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Lévesque, Daniel; Dubourg, Laurent; Mandache, Catalin; Krüger, Silvio; Lord, Martin; Merati, Ali; Jahazi, Mohammad; Monchalin, Jean-Pierre



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# SYNTHETIC APERTURE FOCUSING TECHNIQUE FOR THE ULTRASONIC EVALUATION OF FRICTION STIR WELDS

D. Lévesque[1], L. Dubourg[2], C. Mandache[3], S.E. Kruger[1], M. Lord[1], A. Merati[3], M. Jahazi[2] and J.-P. Monchalin[1]

[1]Industrial Materials Institute, National Research Council Canada, Boucherville, Quebec, Canada
[2]Aerospace Manufacturing Technology Centre, National Research Council Canada, Montreal, Quebec, Canada
[3]Institute for Aerospace Research, National Research Council Canada, Ottawa, Ontario, Canada

**Abstract.** An ultrasonic technique using numerical focusing and processing is presented in this paper for the detection of different types of flaws in friction stir welds (FSW). The data is acquired using immersion ultrasonic technique or laser ultrasonics, while the Synthetic Aperture Focusing Technique (SAFT) is used for numerical focusing. Measurements on the top and far sides of the weld for both lap and butt joints of thin aluminum sheets are investigated. Discontinuities such as wormholes, hooking, lack of penetration and voids are found to be easily detected. The limit of detectability and a comparison with mechanical properties are discussed. Also, the detection of joint line remnants or kissing bonds due to entrapped oxide layers seems possible in lap joint structures using high frequency laser-ultrasonics.

**Keywords:** Friction stir welding, Synthetic aperture focusing technique, Laser ultrasonics, Kissing bond
**PACS:** 81.70.Cv, 42.87.-d, 68.35.bd

## INTRODUCTION

Friction stir welding (FSW) is a solid-state joining process that has found extensive applications in recent years. It is an emerging manufacturing technology that allows creating lighter structures at lower cost than traditional methods. As shown in Figure 1, FSW uses a specially shaped rotating tool consisting of a pin and a shoulder to produce the weld. The motion of the welding tool on the metal plate, usually aluminum, generates frictional heat that creates a plasticized region around the immersed portion of the tool (pin) to produce lap or butt joints. The advancing and retreating sides of the weld correspond to locations where the maximum and minimum relative velocities between the rotating tool and the work piece are observed (see Fig. 1). However, with changes in material conditions or welding parameters, discontinuities such as wormholes, lack of penetration, hooking or voids can be formed. A more difficult situation is the presence of joint line remnants also called kissing bonds which are generally due to the presence of entrapped oxide layers and resulting in inferior mechanical properties in the weld nugget [1].

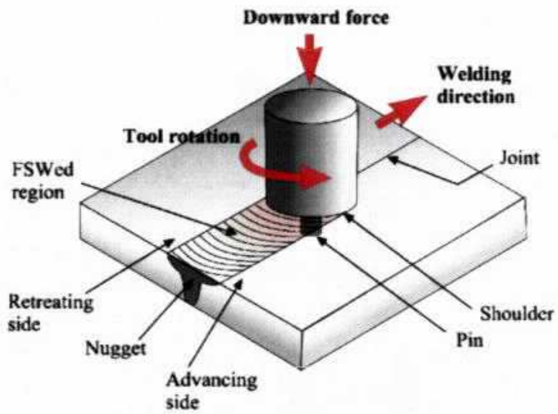


**FIGURE 1.** Schematic of the principle of FSW (butt joint).

For the manufacturing of large size and complex structures, reliable methods have to be found to nondestructively evaluate the integrity of the welds produced by FSW. From the literature, only a few results have been reported to date for the detection of the defects described above [2-4]. Both ultrasonic-based methods and eddy current techniques have been found promising for this purpose; however, their actual performance for detecting these critical defects, particularly for kissing bonds is still uncertain. Moreover, little data exists on the relationship between nondestructive testing information and the quality of the weld in terms of its mechanical performance.

