Non-destructive detection of lack of penetration defects in friction stir welds

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This study focuses on the comparative investigation of different non-destructive inspection (NDI) techniques for detecting the lack of penetration discontinuities in butt joint friction stir (FS) welds. A variably sized lack of penetration has been introduced purposely by progressively changing the tool pin's length. While inspecting the weld from the discontinuity side provids results of higher sensitivity, service inspection of the FS welded components requires evaluation of the welding tool's side, opposite the defect containing one. Non-destructive techniques amenable for inspection from either the tool side or the far side of the weld are analysed, and results from inspection are presented for comparison. Subsequently, bending tests and metallographic examinations were employed to confirm the size of the lack of penetration defects and correlate these results with the NDI capabilities.

Keywords: Non-destructive evaluation, Friction stir welding, Lack of penetration, Eddy current, Ultrasonic waves, Inspection

Introduction

Friction stir (FS) welding uses a tool to generate heat by friction and stir the parent materials; in this process, the heat does not melt, it only plasticises the materials.[1] Friction stir welding is gaining acceptance in the manufacturing of components and structures for transport industries, such as aerospace, automotive, naval and railway.[1] Lower cost, repeatable and fast manufacture, increased strength, good surface finish and environment friendliness (no fumes) are the specific characteristics that contribute to the attractiveness of FS welding to the aerospace industry. Aluminium alloys in the 2xxx and 7xxx series are selected for aerospace applications owing to their high strength and low weight, and FS welding has the potential to replace most of the fastened structures made from these alloys. Unlike fusion welding, FS welding results in components of strength close or similar to the parent materials. On the other hand, since the metal does not melt and no filler material is added, the types of defects found in FS welds are different from those in fusion welding. This aspect raises new challenges for the non-destructive inspection (NDI) technicians who will need to adapt their inspection procedures and the interpretation of the data from other types of conventional weld inspections. Moreover, reliable non-destructive evaluation plays an important role in the acceptance and expansion of this joining technology in the industry.

The FS welding process parameters are greatly affecting the quality of the weld; therefore, the tool design, the welding tool forces, as well as the torque, angle, and position of the pin axis, and the tool's linear and rotational speeds need to be carefully selected.[2,3] They influence a series of interconnected properties, such as the weld's microstructure, hardness, tensile strength, residual stresses and electric conductivity.[1–4] The welding pin exerts in-plane (horizontal) and downward (vertical) forces. Controlling the downward force is important in establishing the weld's penetration depth. However, through an inadequate choice of welding parameters, tool wear and part deformation during welding could inadvertently create lack of penetration discontinuities in FS welds. This type of defect is an important drawback to the acceptance of FS welding in the industry because the root flaws are seen as crack initiation sites and because they have a significant influence on the fatigue behaviour of the welded part.[5,6] For instance, it was found that the fatigue life of a 4 mm thick AA 2024-T3 butt welded specimen containing lack of penetration defects was 33–80 times shorter than that of a flaw free weld.[6]

In this work, various non-destructive evaluation techniques are employed to establish the effect of the pin's length and their capabilities to detect the existence of lack of penetration discontinuities. In fusion welding, this type of flaw is due to inadequate joint penetration at the root of the weld. Although it represents a common type of defect in many different welding processes, it has a higher prevalence in FS welding due to the improper welding tool down force or tool wear-out. The results of the NDIs are then correlated with destructive examinations, such as metallographic observations of the cross-section of the weld, defect size and orientation. Bending tests are also performed in order to confirm the criticality of the certain size lack of penetration defects.

Specimen and inspection techniques

The force exerted on the welding tool facilitates good pin penetration but does not allow the pin to be in

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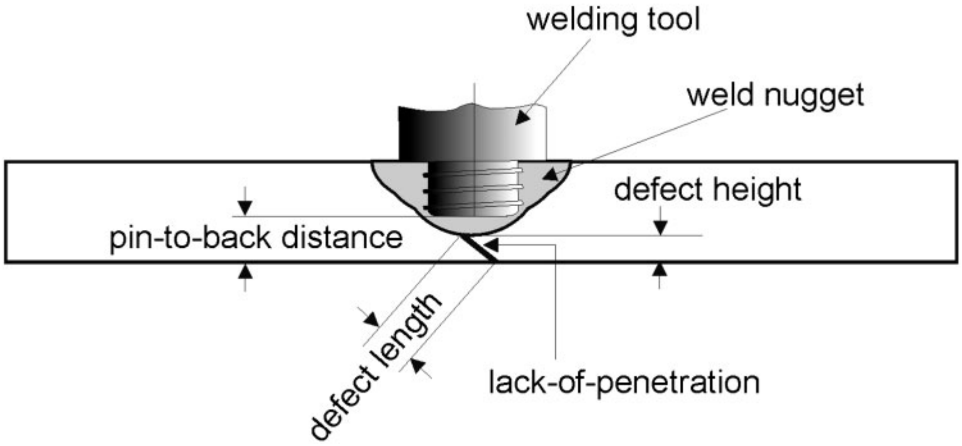
Published by Maney on behalf of the Institute
Received 29 November 2011; accepted 19 January 2012
DOI 10.1179/1362171812Y.0000000007



1 Schematic representation of butt weld including descriptive terminology used in this paper

contact with the backing surface because this could damage the tool and welding setup. In general, the pin to back distance is always >0, but this could induce lack of penetration defects, as schematically shown in Fig. 1. These types of flaws are very common in butt joints.

