NOVEL NONDESTRUCTIVE EVALUATION TECHNIQUES FOR INERTIA-FRICTION WELDS IN A SiC-REINFORCED HIGH-TEMPERATURE ALUMINUM ALLOY

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INTRODUCTION

The feasibility of different NDE techniques for evaluating the microstructural characteristics of the heat- and deformation zone (HDZ) of inertia-friction welds produced in a high-temperature discontinuously-reinforced aluminum (DRA) alloy has been investigated. High-temperature DRA composites have been developed for elevated-temperature application in the aerospace industry by incorporating SiC particulate reinforcement into a rapidly-solidified aluminum alloy [1,2]. The DRA composite used in this study was dispersoid-strengthened 8009/SiC/11p made by Allied-Signal Co. The specimens were first cut into 1"-diameter rods from larger extruded billets. These rods were then inertia-friction welded at different axial forces ranging from 89 kN to 156 kN at 5,000 rpm. Generally, the dynamic flow experienced by the outer and inner HDZ microstructures during the welding process greatly affects weld quality (tensile strength, fracture toughness, fatigue strength, etc.). Ultrasonic evaluation of the characteristic shape and size of the HDZ has been previously showed to yield valuable information on inertia-friction welds of aluminum, steel, and copper [3,4]. Similar methods can be readily adapted to the inspections of high-temperature DRA composite welds, too. In addition, the orientation and density of the flow lines at different distances from the interface can be evaluated to reconstruct the formation of the weld. In most cases, flow lines can be visualized only by selectively etching the polished surfaces of metallurgical samples. Because of the usually very weak ultrasonic contrast presented by such flow lines they cannot be nondestructively detected let alone mapped. We shall demonstrate that the discontinuous nature of the silicon carbide reinforcement allows the particulates to align themselves with the local direction of plastic flow during weld formation, thereby presenting an excellent contrast mechanism for ultrasonic mapping of the flow pattern in the HDZ.

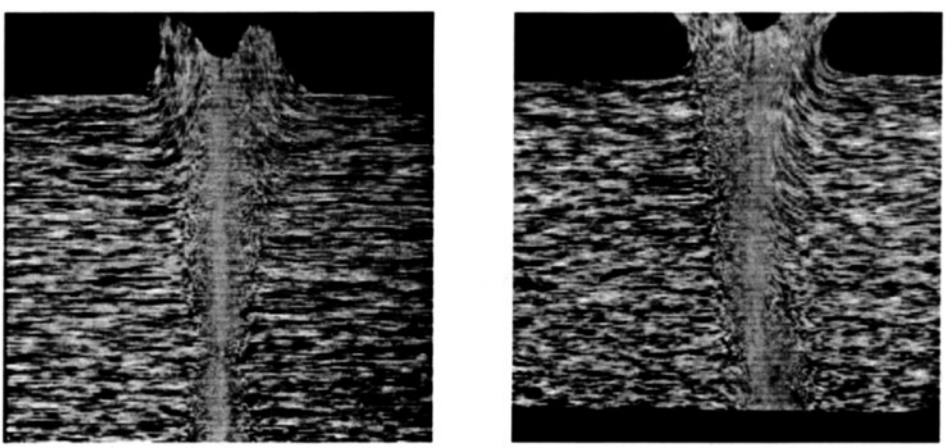
Five NDE techniques were investigated in detail to find the best means to characterize the HDZ: (i) ultrasonic microscopy, (ii) radial ultrasonic backscattering, (iii) radial eddy current measurements, (iv) ultrasonic C-scan imaging, and (v) axial ultrasonic backscattering. These methods will be discussed separately in this order.

ULTRASONIC MICROSCOPY

Figure 1 shows the ultrasonic micrographs of the HDZ for DRA inertia-friction welds produced at axial forces of 112 kN and 156 kN axial forces. Broadband surface wave microscopy was used with a 45 MHz center frequency. This technique [5] differs from conventional high-frequency scanning acoustic microscopy mainly by allowing the separation of the surface wave component from the specular reflection. The micrographs are formed by directly mapping the surface wave amplitude, that is strongly attenuated by inhomogeneities in the specimen. These images clearly show the size and shape of the HDZ. In the base material, the microstructure is preferentially oriented in the axial direction (direction of extrusion). As a result of the substantial plastic flow in the HDZ, the flow lines, and along with them the SiC particulates, turn in the radial direction. Although the main pattern is the same at both forces, the homogenized inner heat-and deformation zone (IHDZ) appears more distinct for the low force while the radial change of the HDZ thickness is slightly more pronounced for the high force.

