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Ultrasonic Evaluation of Friction Stir Welding *

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Abstract: Friction stir welding (FSW) is a new welding technology, which has been applied widely in aerospace, traffic, marine, etc., industries because of its unique mechanical properties and metallurgic structure. It is common importance to find effective nondestructive evaluation technique for FSW because design and manufacturing technology need data as input. A new ultrasonic method, which is based on multiple-incident angle reflection at welds by using spot-focused beam, for evaluation of defects in aluminum alloy FSW has been investigated. The relationship of incident angles and possible directions of defects in FSW with reflective coefficient R has been used to analyze and estimate scanning incident angle range of probe beam. Optimum ultrasonic reflection direction can be obtained during the scanning by using multiple-incident angle method. It is helpful to improve detectability of defects in FSW. The experiment results presented in this paper show that ultrasonic evaluation based on multiple-incident angles by using C-scan technique is an effective nondestructive inspection for FSW. The validity and agreement of the A-scan and C-scan results are validated by a strict destructive testing.

Keywords: Friction stir welding, Ultrasonic evaluation, Multiple-incident reflection

1. Introduction

With increasing applications of friction stir welding (FSW) in aerospace and aviation, traffic, marine, etc., industries the characterization and nondestructive evaluation of defects become one of focal problems because both design and welding need data as input for optimization. Quality control requires a reliable nondestructive evaluation and inspection (NDE&I) for FSW [1, 2]. It is necessary to find effective NDE&I techniques for FSW because of its distinctly different characteristics of the welding zone and defects caused in welds. A few references reported their preliminary investigations on NDE&I methods of FSW [3, 4, 5]. Ultrasonic evaluation method is a potential approach for FSW because defects in FSW will affect uniformity of weld zone, thus, resulting in variation of probe ultrasound propagation. One of the ultrasonic evaluation mechanisms is based on ultrasound reflection at weld defect. It is common awareness of dependence of ultrasonic reflection on orientation of reflectors. In FSW defects usually have complex characteristics in sizes and orientations. So, it is needed to develop effective ultrasonic techniques for finding possible weld defects in FSW. A high resolution ultrasonic NDE&I technique for FSW based on multiple incident angles has been presented in this paper.

2. Multiple incident angle ultrasonic method

The main idea of ultrasonic evaluation method is based on probe ultrasound reflections at reflectors. It is normal rule that the amplitude(s) of reflected echo(es) is(are) dependent

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on properties of reflector(s), orientation(s) of reflector(s) to probe beam as well as the effective reflecting area of reflector(s). Theoretically, defects in materials or welding zone give the effective reflectors for probe ultrasound when a reasonable incident beam is employed. Therefore, it need to keep in one's mind that the possible directions or orientations of defects to be found. It is very important guide for choosing an ultrasonic evaluation method.

Ultrasonic oblique incident method is the popular technique for NDE&I of melted welds because weld defects provide effective reflectors for a reasonable ultrasonic angle beam. Usually a probe beam with fixed angle is used because the directions and orientations of defects in melted welds are not so complicated. But in FSW the situation is much complicated because of particularity and diversity of weld defects. It is difficult to obtain an optimal reflection for all possible types of defects in FSW by using a fixed incident angle beam. Therefore, a multiple-incident angle ultrasonic method is developed to find defects in FSW. The principle of the multiple-incident angle ultrasonic method is illustrated in figure 1. The angle of incident ultrasonic beam can be changed by using a special designed ultrasonic transducer system. The incident angle θ of probe beam varies with the rotation of employed transducer during scanning or a series of probe beams with different incident angles are selected to scan friction stir weld. In this case a flexible refracted probe beam can obtained for ultrasonic evaluation of defect in friction stir welds (see Fig.1).

