ADVANCES IN NDT TECHNIQUES FOR FRICTION STIR WELDING JOINTS OF AA2024

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Abstract

Industrial applications of solid state welding technology have undergone a significant development with the advent of Friction Stir Welding (FSW). Although the good quality of FSW joints some defects may arise which are difficult or even impossible to detect with conventional NDT techniques. This work addresses an innovative NDT Eddy currents probe that was developed and tested for quality assessment of FSW joints of aeronautic aluminium alloy AA2024-T351. The influence of defects with different locations and morphology in joint mechanical efficiency are investigated under fatigue loads. The application potential of the new NDT Eddy currents probe in detecting the different defects is evaluated and compared with other NDT techniques. The results show a strong dependence between FSW parameters and defects formation and the feasibility in using the new NDT Eddy currents probe mainly concerning the detection of root defects which have a critical role in mechanical joint efficiency.

Introduction

Although the friction stir welding (FSW) joints have a better quality compared to the fusion techniques, there are still some defects that may arise and which are very sensitive to small variations in process parameters. The assessment of the role of these defects in the overall resistance of friction stir welded structures under fatigue loading, typical from any aeronautical application, is a crucial issue. The aeronautical industry demands not only the feasibility but also high levels of reliability of the detection procedures for all the FSW defects [1].

Unfortunately, the typical non-destructive testing (NDT) techniques, such as: visual inspection, magnetic particles, liquid penetrant and X-ray, do not enable the detection or quantification of the typical FSW defects. The ultra-sounds and eddy currents NDT techniques, even in their most recent form of evolution: phased array and eddy currents array, allow the detection of most of the defects in FSW joint. However they are very sensitive to coupling and lift-off conditions between the probes and the surfaces under inspection [2]. In this work the technological and physical fundaments of a new probe for NDT inspection are addressed and some experiments are presented enabling to tests and compare different working parameters of the new proposed IOnic probe for NDT inspection of FSW joints.

In order to know the relative importance of different defect types in the mechanical behaviour of FSW structures under fatigue loads, specimens welded by friction stir with two different root defects and one internal defect were tested and correspondent fracture surfaces investigated.
FSW Typical Defects

Typical defects that may arise in FSW joints are represented in Figure 1, resulting from, e.g., imperfect stir of the materials during the processing, inadequate surface preparation, lack of penetration of the pin and non-uniform vertical forging forces along the material thickness. Some characteristic FSW defects are lack of penetration (typically addressed as kissing-bond), root flaw (concerning weak or intermittent linking), voids on the advancing side and second phased particles and oxides alignment under the shoulder.

![Figure 1 – Typical defects on butt joint FSW configuration](image)

The geometry, location and microstructural nature of the FSW defects, which bore no resemblance with defects typical of fusion welding of aluminium alloys, lead to difficulties in identification when using the common NDT techniques [2].

**IONic Probe**

In fact, the high-sensitive lift-off effect of conventional eddy current probes generates a noise which hides the signal produced by the typical FSW small defects, making the detection of those defects impossible. In order to avoid this problem, a new NDT eddy current probe called *IONic Probe* was developed, tested and compared with two other eddy current probes: conventional cylindrical helicoidally coil and spiral plane coil. The preliminary results indicate that the new probe is more reliable in detecting and evaluating depth defects than conventional probes.

The *IONic Probe* [3] consists in two inductors, one exciting coil perpendicular to the surface material and one sensitive coil characterized by a special patented symmetric coil display and a relative position to the first one that minimizes the lift-off effect. With this design the detection of the defects is based in the induced voltage on the terminals of the sensitive coil, rather than in the usual impedance measurements.

In order to validate the concept a prototype was built and tested for two extreme cases of lift-off and conductivity (Figure 2).
Figure 2 shows the typical signal obtained by the IOnic Probe along X and Y directions, starting from the center of the aluminium plate AA2024-T351 and stopping outside the boundaries of this plate. The results indicate that both real and imaginary output voltage are kept constant when the probe is moved along the Y direction, demonstrating the signal independence to the lift-off effect. On the other hand, in the X direction there is a 400% signal change, which confirms the high sensitivity of the probe to the conductivity changes within the material.

The subsequent test consisted in comparing the IOnic probe with conventional cylindrical probes. An aluminium plate AA2024-T351 with 4mm thickness and a standard hole defect of 1mm diameter in the center was used in the experiment. The probes were put 25mm away from the hole and then moved towards the hole in a rectilinear direction until they were brought to a standstill 25mm after the hole. The real and imaginary signal of both probes was acquired along this displacement and the results are given in Figure 3.

