Computational Tools for FSW: Modelling and NDT System

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Abstract:
The good quality of Friction Stir Welding (FSW) joints enabled a significant development of industrial applications of solid state welding technologies. This high quality standard is even more significant when FSW is compared to the fusion techniques. Nevertheless, in FSW joints some defects may arise which are very sensitive to small variations in some process parameters. Moreover, the results from computational modelling of the FSW are only valid for non-defective welds. Thus, in order for modelling of the process do contribute for the industrial consolidation of the FSW process, the experimental implementation results needs to be supported by a reliable Non Destructive Testing (NDT) system. This work addresses an integrated scheme of three computational tools enabling to support the faster establishment of process parameters, addressing the material flow analysis, with numerical coupling between fluid dynamics and solid mechanics; using the analytical iSTIR code; and detecting imperfections with dedicated NDT computational system for FSW containing a new eddy currents probe.

Keywords: FSW; Analytical Modelling; Numerical Modelling; NDT, Eddy Currents Probe

1. INTRODUCTION

The increase of industrial applications of Friction Stir Welding (FSW) is confirming the importance of this process in the scope of joining technologies. Research centers worldwide supported the development of FSW, with more emphasis on experimental work. However, there are some phenomena that are difficult or even impossible to assess experimentally and can only be addressed via computational modelling, e.g., local heat generation, stress and strain rates in the vicinity of the tool or defect formation mechanisms by analyzing the influence of tool geometry in the material flow. Thus a valid model for FSW can generate significant information, contributing for development of tool design and process parameters which will contribute for obtaining defect free welds, increased resistance to fatigue crack growth and corrosion, aiming to predict life [1, 2].

Nevertheless fundamental features typically applied for validation procedures of computational simulation of the FSW process, e.g., thermal field and residual deformation are not affected by the presence, or not, of small defects possible to exist in FSW weld beads, such as, root defects, which may significantly affect the overall performance of the joint [3, 4]. Therefore, a complete system for computational simulation of the FSW process should comprise a NDT online reliable capacity enabling to assess the real quality level of the joints produced with process parameters resulting from modelling.
The bulk material deformation in the region containing fully-plasticized material makes numerical modelling of FSW computationally demanding and complex due to its highly non-linear character both in geometry (large deformations), material behaviour and physical formulation. Also, the viscous-plastic flow of the materials near the tool and the elastic-plastic behaviour of the remaining material, demands an hybrid formulation, coupling fluid and solid mechanics. The model should also consider the heat flow from the weld bead into the rigid surfaces of the tool and anvil because it affects significantly the thermal field in the materials. The correct modelling of material behaviour depending on strain rates and temperature development also has significant importance in FSW modelling [1, 2]. The challenge is then to create a model able to fully describe the process, as illustrated in Figure 1 which represents the coupled thermal-structural-metallurgical nature of the process.

In the present work the strategy adopted for the thermo-structural numerical analysis of the FSW is a fluid dynamics formulation for the steady-state regime in the vicinity of the tool, returning data about the local influence of tool geometry on temperature field and material flow. Based on the updated boundary conditions from the steady-state conditions around the tool, a transient solid mechanics formulation is used to compute the overall structural properties of the joint in the real geometry of the welded parts, e.g., residual stresses and deformations.

In order to overcome the complex coupled phenomena of the FSW process which do not yet allow the establishment of a reliable numerical solution an analytical code is used for the establishment of correlations between FSW parameters and thermal efficiency. An inverse engineering approach based on an experimental/analytical modelling procedure has been implemented.

Towards the complete computational simulation system, both numerical and analytical modelling approaches are complemented with an innovative NDT system based on fuzzy logic algorithm which merges several NDT techniques including a new Eddy currents probe that was developed and tested for quality assessment of FSW joints.

This paper presents a survey on all the elements comprising the complete computational simulation and quality assessment actually implemented. The conclusions address the potential of application of this strategy.

2. NUMERICAL COUPLING FLUID DYNAMICS AND SOLID MECHANICS
2.1. Integration concept of the FSW numerical modelling

For the thermo-structural numerical analysis of the process, a coupled process was implemented based on a specially developed code, INTEGRA3D [5], which bridges two commercial softwares, namely: Fluent, used for the stationary visco-plastic regime analysis of the material flow in the vicinity of welding tool and Abaqus, used for computing the residual deformation and stress fields resulting from transient stress and thermal history.