The present study uses five NDI techniques:

(i) phased array ultrasonic waves
(ii) laser generated ultrasonic waves with synthetic aperture focusing technique (SAFT) processing
(iii) conventional eddy current
(iv) pulsed eddy current
(v) liquid penetrant testing.

They are all used to detect a lack of penetration defect of varying sizes introduced in an Al 2024 butt weld using a controllable pin penetration. All these techniques have their own advantages and disadvantages; the focus of this work is not to quantitatively compare them but to analyse their capabilities in terms of sensitivity to the defect's geometry characteristics. It is important to note that the liquid penetrant and conventional eddy current techniques are applied from the side of the specimen with defect, while the other techniques are applied from the opposite side (the welding tool side) of the butt weld.

The butt weld analysed in this study was produced with an MTS FSW I-STIR equipment. The total welding distance, from pin entry to pin exit, was 345 mm. Coupons (400 × 200 mm) of AA 2024-T3 were machined from 2·56 mm thick plate material, and butt welds were produced with a welding tool made of H13 steel. The rolling direction of the plates was placed parallel to the welding path. The tool consisted of a cylindrical threaded retractable pin having a diameter of 6·3 mm and a smooth concave shoulder with a diameter of 19·0 mm. Plates of similar dimensions were placed on a steel backing anvil and clamped along the two long edges. The welding parameters consisted of a rotational speed of 1000 rev min^{-1}, a travelling speed of 10 mm s^{-1} and a tilt angle of 2°. The tool (i.e. pin and shoulder) penetration increases linearly from 1·2 mm at the beginning of the weld to 2·5 mm at the end of the weld, as schematically illustrated in Fig. 2*a*. The tool uses a retractable pin, whose length varies linearly from the beginning to the end of the weld, while keeping the shoulder penetration constant, at 0·2 mm. This introduces a variable weld depth and, consequently, a decreasing depth lack of penetration discontinuity. A picture of the butt weld specimen after machining is shown in Fig. 2*b*. Finally, the tool side of the specimen is mechanically machined (0·2 mm taken off) to remove any surface asperities resulting from the welding that could influence the NDI results. Figure 2*c* schematically shows the pin and shoulder penetration into the plate. It is important to note that the weld depth is larger than the tool penetration, according to previous observations.[7] This aspect will be discussed further in the 'Destructive testing' section of this paper.

Based on the discussion above, the tool penetration in the investigated specimen, after machining, can be described by the following linear equation, where x is the position along the weld, and $x=0$ represents the weld start

$$\text{Tool\_penetration (mm)} = (1{\cdot}3/345)x + 1{\cdot}0 \qquad (1)$$

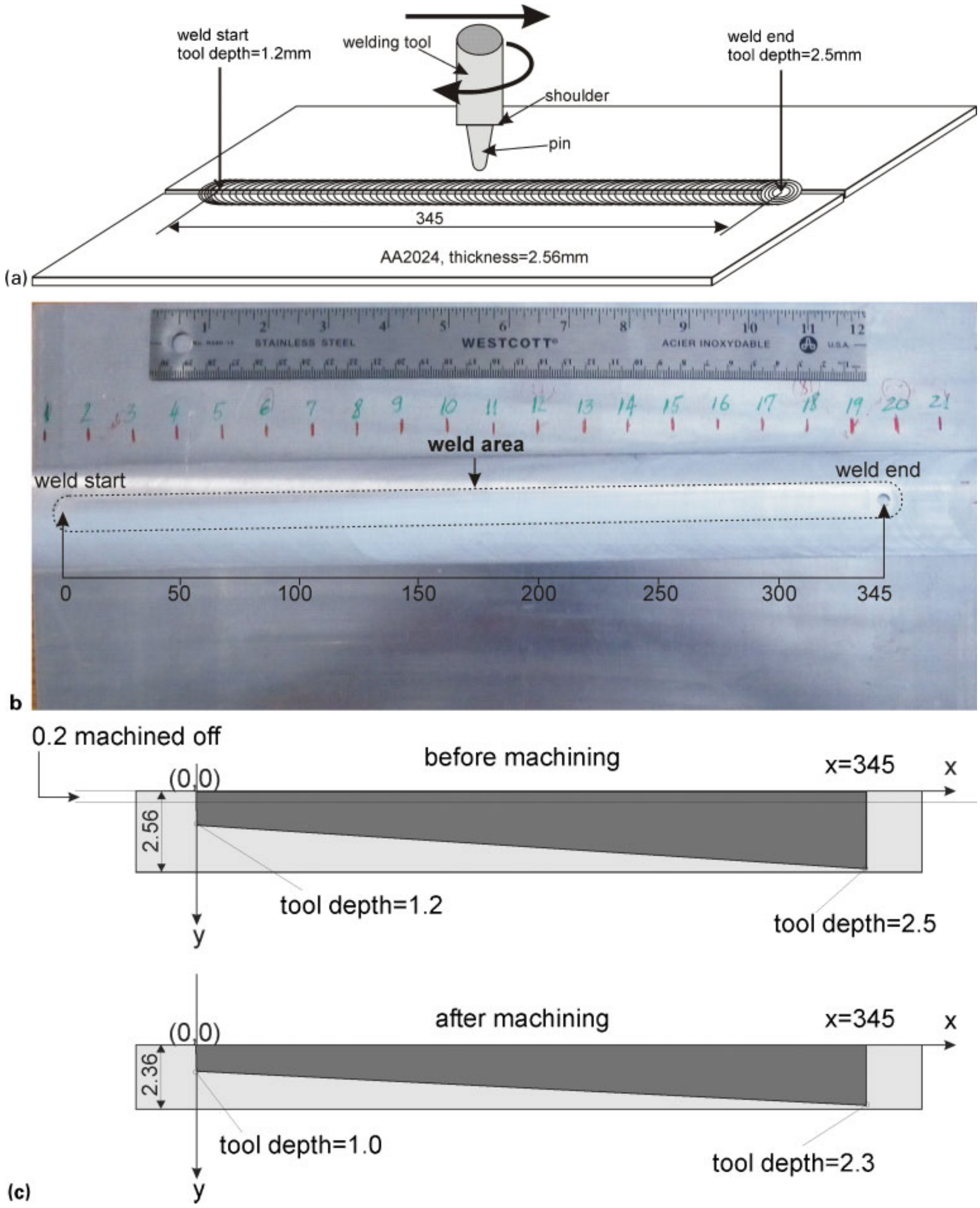
Naturally, after machining, the maximum value of the defect height (as defined in Fig. 1) for the lack of penetration, at any location along the weld, is the coupon thickness, i.e. 2·36 mm, minus the tool penetration. However, in practice, the vertical dimension is much less than this theoretical estimation, as will be discussed in the 'Destructive testing' section.

