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Applying a nonlinear, pitch-catch, ultrasonic technique for the detection of kissing bonds in friction stir welds

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ABSTRACT

Friction stir welding (FSW) is a promising technology for the joining of aluminum alloys and other metallic admixtures that are hard to weld by conventional fusion welding. Although FSW generally provides better fatigue properties than traditional fusion welding methods, fatigue properties are still significantly lower than for the base material. Apart from voids, kissing bonds for instance, in the form of closed cracks propagating along the interface of the stirred and heat affected zone, are inherent features of the weld and can be considered as one of the main causes of a reduced fatigue life of FSW in comparison to the base material. The main problem with kissing bond defects in FSW, is that they currently are very difficult to detect using existing NDT methods. Besides, in most cases, the defects are not directly accessible from the exposed surface. Therefore, new techniques capable of detecting small kissing bond flaws need to be introduced. In the present paper, a novel and practical approach is introduced based on a nonlinear, single-sided, ultrasonic technique. The proposed inspection technique uses two single element transducers, with the first transducer transmitting an ultrasonic signal that focuses the ultrasonic waves at the bottom side of the sample where cracks are most likely to occur. The large amount of energy at the focus activates the kissing bond, resulting in the generation of nonlinear features in the wave propagation. These nonlinear features are then captured by the second transducer operating in pitch-catch mode, and are analyzed, using pulse inversion, to reveal the presence of a defect. The performance of the proposed nonlinear, pitch-catch technique, is first illustrated using a numerical study of an aluminum sample containing simple, vertically oriented, incipient cracks. Later, the proposed technique is also applied experimentally on a real-life friction stir welded butt joint containing a kissing bond flaw.

1. Introduction

Friction stir welding (FSW) is a solid-state joining technology for metallic alloys that is superior to conventional fusion welding [1–4]. The basic concept of FSW is remarkably simple. A rotating tool including a specially designed pin and shoulder travels with a constant transverse speed along the joint line of two pieces of material, which are pushed together. Due to friction between the rotating tool and the workpiece, and severe plastic deformation of the workpiece, localized heating is created, softening the material around the pin. The softened material is then pulled along with the rotating pin, filling the gap between both materials as the tool moves forward. As a result of the whole process, a solid-state joint is produced.

The fatigue properties of FSW are better than for traditional fusion welding methods [3,5]. Nevertheless, they are in general still significantly lower than those of the base material. Process parameters, such as tool pressure, rotational and welding speed, pin and shoulder geometries are crucial factors to control temperature, pressure and material flow, and therefore for the formation of flaws (voids, lack of penetration, kissing bonds, etc.), which can lead to a rapid degradation in strength properties [6]. As a result of non-optimized settings, zones of light contact or incomplete bonding may be initiated in the weld at the interface of the stirred and heat affected zone. In many cases, these so called "kissing bonds" are considered to be the main cause of the reduced fatigue life of FSWs in comparison to the base material, as they are potential sources of fatigue cracks.

Once initiated, fatigue cracks will gradually grow from a kissing bond feature within the material upon further loading and eventually lead to failure of the component. That is why it is important to be able to detect kissing bonds and fatigue cracks in an early stage. These types of defect are particularly worrying since they are difficult to trace using conventional non-destructive testing (NDT) methods such as X-ray and linear ultrasonics. Indeed, the weld may have the appearance of a defect free weld, although it has poor mechanical properties. To solve this problem, an alternative

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approach using nonlinear ultrasonic techniques can be proposed [7–9]. Nonlinear ultrasonic techniques are based on the analysis of amplitude dependent wave propagation characteristics, such as harmonic generation, nonlinear wave speed and nonlinear attenuation, created at the defect location. These techniques have proven to be far more sensitive to incipient damage than conventional ultrasonics, as shown in applications to detect delaminations in composites [10–12], fatigue cracks in concrete [13–16], etc. Yet, they have never been applied to FSWs. The hypothesis is that a 'bad' FSW, containing kissing bonds or cracks, behaves substantially more nonlinearly than a 'good' FSW (without kissing bonds, nor cracks). A 'good' FSW behaves mostly linearly, apart from the nonlinearity caused by the severe plastic deformation induced by the FSW process, whereas for a 'bad' FSW, an extra amount of nonlinearity is caused by the typical clapping behavior of the kissing bonds or cracks, observable in a significant higher generation of harmonics and/or subharmonics. The degree of harmonic generation provides information about the extent to which the defect behaves nonlinearly. However, as the provoked nonlinear behavior depends both on the local equation of state (through the nonlinear material properties) and on the internal stresses, kissing bonds will only be properly activated when the local ultrasonic wave amplitude is sufficiently large to induce clapping and ratcheting of the imperfectly bonded interfaces. As such, nonlinear ultrasonic methods generally require high excitation amplitudes ("finite" amplitudes), as can be achieved for instance by focusing transducers.