The concept of integration of the two approaches is based on the fact that FSW process has two distinct regions with different material behaviour: The zone near the tool where the material undergoes viscous-plastic behaviour; and the remaining domain having elastic-plastic behaviour. The integration of these two computational approaches, which is represented in Figure 2, starts with the 3D stationary fluid dynamics analysis, from Fluent, considering the tool geometry effect on the material flow. The temperature and pressure results from Fluent are then extracted from a pre-defined boundary of a cylinder with the same axis of the tool, and with approximately the same diameter of the shoulder, and imposed as boundary conditions in the 3D transient computational solid mechanics analysis in Abaqus.

The integration of these two complementary solutions is made via a code named INTEGRA3D [5]. This routine receives as input the file the temperatures and pressures from Fluent and an Abaqus file with the mesh generated in the real geometry of the parts being joined. The result is the creation of an input file, for Abaqus, with the temperature and stress to be imposed step-by-step, during the entire welding simulation of the transient state. The routine produces a number of files Step, equal to the number of steps in which the analysis is divided.

Besides the residual stress and strains, thermal field in the real geometry and the influence of the tool geometry in the material flow it is also possible to determine strain rates, and FSW parameters such as, the torque and the forces in the travel direction, transverse direction and vertical forging direction.

2.2. Modelling methods and material models for both analysis regimes

Both computational analyses are performed based on implicit integration scheme, but the steady-state fluid dynamics analysis (Fluent) uses finite volume method with Eulerian approach and the transient solid mechanics (Abaqus) uses finite element method with Lagrangean approach. Also, the different material deformation regimes demands different material behaviour models.

The modelling of the steady-state deformation regime in the vicinity of the tool requires a viscosity function to simulate the non-Newtonian material flow behaviour. For this purpose it is used the Zener-Hollomon parameter, $Z$ (Eq. 1), which describes the influence caused by local temperature and strain.
rate. The final form of the viscosity $\eta(T, \dot{\varepsilon})$ used to simulate the FSW process in the viscous-plastic domain is described in Eq. 2 [6]. Where: $T$ – Absolute temperature [k]; $\dot{\varepsilon}$ - Effective strain rate [1/s]; $Q$ – Activating heat energy [J/mol]; $R$ – Universal gas constant [J/(mol.K)], $A$, $\alpha$, and $n$ are dimensional fitting constants.

$$\sigma = f\left(\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)\right) = f(Z)$$

$$\eta(T, \dot{\varepsilon}) = \frac{1}{3\dot{\varepsilon} \alpha} \ln\left(\frac{Z(T, \dot{\varepsilon})}{A}\right)^{1/n} + \left(\frac{Z(T, \dot{\varepsilon})}{A}\right)^{2/n} + 1\right)^{1/2}$$  

For the modelling of the elastic-plastic deformation regime of the material it is considered: Young modulus and Poisson coefficient as constant values and temperature dependent values for the following physical properties: Conductivity, specific heat, thermal expansion, yield and ultimate stress/plastic strain. Residual stress and deformations result mainly from thermal expansion due to thermal cycle of the weld process, considering Eq. 3.

$$\varepsilon_{\text{thermal}} = \alpha_{\text{expansion}} \Delta T \Rightarrow \sigma = E (\dot{\varepsilon} - \varepsilon_{\text{thermal}})$$

### 2.3. Application Sample

In order to illustrate the integrated concept for the computational numerical modelling of the FSW process an application sample will be presented. The simulation will address a FSW joint between two plates of AA2024-T4. The tool used in experimental trials has a shoulder diameter of 13mm and a cylindrical ISO M5 threaded pin with a length of 3.9mm. The main welding parameters are the vertical downward force of 11kN, tilt angle of 3 degrees, rotation speed of 800rpm and travel speed of 100mm/min.

The results obtained from the numerical analysis were validated by comparing the resultant thermal field and the temperatures measured experimentally with thermocouples located at the mid-thickness of the plates, for different distances from the center of the weld bead at both retreating and advancing sides. The results obtained, did shown a very good agreement between experimental and numerical results for the distances less than 20mm, increasing the error up to about 25% for higher distances from the center of the nugget. These facts means that the thermal field imported from Fluent analysis has a good quality and that the equivalent convective losses coefficient considered for the workpieces in Abaqus should be a little higher.

