUREMENTS

Because single crystal superalloys such as CMSX-4 are anisotropic materials, the material properties such as elastic modulus are related to the crystalline orientation of the material. By obtaining longitudinal wave velocities as a function of orientation, some measure of variation in the elastic stiffness as a function of orientation can be found. It is also important to know the variation of longitudinal velocities in order to predict the

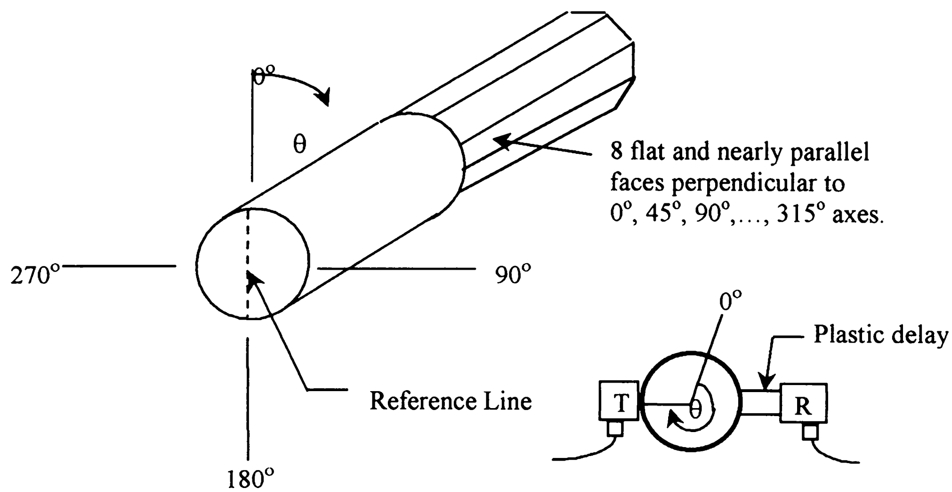

Figure 1. Method for measuring longitudinal wave velocities in CMSX-4 single crystal sample.

sensitivity of specimen orientation for immersion testing of single crystal specimens with complex geometries.

The longitudinal velocity of the material along the growth direction was found previously to be 5.28 ± 0.05 mm/μs[5]. In order to measure the longitudinal wave velocities of CMSX-4 perpendicular to the crystal growth direction, a cylindrical single crystal specimen was fabricated with the crystal growth direction lying parallel to the axis of the cylinder. The length of the cylinder was 2" and the diameter was 0.625". On one half of the cylinder eight flat and nearly parallel faces were machined resulting in an octagon shape. The single crystal specimen was x-rayed and a reference line was placed by EDM (electrodischarge machining) through the center of the round end of the specimen to mark one of the [100] type directions.

The velocity measurements were performed using a pair of 20 MHz, 1/8" diameter, contact transducers; one of the transducers was equipped with a plastic delay. The velocity was measured by pulse overlap (the time difference between "reference only" and "reference + sample" was measured, using the plastic delay as the reference material) as shown in Figure 1. (Measurements were taken every 11.25° around the cylinder.)

The longitudinal velocities measured varied between 5.31 mm/μs and 6.13 mm/μs. A plot of the velocities as a function of angular position is shown in figure 2. The round surface of the specimen was polished and etched. The directions corresponding to the minima in velocity coincided very well with the directions of the dendritic growth, as the micrograph of the etched surface shows. The EDM reference line was found to be off of the [100] direction by about 9°. The minimum velocity (5.31 mm/μs) was nearly the same as that along the crystal growth direction. The higher velocity in the [110] direction than that in the [100] direction is to be expected.