The ultrasonic technique presented in this paper uses numerical focusing and processing for the detection of different types of flaws in FSW. The data is acquired using an immersion technique or laser-ultrasonics, and the Synthetic Aperture Focusing Technique (SAFT) is used for numerical focusing. Measurements on the far and near sides of the weld for both lap and butt joints of 1 to 2.5 mm thick aluminum sheets are investigated. The limit of detectability and a comparison with mechanical properties are also discussed.

## ULTRASONIC INSPECTION WITH SAFT

The approach used to identify the different types of flaws in FSW is illustrated in Figure 2. For use with SAFT, the generation and detection zones overlap at the surface of the part. An immersion technique with a piezoelectric transducer focused on the surface can be used. A broadband focused transducer from Panametrics provided frequency content up to 50 MHz. Alternatively, laser-ultrasonics, which uses lasers for the generation and detection of ultrasound, can be considered for non-contact inspection [5, 6]. To achieve much higher frequencies, the generation of ultrasound was performed in the slight ablation regime with a 35 ps duration Nd:YAG laser in its $3^{rd}$ harmonic and a spot of about 50 μm. The detection uses a long pulse Nd:YAG laser and demodulation was performed with a photorefractive interferometer. Frequencies up to 220 MHz were successfully generated and detected in the welded region. Mechanical scanning along two axes was performed for data acquisition of all waveforms with a step size of 0.1 mm.

For the numerical focusing, a SAFT algorithm in the Fourier domain for time-efficient reconstruction that can take into account surface variations induced by the FSW tool was used [7, 8]. Processing the data with SAFT allows synchronization of the ultrasonic signals scattered back in different directions from each point in the weld region. The numerical focusing presents similarities with ultrasonic phased array system but makes it easier for detecting flaws at shallow depths such as those found in the joining of thin plates. Both immersion and laser-ultrasonic results with SAFT are presented in the following sections.

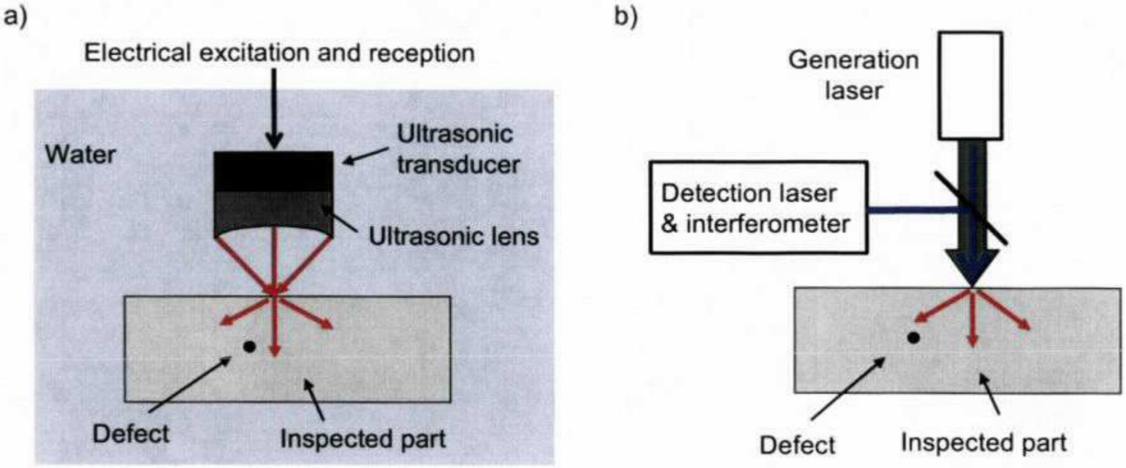


**FIGURE 2.** Measurement setups that can be used for inspection of FSW with SAFT. a) Immersion technique and b) laser-ultrasonics.

## RESULTS ON LAP JOINTS

All welds were produced on a MTS I-STIR FSW machine. The standard tool with a scrolled shoulder (19-mm diameter) and a pin (6.3-mm diameter pin) was used for all welds. The tool tilting angle was adjusted at 0.5°. Three lap joint samples using FSW for aerospace application, consisting of a 1.5 mm thick plate of Al-7075 on top of a 2.5 mm thick plate of Al-2024, were performed with different pin shapes (truncated pin, no-threaded cylindrical pin and threaded cylindrical pin) and welding parameters (welding speed, tool rotation speed, shoulder penetration) in order to create different defects.