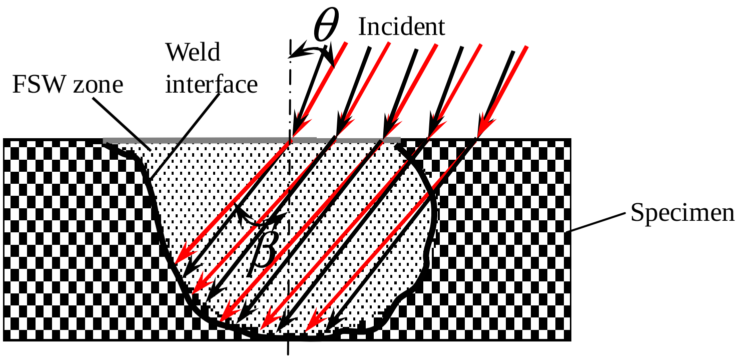


Figure1. Illustration of formation of multiple incident ultrasound probe beam

Change of incident angle may have an effect on ultrasonic wave reflection at defects. Figure 2 gives the estimation of ultrasonic reflection coefficient R varying with incident angle in aluminium alloy. The coupling media is supposed to be water. For transverse wave the R will decrease from 0.70 to 0.68 when incident angle increase from 15° to 26°. The change in R is rather tiny. So, it can ignore the effect of incident angle on ultrasonic reflection in this case.

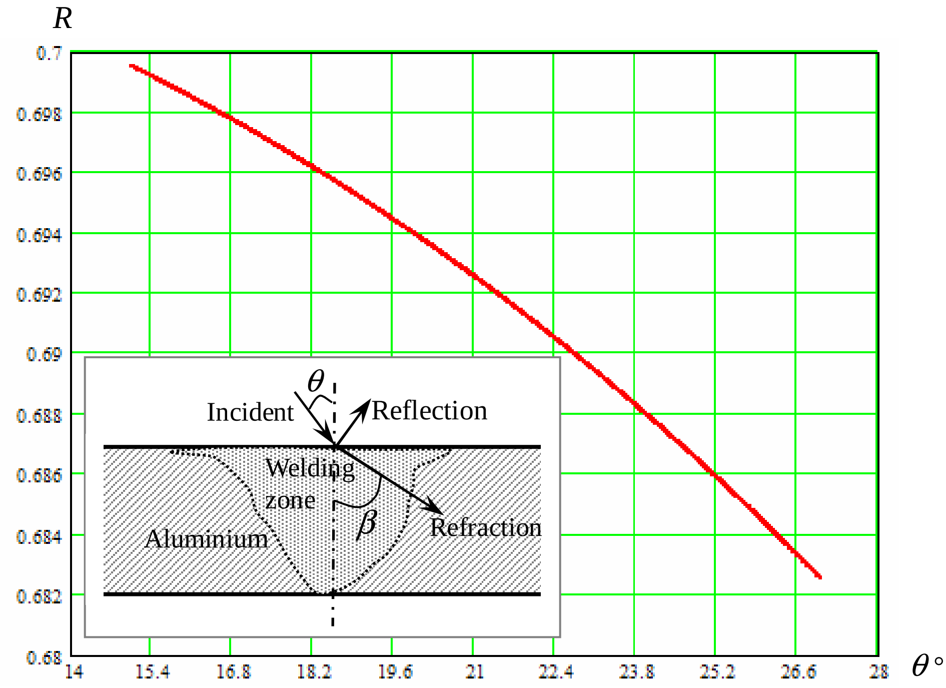


Figure 2. Estimation of the effect of incident angle on reflection coefficient

3. Experimental setup and specimens

Figure 3 give the illustration of employed ultrasonic scanning system with multiple-incident angles, which was designed by Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI). It consists of ultrasonic transducer with high resolution, ultrasonic unit, data acquisition, imaging and control unit and multi-axes mechanical system. The incident angle of probe ultrasonic beam can be changed under the control of the scanning system as required. A special software-electronic gate technique is designed for constructing T-scan (a series of C-scan) and B-scan images in the signal acquisition. An high resolution ultrasonic focal transducer is employed. Its focal spot is 0.5mm. Its frequency is 5MHz.

