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Nondestructive Ultrasonic Inspection of Friction Stir Welds

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Abstract

Friction Stir Welding (FSW) is a relatively new solid-state welding procedure developed at The Welding Institute (TWI-UK) and the technique is widely employed for welding aluminum alloys in various applications. In order to examine the quality of the welds and to detect a variety of welding flaws such as wormholes and root-flaws, it is required to develop a methodical inspection technique that can be used for the identification and localization of such defects. The most prevalent and risky defect in this type of welding is the barely visible root flaw with a length varying from 100-700 µm. Due to the extreme characteristics of the flaw, off-the-shelf ultrasonic weld inspection methods are not always able to readily detect this type of minute defect feature. Here, we propose a novel approach to characterize root flaws using an oblique incident ultrasonic C-scan backscattering analysis. The implementation consists of an immersion ultrasonic testing method in pulse echo (i.e. backscatter) mode with a 3.5 MHz transducer, and makes use of an empirical procedure to engender of a shear wave dominated excitation at the root surface, and to properly gate the received signal for root flaw examination. By scanning the surface above the welded component, a C-scan image displaying the backscatter response from the root surface of the nugget zone can be obtained which allows a simple interpretation of the root flaw status of the weld.

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Keywords: Friction stir welding; Immersion ultrasonic testing; Bacscattering method; Lack of penetration defect; Kissing bond; Root flaw

1. Introduction

High strength aerospace alloys such as the 2XXX and 7XXX series are unweldable using either Gas Tungsten Arc Welding (GTAW) or Gas Metal Arc Welding (GMAW) due to concerns about hot-cracking. To solve this issue, The

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Welding Institute (TWI-UK) has introduced a method called Friction Stir Welding (FSW). In this joining technique, an inconsumable rotary tool plunges into the two metals' faying surfaces and stirs them as the tool traverses along the weld path. This solid-state welding procedure softens the metal components by the heat generated by friction of the tool's shoulder and probe with the workpiece (Mishra & Ma, 2005; Nandan, Debroy, & Bhadeshia, 2008).

Imperfections in the FSW procedure or the presence of material inhomogeneities, may lead to welding flaws. Root-flaws are one of the prevalent defects in the friction stir welded components. They may be caused by insufficient probe penetration which may generate partially open cracks and/or kissing bond defects. The presence of root flaws thus result in a degradation of the material properties of the welded metal. Therefore, two independent approaches should be exploited for avoiding these kind of defects in welded components including (1) the optimization of the welding parameters in terms of tool design, rotation and travel speed, and (2) the development of nondestructive testing and evaluation techniques for the quality assurance of welded structures (Ji et al., 2013; Zhou, Yang, & Luan, 2006).

Several nondestructive testing techniques, including ultrasonic phased array and eddy current methods, have been reported for the inspection of friction stir welded structures. Nevertheless, it is still an ongoing research topic to unearth an appropriate and a reliable inspection method (Bird, 2004; Mandache, Levesque, Dubourg, & Gougeon, 2012; Rosado et al., 2014).

The present paper reports on the results of a research study that was conducted to evaluate the utility of a modified ultrasonic inspection method for root flaw detection. This paper is organized as follows: section 2 provides details on the ultrasonic measurement set-up and the measurement procedure. The third section discusses the data analysis results and conclusions are given in section 4.

2. Ultrasonic measurement system and measurement procedure

Ultrasonic immersion measurements on 7XXX aluminum alloys were carried out using a 3.5MHz planar transducer in backscattering mode. The measurement system is equipped by an automated 3-axis scanner to perform an oblique incident backscatter C-scan measurement above the sample. The incidence angle of the emitter/receiver is fixed to an angle larger the longitudinal critical angle in order to select only shear propagating waves in the plate, which are known to be more sensitive to damage than longitudinal waves, and which simplify the interpretation.

In order to assure the acquisition of a shear wave reflection from the back wall of the sample, one can calculate the transducer's vertical offset distance to the workpiece based on the shear velocity, thickness, incidence angle and Snell's law. Though, because of uncertainties of the material parameters and measurement errors in the system, the calculated offset distance is not always coincides with the true value. Therefore, an empirical approach to determine the accurate vertical offset distance was implemented by performing a vertical scanning of the sample. In this approach, two identical Panametrics transducers were employed in a pitch-catch mode (same fixed incidence angle for emitter and receiver, same distance from the plate surface). The maximum amplitude of the received echoes, plotted as a function of the vertical offset distance, is shown in Fig. 2 . The last peak (with the highest amplitude, corresponding to the highest offset value) corresponds to a direct reflection from the upper surface. The second last peak then corresponds to the direct back-wall reflection. Using this knowledge, the measurement system can automatically adjust the vertical distance to the plate surface for the C-scan evaluation to the second peak's vertical position.

Fig. 1. Immersion ultrasonic measurement set-up.