RADIAL ULTRASONIC BACKSCATTERING

Figure 2 shows the schematic diagram of ultrasonic backscattering measurement from the radial direction. In contrast to the previously discussed acoustic microscopic inspection, for which the specimen has to be cut open and therefore destroyed to study the HDZ, radial backscattering measurements [4] can be performed nondestructively since only



112 kN 156 kN

Figure 1. Ultrasonic micrographs of the HDZ in DRA inertia-friction welds made at two different axial forces (x3.75).

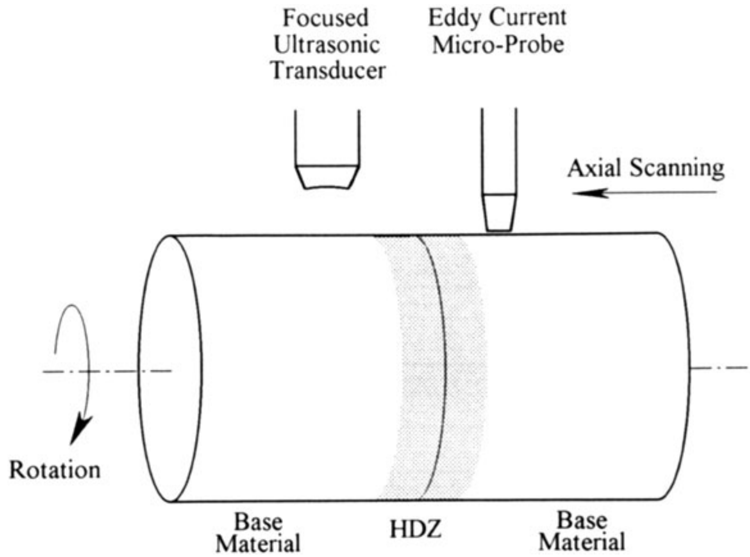


Figure 2. Schematic diagram of ultrasonic backscattering and eddy current conductivity measurements from the radial direction.

the extruded flash has to be removed from the surface of the specimen. A 25-MHz, 1"-focal-length immersion transducer was used to measure the ultrasonic backscattering from a 3-mm-thick region at 4 mm depth below the surface. The transducer is scanned over a length of 1.8" along the axis as the specimen is slowly rotated around a full 360 degrees. As shown in Fig. 1, in the base material the microstructure is preferentially oriented in the axial direction and presents very strong scattering for the radial ultrasonic waves. In the outer HDZ, the flow lines turn in the radial direction and present much weaker scattering. Naturally, the highly homogenized inner HDZ layer causes negligible scattering from any inspection direction. As a result, the HDZ shows up as a weakly scattering region surrounded by the highly scattering base material. Because of inevitable misalignments during welding, the local thickness of the HDZ can change as much as 10% between the thinnest and thickest points separated by 180 degrees. Figure 3a shows the average backscattering profiles for two specimens. The average thickness of the outer HDZ seems to be app. 5 mm and essentially unaffected by the welding force. This is in good agreement with our expectations based on Figure 1. The main changes in the HDZ structure as the welding force is increased are associated with the decreasing thickness of the homogenized IHDZ and the sharpening radial shape of the HDZ, while the thickness of the outer HDZ at the periphery seems to be much less affected.

RADIAL EDDY CURRENT MEASUREMENTS

Radial eddy current conductivity measurements require essentially the same geometrical arrangement used for ultrasonic backscattering (see Figure 2). The main difference is that a small-diameter probe is used to measure the conductivity profile in and around the HDZ at 500 kHz, where the penetration depth is less than 200 μm. Figure 3b illustrates that the electrical conductivity significantly increases in the HDZ, probably because of the preferential orientation of the non-conducting SiC particulates in the conducting matrix. This technique distinguishes a little better between low and high force welds. The thickness of the high-conductivity band slightly decreases from 8 mm to 7 mm with increasing force. The larger overall values are partly due to the larger (approximately