Figure 3 shows an ultrasonic SAFT image of a cross-section (as B-scan) and corresponding metallography of a lap joint. The presence of hooking near the interface in both the advancing side and the retreating side is well observed. Results are shown for immersion on the weld side (tool side), but good images were also obtained from the opposite side with the indication going down. SAFT reconstruction is found very useful for the identification of such defect by properly reducing the size of indications having a parabolic shape. The SAFT image also shows a void at this particular location along the weld. Figure 4 shows an overview of the joint with SAFT images of subsurface planes near the interface level.

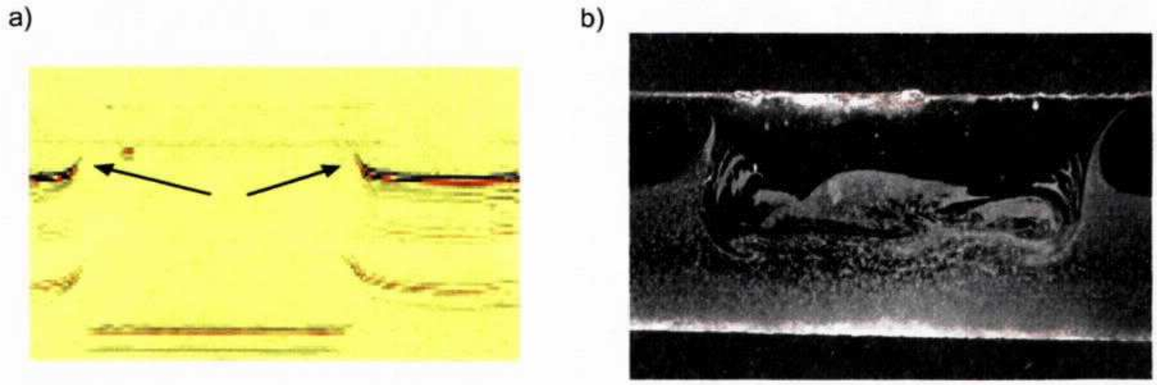


**FIGURE 3.** Cross-section of a first lap joint with the presence of hooking. Welding parameters: truncated pin, welding speed of 500 mm/min, spindle speed of 800 RPM, shoulder penetration of 0.1 mm. a) SAFT image obtained by immersion on the weld side and b) corresponding metallography.

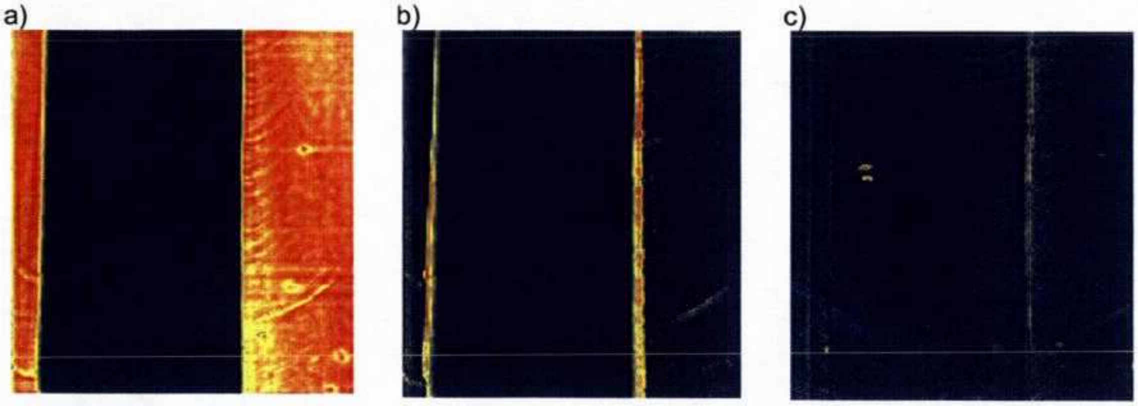


**FIGURE 4.** SAFT image of sub-surface plane a) at the interface, b) 0.2 mm and c) 0.4 mm above the interface of the first lap joint in Figure 3 in the presence of hooking.