MEASUREMENTS ON I-BEAM SPECIMEN

In order to assess the sensitivity of ultrasonic scanning and imaging for detecting flaws in a geometry such as a turbine blade, an I-beam specimen was fabricated. Figure 3

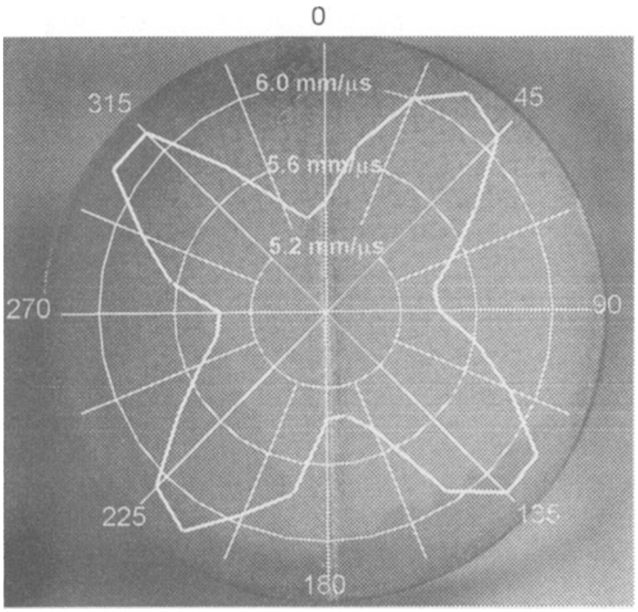

Figure 2. Longitudinal Velocity (mm/μs) vs. angle from reference line (degrees) superimposed on a micrograph of the etched end of specimen.

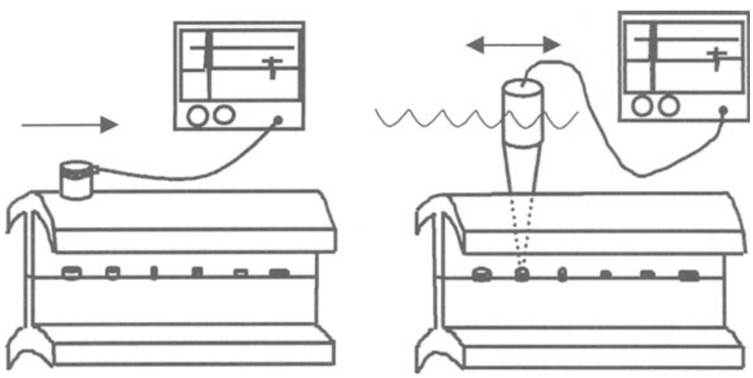

Figure 3. Contact and immersion testing of I-beam specimen.

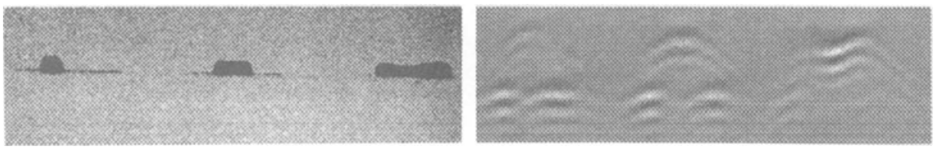

Figure 4. Micrograph (left) and B-scan of three slot defects (1/32", 1/16" , 1/8") and disbond at bondline.

shows the I-beam specimen and the test configurations for contact and immersion ultrasonics. The dimensions and geometry of the specimen were selected to represent a typical section in the actual blade. The specimen was 2.2" long and 1.2" high. The thickness of the web was 0.18". Six machined defects were introduced at the bond plane of the specimen to simulate flaws that could occur in the finished blade. These machined defects included flat bottom holes (FBH's) and slots ranging in size from 0.031" to 0.125". In addition to the six EDM'd defects, there were unintentional unbonded regions at the bondline adjacent to each of the machined defects. Figure 4 shows a micrograph of the three slot defects and the associated unbonded regions along with a B-scan of the same region obtained in an ultrasonic immersion scan. The B-scan shows that it was possible to resolve the top of the machined defect from the unbonded regions on the bondline.

The I-beam specimen was also tested with a 20 MHz contact transducer of 0.125" diameter. The amplitude of the reflected signal from the bond surface was measured and plotted against the test position along the length of the I-beam as shown in figure 5. Each of the machined defects was detected, furthermore, the peak amplitude associated with each of the flaws showed good correlation with their cross-sectional area.

