Mechanical Systems and Signal Processing 101 (2018) 516–534

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Detection and assessment of flaws in friction stir welded joints using ultrasonic guided waves: experimental and finite element analysis

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ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form 20 July 2017
Accepted 2 September 2017

Keywords:
Lamb waves
Weld inspection
Structural health monitoring
Friction stir welding
CT scanning
Finite element analysis

ABSTRACT

Ultrasonic guided waves (GWs), e.g. Lamb waves, have been proven effective in the detection of defects such as corrosion, cracking, delamination, and debonding in both composite and metallic structures. They are a significant tool employed in structural health monitoring.

In this study, the ability of ultrasonic GWs to assess the quality of friction stir welding (FSW) was investigated. Four friction stir welded AZ31B magnesium plates processed with different welding parameters and a non-welded plate were used. The fundamental symmetric (S_0) Lamb wave mode was excited using piezoelectric wafers (PZTs). Further, the S_0 mode was separated using the "Improved complete ensemble empirical mode decomposition with adaptive noise (Improved CEEMDAN)" technique. A damage index (DI) was defined based on the variation in the amplitude of the captured wave signals in order to detect the presence and asses the severity of damage resulting from the welding process. As well, computed tomography (CT) scanning was used as a non-destructive testing (NDT) technique to assess the actual weld quality and validate predictions based on the GW approach. The findings were further confirmed using finite element analysis (FEA).

To model the actual damage profile in the welds, "Mimics" software was used for the 3D reconstruction of the CT scans. The built 3D models were later used for evaluation of damage volume and for FEA. The damage volumes were correlated to the damage indices computed from both experimental and numerical data.

The proposed approach showed high sensitivity of the S_0 mode to internal flaws within the friction stir welded joints. This methodology has great potential as a future classification method of FSW quality.

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1. Introduction

Friction stir welding (FSW) is recognized as a novel, environmentally friendly, solid state welding process [1] that was invented and validated by W. Thomas and his colleagues at The Welding Institute in the UK in 1991 [2,3]. It is being widely used in the automotive, aerospace, and naval industries. The welding process is carried out at a temperature below the melting points of the welded metals [4,5]. The metal is thereby exposed to minimal heat, leading to many advantages such as

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http://dx.doi.org/10.1016/j.ymssp.2017.09.003
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good steadiness of dimensions, control of weld quality, exceptional mechanical properties of the weld zone, reduction of porosity and solidification cracking, minimization of the need for surface cleaning, and reduction of environmental impact [1,6]. FSW is carried out using a non-consumable rotating cylindrical tool with a shoulder and a pin. The pin is inserted into the adjacent edges of the sheets/plates to be joined, then translated along the line of the joint. The pin is slightly shorter than the required weld depth, and the shoulder is pushed down on the plates' surfaces, causing a high frictional force while rotating. As a result, the tool provides the heating to the workpiece and further ensures the flow of the material to produce the joint.

Several disadvantages, though not major, are associated with this welding technique; they include the hole that is left behind when the tool is withdrawn from the workpiece, the need for a large downward force, and the constraints on the possibility of generating different weld profiles – although the latter may not be a major issue with the advances in robotic systems and automation [7].

The spindle speed and the tool feed both influence the quality of the produced weld, besides other variables such as the tool geometry, the tool materials, and the sheet materials. Optimizing the welding parameters is crucial to reduce surface and internal defects and hence increase the integrity of the weld. Much research effort over the years has focused on improvement of the microstructure in FSW joints, in particular, reducing the intermetallic phase and characterizing the grain size and hardness of the mixed materials at the interface. These efforts have further led to optimization of the welding process parameters and have engendered interest in the research community to improve the FSW process of bimetallic structures [8–13].