A series of FSW specimens are prepared in our investigations. The materials of specimen are aluminium alloy. Their thickness cover 1 mm up to 20 mm. no man-made defects are induced in the specimens. So, the quality of specimens is associated with welding process and parameters.

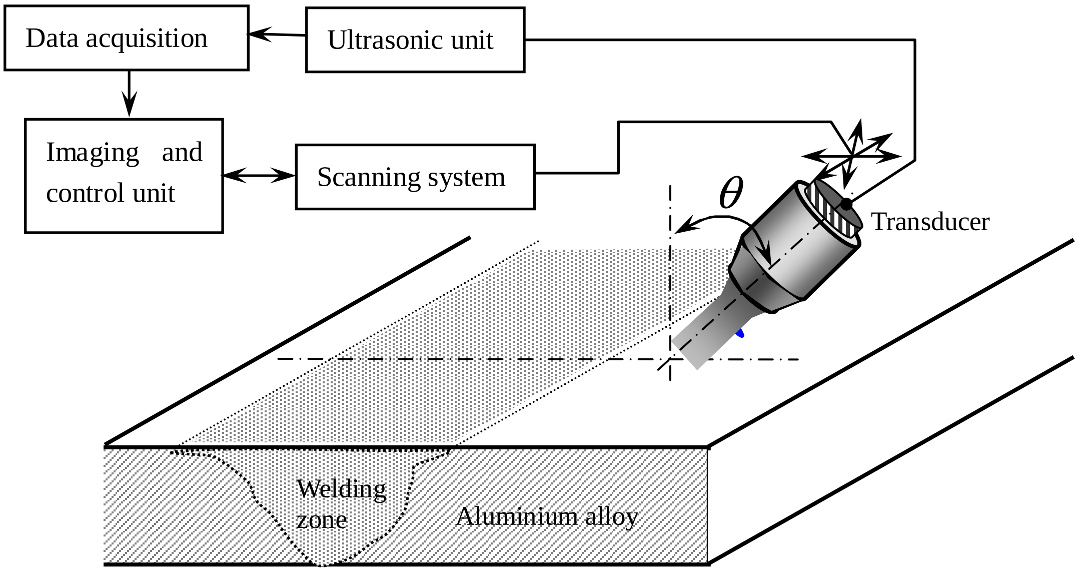


Figure 3. Experimental setup of the ultrasonic scanning system with multiple incident angles

4. Results and analysis

Figure 4(a) is a typical ultrasonic echo pulse patterns from specimen No.2. Thickness of the specimen is 3mm. The incident angle corresponding to the result is 16°. Echo pulse ***I*** is from ultrasonic reflection at specimen surface of weld zone. No distinct echo pulses resulting from reflections at the weld zone are seen in figure 4(a). It is believed that the weld zone corresponding to echo signal is free of defect. This assumption is supported by a destructive testing. Figure 4(b) is an optical micrograph of the cross-section. No defects are found in it besides the friction stir prints, as the one of them marked by the white arrowhead in figure 4(b). The tiny echo pulse ***F*** may come from the probe ultrasound reflections at these friction stir prints.

