ULTRASONIC EVALUATION OF TRANSIENT LIQUID PHASE BONDING IN SINGLE CRYSTAL SUPERALLOY CASTINGS

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INTRODUCTION

Transient liquid phase bonding (TLPB) is an effective means for joining high performance metal components. It differs from welding and conventional brazing in that it produces very little chemical segregation or microstructural demarcation at the bond-line. The method of transient liquid phase bonding was originally developed in the 1970's [1] and has been used in the joining of titanium and nickel based superalloy components. In this method, a bonding alloy containing a melting point suppressing element is sandwiched between the parent metals to be joined. The temperature is raised to a point where the bonding alloy melts but the parent metals remain solid. The melting point suppressing element then diffuses away from the bondline, thus raising the melting point and solidifying the bond. Since the temperature never exceeds the melting point of the parent metal, single crystals may be joined without destroying their crystalline structure.

This paper reports ultrasonic evaluation of the bondline between single crystals of nickel-based CMSX-4 alloys [2,3] joined by the transient liquid phase bonding technique. The approach of the study was to first evaluate the sensitivity of ultrasonic scanning and imaging for detecting defects at the bondline in a set of calibration samples containing artificial flaws, and then use the ultrasonic technique to evaluate the unknown bondline conditions in a number of transient liquid phase bonded plates of CMSX-4 superalloys.

DETECTION SENSITIVITY STUDY USING CALIBRATION SAMPLES

In order to assess the sensitivity of ultrasonic scans for detecting defects at the bondline, a set of calibration samples were prepared. These samples were fabricated by

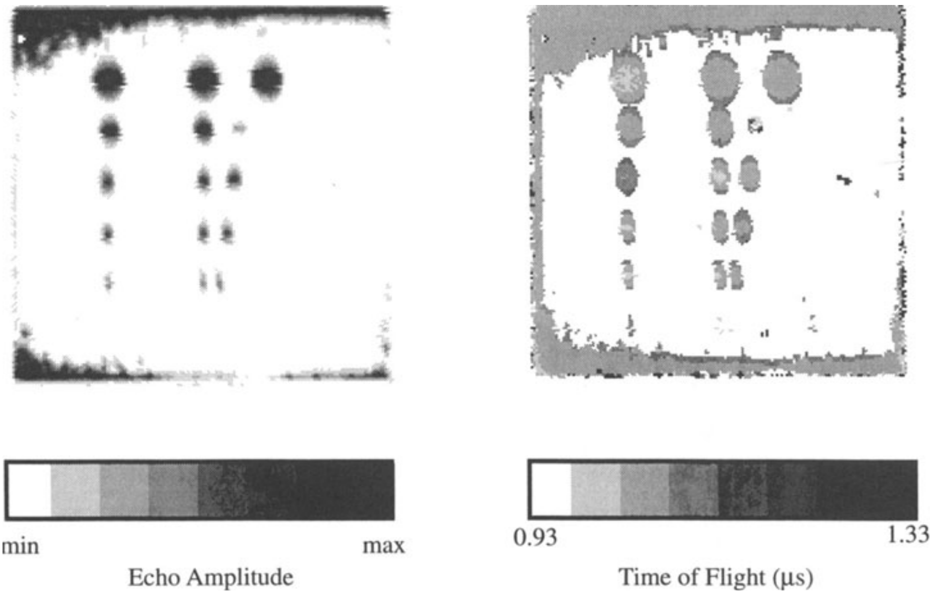


Fig. 1 Amplitude and time of flight C-scan images of a calibration sample containing flat bottom holes.

bonding two single thin plates together; each plate was 1.5" x 1.5" x 0.125" and the crystal growth direction (nominally along the [001] crystallographic axis) was in the plane and parallel to one edge. Machined defects were introduced to simulate bondline porosity, fit-up mismatch, cooling cavities, and a grain boundary due to misorientation. To simulate bondline voids, flat bottom holes from 1/64" diameter to 1/8" diameter were introduced by electrodischarge machine (EDM). As a comparison, one #1 spherical bottom hole (1/64" diameter) was also introduced. These holes were drilled through the lower half of a bonded plate to the depth of the bondline. Ultrasonic detection of these defects was conducted from the top using a 15 MHz, 0.5" diameter transducer with a 2" focal length in water. The focal point was placed at the bondline and a raster C-scan was made using the amplitude and time of flight of the flaw echo. All flat bottom holes and the #1 spherical bottom hole were detected, as shown in Fig. 1. Several interesting results were observed. One of the #5 flat bottom holes gave an abnormally weak signal due to the fact that it was drilled to a wrong depth. The images of the round holes were distinctly elliptical, due to the presence of two "halo" caps at the top and bottom. The long axis of the ellipses was perpendicular to the crystal growth direction of the bonded plates. This phenomenon was reproducible and seemed to be associated with the velocity anisotropy [4] of the single crystal plates. Finally, there were some unbonded regions near the edges of the bonded plate.