Non-destructive inspection

Using the butt joint FS welded coupon described in the previous section, the results obtained with five different NDI techniques are presented here. Liquid penetrant and conventional eddy current techniques were used to inspect the weld from the far side, i.e. the side that contains the lack of penetration defect, while the three other techniques (pulsed eddy current, phased array ultrasonic waves testing and laser generated ultrasonic waves with SAFT) were used to inspect the weld from the welding tool side, i.e. the opposite side with respect to the lack of penetration defect. In what follows, only summary descriptions of the underlying principles of the non-destructive testing techniques and data processing algorithms are given. Detailed information regarding the NDI techniques can be found in the references provided.

Ultrasonic testing

Ultrasonic waves propagating in a specimen under test provide great information about its non-visible structure based on the transmitted and/or reflected signals. Ultrasonic waves are commonly used in the inspection of welds; however, for the present case, there are some additional complexities associated to the small thickness

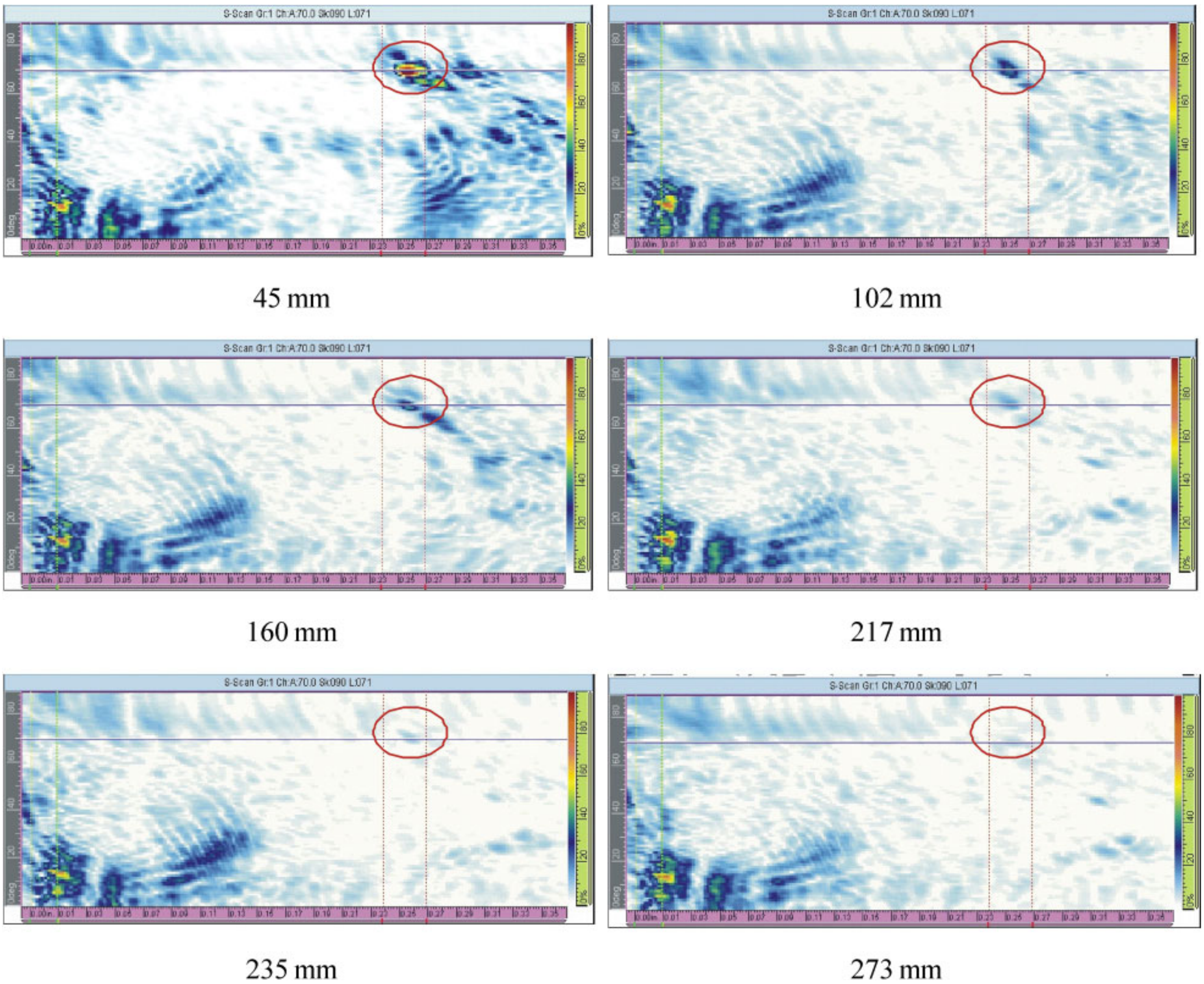


2 ***a*** **schematic drawing and dimensions of butt weld,** ***b*** **picture of specimen from tool side after removal of weld asperities (0·2 mm of thickness) and** ***c*** **schematic (not to scale) of tool penetration depth before and after surface machining of weld: all dimensions are given in mm**

of the specimen, leading to difficulties in focusing the ultrasonic beam on the area of interest.

Phased array ultrasonic waves

Phased array ultrasonic wave testing has gained NDI acceptance in the last few years, and it is now customarily employed in weld inspection applications. Its advantages over conventional ultrasonic inspections come from the use of multiple wave generating elements and the ability to focus and stir the ultrasonic beam without movement of the probe, while the images are formed by constructive interference.[8,9] On the testpiece under study, the phased array ultrasonic testing was performed at discrete locations, at intervals of 19 mm along the weld, in order to capture information regarding the lack of penetration discontinuity. The inspections were performed from the tool side (opposite to the discontinuity side) using a linear array of 16 elements, creating waves of 10 MHz frequency, adapted with a shear wave wedge able to generate waves at 60° incidence in steel. The wedge and array assembly were able to generate a beam spread between 45 and 70° in the specimen under