Correlation of Phased Array Inspection and Fatigue Performance of FSW Joints

A method was established for determining whether a weld was correctly forged, and the correlation between the defect criteria level and fatigue life was demonstrated

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Friction stir welding (FSW) of aluminum alloys is now an established joining technique, and there is increasing application of FSW to the joining of critical components and structures. Much emphasis has been placed on optimizing tool design and process parameters to ensure joint quality. However, flaws may still be created in the production environment if the limits of the “process window” are exceeded. As FSW is a machine/automated process, once the process has been designed and tested, defect production should not occur but, like all processes, process control can become out of limits or unforeseen circumstances can affect the quality of the weld. For this reason, good NDE is required for the detection and characterization of production flaws. This article is based upon a project correlating NDE data against fatigue performance of FSW joints. A method for determining whether the weld has been correctly forged was established, and the correlation between the defect criteria level and the fatigue life was demonstrated.

Friction Stir Welding

Friction stir welding is a solid-state joining process that produces a fully consolidated weld (Ref. 1). Welds are made by plunging a rotating cylindrical tool into the joint to be welded. The heat the friction generates is sufficient to locally soften the workpieces, and the rotating motion of the tool stirs the workpieces together as the tool is advanced along the joint line.

The technique has many advantages. The process can be fully mechanized, allowing the production of welds with a consistently high quality. There are also practical advantages such as low shrinkage and distortion, and no porosity (Ref. 2).

Welding Procedure

All welds were made using TWI’s ESAB SuperStir friction stir welding machine. The tool probe was machined to be 0.15 mm shorter than the total material thickness, and the machine spindle was tilted 1.5 deg away from the direction of weld traverse. The weld was made at 350 rev/min at 210 mm/min travel speed.

Fig. 1 — Pictures of the weld nugget structure from a good weld.
Weld Flaw Definitions

There is often confusion between terminology such as flaws and defects. To avoid misunderstandings, this article defines these differences.

A defect is an imperfection that has been shown to compromise the integrity of the structure, and its presence is therefore intolerable. A flaw is defined as an imperfection whose significance has not been established, and which could be possibly tolerated in the structure. Thus, all the imperfections generated for the present study are termed flaws. There are two categories of flaws in friction stir welds: volumetric and joint line flaws (Ref. 3).

Volumetric Flaws (Voids)

Imperfections in a friction stir weld due to a lack of material are termed volumetric flaws or voids. Voids may be caused by inadequate material flow either due to tool features or selection of an excessive welding speed. Inadequate consolidation of the softened material due to a reduced forging pressure, inadequate material clamping (plates separate during the welding), or the presence of a significant gap along the joint line because of poor fitup may also cause voids.

Joint Line Flaws (JLF)

In friction stir welding, the original joint line can still be traced, and it is referred to as a joint line remnant. Detailed examination shows that it consists of oxide particles delineating the original joint line. Thus, the presence of a joint line remnant should not be necessarily considered a flaw.

The most serious defect associated with the joint line remnant is located at the weld root. The extreme condition is a lack of bond caused by incomplete penetration, which could be caused by a shortened pin or by poor control of tool position or force.

The most difficult flaw to quantify is a region of weakly bonded material in the root of the weld. Such regions can exist at the end of root flaws, but will always follow the path of the joint line remnant. They are very difficult to detect nondestructively since a bond exists.

From previous published work (Ref. 4) and discussions with the aircraft industry, it was clear that conventional flaws, for example voids and incomplete bonds, could be detected by the conventional ultrasonic method. While the vast majority of FSW joints are expected to be free of defects, it is not always possible to assume that they are completely flaw free. To improve confidence in the design, manufacture, and application of FSW joints, manufacturers are seeking data on the properties of welds containing flaws and requiring validated inspection techniques to detect those flaws on-line, after manufacture, and in service.

To establish a correlation between mechanical properties and NDE performance, a number of welded plates were produced. The project used 4-mm-thick aluminum 2024-T3. This project generated a number of defect types, but this article concentrates on the correlation of NDE results and fatigue life, and presents the results for the joint line flaw (JLF) welds as follows:

- Plate 1: good control weld as shown in Fig. 1, where the weld root is fully penetrated.
- Plate 2: 0.3-mm shortened pin.
- Plate 3: 0.5-mm shortened pin as shown in Fig. 2. The figure shows that the weld root has a similar undisturbed structure as that of the base plate.
It should be noted that the dimensions of the flaw produced by this approach will not necessarily correlate exactly with the length of the pin reduction, and may vary along the length of the weld within machine positional accuracy.

Development Strategy

As reported previously (Refs. 4, 5), ultrasonic phased array inspection is a relevant method to inspect FSW. Metallurgical properties affect ultrasonic transmission. The forging of the metal by the FSW tool refines and reorients the grain structure, resulting in reduced backscattered amplitude from the grain structure of the weld nugget as compared to that of the base metal.