One calibration sample contained three concentric circular channels at the bondline. The largest outer channel was 0.2" wide by 0.050" deep, and the smallest inner channel was 0.050" wide by 0.010" deep. Ultrasonic C-scans clearly imaged the three circular channels. The time of flight values of the three rings corresponded to their actual depth. These

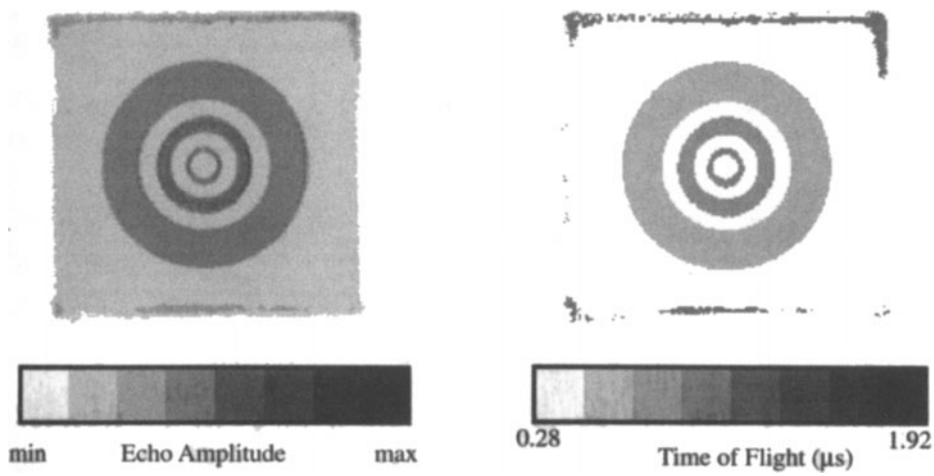


Fig. 2 Amplitude and time of flight C-scan images of a calibration sample containing three circular channels.

results are shown in Fig. 2. This sample was well bonded and showed no sign of unintended disbonds. To simulate fit-up mismatch, shallow grooves were machined into one half of the single crystal plates before bonding. The depths of the machined grooves in this calibration sample were 0.010" (horizontal grooves), 0.050" (vertical grooves) and 0.002" (diagonal grooves). Ultrasonic images of this sample, depicted in Fig. 3, showed that the transient liquid phase bonding process did not cause the grooves to become filled, even for the shallowest depth of 0.002" with the exception of only one place near the upper left corner. Quantitative measurement of the time of flight on the C-scan image yielded the following depth for the three grooves: 0.009", 0.004" and 0.002", which were in good agreement with their machined depths. In addition to the machined grooves, this sample showed a number of unbonded regions of irregular shape.

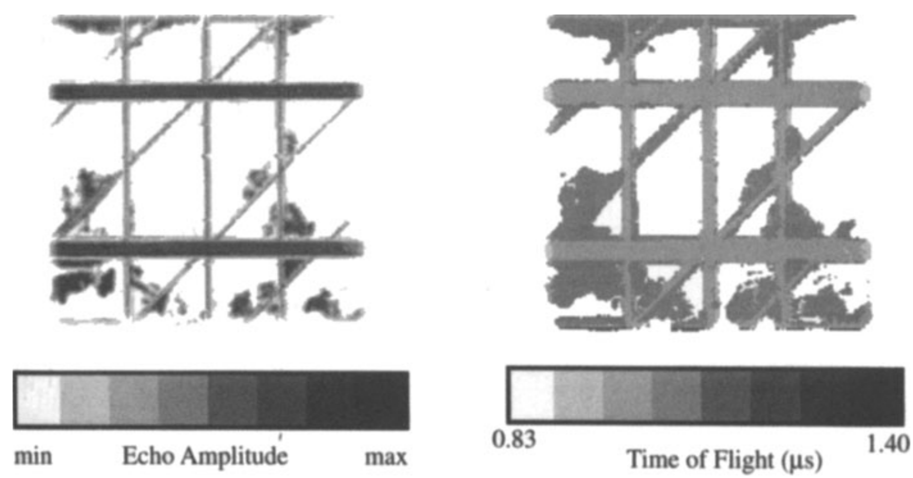


Fig. 3 Amplitude and time of flight C-scan images of machined grooves in a calibration sample.

