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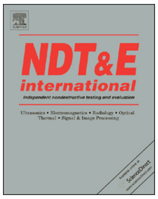

Non-destructive ultrasonic examination of root defects in friction stir welded butt-joints

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ABSTRACT

As a solid-state welding process, Friction Stir Welding (FSW) offers a variety of advantages over traditional welding processes. Problems that are typically occurring due to the cooling of the liquid phase, such as solidification cracking and formation of porosity, generally do not occur in FSW. Nevertheless, as a result of suboptimal settings of the welding process parameters and certain uncontrollable conditions, FSWs are still associated with a number of specific flaws, e.g. root flaws and wormholes.

Ultrasonic non-destructive testing and evaluation techniques (NDT&E) can be used for quality assessment of friction stir welded joints. In this paper, a novel approach for the detection of root flaws is proposed using an immersion ultrasonic testing method in oblique incidence and backscatter mode. The backscattered energy C-scan images obtained after an empirical positioning and proper time gating can be straightforwardly interpreted by direct comparison with typical 'flaw' patterns, allowing for identification and localization of the root flaws in the weld. The method is illustrated for FSW butt joints of the AlZnMgCu (7XXX series) alloy.

1. Introduction

After the major advances in arc welding technology during the 1930s, it took another 60 years to establish a new joining technique, called Friction Stir Welding (FSW). FSW is a solid-state joining process invented by W. M. Thomas at The Welding Institute (TWI-UK) [1,2]. The FSW process is based on heat generated by a non-consumable rotating tool that is plunged into the faying surface of two samples until the shoulder touches the surface of the samples, and then traverses along the joint line of the work-pieces (see Fig. 1) [3]. Primary sources of the heat generated during the process are friction between the work-piece and the rotating tool shoulder, and adiabatic heat transfer within the material [4,5]. The local increase in temperature softens the material and induces plastic deformation in the solid-phase. There is no weld pool in the friction stir welding anymore. Till now, numerical and empirical investigations to thoroughly understand the heat transfer and material flow phenomena in the FSW process are still ongoing [6,7].

FSW was initially used for aerospace aluminum alloys, because of their low arc weldability, e.g. on AlCu type (2XXX series) and AlZnMgCu (7XXX series) alloys [4,8,9]. The mechanical properties of the arc welded joint in these alloys can be seriously compromised by a dendritic structure formed in the fusion zone [9,10]. In recent years, attempts have been made to join other dissimilar metals like Al–Ti [11,12], Al–Cu [13,14], Al–Steel [15] and Al Matrix Composites (AMCs) [16] using FSW. Currently, the method is being used in a broad range of industrial applications including aerospace, automotive, pressure vessel construction, shipbuilding and offshore construction.

While the parent material of Al-alloys generally contains pancake-shaped grains with nonequiaxed subgrains inside [17], the FSW process creates three distinctive regions in the weld zone. These are known as the Heat-Affected Zone (HAZ), the Thermo-Mechanically Affected Zone (TMAZ) and the dynamically recrystallized zone (DXZ) around the weld center [10]. The DXZ, which is often also referred to as the nugget zone [18], is characterized by a fine grain equiaxed structure. However, variations in the grain size may occur going from the bottom to the top of the weld zone due to the temperature profile and the heat dissipation in the nugget zone [4]. Mishra et al. also proclaimed that the grain size may be influenced by other welding parameters, by the parent material composition, the geometry of the tool and others [4,19]. According to Cabibbo et al., the average grain size of the nugget zone is finer than the parental material in 6XXX aluminum alloys by a factor of approximately 40 [20]. Unlike the nugget zone, the HAZ has not

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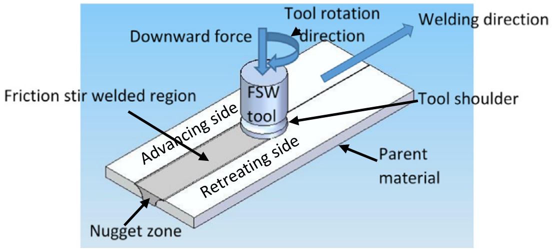

Fig. 1. Schematic drawing of the friction stir welding procedure.

been mechanically disturbed by FSW, but only thermally. Therefore, this zone retains an approximately similar grain morphology as the base metal [20]. Finally, the TMAZ is the transition zone between the base metal and the nugget zone. It can be distinguished by a highly deformed structure with elongated grains [18,21]. As a result, an upward flowing pattern of elongated grains (relative to the parent plate) can be observed around the nugget zone in the TMAZ [4,17,22]. Di Paola et al. have shown that there is a significant difference in dislocation density between the TMAZ and the nugget zone, the concentration being low in the crystallized zone compared to the non-recrystallized region [22]. In addition, Cabibbo et al. extensively reported that the pattern of the grain flow on the retreating side is much larger and broader than that on the advancing side [20]. Furthermore, Kadlec et al. recently showed that the interface boundary between the TMAZ and the nugget zone on the advancing side is more distinct than on the retreating side since the tool displacement and the torsion speeds are enforcing each other on the advancing side [23]. Note that “the advancing side” is the side of the tool where the local direction of the tool surface due to the tool rotation and the welding direction are in the same direction, whereas they are in the opposite direction along the retreating side (see Fig. 1).