test. The probe was positioned away from the weld location and oriented in such a way that the emerging ultrasonic beam is perpendicular to the weld length axis. Selected results are shown in Fig. 3 as sectorial scan presentations. The lack of penetration indications are seen between the vertical cursors, corresponding to a range of sound path length from 5·94 to 6·83 mm from the probe, as theoretically predetermined based on the wave propagation principles. The colour intensity is proportional to the reflected signal amplitude and, consequently, to the lack of penetration size. Based on the discrete inspections presented, the phased array ultrasonic wave technique could detect reflections from the discontinuity up to positions of >160 mm but <179 mm from the start of the weld. Although indications between the cursors at



3 Phased array ultrasonic sectorial scans at various locations along butt weld (distances from beginning of weld)

217 and 235 mm could be seen in the following results, these do not exceed the background noise level of the signal; therefore, they could not be reliably attributed to the presence of discontinuities in the weld.

Synthetic aperture focusing technique

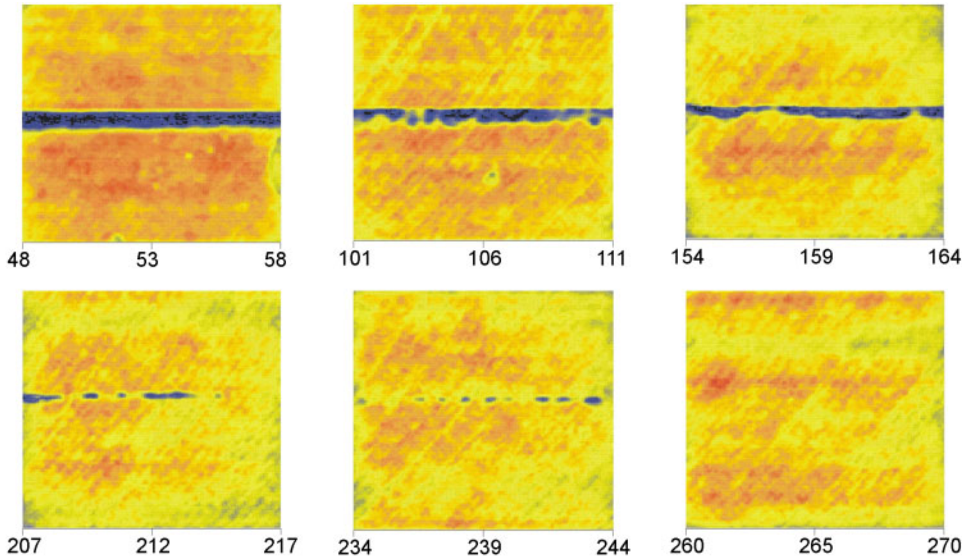
The SAFT algorithm uses Fourier time domain information and allows synchronization of the ultrasonic signals scattered back in different directions from each point in the weld region.[7] For these scans, the spatial sampling step was selected to be 0·1 mm for both x and y directions. The technique used laser generated ultrasonic waves with a spot size of ~50 μm from a 35 ps duration Nd/YAG laser in its third harmonic. The detection used a long pulse Nd/YAG laser, and demodulation was performed with a photorefractive interferometer; frequencies of up to 220 MHz were successfully used in this inspection. The images shown in Fig. 4 represent the SAFT processed laser ultrasonic inspections corresponding to six different pin locations along the weld. The scans are individual areas of 10 × 10 mm, and surface machining of the part is visible as lines from the bottom left corner to the top right corner. Clear indications of lack of penetration are visible in the scans closer to the weld start. Towards the middle of the weld, as in the scan after 164 mm, an interrupted lack of penetration indication could be seen; however, for a coordinate along the length of the weld of >245 mm, no lack of penetration is observed, and the weld is considered free of these types of discontinuities. According to equation (1), at a coordinate equal to 245 mm, the tool penetration depth is 1·92 mm in the 2·36 mm total thickness specimen.