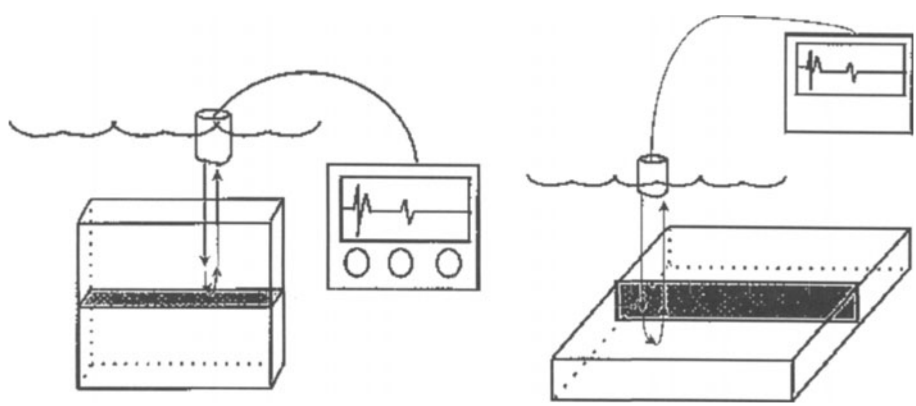
These unbonds were verified by cutting along one edge, followed by polishing and microscopy. To simulate a large angle grain boundary, two single crystal plates were rotated by 75 degrees relative to each other and then bonded. The resulting bondline was found to be essentially non-reflecting for normally incident longitudinal waves, but can be detected by the use of a shear wave pulse. This was because the shear wave velocity depended upon the vibration direction in relation to the crystal growth direction.

The study of ultrasonic flaw detection sensitivity showed that amplitude and time of flight C-scans using a focused beam at a relatively high frequency of 15 MHz had excellent sensitivity. All the machined defects and the un-intended unbonds were revealed.

ULTRASONIC NDE OF BONDED CMSX-4 PLATES

Having established the flaw detection sensitivity of the ultrasonic scan technique, the procedure was applied to the evaluation of a series of bonded plates of single crystal CMSX-4. The plates were typically 3" x 3" x 0.4" in size and contained a butt joint with a 0.4" x 0.4" x 3" bond plane. The bond plane conditions were evaluated by conducting "end-on" C-scans with a 20MHz, 1/8" diameter, unfocused transducer. In order to evaluate the base metal near the bondline for possible spurious grain growth, the plates were also scanned in the "flat-on" geometry using the same transducer. Figure 4 shows the two scan geometries.

The as-cast surfaces of the plates were somewhat irregular; the flat-on scan images were affected by the surface irregularities. For this reason, the central stripe containing the bondline was machined flat and parallel on both sides of the plate to eliminate the surface effect. Figure 5 shows the flat-on scan images of three selected samples. The one on the left showed no crystal growth anomaly in the central stripe. The middle sample showed a spurious growth that extended across its width. The sample on the right showed severe change of crystal orientation near its bottom. The flat-on scan was found to be quite useful in detecting



Images based on amplitude and time of flight from bondline.
20Mhz center frequency,
1/8" diameter, no focus

Images based on amplitude and time of flight of backwall surface echo.
20Mhz center frequency,
1/8" diameter, no focus

Fig. 4 Ultrasonic imaging of bonded CMSX-4 plates in the end-on and flat-on geometries.