Immersion C-scan was performed using a 15 MHz, 0.5"diameter probe with a 3" focus in water. The focal point was placed on the bond surface and a raster C-scan (Figure 6) was made using the amplitude of the echo reflected from the top of the flaw. Each of the six machined defects were imaged. The size of the machined defects was in good correlation with the size of imaged flaws shown in the C-scan.

MEASUREMENTS ON A BONDED BLADE

In order to assess the capability of ultrasonic testing and imaging for detecting flaws in a production blade, testing was performed on an actual bonded blade. A completed blade weighs nearly 30 pounds and has an overall length of over 12". A photograph of one half of the blade is shown in Figure 7.

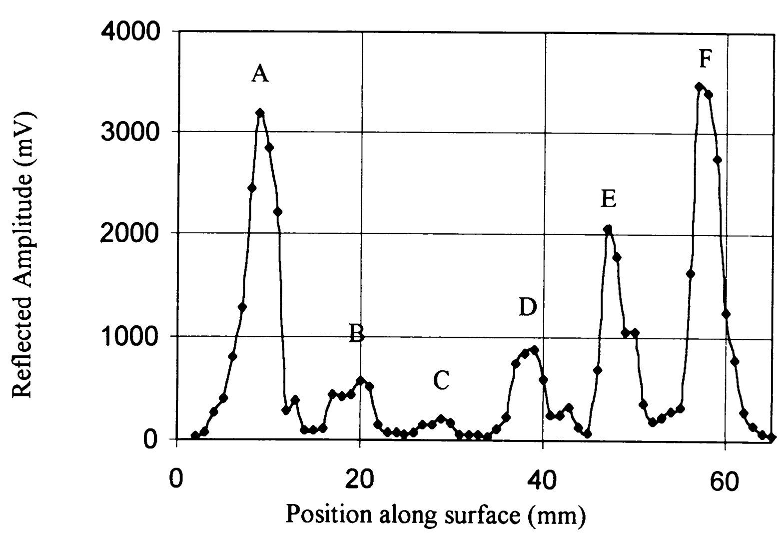

Figure 5. Results on I-beam specimen in contact mode.
A: 0.125" dia FBH, B: 0.063" dia FBH, C: 0.031" dia FBH,
D: 0.031" wide slot, E: 0.063" wide slot, F: 0.125" wide slot

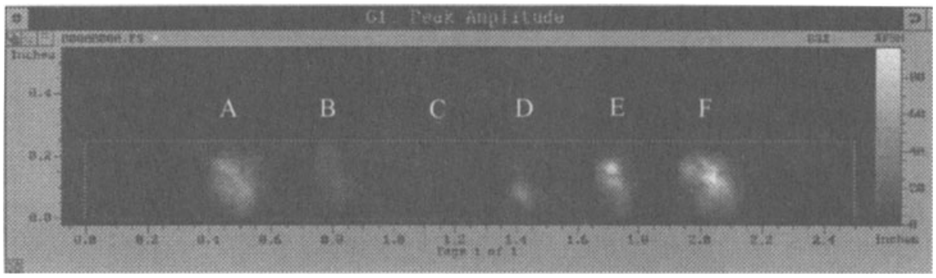

Figure 6. Results on I-beam specimen in immersion mode.
A: 0.125" dia FBH, B: 0.063" dia FBH, C: 0.031" dia FBH,
D: 0.031" wide slot, E: 0.063" wide slot, F: 0.125" wide slot

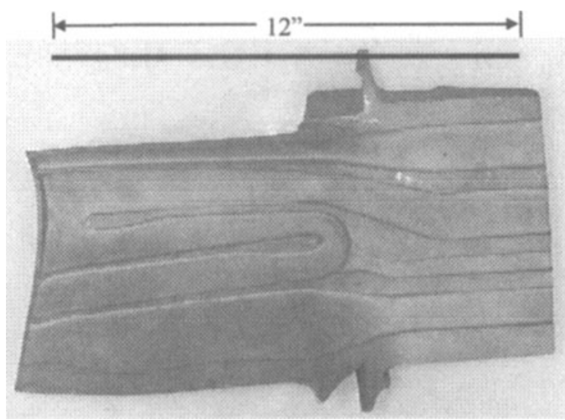

Figure 7. Convex half of blade prior to bonding.