### 2.3.1. Fluid dynamics modelling of stationary state – Fluent

To model FSW process is mandatory to perform a 3D analysis, because the material flow, near the tool, does not have any plane or line of symmetry [1, 2]. Nevertheless, it is feasible to consider laminar steady-state condition for the material flow in the vicinity of the tool. The geometry model implemented considers an axial symmetric tool, inserted in a square plate surrounding the tool. The plate dimensions considered are such that boundary conditions do not interfere with the material flow in vicinity of the tool.
Figure 3 – Results from fluid dynamics modelling

From the analysis of the velocity field at the mid-thickness section, represented in Figure 3a), it is possible to conclude about the existence of a thin layer of material following the rotation of the tool and the big concentration of the velocity gradients near the pin. This fact emphasizes that, at least for these welding parameters, only the material near the tool undergoes extreme strain rates. Figure 3b) emphasizes the absolute need of a 3D analysis for modelling FSW. In fact, there is a strong 3D displacement during the FSW processing represented by the flow lines of the points initially located at the mid-thickness section.

2.3.2. Solid mechanics modelling of transient state in real geometry – Abaqus

The present analysis develops over three major stages: the first stage takes a period of time of 300s and runs the heating of the abutting plates by superimpose step-by-step, simulating the real travel speed over the weld joint, the thermal and pressure boundary conditions predetermined in the steady-state viscous analysis; The second stage considers a period of time of 80s and starts with the thermo-mechanical conditions attained at the end of the weld processing and runs the cooling of the workpieces, holding the mechanical constrains; The final step starts with the thermo-mechanical conditions attained at the end of the previous stage and runs the release of the workpieces from the mechanical constrains. The first two stages are coupled temperature-displacement analysis and the third stage is an elastic-plastic static analysis.

As a sample of the detailed results that are possible to obtain from this analysis procedure, Figure 4 shows the residual stress field in the overall deformed shape of the plates after FSW processing cycle. Considering the yield strength of the AA2024-T4 at room temperature as about 340MPa, only at the end of the weld bead the residual stress reach this level of stress. Most of the weld bead and heat affected zone is subject to about 180MPa. The remaining material of the workpieces is under very low levels of stress.
3. FSW ANALYTICAL MODELLING - iSTIR

In this section it will be demonstrated the feasibility of using the analytical code, iSTIR [7, 8], for the establishment of correlations between FSW parameters and the thermal efficiency. An inverse engineering approach based on experimental/analytical modelling procedure and represented in Figure 5, is implemented. The complete formulation supporting the iSTIR code is detailed in [7], and a review of its fundamentals is presented in [8].

Two application samples are conducted on AA2024-T351 plates for different vertical downward forces and different ratios between rotation and travel speeds (weld pitch ratio), defining cold (lower level of heat input), intermediate (intermediate level of heat input) and hot (higher level of heat input) FSW conditions [9].

During the trials the temperatures and the mechanical parameters, i.e., in-plane advancing force, Fx, in-plane deviation force, Fy, vertical downward force, Fz, and torque, Mz, applied by the tool into the parts, have been recorded. The mechanical information allows to assess the total mechanical power delivered by FSW tool into weld joint, and the experimental thermal field is used as input for the analytical code, resulting the thermal efficiency for each condition. Application 1 aims at establishing correlations between thermal efficiency and process parameters, and application 2 allows the comparison between thermal efficiency and mechanical efficiency evolution.

The set of parameters associated with the 3 different FSW conditions, for both application samples, are presented in Table 1.
Vertical downward force, $zF$ = kN

<table>
<thead>
<tr>
<th>FSW condition</th>
<th>Rotation speed $[\omega] = \text{rpm}$</th>
<th>Travel speed $[v] = \text{mm min}^{-1}$</th>
<th>Weld pitch $[a] = \text{mm rot}$</th>
<th>Vertical downward force, $F_z$ = kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>800</td>
<td>100</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Intermediate</td>
<td>200</td>
<td>2</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Cold</td>
<td>400</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 1 – Set of parameters implemented for the three different FSW conditions

### 3.1. Results of Application 1

Using Eq. 4 is now possible to calculate the thermal efficiency, $\eta_{therm}$. Moreover, it is possible to establish the thermal efficiency correlations with some relevant FSW parameters, i.e., weld pitch, $($$/v$$)$ and vertical downward force, $F_z$. The results for Application 1 are presented in Figure 6, where it can be observed that the maximum value reached is related with intermediate FSW condition, for both vertical downward forces, $F_z = 11\text{kN}$ and $F_z = 14\text{kN}$. The increase of the vertical downward force does not show to affect significantly the development of the heat power nor the FSW process thermal efficiency.