A second lap joint is presented in Figure 5 with hooking in the advancing side, as well as indications of a wormhole above the interface. A wormhole occurs when the ratio of the welding speed over the tool rotation speed is too low [9]. These results are for immersion on the weld side (tool side). Figure 6 shows SAFT images obtained from the opposite side using immersion (frequencies up to 50 MHz) and laser-ultrasonics (frequencies up to 220 MHz). The presence of hooking defect going down on one side as well as a similar wormhole, below the interface when viewed from weld side, are well observed with better resolution using laser-ultrasonics. More importantly, a kissing bond present in the weld is detected by laser-ultrasonics as a slight reflection along the interface and above that from the weld surface.

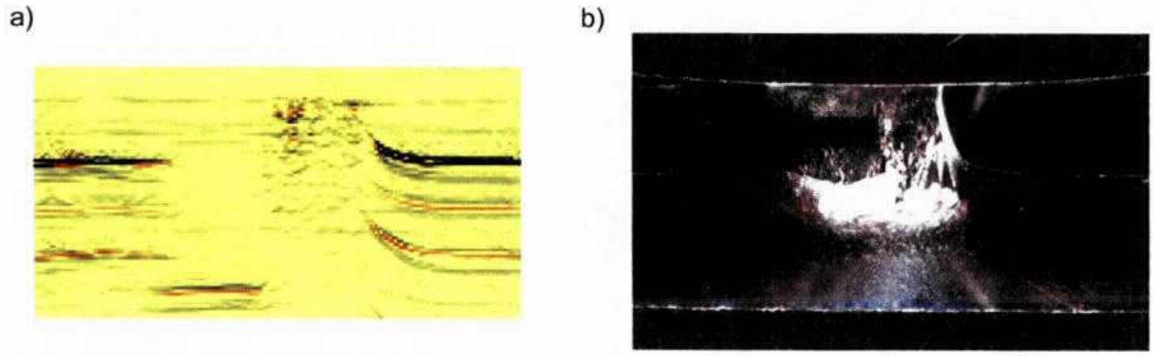


**FIGURE 5.** Cross-section of a second lap joint with many defects. Welding parameters: no-threaded cylindrical pin, welding speed of 500 mm/min, spindle speed of 1000 RPM, shoulder penetration of 0.1 mm. a) SAFT image obtained by immersion on the weld side and b) corresponding metallography.

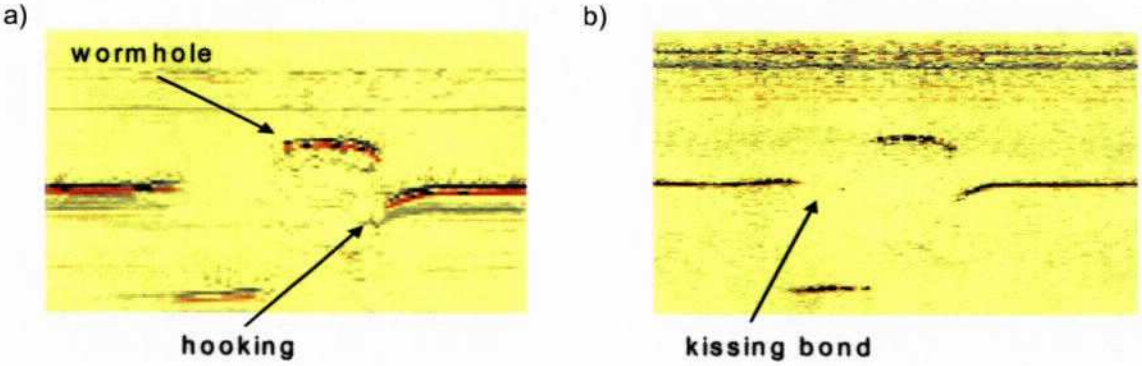


**FIGURE 6.** Cross-section of the lap joint in Figure 5, with inspection from the far side of the tool. SAFT image using a) immersion and b) laser-ultrasonics.