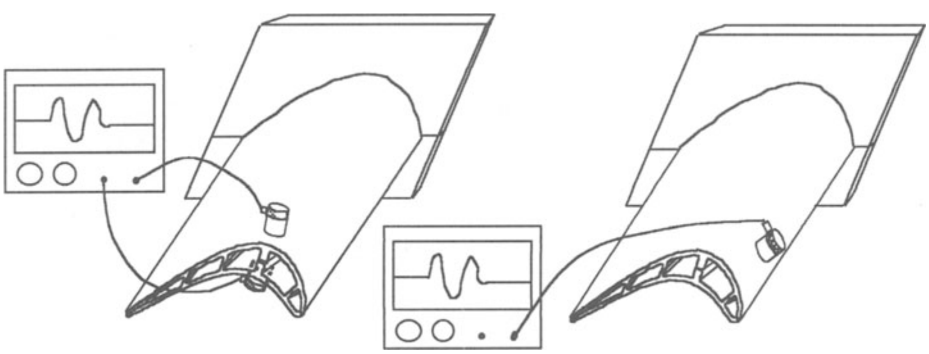

Figure 8. Through transmission (left) and pulse echo testing of bonded blade.

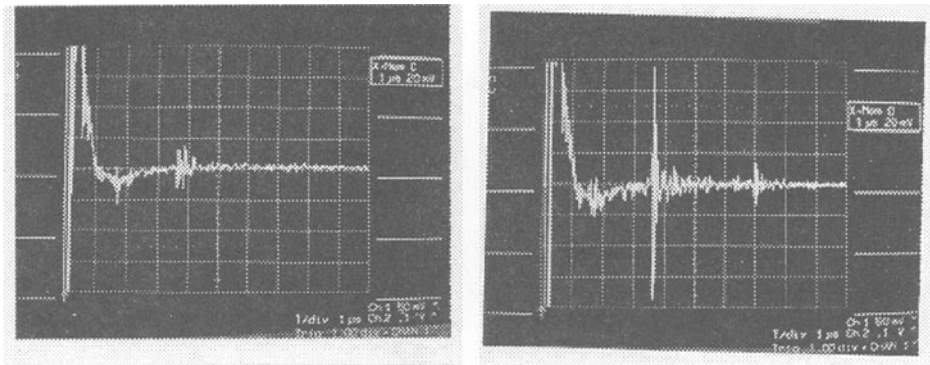

Figure 9. Low reflectivity of a good region of the bond (left) and high reflectivity of a poor region of the bond (right).

Although no intentional defects were placed in the bonded blade, the quality of the bonded surface along the internal ribs was evaluated using contact mode through transmission, contact mode pulse echo, and pulse echo immersion mode tests. In contact through transmission tests (shown in Figure 8) a pair of 10 MHz, 1/4" contact transducers were placed on opposite sides of the blade along each of the ribs. The transmitted signal was measured every 1 cm along the length of each rib. Because a good TLPB bond is virtually invisible to ultrasound, any location where no signal was transmitted was assumed to be a disbonded region. Two such regions were found on the bonded blade. One of these was near an edge and the two halves were visually not in contact. At the second location the lack of transmitted signal indicated a disbond length of 10 mm.