The inspection technique is designed to detect both conventional flaws (volumetric and joint line) and the presence of the specific FSW flaw: joint line remnant. Although joint line remnant flaws are commonly so tight that they cannot be detected directly (unless they are so severe that they could be classified as an incomplete bond), weld quality can be assessed on the grounds of ultrasonic grain noise. The average value of the grain noise is calculated in both weld nugget and base plate then compared. This comparison is used to measure the quality of the weld root region.

Inspection Development

The phased array inspection was performed from the weld cap side of the plate. The characteristic grain structure difference between the base material and the weld nugget was best provided with a 15-MHz linear array probe using a beam angle of 70 deg, with 32 active elements having 0.2-mm pitch. To achieve adequate ultrasonic coupling of the probe, the surface finish of the component was required to be good and water was required as an ultrasonic couplant. A schematic illustration of the ultrasonic phased array probe is shown in Fig. 3.

Data Analysis

The scans are displayed as a combination of images in the TomoView software. The forging of the metal by the FSW tool refines and reorients the grain structure, resulting in reduced backscattered amplitude (or "noise") from the grain structure of the weld nugget as compared to that of the base material.

To provide a stable assessment of the root area of the weld, noise amplitude measurements were produced by normalizing the noise measurement against the noise measure in the base material. An illustration of the data sample positions is shown in Fig. 4.

Ultrasonic Inspection Results

A sectional view and a plan view of the ultrasonic data are given in Fig. 5A–C, where the black dashed line represents the position of the weld nugget.

The through-wall placement of the sample box is a compromise between detection of unwanted sample surface noise and detection of small flaws. As illustrated in Fig. 4, the indication from a small surface scratch provides a signal to a depth of about 0.5 mm from the bottom surface of the plate. This signal does not indicate that the scratch was 0.5 mm deep; in fact, it was < 0.1 mm. The arc signal is a measure of the UT beam width. For this reason, a compromise has to be reached between detection of welding flaws and detection of natural marks on the surface of the component. In this case the sample box was placed at a distance of 0.5 mm from the bottom of the plate to minimize the signals from the plate surface but capture the signal from a flaw.

When the weld has been properly manufactured, the ultrasonic level of the weld root should be lower than that of the base material. If the weld root has not been fully forged, then the noise level will be equal to that of the base plate, and if there is an open conventional defect such as an incomplete bond, the noise level will be higher than that of the base material. By comparing the level inside the root to that of the base material, the operator has a powerful tool for estimating the pin penetration and the likelihood of a flawed weld.
Table 1 gives detailed noise analysis results for each plate at three positions along the weld (50, 100, and 150 mm from scan start). In addition to the noise ratio measurements, the average and range are given for the weld root of each weld.

The ultrasonic data presented in Fig. 5A show no flaw indications. The weld root is fully penetrated on the full length of the plate. The average noise ratio for this plate is 0.28 with a range of 0.02. This analysis shows that the recorded grain noise in the weld root was constant and approximately one quarter of that of the base material, which indicates a highly grain-refined weld root. Furthermore, the range indicates that the welding quality was very consistent.

Figure 5B shows a sectional view where the weld appears to be fully forged and a further section where there is a flaw signal in the middle of the weld root. The plan view shows intermittent indications along the centerline of the weld.

The average noise ratio for this weld is 0.63 with a range of 0.42. The noise analysis shows that the noise is approximately twice that of Plate 1 with a large variation (0.42) of noise ratio with respect to axial position. Additionally, where there is a point indication in the plan view, the sectional view shows a not fully forged weld with a darker zone in the root than for a good weld. Hence, in addition to the positive indication, there is evidence that the weld is not fully forged.

Figure 5C shows the ultrasonic image of the weld where a flaw appears in the weld root for the majority of the inspected FSW length. The average noise ratio for this weld is 4.0 with a range of 1.73. This defect is analyzed by conventional data analysis as an incomplete bond and is highlighted on the plan view. The noise ratio measurement indicates that the noise in the weld is higher than that of the base plate, and for this reason, there must be an open ultrasonic reflector. This result is consistent with the macrosection shown in Fig. 1 where an incomplete bond flaw was visible in the root. The large range of noise ratio readings indicates that the flaw size varies considerably with axial position; this is also clear from a comparison of the two sectional views in Fig. 5C.

### Endurance Fatigue Testing

#### Test Specimens

Fatigue test specimens were designed with the weld at the center and oriented in the transverse direction with respect to the direction of loading, and a minimum of five tensile tests were performed per weld. As noted previously, the weld cap was machined flush before extracting the specimens to avoid a life reduction due to the surface roughness.

#### Fatigue Testing

Endurance fatigue tests were conducted in a 100-kN-capacity
Amsler Vibrophone testing machine. The tests were carried out under constant amplitude axial loading, in air and at room temperature. More details about the tests including the applied stress ranges, the cycling frequency, and the applied stress ratio are given in Table 2 (R = σ_{min}/σ_{max} where σ_{min} is the minimum and σ_{max} is the maximum stress in each cycle). Stress ranges were chosen to give fatigue lives in the range of 10^4 to 10^7 cycles, although in the event none of the specimens that failed from flaws gave lives above 10^6 cycles. The specimens were tested to complete failure or the occurrence of a through-thickness crack. A run-out endurance of around 10^7 cycles was adopted, at which point testing was stopped if the specimen showed no signs of fatigue cracking. Some such specimens were subsequently retested at higher stress ranges to increase the available database.