Eddy current testing

The eddy current non-destructive testing method consists of electromagnetically inducing a current flow in an electrically conductive testpiece by passing a time varying current through a coil. The eddy currents are creating a response magnetic field to the excitation one that depends on the material properties, geometry and encountered discontinuities. The method has several variants, depending on the excitation waveform, type of sensing and data representation; the communalities among them are that they cannot penetrate large distances in the material, maximum of a few millimetres, and that they are applicable only to electrically conductive parts. In this paper, the two most known eddy current techniques are used: conventional and pulsed ones.

Conventional eddy current

In conventional eddy current testing, a sinusoidal waveform is used for excitation, while the response signals are represented on an impedance plane diagram, as changes in the resistive and reactive components of the impedance of the coil. This technique lacks the capability of probing deeper than a few millimetres in



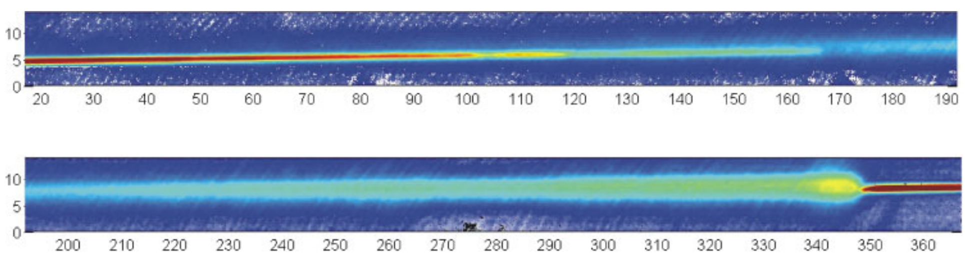
4 Laser generated ultrasonic wave testing with SAFT processing at different locations along weld; coordinates indicate distance from beginning of weld

the material; therefore, it is being considered a surface or near surface inspection. In this experiment, a 400 kHz sinusoidal waveform was used for the excitation of an absolute coil, i.e. used for both driving and sensing the eddy current in the FS weld. The probe, model ECNDT PA 0050, was connected to a commercial Zetec MIZ 27 instrument that was interfaced with a computer. Scanning was performed from the far side of the weld, the one that contained the lack of penetration. The probe was sampling the weld surface at every 0·1 mm. In Fig. 5, the results of this inspection are shown in two sections, identified as the coordinate along the weld (0 mm for the beginning of the weld and 345 mm for its end). The colour changes are due to changes in the coil impedance induced by the testpiece. It should be noted that the data presented in Fig. 5 are liftoff compensated at the acquisition time. The liftoff represents the changes in coupling between the probe and the specimen due to minute variations in the distance between the two along the inspection. Moreover, the raw data are post-processed, normalised, in order to display clearly the lack of penetration discontinuity. The lack of penetration is seen as an almost horizontal line up to ~165 mm from the start of the weld. In the section after the end of the weld (after 345 mm coordinate), the two plates are in contact but not welded. The eddy current response corresponding to this is similar to the one of a large crack.

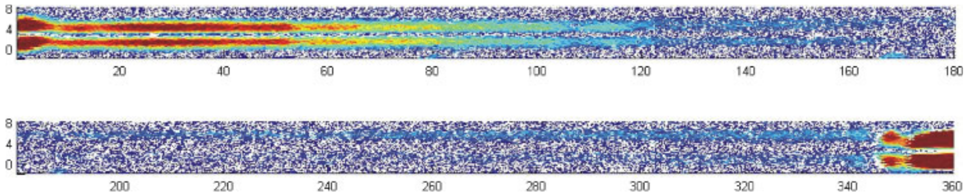
Although the lack of penetration is the thin line of the upper picture of Fig. 5, towards the end of the weld, a low intensity, wider area is related to the changes in the electrical conductivity in the absence of defect. It was previously shown that the electrical conductivity changes by up to 4% International Annealed Copper Standard (IACS) as a result of FS welding of aluminium alloys.[10] Moreover, in recent studies, this property correlated well with changes in hardness and microstructure variations.[10,11] Therefore, eddy current evaluation of FS welds could have a double role: one in the detection of defects and the other as a material characterization technique through electrical conductivity measurements.