After having set the incidence angle and vertical offset, oblique incident backscatter C-scan measurements were carried out on a number of the friction stir welded samples. The C-scans, consisting of A-scans over a 2D surface, were performed using pulse-echo mode with a 3.5MHz frequency transducer. The signals were generated and received by means of Panametrics pulser-receiver and digitized using a NI PXI 5122 data acquisition card. The entire measurement system, including the analysis of the recorded signals, is controlled by LabVIEW.

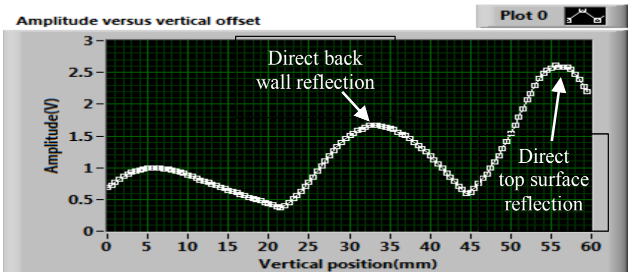

Fig. 2. Vertical scanning measurement on the weld metal to determine the ideal vertical offset to the plate and assure the acquisition of the back wall reflection.

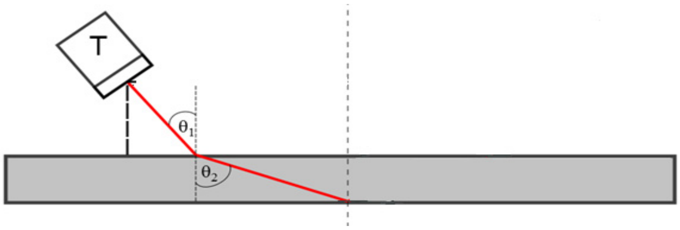

Fig. 3. Schematic representation of the ultrasonic immersion measurement set-up using a pulse echo mode for the sample analysis. The transducer/receiver is denoted by T. The vertical offset and the incidence angle remain fixed during the entire C-scan.

3. Results

As a result of the friction stir welding process, the parent material microstructure changes drastically, resulting in fairly different microstructures for the nugget zone, the Thermo-Mechanically Affected Zones (TMAZ), the Heat Affected Zone (HAZ) and the base metal. The nugget zone (central zone of the weld) constitutes the region of interest for the weld inspection. This is the primary region where root-flaws may occur.

In the analysis of the C-scan data, each A-scan signal was first gated based on the pitch-catch arrival time. It was then processed to obtain the energy in the entire frequency band, according to the equation below:

$$P(x,y) = \frac{1}{N}\sum_{f=0}^{F_N} PSD(f) \quad (1)$$

where $PSD(f)$ denotes the Power Spectral Density, and F_N is the Nyquist frequency which is 50Ms/s in our evaluation. $P(x,y)$ is a pixel value of C-scan image in each position along and from the weld centerline.

Fig.4 illustrates the C-scan image of a 7XXX butt-welded joint. The vertical and the horizontal axes represent the distance from and along the weld centreline, respectively. To guide the eye, one can observe two horizontal dark lines representing the Thermo-Mechanically Affected Zones (TMAZ). The region between the horizontal TMAZ lines corresponds to the nugget zone. The width of the nugget zone has been marked on the image and depends on the probe's diameter. As can be observed from Fig.4, the TMA zones give rise to the highest PSD values due to its elongated and coarse grain morphology compared with the other microstructures of the friction welded sample (Hatamleh, 2008). If no defects are present in the weld, the PSD values in the nugget zone are substantially lower.

However, for this sample, we can also observe distinct marks with high PSD values inside the nugget zone, which correspond to elevated amplitudes of the backscattered echo by small root-flaw defects.

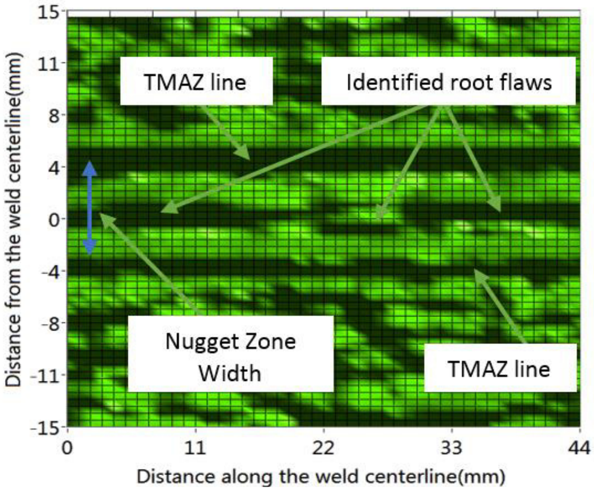

Fig. 4. Top view of the PSD analysis of oblique incident C-scan measurements for a welded 7XXX alloy sample.

4. Conclusion

The results of this original approach confirm that oblique incidence C-scan measurements, implementing an empirical focusing method rather than a theoretical calculation for the vertical offset distance adjustment, in addition to an appropriate timing gate and a suitable data presentation, could be a reliably technique to be used for the inspection and interpretation of root-flaws of friction stir welded components.

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