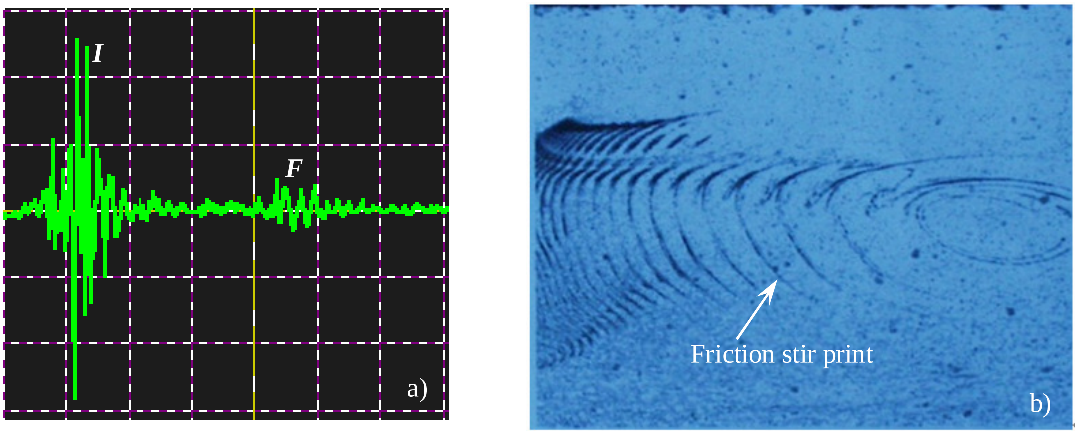


Figure 4. Typical echo pulse pattern and optical micrograph of specimen No.2. (a) Echo pulse pattern, (b) Optical micrograph in cross-section (×20)

Specimen No.1 was scanned by using the experimental setup. Thickness of the specimen is 2.7mm. The material is aluminium alloy. A defect was found in the specimen according to the echo signals from the welding zone, as marked in figure 5(a). Figure 5(b) is a typical echo pulse pattern from the marked weld zone with defect. The incident angle is 16°. Echo pulse signal ***D*** is believed from ultrasonic reflection at defect in the marked weld zone. It is supported by the optical micrograph in figure 5(c), which is the cross-section of the marked weld zone with defect (see figure 5(a)). A defect in the cross-section is seen well in figure 5(c), as the dark spot showed by the arrowhead. The echo signal ***D*** resulting from the defect is very strong at the incident angle 16° although is the defect is very small.