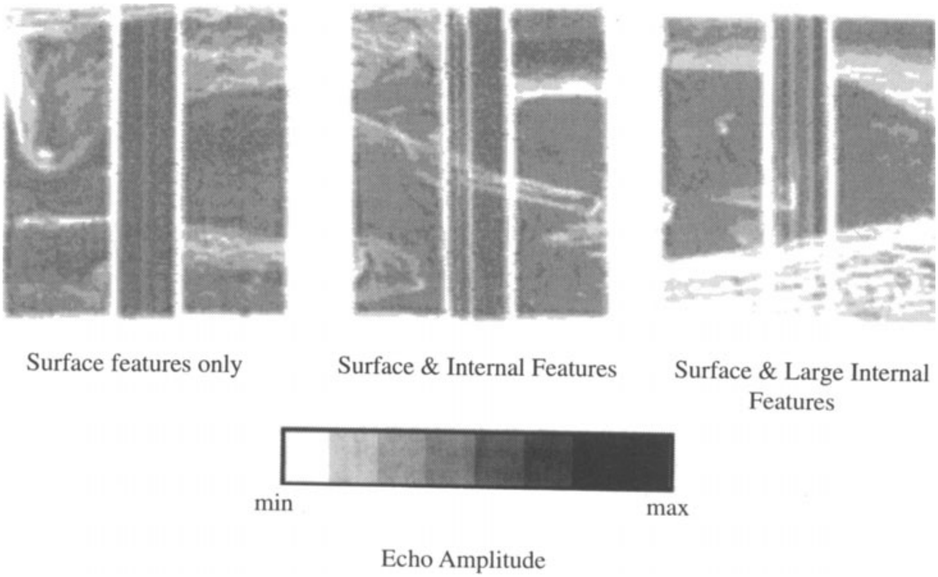


Fig. 5 Ultrasonic amplitude C-scan images of three bonded plates with machined central stripes.

crystal growth anomalies. Changes in crystal orientation manifested themselves as changes in both ultrasonic echo amplitude and time of flight. Both severe changes and subtle changes were observed. Localized spurious crystal growth could skew the propagation of the ultrasonic waves and generally resulted in large reductions of the reflected echo amplitude. Gradual changes of the crystalline direction have also been observed; one of the plates showed a gradual change of time of flight over a 1" distance that corresponded to a change of 7% in the apparent wave velocity. It is clear that ultrasonic scans are very useful in evaluating the crystalline homogeneity of a cast part.

The integrity of a transient liquid phase bond in nickel based alloys may be judged from its reflectivity to ultrasound. Since the TLPB technique produces a thin bondline with very little chemical and structural changes, a TLPB bond free of unbonded regions and porosity is expected to have a very low ultrasonic reflectivity. This has generally been confirmed by the experimental results obtained in this study. For the bonded CMSX-4 plates, the bondline conditions were examined by conducting ultrasonic scans in the end-on configuration. The transducer used for these scans was a 20 MHz, 1/8" diameter, unfocused immersion transducer. The images were based on the amplitude of the echo reflected from the bondline. Figure 6 shows the end-on scan images of three bonded plates with widely different reflectivity. The top sample had very low reflectivity, the middle sample had moderate reflectivity, and the lower sample had high reflectivity in its central region. Several considerations should be taken into account in the interpretation of the end-on scan images. First, the sidewalls of the plate may have constrained and affected the propagation of the ultrasonic pulse in the end-on scan geometry. Secondly, the size of the beam at the bondline was not expected to resolve small unbonds or pores on the bondline. For these reasons, the presence of a high reflectivity region in the center portion of the lower plate in Fig. 6 does

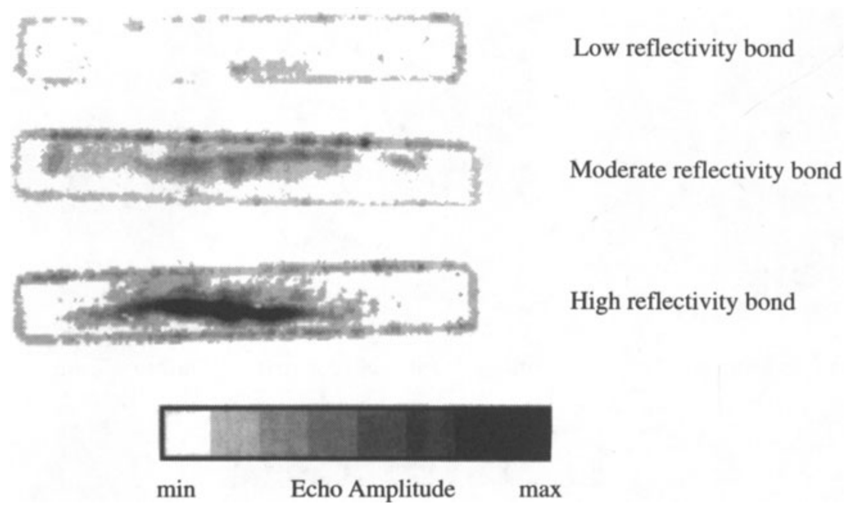


Fig. 6 Ultrasonic amplitude C-scan images of three bonded CMSX-4 plates with different reflectivity for ultrasound.

not necessarily indicate a continuous region of unbond. In fact, this plate has subsequently been sectioned perpendicular to the bondline into five bars. The side surface of the sectioned samples were polished and micrographed. The bondline of the center portion was found to contain some porosity, whereas no pores were found near the outer ends of the plate. Results of the destructive examination were consistent with the ultrasonic reflectivity of the bondlines. These polished surfaces were also etched for crystallographic examination. Etching clearly revealed the dendrites along the crystal growth direction (perpendicular to the bond). The location of the bondline was easily seen because the two sets of dendrites on the two sides of the bond did not line up. Other than having different amounts of porosity, the etched images of the bondline at the center portion and at the outer ends appeared to be very similar.