**Fatigue Test Results**

The fatigue test results are presented in Fig. 6. The majority of specimens containing flaws failed from a flaw on the weld centerline. However, specimens from the flaw-free plate and some specimens from Plate 2 failed in the base plate, away from the weld.

**Nominally flaw-free weld, Plate 1.** These specimens were tested at stress ranges between 100 and 200 MPa. Only three of the six specimens failed in the weld. Two others failed from the edge of the specimen in the base plate away from the weld, while the third failed where the specimen was gripped in the wedge jaws of the testing machine. There are too few results to establish statistical limits, and therefore a scatterband bounding the results has been estimated by eye.

**0.3 shortened pin, Plate 2.** Apart from one case of base metal failure, all specimens from this plate failed in the weld. The welding method produced definite evidence of joint line flaws, especially incomplete bond; therefore, it is not surprising to find that fatigue cracking always initiated at such flaws on the weld root side. However, the fatigue test results are compared with the reference scatterband for flaw free, and a large variation in fatigue life can be observed. This large variation is thought to be a reflection of the intermittent nature of the flaws. The presence of the flaws has reduced the fatigue performance of the welded joints considerably, all the failures being obtained at stress ranges below the apparent fatigue limit of the flaw-free weld. Compared with the reference scatterband, the reduction in fatigue strength ranges from about 30% to 40%. It is noticed that for the same stress range 75 MPa, the endurance varies greatly showing highly variable flaw depths. This result correlates well with the NDE results as shown in the plan view (Fig. 3B), and with the weld ratio analysis that provides a large range.

**0.5 shortened pin, Plate 3.** The stress ranges for test on this welded joint were chosen on the basis of both the intended flaw size and the NDE results, which reported near uniform incomplete bonding. Thus, four specimens were tested at 50 MPa and one at 100 MPa for direct comparison with the Plate 2.

The fatigue test results are compared with the reference scatterband for a flaw-free weld in Fig. 6. Due to the near uniform incomplete bond of 0.5 mm, all the welds failed from the flaw at the weld centerline. As it can be seen in Fig. 6, there was very little scatter in the fatigue lives obtained from the four specimens tested at 50 MPa. It shows that the defect was constant all along the weld and confirms the consistently high noise ratio results and the large visible flaw in the plan view in Fig. 5C.

**Discussion**

A simple summary of the results is presented in Table 3, which shows that the lowest average noise ratio provides the highest weld quality whereas higher average noise ratio provides lower fatigue strength.

<table>
<thead>
<tr>
<th>Plate number</th>
<th>Welded joint details</th>
<th>Average noise ratio</th>
<th>Fatigue strength as percentage (stress applied) of flaw-free weld</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flaw free</td>
<td>0.28</td>
<td>100</td>
<td>Equivalent to base material</td>
</tr>
<tr>
<td>2</td>
<td>Up to 0.3 mm incomplete penetration</td>
<td>0.63</td>
<td>60–70</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.3–0.5 mm incomplete penetration</td>
<td>1.07</td>
<td>40–55</td>
<td></td>
</tr>
</tbody>
</table>

With Plate 2, the flaws were produced using a FSW pin shortened by 0.3 mm. It is fairly clear that the ultrasonic inspection method has the ability to detect the variations in flaw sizes in an FSW joint. Presence of a flaw is shown by an increase in the weld root noise, which ranges from 1.5 to almost 3 times that of the good weld. It is a closed flaw as the noise ratio is less than 1.0. The ultrasonic results agree with the fatigue results; both show a large scatter in the result obtained from the specimens tested.

The flaw size variation has been further confirmed by the analysis of the fracture faces from two specimens shown in Fig. 7A, which show that the original flaw varies from 0.198 to 0.390 mm.

Figure 7B shows a constant incomplete bond about 0.5 mm at the root of the weld, which was consistently detected with a high noise ratio by the ultrasonic phased array method. The result correlates with the fatigue test where very little scatter in the fatigue lives was obtained from the four specimens tested at 50 MPa, showing that the defect was constant all along the weld.

**Conclusion**

◆ The results demonstrated a strong relationship between the NDE results and the fatigue performance for the Al 2024 T3 FSW joints. The NDE results allow a quantitative assessment to be made about the stirring quality of the weld; in turn, the possible presence of a joint line remnant.

◆ The NDE method is able to discriminate between a correctly forged weld nugget and the base material.

◆ The NDE method is fully able to detect joint line remnants down to 0.2 mm in height, flaws that cause a reduction in fatigue performance.

◆ The NDE method can demonstrate variances in weld quality.

◆ A method has been established to measure the quality of the weld even if there is no direct signal from a flaw.

**References**