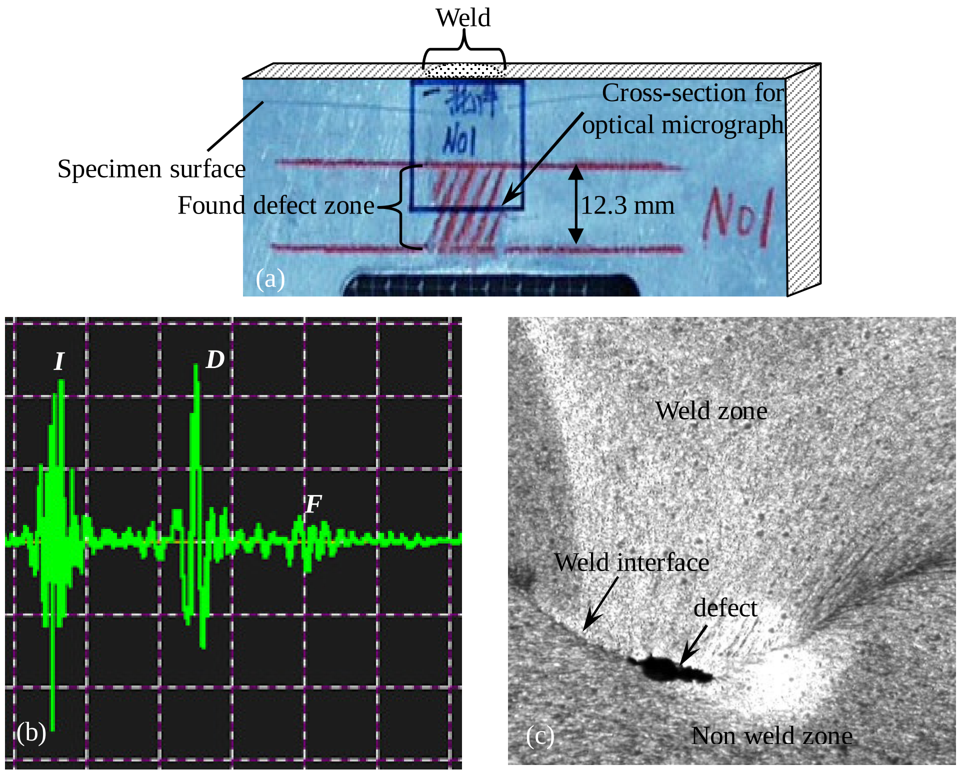
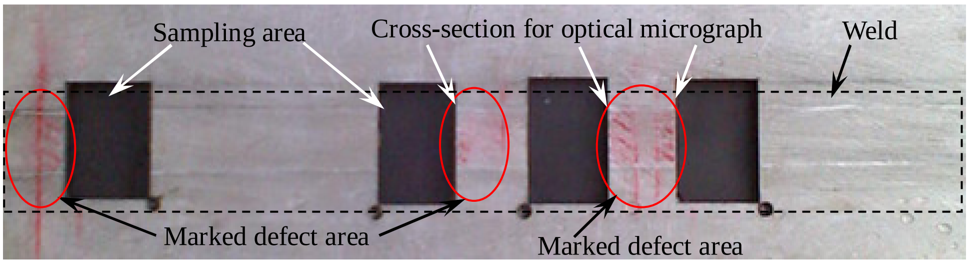
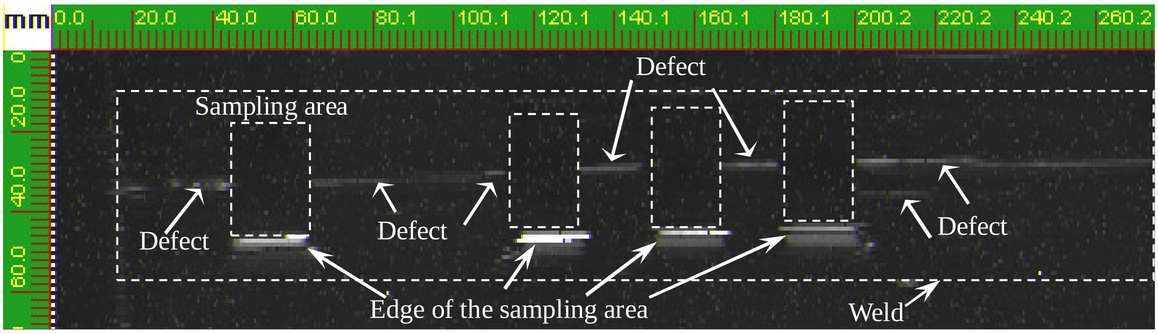


Figure 5. The found defect zone and its typical echo signal as well as optical micrograph. (a) The found defect zone in specimenNo.1, (b) Typical echo signal from the found defect zone marked in (a), (c) Typical optical micrograph of the marked cross-section in (a) (×25)

Figure 6(a) is the photo of specimen No.1. Four marked weld zones were cut for optical micrograph checking validity of A-scans. One of the results is presented in figure 5(c). Then the weld in specimen No.1 was scanned by using the established ultrasonic scanning system. A C-scan is presented in figure 6(b). The scanning direction is along weld. The defects are showed well in figure 6(b), as the white lines marked by the white arrowheads. It is clear that the defect runs through the whole weld besides the four sampling areas for optical micrograph. The edges of the four sampling areas also can be seen well in the C-scan. It also shows a good agreement with the results in figure 5.



(a) A photo of the specimen No.1



(b) C-scan of the weld in specimen No.1

Figure 6. Weld in specimen No.1 its C-scan

4. Conclusion

(1) Optimum ultrasonic reflections at defects in aluminium alloy FSW can be obtained by using multiple-incident angle ultrasonic method. Theoretical estimation shows that effect of incident angle on reflection coefficient is very tiny.

(2) The echo signals resulting from welds show a good detectability to small weld defect. And the validity and agreement are validated by a series of strict destructive testing.

(3) The ultrasonic C-scan technique provides full visualization of the defect in friction stir welds.

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