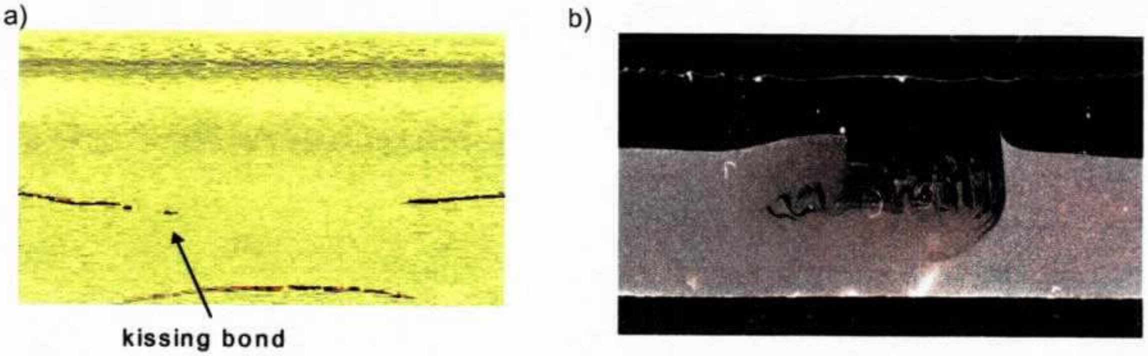


**FIGURE 7.** Cross-section of a third lap joint with a kissing bond. Welding parameters: threaded cylindrical pin, welding speed of 500 mm/min, spindle speed of 1000 RPM, shoulder penetration of 0.2 mm. a) SAFT image obtained by laser-ultrasonics on the far side of the tool and b) corresponding metallography.

This capability is confirmed by the detection of another kissing bond defect in a different sample as illustrated in Figure 7. The kissing bond is at least partially identified above the weld surface (the bottom surface in the figure) using high frequency laser-ultrasonics. However in this case, the smaller hooking observed on the advancing side in the metallography could not be detected by the technique.

## RESULTS ON BUTT JOINTS

Two sets of samples using FSW for aerospace application were welded in butt configuration. The first set was performed on 2-mm thick AA7075-T6 sheets with a tool composed of a concave shoulder (diameter of 10 mm) and threaded cylindrical pin (pin diameter of 3 mm). The pin length was purposely made too short (1.2-mm long) in order to generate a lack of penetration (LOP). Figure 8 shows a SAFT image and the corresponding metallography of a cross-section of a butt joint with a constant LOP. Measurements were made by laser-ultrasonics on the weld side to detect the LOP on the opposite side. The LOP is well observed and appears as a lack of signal of the longitudinal (L) wave near the bottom surface. From metallography, the LOP shown has a width of 6 μm and a depth of 0.6 mm, but the detection of a 0.3 mm deep LOP in a similar specimen was also observed. However, the quantitative estimation of the depth appears difficult, a situation similar to that found in a previous work for crack detection [10]. Also, the shear wave, usually generated in laser-ultrasonics, was too weak in this Al alloy and not practical for SAFT reconstruction.

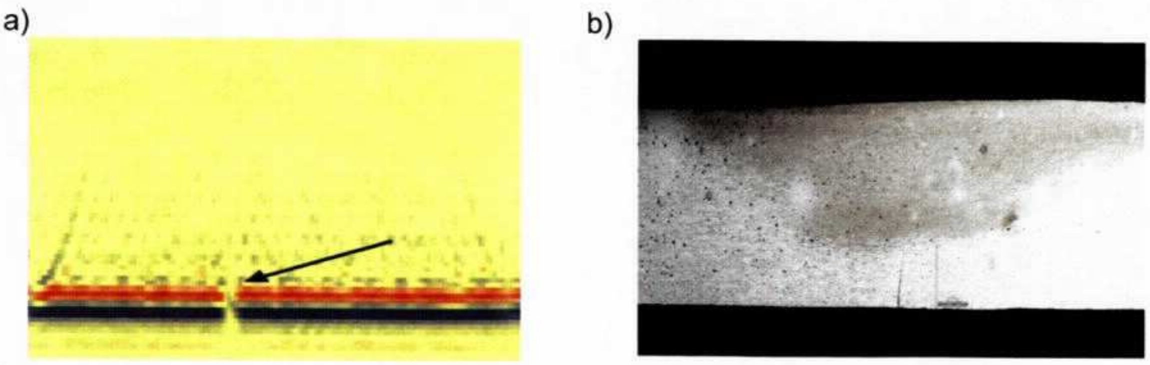


**FIGURE 8.** Cross-section of a butt joint showing a lack of penetration in 2-mm thick AA7075-T6 butt weld. a) SAFT image and b) corresponding metallography.