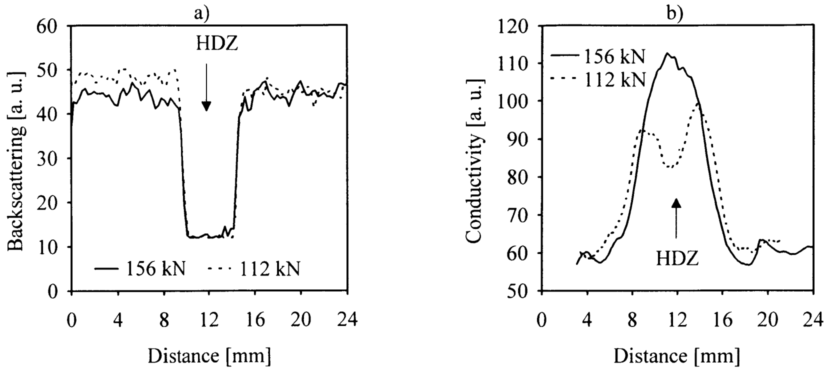


Figure 3. Average ultrasonic backscattering (a) and eddy current conductivity (b) profiles for two specimens.

2-mm-diameter) probe compared to the much smaller (0.3-mm-diameter) focal spot of the ultrasonic transducer. In addition, the eddy current probe measures the width of the HDZ at the periphery, where it is 20-30 % wider than at 2/3 of the radius, where the ultrasonic measurement is taken. Eddy current inspection also reveals the presence of a somewhat less conducting IHDZ around the bondline in the low-force weld. It is probable that the corresponding layer in the high-force weld is simply too thin to be resolved by our eddy current probe.

ULTRASONIC C-SCAN IMAGING

Figure 4 shows schematically the cross sectioning of the HDZ for ultrasonic C-scan imaging. A 25-MHz, 1"-focal-length immersion transducer was used to map the ultrasonic backscattering from different depths. 0.1-μs-long gating was used, that corresponds to app. 0.36 mm layer thickness. Figure 5 shows the ultrasonic images of the flow patterns 0.18 mm

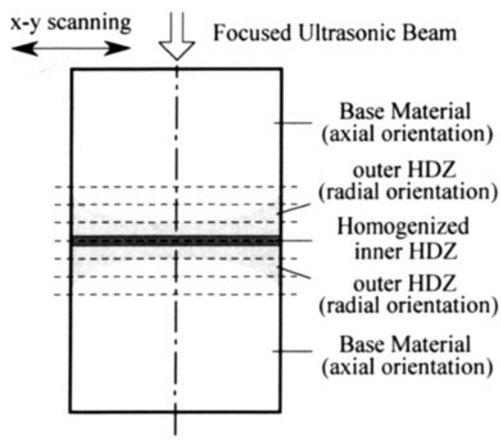
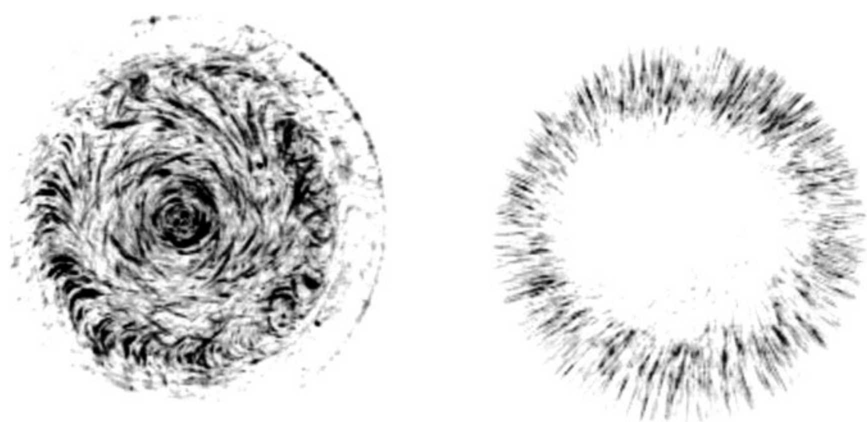


Figure 4. Cross sectioning of the HDZ in ultrasonic C-scan imaging.