The amplitude of real and imaginary part of the output voltage for the IOnic probe is respectively two and five times bigger than for the conventional probe. It means that the IOnic is more sensitive and therefore more reliable for defect detection.
A third experiment was developed, where the lift-off and conductivity changes in the impedance diagram of the IOnic probe were compared with three different types of planar spiral coils: 20 circular, 10 circular and 10 squared coils (Figure 4). All coils were printed on a circuit board and have a thickness of 90µm, a height of 30µm and a distance between two successive coils of 90µm. These types of probes have been suggested to have a high potential for several NDT applications, due to their close proximity to the surface material and the possibility of being printed on a flexible sheet.

The lift-off noise tests were conducted on standard thin film polymers of different thicknesses on top of the material surface and the conductivity tests were carried out on four different materials: Cu, AA2024, AA5083 and 99.94-wt% Pb with 100%, 37.8%, 29.9% and 8.1% of the IACS respectively. The results depicted in Figure 4 reveal that the signal of the planar spiral coils is much more sensitive to the lift-off effect than to the conductivity changes (Figure 4a), while the IOnic probe signal has a much greater response to the conductivity change when compared with the lift-off signal (Figure 4b).

The reliability of the eddy current probes for NDT applications is strongly dependent on a superior response to the conductivity changes than to the lift-off. Therefore the IOnic probe is a considerable improvement to the spiral plane coil probes.

**Assessment of the Influence of Typical FSW Defects in Fatigue Behaviour**

In order to assess the influence of some of the most typical defects in FSW joints, non-defective and defective weld joints, with three different defect types, were produced in aeronautical aluminium alloy AA2024-T351 with a thickness of 4mm. The characterization of these defect types is described in Table 1. Two different tools (a combination of one shoulder with two different pins) were implemented to produce the 4 different FSW joint conditions (Defect Type: 0, I, II and III), as shown in Figure 5. The shoulder with 2 spiral striates has an outer diameter of 14mm and the 2 pins are about 5mm in diameter. Other process parameters were rotation speed of 710rpm, travel speed of 224mm/min and tilt angle of 0.5degrees.

In summary, the two different root defects: Defect Type I and Defect Type II, were obtained by decreasing the pin length from the non-defective weld joint (Defect Type 0). The internal defect (Defect Type III) was obtained by the application of a cylindrical smooth surface pin, with 3
small helicoidal groves at the tip of the pin, which along with the correct pin length enabled to prevent root defects.

<table>
<thead>
<tr>
<th>Defect Type Code</th>
<th>0</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Not Defective</td>
<td>Root Defect Type I (Particles Alignment)</td>
<td>Root Defect Type II (Kissing-Bond)</td>
<td>Internal defects (Voids)</td>
</tr>
</tbody>
</table>

Table 1 – Establishment of the 4 different Defect Types included in the FSW joints produced

![Figure 5](image.png)

Figure 5 – Two different FSW tools used to produce the 4 different Defect Types

In order to investigate the fatigue behaviour of the AA2024-T351, base material and friction stir welds specimens, including the 4 different defect types, were prepared in the as welded condition. The fatigue tests are performed on an Instron, model 8874, with a load cell of 25kN. Stress ratio R is 0.1. Oscillation frequency was typically set to 10Hz. The S-N curve results obtained are presented in Figure 6.

![Figure 6](image.png)

Figure 6 – Fatigue resistance results for base material and 4 different defect type conditions. a) S-N curve; b) Number of cycles efficiency relatively to the base material performance
Figure 7 – SEM fractography’s illustrating the localization of cleavage planes in the vicinity of Defect Types I, II and III. a) Root Defect Type I; b) Root Defect Type II; c) Internal Defect Type III; d) Detail of c)

The analysis of the fatigue results (Figure 6) both emphasizes the good quality of the Defect Type 0 FSW joints, with a behaviour very near to the base material, and the important role that all the three defect types play in the loss of mechanical resistance. Among the three different analyzed defects, root defects are definitely the ones that show higher loss of properties under fatigue loading.
In Figure 7, it is possible to confirm the higher length of the root Defect Type II, when compared to the root Defect Type I resulting in lower life under fatigue loading. Figure 7 also shows the deformation pattern in the vicinity of the internal void of the specimens with the Defect Type III.

Conclusions

The three experiments presented in this paper show that the results of the IOnic probe exceed the performance of conventional probes. These results are encouraging but still preliminar and further studies are currently being conducted to assess the potential of the IOnic probe to detect FSW defects.
The influence of the root defects in the loss of mechanical strength of friction stir welded structures under fatigue load, typical from any aeronautic application, is very significant. Moreover these types of defects are the ones that are more difficult to identify from the application of previous NDT techniques very sensitive to coupling and lift-off conditions.

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