Pulsed eddy current

The pulsed eddy current uses a square waveform to drive the excitation coil instead of a sinusoidal wave excitation, as for the conventional eddy current testing. In general, this technique is capable of probing the material deeper than the conventional eddy currents do.[4,12] Another significant difference is that the signals are recorded in the time domain and not on an impedance plane diagram, as was the case of the former technique. In this inspection, a probe containing two coils, one for excitation and one for recording, placed side by side and aligned with the weld length, was used for scanning. The scanning resolution was set to 0·2 mm on each direction. Again, the recorded signals were post-processed, applying liftoff compensation, background subtraction and image filtration algorithms, as described elsewhere.[4] The results obtained along with this technique are shown in Fig. 6. In this representation of the inspection, the defect boundaries are more visible, rather than the defect itself. The continuous scan (broken down in two sections in



5 Conventional eddy current inspection results presented in two sections along weld



6 Pulsed eddy current inspection results; coordinates indicate distance from beginning of weld

Fig. 6) indicates detection of the lack of penetration discontinuity up to coordinates equal to 160 mm from the weld start, although some unreliable indications after that position are seen in Fig. 6. This might be due to a widening of the defect or heat affected conductivity changes.

Liquid penetrant testing

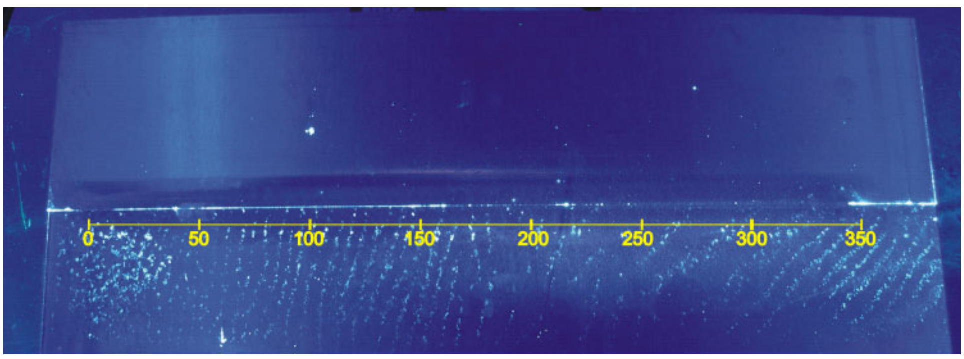
The liquid penetrant inspection method uses capillarity principles to detect tight defects open to the specimen's surface. A fluorescent liquid is applied evenly to the far side surface of the weld, and time was allowed for this to penetrate open discontinuities.[13] While the surface liquid is wiped or rinsed away, a quantity remains entrapped in the discontinuity, and then it is drawn out by using a developer, followed by visual analysis under ultraviolet light. Indications of discontinuities, their location and size, could be determined based on the fluorescent dye visible on the surface. A photograph of the FS butt welded specimen under ultraviolet light is shown in Fig. 7. It is important to note that there are clear indications before the weld start and after the weld end, where the two plates are in contact but not welded. The lack of penetration defect is more evident between the 0 and 110 mm coordinates on the weld, a fact also observed with the conventional eddy current inspection, as seen in Fig. 5. However, less intense indications could still be observed until ~190 mm from the weld start.

Destructive testing

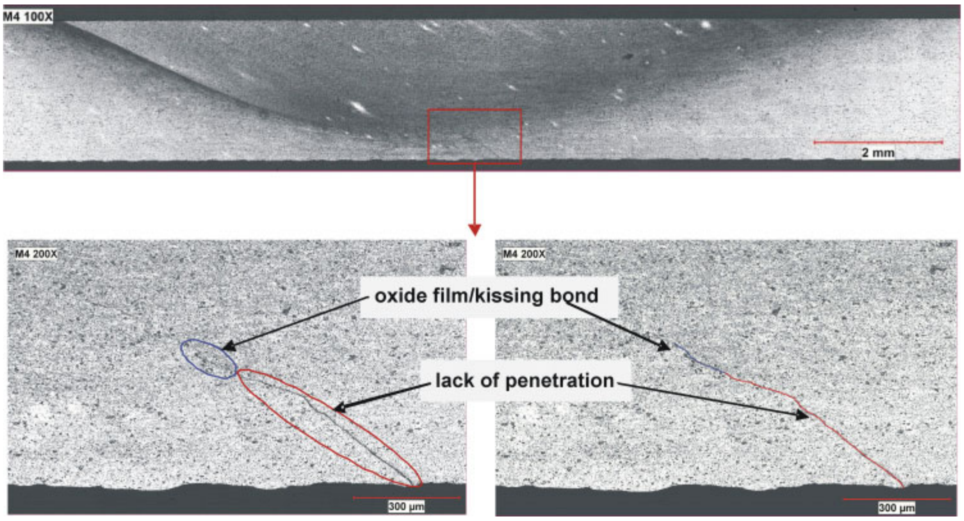
Metallographic examinations performed at 13 locations along the length of the weld revealed the presence of lack of penetration defects until ~150 mm from the weld start. However, besides lack of penetration, another type of defect is present, consisting of a thin layer of oxide, customarily called 'kissing bond'.[1] Kissing bonds are known to be present at the intimate contact of two adjacent surfaces but without actual metallurgical bond and lack of cohesion forces. These types of defects propagate from the tip of the lack of penetration and along the weld nugget boundary. Another observation of the metallographic analysis is that the lack of penetration defect is not perpendicular to the surface of the coupon, but it has an oblique orientation, making an angle with the surface normal (vertical) starting at ~20°, and it increases as the tool depth progresses, reaching a value of 59° at 150 mm from the weld start. This orientation of the defects is expected due to the stirring of the plasticised metal and to the geometry of the pin. Figure 8 shows one of the metallographic images at a distance of 95 mm from the weld start. The magnified photograph tries to identify the two types of discontinuities: lack of penetration and kissing bond. It is important to note that this defect makes an angle of 57° with the vertical, and while the total defect length is 0·701 mm, its height is only 0·364 mm. This aspect was emphasised earlier in Fig. 1. Moreover, the kissing bond is found to deviate even more from the vertical axis as the weld progressed. It was found through metallography that the kissing bond angle with the vertical increases from 68° at 176 mm from the weld start to 80° at 257 mm coordinate (the last location where the defect is observed before the end of the weld).