above and below the bondline in the 156 kN specimen. Naturally, the rotation directions are opposite on the two sides of the bondline. The flow lines are very strong and their spiraling indicates an increasing radial velocity at the periphery of the weld. Figure 6 shows the ultrasonic images of the flow patterns at and far away from the bondline in the same specimen. The thickness of the homogenized inner HDZ layer cannot be fully resolved at this frequency. Although there is a perceivable reduction in the strength of the scattering, fragments of the nearby flow lines from both above and below the thin homogenized IHDZ are also apparent. Far away from the bondline, flow lines are observed only at the periphery of the weld. This could be expected since the HDZ thickness is much larger there than at the center. The characteristic shape of the flow pattern greatly varies with changing welding force. Figure 7 shows the comparison between high and low force specimens 0.54 mm away

-0.18 mm +0.18 mm

Figure 5. Ultrasonic images of the flow patterns 0.18 mm above and below the bondline in the 156 kN specimen.



at the bondline -1.08 mm

Figure 6. Ultrasonic images of the flow patterns at and far away from the bondline in the 156 kN specimen.

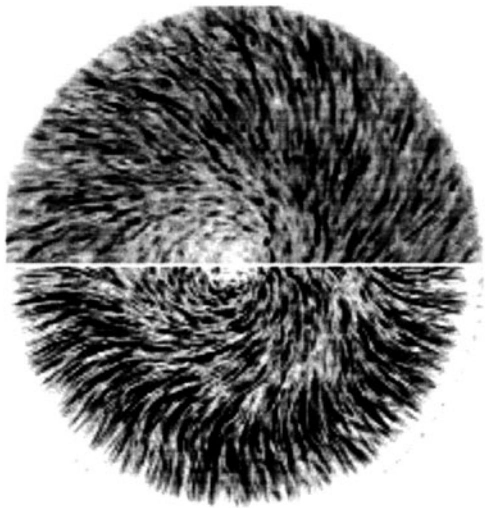


Figure 7 Comparison of the flow patterns in high and low force specimens.

from the bondline. At high welding force, the flow lines are essentially radial at the periphery. In comparison, at low welding force, the flow lines are less outward oriented and maintain an azimuthal component even at the periphery. The flow angle appears to be very sensitive to the welding force, therefore it is a primary candidate for quantitative characterization of the dynamics of weld formation.

AXIAL ULTRASONIC BACKSCATTERING

The previously described ultrasonic C-scan imaging technique provides a detailed map of the radial distribution of the flow pattern in different cross sections of the HDZ at varying distances from the bondline. The corresponding axial distributions at varying radial distances from the axis also contain valuable information on the HDZ structure, but are less readily obtainable from these images. The axial distribution can be more easily measured by considering the average backscattered intensity from a small region rather than resolving individual flow lines within that region. This quantity can be determined as a function of depth at any radial position by simply rotating the specimen and averaging the measured ultrasonic intensity. As an example, Figure 8 shows the averaged axial backscattering profiles from the 156 kN specimen at eight different radial distances from the axis at 25 MHz. Since rotation of the specimen does not involve any motion at the axis, we cannot get an average profile exactly at the center. Close to the center, the HDZ is very thin and the homogenized IHDZ is, although perceivable, not fully resolved. Farther away from the axis, the HDZ becomes much thicker and the weakly scattering homogenized IHDZ at the bondline becomes more visible. The overall thickness of the HDZ appears to be lower than the roughly 5 mm determined from the radial scattering measurements. This is because scattering is highly oriented in directions normal to the flow lines. Radial scattering indicates the outer thickness of the HDZ, where the flow lines start to turn away from the axial direction. In contrast, axial scattering indicates the inner thickness of the HDZ, where the flow lines start to turn away from the radial direction. Between these two limits the flow lines are neither parallel nor perpendicular to the axis. This distinction between the