Inappropriate selection of welding parameters during the FSW process can cause one or several types of defect within the welded zone, such as worm hole, scalloping, ribbon flash, surface lack of fill, nugget collapse, and surface galling, as indicated in Fig. 1 [14]. Thus, quality inspection of the resulting weld is a necessity to ensure adequate performance during service. Internal defects (e.g. worm holes) are usually difficult to detect, therefore, weld inspection requires the use of either destructive or advanced techniques. Moreover, monitoring the quality of welds is essential for detecting and correcting any variation in the weld conditions or for recalibrating the welding parameters when needed.

Various NDT methods are currently available for quality control of welds, including visual inspection, acoustic emission, eddy-current, and ultrasonic inspection. Visual inspection is limited to surface defects, and the other techniques can only provide local evaluation of a specific region on the structure. These techniques are labor intensive, costly, and time-consuming when used for inspecting large structures. They also require experienced personnel and, most importantly, cannot be performed without disrupting the functionality of the inspected structure [15].

GWs have been proposed as an essential tool to be implemented in SHM systems in order to provide continuous monitoring of metallic and composite structures due to their ability to propagate for long distances in simple and complex

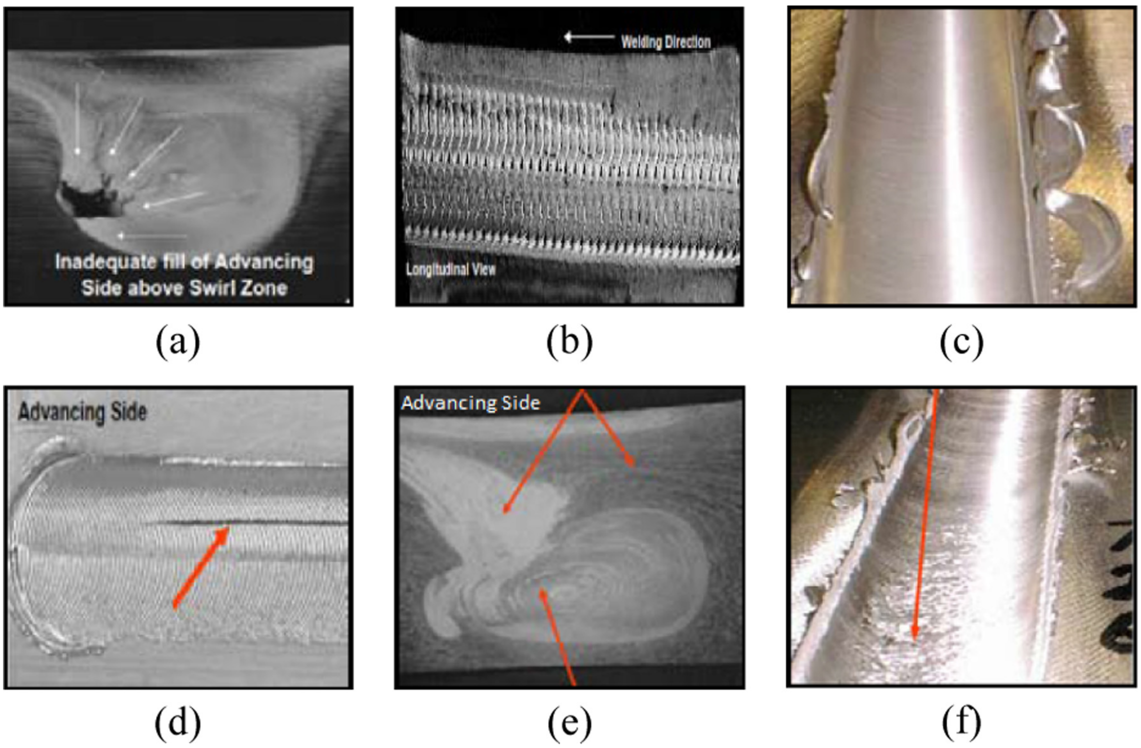

Fig. 1. FSW defects, (a) to (f): worm hole, scalloping, ribbon flash, surface lack of fill, nugget collapse, and surface galling [14].

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