$$
\eta_{therm}\left(\frac{\omega}{v}; F_z\right) = \left(1 - \frac{P_{therm}}{P_{mech}}\right) \times 100\% \tag{4}
$$

![Figure 6 – Thermal efficiency and respective correlations with the FSW parameters: weld pitch ratio ($\omega/v$) and vertical downward force, $F_z$, for all the experimental trials performed in Application 1](image)

### 3.2. Results of Application 2

The novelty of Application 2 is the possibility of establishing a comparison between the trends of the thermal efficiency correlation and the mechanical efficiency relatively to the base material, determined in specimens from the welded plates for the different weld pitch ratios.

Table 2 presents a summary of the mechanical properties of the base material and FSW joints of Application 2. From the analysis of Figure 7 it is possible to observe the same trend of both thermal efficiency correlation and mechanical efficiency of the welded joints. Thus it is possible to conclude about the feasibility of accomplishing the perceived needed relationships between FSW parameters and mechanical properties of the FSW joints via assessment of the thermal efficiency during the steady-state regime of the process.
Table 2 – Mechanical properties of the base material and FSW joints of Application 2

<table>
<thead>
<tr>
<th></th>
<th>Base material</th>
<th>Weld pitch ((\Omega / v))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>8 (Hot)</td>
</tr>
<tr>
<td>Yield tensile strength [MPa]</td>
<td>333</td>
<td>301</td>
</tr>
<tr>
<td>Ultimate tensile strength [MPa]</td>
<td>478</td>
<td>421</td>
</tr>
<tr>
<td>Elongation [%]</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Minimum hardness [HV02]</td>
<td>142</td>
<td>110</td>
</tr>
</tbody>
</table>

Figure 7 – Comparison between the trends of the thermal efficiency correlation and the mechanical efficiency to base material for the three different weld pitch ratios of the Application 2

4. QUALITY ASSESSMENT OF FSW JOINTS

The precedents FSW computational modelling based on numerical and analytical analysis are only valid for non-defective welds. The results from those computational tools will not agree with the real mechanical properties of the FSW joints if some imperfections occur during the welding. Thus, in order for modelling of the process to contribute for the industrial consolidation of the FSW process, the experimental implementation results needs to be supported by a reliable NDT system.

4.1. NDT Targets Imperfections on FSW

In that section it will be analyzed the influence of different locations and morphology of FSW imperfections, in terms of mechanical efficiency of the joints under fatigue loads, in order to define the NDT targets imperfections on FSW. For this propose a non-defective and defective weld joints, with three different defect types were produced in aeronautic aluminium alloy AA2024-T351. The characterization of these defect types is described in Figure 8.

Figure 8 – Establishment of the different defect types
The analysis of the fatigue results (Figure 9) 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. Those imperfections are thereby the NDT targets defects of FSW because the other type of imperfections (e.g. thickness reduction and flash formation) may be inherent to the process itself and are impossible to be avoided or may be evaluated without need of NDT.

Figure 9 – S-N curve for base material and 4 different defect type conditions

4.2. Quality Assessment of FSW: a paradigm in NDT

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 very difficulties in identification when using the common NDT techniques [3]. The conventional eddy current probes, for instead, present a significant drawback, which is the high sensitivity to the lift-off effects. This effect generates a noise which hides the signal produced by the defects, making the detection of small defects difficult or even impossible. Figure 10 illustrate these difficulties, presenting the impedance measurements for no defect and root defective weld beads using a conventional planar spiral eddy current probe: the 3 lines are very similar which means that the conventional probes have very low sensitivity to root defects. The reason is that the impedance changes are mainly due to the presence of the weld bead, instead the presence of a defect.

Figure 10 – Impedance changes for no defect and root defective weld beads
4.3. Integrated NDT System using new eddy current probe

In order to overcome the problem of FSW non-destructive inspection, a new concept of eddy current probe was developed which is not sensitive to the lift-off effect, increasing its reliability for NDT of FSW. The IOnic probe [10] (Figure 11) 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.

Figure 11 – The IOnic Probe prototype

Figure 12 shows a comparing test between IOnic probe and 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. 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.