Even though quantitative determination of depth is uncertain, a comparison of the limit of detectability with mechanical performance was investigated. For this purpose, a second set of butt welds was performed on 2.5-mm thick AA2024 sheets with a tool composed of a scrolled shoulder (diameter of 19 mm) and a threaded cylindrical pin (pin diameter of 6.3 mm). For this experiment, the pin penetration was progressively increased from 1.2 mm to 2.5 mm during welding along the 355-mm in length joint. This operation introduced a variable weld depth and, consequently, a gradual LOP on the back-side of the weld. Metallographic examination at several locations along the weld revealed a LOP for a total penetration of the rotating tool (shoulder and pin) less than 2.2 mm from the top surface. It is important to note that, to produce a good weld, it is not necessary for the pin to touch the bottom surface of the plate because of the stirring action of the pin during FSW.

Different scans using laser-ultrasonics of dimensions 10 mm x 10 mm were performed along the weld at regular intervals. Figure 9 shows the SAFT images of the bottom surface at different locations, with the numbers giving the pin penetration at the center of each image, increasing only slightly from left to right. Indications of LOP along the weld are well observed for pin penetrations less than 2.2 mm, starting from a continuous line to an irregular trace. The irregular appearance of a LOP could imply that many cross-sectional views are required for evaluating the weld quality by metallography. Also, the mixed or alternate presence of LOP with vertical kissing bonds that are more difficult to detect is possible.

As an evaluation of the mechanical performance, bending tests were performed on different portions of the butt joint sample with variable pin length. Figure 10 shows the back-side of small coupons after bending taken at various locations corresponding to different pin penetrations. Using optical microscopy, no failure was observed for pin penetration larger than 2.14 mm. This is in good agreement with the SAFT results as well as those from metallography.