The difficulty to trace kissing bonds in FSWs, together with the fact that, in most cases, the defects are not directly accessible from the exposed surface, are important drawbacks preventing the widespread use of FSW in industrial applications, where the quality standards are highly demanding. In the present paper, we will therefore propose a novel, nonlinear, ultrasonic NDT technique capable of detecting small kissing bond flaws, even when the inspected material is only accessible from one side, and when certain constraints regarding the quality of the upper surface have to be taken into account. The technique is based on the use of two single element transducers with properly curved surfaces. The first transducer transmits an ultrasonic signal that, due to the curvature of its surface, focuses the ultrasonic waves at the bottom side of the sample where cracks are most likely to occur. The large amount of energy at the focus activates the kissing bond, resulting in the generation of nonlinear features in the wave propagation. The distorted ultrasonic wave is then captured by a second (similarly) curved transducer operating in pitch-catch mode and the presence and severity of the kissing bond flaw can be quantitatively measured by post-processing the received signals in the frequency domain.

The paper starts with the description of the particular design of an ultrasonic single element transducer with a curved surface for emission, allowing the energy to focus at a predetermined location. The design is based on Fermat's principle, stating that the path of a sound wave to travel between two points is the path that can be traversed in the least amount of time. The potential to focus ultrasonic waves in a plate-like structure using this type of transducers is illustrated by simulations performed using the commercial software package COMSOL Multiphysics. In the second part of this paper, the performance of the proposed focused, shear wave technique, to detect small kissing bonds is illustrated using a numerical study of an aluminum sample containing a vertically oriented kissing bond defect. The model allows to predict and analyze the nonlinear contribution in the received signals and to illustrate the use of a pulse inversion technique to enhance the defect detection. In the last part of the paper, the proposed pitch-catch technique, in combination with the pulse inversion technique, is applied on a real-life FSW sample containing a kissing bond flaw at the root of the FSW joint.

2. Focused shear wave technique

As mentioned in the introduction, the proposed nonlinear ultrasonic inspection method will be based on an analysis of nonlinear features generated by finite amplitude waves. In order to obtain the maximum energy at the presumed damage location (bottom of the plate) and apply the displacement polarization which is most sensitive to defects, we have chosen to work with focused shear waves to foster this nonlinear ultrasonic testing application. The realization of finite amplitude shear waves inside the solid medium, without the presence of longitudinal waves, can be obtained by focusing a sound beam coming from the surrounding air or water at angles larger than the longitudinal (first) critical angle [17]. This way, the focused sound beam will be converted into a single shear wave beam when entering the solid material. At the same time, at least for planar geometries, this will allow a relatively simple interpretation of the recorded data. Indeed, when both longitudinal and shear waves are allowed to propagate into the sample, the presence of the two wave types and their mode conversion will make the data interpretation complicated. Thus, as a starting point for the inspection technique, we desire to create high amplitude shear polarized waves to activate the crack surfaces.

2.1. Fermat surface design

The design of a transducer surface that is particularly suited to focus shear waves at a fixed location (damage site at the bottom of a plate) can be accomplished by following the principle of the Fermat surface. The idea and concept of a Fermat transducer to focus ultrasonic waves is not new, though it has not yet been applied to nonlinear ultrasonic measurements [18]. As for completeness, the particular design of the Fermat surface is briefly discussed. Consider the geometry of a flat aluminum plate, with thickness d, surrounded by water, as presented in Fig. 1 (other geometries, e.g. considering contact wedges instead of water as immersion medium, can be constructed in a similar manner). The velocity of the longitudinal and shear waves in the plate is respectively represented by v_{sol}^L and v_{sol}^S, and the velocity of the sound waves in water is v_{liq}. The FSW zone has a length $2Z$. This is the zone that should be avoided by the incident and reflected sound waves as the surface is corrugated along this zone due to the FSW process. If we suppose that the origin of the coordinate system is at the center of the FSW zone on the top surface of the plate, the intended focus point F (i.e. the kissing bond region) then corresponds to position $(0, 0, -d)$. For an arbitrary point P, defined by its coordinates (x, y, z) as indicated in Fig. 1, the time for a longitudinal wave starting at P, transformed at the interface into a shear wave inside the solid, to arrive in the intended focus point F is:

$$t(x, y, z) = \frac{z}{v_{liq} \cos \alpha} + \frac{d}{v_{sol}^S \cos \beta}, \qquad (1)$$

where the relationship between α and β is given by Snell's law:

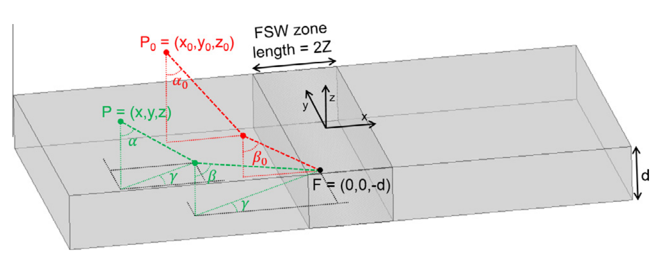

Fig. 1. Definition of the geometry for the ultrasonic testing techniques.