Figure 9 shows the maximum unweld thickness of the coupon, as the total thickness of the coupon minus the tool depth, but also the vertical size of the defects (i.e. defect height) – here including the lack of penetration, oxide film (kissing bond) and total defect (lack of penetration and kissing bond). As it could be seen from the plot, the actual weld depth is larger than the tool penetration depth by a varying range, i.e. from 0·35 to 0·64 mm. The tool penetration depth varies linearly from 1·0 to 2·3 mm, as shown in Fig. 2*c* (plus the surface machining of 0·2 mm of the thickness). Moreover, while the lack of penetration defect is present to up to 150 mm from the weld start, the kissing bond was observable until ~260 mm from the weld start.

Bending tests were performed on 12 equidistant specimens along the weld, according to standards.[14] Figure 10 shows the results of the bending tests at the



7 Liquid penetrant inspection results from far side of specimen photographed under ultraviolet light: coordinates along weld are given in millimetres



8 Metallographic examinations at 95 mm from weld start, where both lack of penetration and oxide film/kissing bond defects are present: magnified section is presented twice for better visibility (on right with lack of penetration defect identified by red colour and kissing bond by blue colour)

same discrete locations at which the ultrasonic inspections were presented. The overall observation is that the bending causes the specimen to break when the lack of penetration defect is present, and it only creates cracks when just kissing bonds were identified through metallographic analysis.

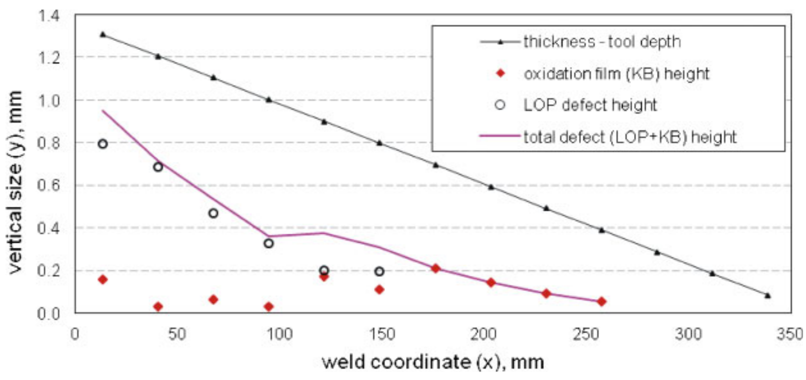
Summary and discussions

According to the destructive testing and metallographic examinations, the lack of penetration is confirmed up to 149 mm from the weld start, while at 176 mm, the lack of penetration is no longer observed, while kissing bonds are present up to a coordinate of 257 mm. Conventional eddy current and liquid penetrant techniques investigated the FS weld from the discontinuity side, and they are discussed here first.