To further examine the bondline porosity and its distribution, the sectioned samples were machined to remove most of the material on one side of the bondline, with a layer of only 2 mm covering the bondline. A *focused* transducer (20 MHz center frequency, 1/4" diameter) was used to produce a close-up ultrasonic image of the bond plane. The results are shown in Fig. 7. The center portion of the bond again showed high reflectivity over most of the area, whereas the pieces on the outer ends, machined and scanned in the same manner, showed much lower reflectivity. For the high porosity center portion, the sizes of the high reflection features in the ultrasonic image were quite similar to the pore sizes revealed by polished and micrographed cut surface. There was good reason to believe that the resolution of the ultrasonic images in Fig. 7 was beginning to resolve individual pores on the bond plane.

CONCLUSION

Ultrasonic imaging has been proven effective in detecting defects at TLPB bondlines, including voids, inclusions, unbonds, and large angle grain boundaries. Imaging results in a

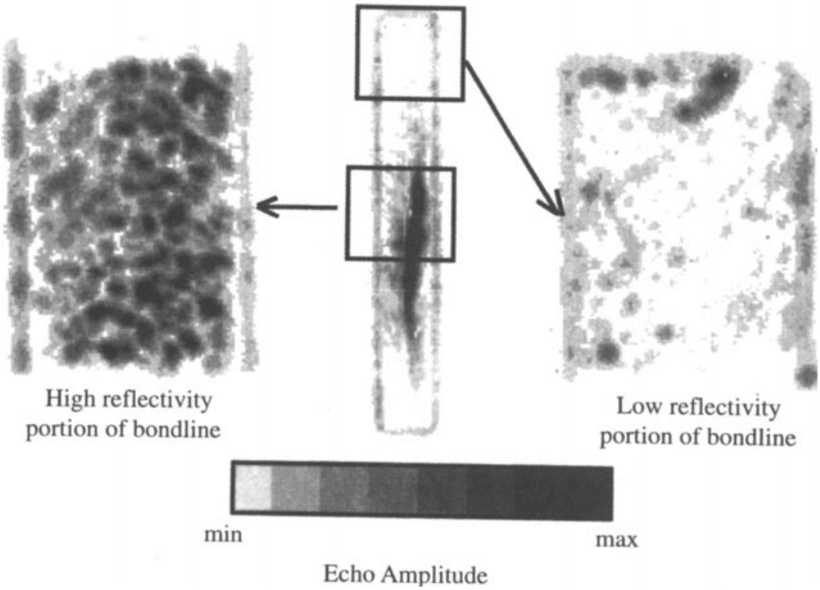


Fig. 7 Close-up scans of small regions (0.37" x 0.52") of the bond plane using a 20 MHz, 1/4" diameter, 2" focal length (in water) transducer through 2 mm of metal.

set of calibration samples showed that #1 flat bottom holes and #1 spherical bottom holes were both detectable at a depth of 1/8" using a 15 MHz focused transducer. Dimensional measurements based on time of flight for internal structures such as channels or grooves were found to be highly accurate, at least to 0.002". The anisotropic ultrasonic velocity played a role in producing elliptical images for the round flat bottom hole defects. The low ultrasonic attenuation in single crystalline CMSX-4 material (resulted in a signal amplitude 4 times greater than in its conventional cast polycrystalline counterpart) was crucial to the high NDE sensitivity achievable in bonded single crystal parts.

Ultrasonic C-scan was found to be very effective in revealing anomalies in CMSX-4 single crystal casts. Boundaries of large crystalline grains and localized spurious crystal growth were easily imaged. Ultrasonic pulse-echo C-scans can be used to map out the reflectivity of a bond plane. Among the bonded CMSX-4 plates tested, higher ultrasonic reflectivity was found to correlate with a higher degree of bondline porosity.

Based on this feasibility study conducted on bonded single crystal plate specimens, ultrasonic measurements can be used for the flaw detection and quality assessment of bonded single crystal components. In principle, the entire ultrasonic inspection process of a single crystal part can be modeled, based on complete crystalline orientation information of the part.

ACKNOWLEDGMENT

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