In contrast to traditional welding procedures, FSW can successfully avoid solidification flaws such as porosity and hot cracking in the weld region due to the solid-phase characteristics of the joining procedure [8,24]. However, other flaws, such as lack of penetration (LOP), wormholes (tunnel defects), kissing bonds and lazy S features (also called zigzag line defect, Joint Line Remnant (JLR) or entrapped oxide defect) are common in FSWs [3,25]. The latter mostly occurs due to the presence of a continuous oxide film in the weld zone coming from an initial oxide layer on the butt surfaces [26–29]. When the entrapped oxide film is connected to the root of the friction stir welded joints, the lazy S features are called kissing bonds, weak bonds or root-flaws [8,25,27,30,31]. Material properties, tool design [32,33] and critical operation parameters (including rotation and translation speed [34], tool plunge depth, spindle tilt angle, forge force and fixture clamping condition) play an important role in the formation of flaws and in the quality of the [8,25,27,35–38]. Welding conditions such as insufficient tool plunge depth, low tilt angle and insufficient heat-input may result in the formation of kissing bond flaws at the weld root [8,25, 27,30]. LOP defects, on the other hand, occur when both sides of the root region are not properly forged. In this case, the original parent metals of the faying surfaces of the butt-joint root region are still undisturbed and the defect is parallel to the faying surface [39]. Additionally, kissing bond defects might originate from the tip of LOP defects. In more general terms, Arbegast has identified defects in FSWs as either flow-related (e.g. wormholes and surface galling) or geometry-related (e.g. LOP and lack of fusion (LOF) defects) [35].

Defects in FSWs, particularly root flaws exceeding a certain size, may have an adverse effect on the mechanical properties and fatigue resistance of the friction stir welded joint components. Bending loading may cause a LOP defect containing welded joint to break in a brittle manner, whereas the joint more likely will develop surface cracks in the presence of a kissing bond defect at the root [27,40]. Furthermore, kissing bond flaws are preferred sites for macrocrack initiation [23,30,41–46], thereby reducing the strength properties of the material. In view of achieving defect-free welded joints, further optimization of the FSW control variables is important [47–53]. On the other hand, high level quality assurance techniques need to be developed and implemented to assess potential defects in the welds due to uncontrollable variables, e.g. slight thickness variation or material heterogeneity and/or the uncertainty in other welding parameters [54]. Common non-destructive techniques include fluorescent penetrating fluid inspection [55], ultrasonic testing, acoustic emission [56], X-ray [57], eddy current, magnetic methods [58], and ultrasound-excited infrared thermography [59]. Many of these conventional non-destructive testing (NDT) methods can be easily used for the detection of volumetric faults (tunnel defects and voids). However, in many cases, they are insensitive and sometimes impractical for the more challenging root flaws [8,55]. For instance, in order to obtain satisfactory results, the fluorescent penetrating fluid inspection method requires access to the back side of the butt-joint structure [55]. Digital X-ray radiography and lock-in infrared thermography have been exploited to examine sub-surface tunnel defects in FSW joints [60,61]. LOP defects can only be detected using radiographic inspection, if their size is greater than or equal to 30% of the material thickness [62]. In recent years, eddy current NDT of FSW root flaws has been reported [63–65]. Santos et al. have stated that eddy currents could detect superficial defects at about 60 μm deep from the far side, i.e. the side that contains the root flaw [66]. The use of conventional ultrasonic techniques has shown that it is not straightforward to detect small defects at the bottom of the weld or tiny root flaws in friction stir welded joints [67]. To transcend this, several studies have invested in advancing and optimizing these ultrasonic techniques. Hedin et al. have reported the detection of voids with an average size of 200 μm in friction stir welded T-joints using laser ultrasonics [68]. Other studies demonstrated the use of laser ultrasonics with frequencies up to 220 MHz to detect LOP defects, hooking and void flaws in lap and butt-welded joints [69,70]. Detection of weak bonds using leaky surface acoustic waves at frequencies in the range of 0.4–2 GHz has also been reported [71]. Using acoustic lenses, C-scan images have been obtained with high resolution in the order of 1.5–3 μm. Martin et al. successfully examined welded joints (diffusion welding, electron-beam welding and TIG welding) using normal and angle-beam immersion ultrasound in a pulse-echo mode with a central frequency of 15 and 25 MHz for the detection of inclusions (tungsten wire) and artificial longitudinal and cross holes [72]. Multiple-incident angle ultrasonic methods were evaluated by Liu et al. using an immersion system. They concluded that the effect of the incident angle on the reflection coefficient of small void defects at the bottom of the weld is very small [73]. Kinchen et al. validated the detection of LOP defects at 25–30% of the thickness using a modified RD/Teck Phased Array UT system [62]. In the framework of the “Qualistir” project [74], Bird et al. have focused on the detection of entrapped oxide flaws using a 10–15 MHz phased array system. In their early experiments, using focused 10–30 MHz immersion probes in backscattering mode, the signal-to-noise ratio was very low for reliable detection of kissing bond defects from back-reflected signals. As an alternative, they proposed a noise distribution analysis, i.e. investigating the ratio of the parent metal noise to the weld root noise [29,75,76]. Iwaki et al. proposed an electronic scanning in pulse-echo mode using a 10 MHz phased array to detect near surface imperfections and root flaws, and they investigated the effect of different incident angles on the resulting defect maps along the welding direction [77,78]. Lastly, Tabatabaeipour et al. have proposed a contact nonlinear