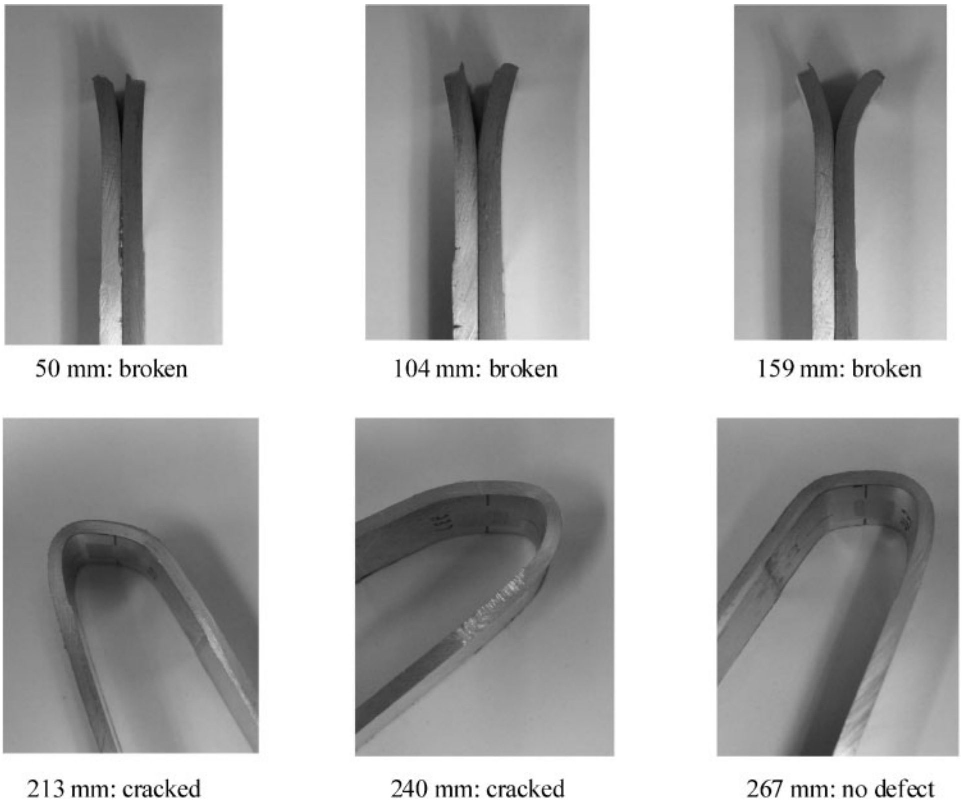
The liquid penetrant inspection technique clearly indicates the presence of a surface opened discontinuity up to 110 mm from the weld start. Reduced intensity continuous fluorescent indications are found up to 140 mm, after which the results are spotted until 190 mm (as seen in Fig. 7). It is important to note that this is a qualitative technique, and it only depends on whether the defect is open to surface or not. Given the 'no width' characteristic of a kissing bond defect, the liquid penetrant technique is not expected to give any indication of this type of discontinuity. Correspondingly, lack of penetration is not found to exist with liquid penetration inspection at 176 mm, where the destructive testing confirms the inexistence of lack of penetration and beyond. However, the discontinuous indications might correspond to local spots where lack of penetration exists in conjunction with kissing bonds.

Since in eddy current inspections, both conventional and pulsed, the induced current flow is parallel to the surface of the specimen, disruptions in their path are due to the portion of the defect perpendicular to the surface of the weld. As it was observed from the destructive testing, the defect has a slanted orientation, reaching angles up to 60° with the vertical for the lack of penetration defect and as large as 80° for the kissing bond types of discontinuities. Conventional eddy current gives out indications of the lack of penetration defect until ~165 mm (Fig. 5). Kissing bonds are not identifiable with this type of inspection due to both contact of the defect faces and defect orientation with respect to the eddy current flow.

Phased array ultrasonic waves, pulsed eddy current as well as laser ultrasonics with SAFT analysis were used to investigate the defect from the tool side, meaning that the input signal had to be transmitted through the welded material before interacting with the defect, overcoming wave attenuation and skin depth effects. Phased array ultrasonics and pulsed eddy current gave results similar to the ones obtained with inspections



9 Vertical size of discontinuities along weld length (LOP: lack of penetration, KB: kissing bond)



10 Specimens of bending tests and results: coordinates indicate distance from weld start to centre of specimen (each specimen had width of 18·8 mm)

from the discontinuity side of the specimen, i.e. liquid penetrant and conventional eddy current. The phased array ultrasonic wave technique successfully identified the lack of penetration defect, up to 160 mm from the weld start, as seen in Fig. 3. However, the kissing bonds are not detected by this technique due to the defect orientation because the setup was optimised in order to detect defects that are perpendicular to the weld. The SAFT processing of laser generated ultrasonic waves of high frequencies is the only technique that detects both the lack of penetration and the kissing bond types of defects, but without differentiating between the two.

Conclusions

This study investigated the capabilities of five different non-destructive testing techniques in inspecting lack of penetration discontinuities in butt joint FS welds. A specimen with a varying lack of penetration, introduced by adapting the welding tool penetration, was specially manufactured for this purpose. Two of the five inspection techniques, i.e. conventional eddy current and liquid penetrant, were used to investigate the weld from the side with lack of penetration. The other three techniques, i.e. phased array ultrasonic waves, laser generated ultrasonic waves with SAFT processing and pulsed eddy current, were used to inspect the specimen from the welding tool side, which is opposite to the defect containing side. Although the first two techniques have certain advantages and provided more reliable results because they investigate the defect containing side of the specimen, the other three techniques are more realistic from a practical point of view, where in most of the cases the weld surface from the tool side will be the one exposed for inspection. All the inspection techniques revealed the presence of the lack of penetration discontinuity up to at least 150 mm from the weld start, corresponding to a defect height of 0·2 mm (total defect length of 0·357 mm, as confirmed through destructive examinations). The liquid penetrant technique showed the presence of the defect until up to 190 mm from the weld start. The SAFT processing of the laser generated ultrasonic waves detected both lack of penetration and kissing bond types of defects up to $\sim$245 mm from the weld start. Bending tests demonstrated that, when lack of penetration defects are present, the coupons break, while when kissing bonds exist by themselves and not accompanied by lack of penetration, the bending specimens do not break but show only surface cracking. Interestingly, for the bending coupon presenting a kissing bond of 0·33 mm in length (only 0·056 mm vertical height), the specimen does not show any sign of damage after performing the bending test.

Acknowledgements

The authors would like to thank M. Brothers from the Institute for Aerospace Research as well as M. Patry, M. Lord and F. Nadeau from the Industrial Materials Institute of the National Research Council Canada for their contributions to this project.

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