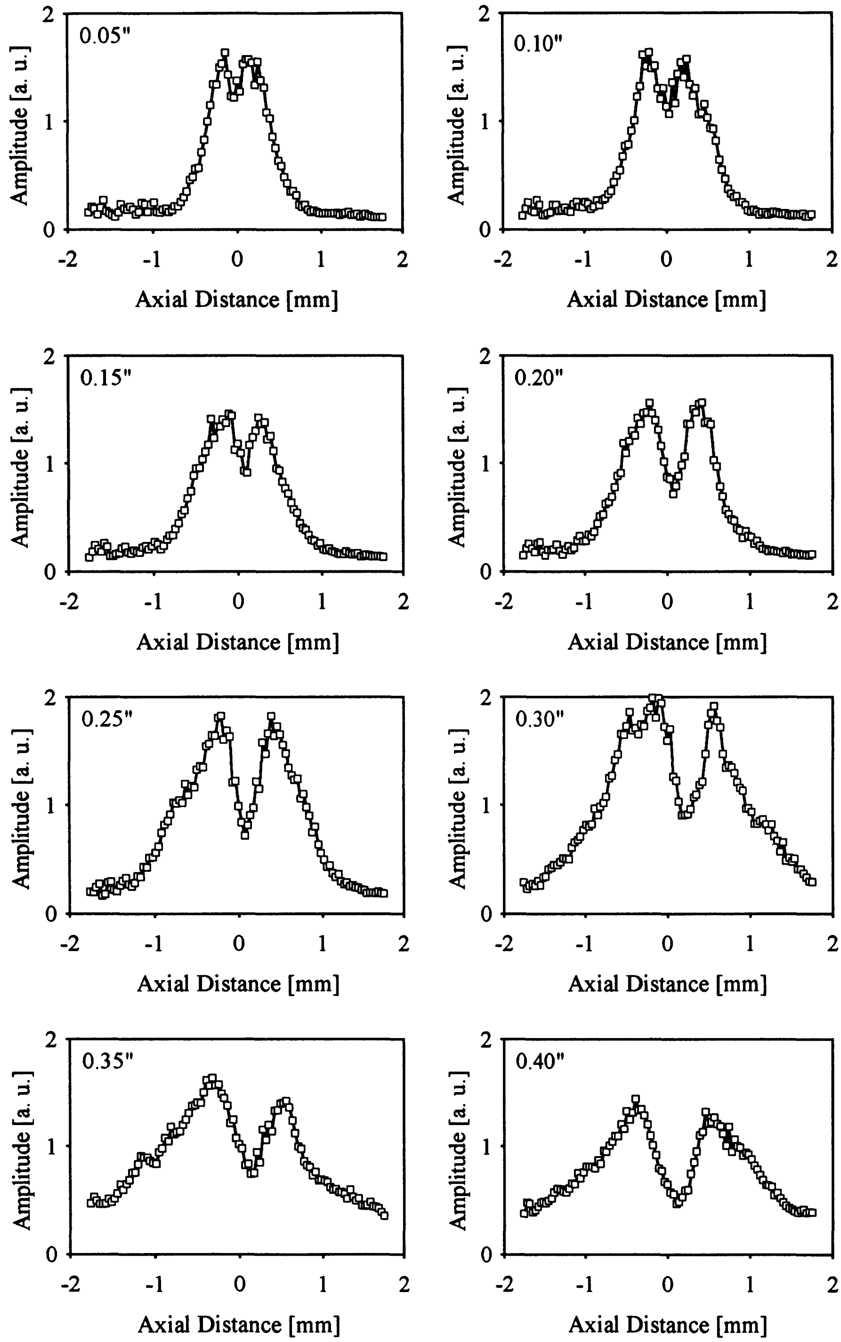


Figure 8 Averaged axial backscattering profiles from the 156 kN specimen at eight different radial distances from the axis at 25 MHz.

scattering profiles obtained from the axial and radial directions allow us to characterize the HDZ in more detail.

CONCLUSIONS

Five different NDE techniques were investigated to find means to characterize the microstructure of the heat- and deformation zone of inertia-friction welds produced in high-temperature discontinuously-reinforced aluminum. Ultrasonic microscopy based on surface wave attenuation provides a detailed picture of the microstructure, but requires direct access to the cross section to be imaged. Radial ultrasonic backscattering can measure the thickness of the outer HDZ at the periphery if the flash is removed. Eddy current conductivity measurements in a similar geometrical configuration provide more detailed profiles of the inner and outer HDZ at the periphery at the expense of greatly reduced penetration depth. Ultrasonic backscattering measurements from the axial direction clearly revealed evolution of the microstructure across the weld HDZ. The unusually strong scattering appears to originate from a heterogeneous and directionally-oriented microstructure that is deformed in a radially outward direction during the inertia-friction welding process. Ultrasonic C-scan imaging provides a detailed picture of the dynamic flow experienced by the outer and inner HDZ microstructures during the welding process, such that the characteristic shape and density of the flow lines at different distances from the interface can be evaluated to reconstruct the formation of the weld. Finally, axial ultrasonic backscattering allows the effective examination of the main features of the flow pattern and the shape and size of the outer and inner HDZ.

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