Figure 12 - Real and imaginary signal of IOnic and conventional cylindrical probes

(f=85 kHz; I=50mA)

In order to increase the reliability of the FSW inspection, an on-line NDT integrated system employing a data fusion algorithm with fuzzy logic and fuzzy inference functions was developed. The complementarily, diversity and redundancy of the data acquired from several NDT techniques generates a synergic effect that is used by the software to achieve a better result. The objective of this
computational NDT tool is to improve the confidence of inspection based on Relative Operating Characteristics (ROC) and Probability of Detection (PoD) [11].

The Quantitative Non Destructive Testing for FSW (QNDT_FSW) incorporates three, distinct NDT techniques: 4 MHz creeping ultrasonic, 15 MHz Time of Flight Diffraction (ToFD), 20 kHz and 2 MHz eddy current. These techniques were selected to detect, as much as possible, the position and diversity of imperfections in FS welds. The system was tested in AA5083-H111 welded samples. The complete formulation supporting the QNDT_FSW code is detailed established in [11].

Among the several FSW trials performed to validate and implement the QNDT_FSW system, one application samples are presented. The results of testing the QNDT_FSW system are presented in terms of equivalent imperfection indices called the Root Imperfection Index (RII) and the Internal Imperfection Index (III). These imperfection indices were calculated with the fusion inference functions and represent the data fusion result for all of the NDT techniques used. An imperfection index equal to 100 % means a high-imperfection weld section, similar to the high-imperfection weld standard. An imperfection index equal to 0 % means an imperfection-free weld section, similar to imperfection-free weld standards.

Figure 13 presents the results of applying the QNDT_FSW system to 3 different FSW trials. The trials were performed with a pin length of 6.8 mm, a tilt angle of 2º, and a rotation speed of 710 rpm. The difference between these 3 trials was a change in the travel speed. In section 1 to section 11, the travel speed was 160 mm/min; from section 11 to section 12, the travel speed was 224 mm/min; and from section 12 to section 22, the travel speed was 320 mm/min. Based on a comparison (see Figure X) of the RII and III results with the macroscopic, visual, and radiographic test results, the following conclusions were made:

- The exit holes located at sections 1, 12 and 22 were detected by both imperfection indices;
- In section 8, the III revealed a cavity, which was corroborated by radiographic testing and visual inspection as the cavity breaks the surface of the workpiece. Moreover, the RII was not affected, which confirmed the independence of both imperfection indices;
- Sections 14 to 18 present a very low III, which was corroborated by radiographic testing. RII was able to detect small, root imperfections, as confirmed by metallographic cross-sections of the weld. Emphasis should be given to the fact that in these sections, radiographic testing cannot detect a root imperfection;
For the 3 FSW trials, the RII increased as the travel speed increased. This behaviour was expected because the pin length was 0.2 mm shorter than the plate thickness. This created a small root imperfection that increased in size as the travel speed increased.

The RII and III, when compared to visual, radiographic, metallographic analysis of the face and root surfaces, confirm the feasibility in detect weld imperfections.

5. CONCLUSIONS

1) Computational analytical and numerical modelling considering the FSW main features in the formulation can result in very useful outputs, e.g., correlations between FSW main parameters and joint properties enabling fast and effective mechanical design procedures for FSW joints, and selection of FSW parameters, nevertheless these computational modelling results are not sensible to joint defects and therefore NDT testing should be implemented simultaneously with the application of computational modelling tools.

2) The complete assessment of FSW features via numerical modelling of the FSW process can be a very useful tool for an efficient transfer of FSW to industrial applications but it is an highly complex challenge mainly because it is very difficult to obtain material data depending on temperature and strain rates for most of the engineering materials. To obtain simple and general FSW process useful information an analytical strategy based on an inverse engineering approach based on monitoring real thermal field data and mechanical loads delivered by the tool into the plates, was implemented.

3) Concerning the NDT techniques equivalent defective indexes are proposed for evaluating the relevance of the root (RDI) and internal (IDI) defects. The innovative data fusion algorithm based on fuzzy logic and fuzzy inference functions disclosed a general powerful data fusion NDT approach and the RDI and IDI when compared to other NDT techniques enable to conclude that both defect indexes do reflect the real quality of the weld joints. Moreover, results indicate that the merge of several NDT techniques is an improvement when compared to the individual use of each one.

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7. REFERENCES