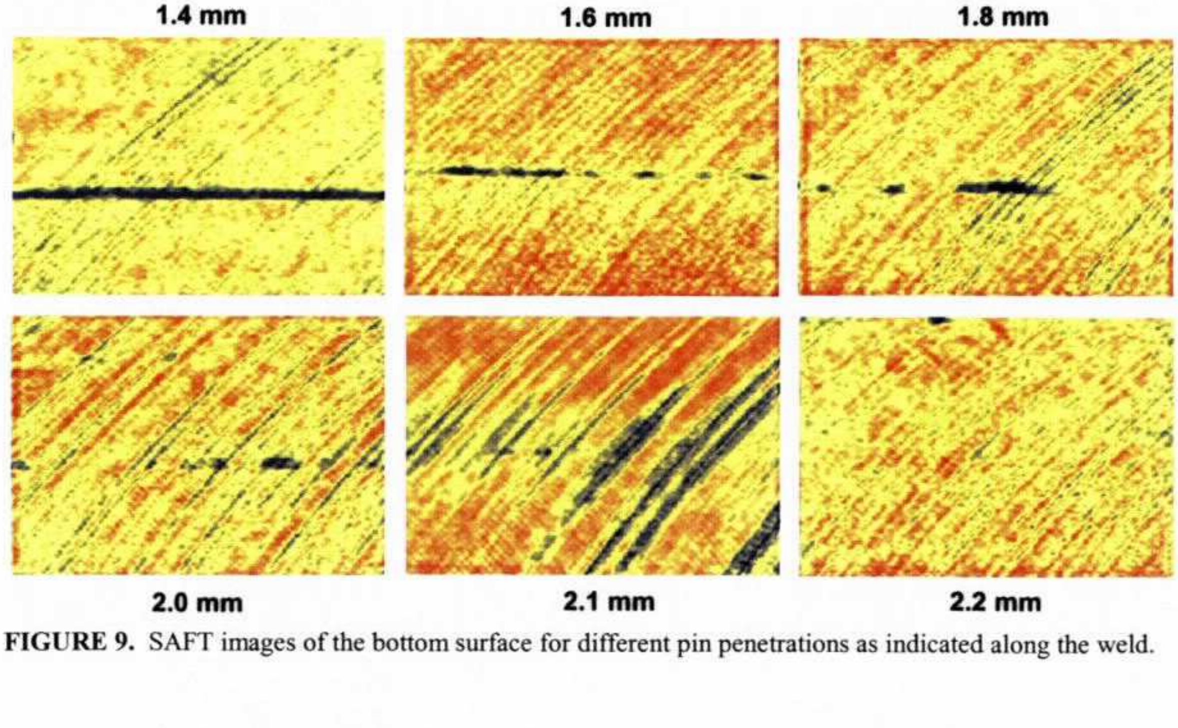


**FIGURE 9.** SAFT images of the bottom surface for different pin penetrations as indicated along the weld.

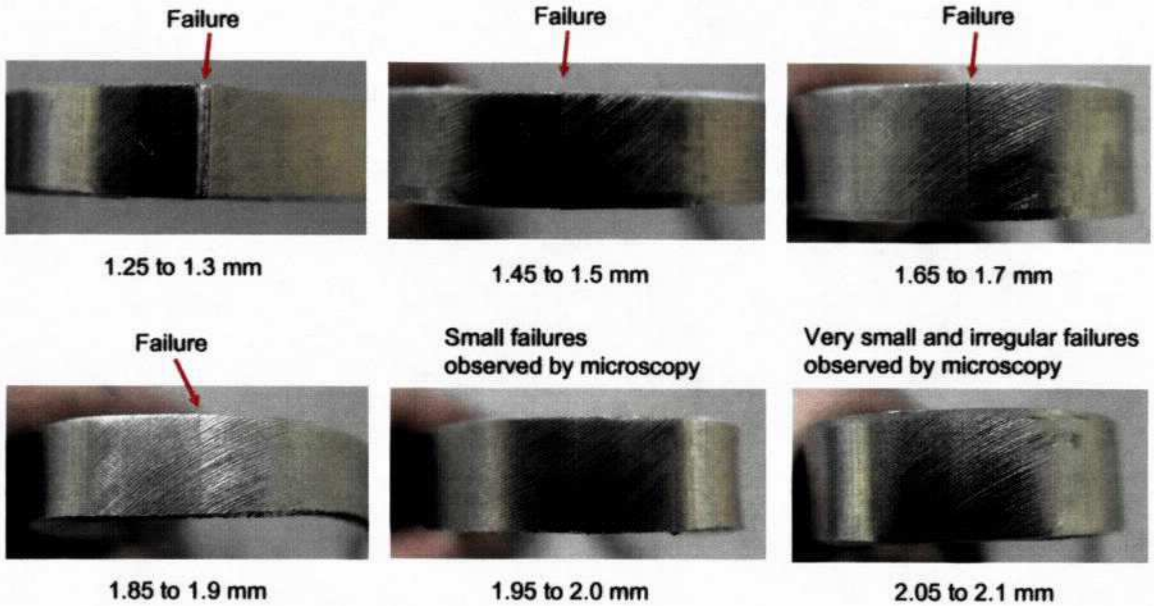


**FIGURE 10.** Bending test results for different pin penetrations as indicated along the weld.

## CONCLUSION

The good performance of SAFT for the evaluation of friction stir welds using immersion ultrasonic technique and laser-ultrasonics is demonstrated. Measurements on the same or opposite side of the weld (with respect to the welding tool) for both lap and butt joints of 1 to 2.5-mm thick aluminum sheets were carried out and the results analyzed. Discontinuities such as wormholes, hooking, lack of penetration and voids were clearly detected. Moreover, the detection of kissing bonds seems possible in lap joints using high frequency laser-ultrasonics. Lack of penetration defects like were shown to be irregular, which means that many cross-sectional views may be required when using metallography. Also, the limit of detectability may coincide with the conditions of reduced mechanical properties. The approach could allow fast scanning for weld integrity assessment along the tool path.

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