As was done with the I-beam specimen, the bonded blade was also evaluated with pulse-echo contact testing as shown in Figure 8. A 15 MHz, 0.25" contact transducer was moved along the surface of the blade along a rib with the bonded surface. At the location where a disbond was present, a high amplitude echo with a time of flight corresponding to the bondline was observed, indicating a lack of bond (right photo in Figure 9). At a location 15 mm away the echo amplitude associated with the bond surface was very low, indicating a better quality bond (left photo in Figure 9). An ultrasonic C-scan was made in the region of the bonded blade where a disbond was detected using contact testing. It was noticed that the bond surface was not transparent and that a weak echo (slightly above the noise in the system) was reflected even in well bonded regions. This enabled a C-scan based on time of flight of the echo from the bond surface to reveal the outline of the rib. This outlined region was then examined in the C-scan based on the amplitude of the reflected signal from the bondline. The highly reflecting region of the amplitude C-scan was in good agreement with the size of the suspected disbond observed in contact testing. The C-scan images based on time of flight and amplitude of the reflected signal from the bondline are shown in Figure 10.

CONCLUSIONS

Ultrasonic testing and imaging has proven effective in detecting defects in TLPB bondlines of specimens simulating the geometry of a turbine blade. A flat bottom hole with a diameter of 1/32" was found to be detectable with a 20 MHz 0.25" diameter contact probe. The same flat bottom hole could be imaged in a C-scan using a 15 MHz, focused probe. In both immersion and contact testing the amplitude of the signal reflected from a defect showed good correlation with the size of the defect.

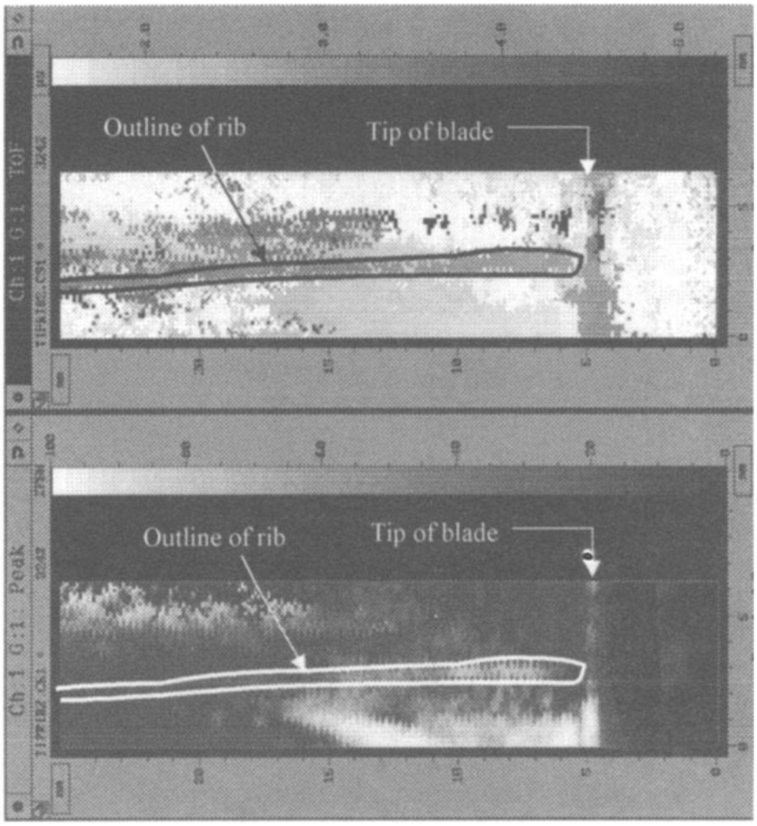

Figure 10.Time of flight C-scan (top) and amplitude C-scan (bottom). High amplitude (lighter gray) in amplitude C-scan indicates lack of bond.

An unbonded region in a production turbine blade measuring approximately 10 mm was detected. As with the I-beam specimen, the results obtained with immersion and contact testing showed good correlation.

Based on this study conducted on a turbine blade and on a bonded blade, ultrasonic measurements can be used for flaw detection and quality assessment of bonded single crystal turbine blades. In principle, the entire ultrasonic inspection process of a single crystal part can be modeled, based on the complete geometry and crystalline orientation of the part.

ACKNOWLEDGEMENT

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