Numerical Analysis of Friction Stir Welding of Stainless Steel Lap Joints

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Abstract
Although mainly used for aluminum alloys Friction Stir Welding can be successfully applied also to steels. Additionally, most of the literature is focused on butt joint configurations. In the paper a continuum based FEM model for Friction Stir Welding of lap joint made out of thin stainless steel sheets is proposed, that is 3D Lagrangian implicit, coupled, rigid-viscoplastic. The model, whose potential has been analysed though temperature distribution comparisons, is able to predict temperature, strain and strain rate distributions, together with thermal and mechanical loads on the welding tool, at the varying of the main process variables. In this way the FEM model can be applied for effective process and tool design.

Keywords
Friction Stir Welding, FEM, stainless steel.

1 INTRODUCTION
It is well known that Friction Stir Welding (FSW), presented and patented by TWI in 1991, is nowadays a very effective welding technology even with the so called difficult to be welded or even unweldable materials, such as aluminum alloys, since no melting is reached. In the most recent years several researches have been developed on FSW with the aim to fully highlight and optimize its process mechanics, material flow, metallurgical aspects, and both static and dynamic resistance [1-6] However, a significant smaller number of paper can be found in literature dealing with FSW of high melting materials, as steels, titanium alloys and other high resistant alloys [7, 8]. On the other hand in the recent years the increase in the demand for safer and lighter structures in the automotive, shipbuilding and heavy manufacturing industries, has leaded to a renewed emphasis on steels and the related welding problems [9]. In particular traditional fusion welding processes often present microstructural embrittlement caused by significant post-welding thermal gradients, hydrogen cracking, welding fumes, large distortion and large residual stresses [10]. In turn, solid state processes are able to minimize or even avoid such drawbacks, due to the lack of melting and lower temperature reached during the process. Friction Stir Welding (FSW) is a solid state process in which, considering butt joints, a specially designed rotating pin is inserted into the adjoining edges of the sheets to be welded and then moved all along the welding line.

As far as FSW of steels is regarded, a few research works show how FSW can effectively eliminate the welding problems proper of fusion welding processes for carbon steels having carbon contents up to 1.02 wt%9,11, mild steels12, DH36 steel13 and stainless steels [11-13]. In particular duplex stainless steels exhibit the best mechanical performances when about an equal proportions of ferrite and austenite phases is obtained. It is well known that duplex stainless steels are characterized by a good weldability, but the thermal cycle they undergo to during traditional fusion welding processes destroys the favourable duplex microstructure17. In this way FSW can be once again considered as a valid alternative to obtain sound joints preserving good mechanical characteristics. On the other hand it should be noticed that most of the knowledge available on FSW is relative to light alloys, and in particular aluminum alloys. Nandan et al. [14] highlighted three main reasons for that, namely the difficulties in the choice of the tool material that has to undergo to significant thermal and mechanical stresses and the subsequent high cost of the tool itself, the possibility to obtain sound steel joints by traditional processes, for which the needed know-how is easily available and, finally, the lack of knowledge on the consequences of phase transformations accompanying FSW and related to the variety of steels available; being the number of steels larger than for any other alloy system, several time and resources consuming experimental campaigns are required to optimise the process for given joint properties.

As far as lap joints are considered, the number of available publication is even smaller. Ghosh et al. [15] studied the lap joints between high strength martensitic steel sheets under different heat input and cooling rates. The microstructural modification induced by the process on the utilized commercial M190 martensitic steel were correlated to the input process parameters. In [16] mixed material lap joints were obtained out of AISI304 stainless steel and CP-Ti. The metallurgical and mechanical interlock
features at joint interface, due to complex materials flow, were highlighted.

Due to the complexity of the process, numerical simulation can represent the optimal solution in order to perform an efficient and effective process optimization with affordable costs. However, numerical simulation of FSW is very challenging, due to the high levels of strain and strain rates occurring together to the complex material flow involving the material around the pin. At the moment, the number of publications dealing with FEM model for FSW of steels is extremely low. In literature are present two main categories of numerical models for FSW: Computational Fluid Dynamics (CFD) based and Arbitrary Lagrangian Eulerian (ALE) based ones. CFD based models allows a better and more detailed analysis of material flow at the varying of the geometrical (tool design) and technological process parameters. On the other hand, solid mechanics based models can be the most effective way to highlight, at the same time, the actual distribution of field variables, the forces on the tool as well as qualitative representations of material flow. The main drawback is the CPU time, that is larger than the one required by CFD based models. A first attempt to model FSW of steel is reported in the paper by Cho et al. [17], where a 2D model is developed in order to predict the main field variables distribution and the material flow. Although the comparison with experimental results shows a good correlation between the numerical response and the actual joint mechanical properties, the use of a 2D model represents a severe limitation. Zhu and Chao presented a three-dimensional nonlinear thermal and thermo-mechanical numerical model, developed on a homemade simulation code, with the aim to highlight the variation of transient temperature and residual stress [18]. The authors presented the results of a 3D Fem model for FSW of butt joints made out of AISI304 stainless steel sheets [19]. The model was validated with literature data and different sets of process parameters were evaluated.

In this paper, a fully 3D FEM model for the FSW process is proposed, that is thermo-mechanically coupled and with rigid-viscoplastic material behaviour, for FSW of AISI304 lap joints. The main field variables distributions, together with thermal and mechanical loads on the welding tool, are calculated.

2 NUMERICAL MODEL
A fully 3D FEM model for the FSW process of AISI304 stainless steel has been presented by the authors and validated by comparing measured and calculated temperatures [19]. The acquired know-how has been used for the set-up of the present model that is thermo-mechanically coupled and with rigid-viscoplastic material behaviour. A unique feature of the model is the representation of the overlapping sheets as a continuum. This hypothesis avoids the numerical instabilities that result from the discontinuities present at the edge of the two sheets. The commercial FEA software DEFORM-3D™, Lagrangian implicit code designed for metal forming processes, is used to model the FSW process. The workpiece is modelled as a rigid visco-plastic material, and the welding tool is assumed rigid. This assumption is reasonable as the yield strength of the sheet is significantly lower than the yield strength of the tool. A rigid-visco-plastic material model with Von Mises yield criterion and associated flow rule is used. It should be noticed that an elastic-plastic material model would results in even more accurate results and would allow the calculation of residual stresses after welding. However an elastic-plastic material characterization leads to numerical instabilities and dramatically increases the CPU time.

The FSW modelling is divided into two stages: 1) sinking stage and, 2) welding (advancing) stage. In other words, FSW is modelled from its initial state to steady state. The sinking stage is modelled to obtain high enough temperature for the subsequent welding process and the advancing stage is modelled to investigate the thermo-mechanical phenomena in the formation of weld nugget. In the present work the AISI 304 stainless steel has been considered for the workpiece material. For the thermal characteristics of the material taken into account, temperature dependant thermal conductivity k and thermal capacity c, taken from literature for stainless steels, have been utilized (table 1) [19]. It should be noticed that even if a constant thermal capacity and thermal conductivity assumption would have linearized the thermal equation and speeded up the simulation, a strong variation of such coefficients, especially thermal capacity, with temperature is observed for the considered material and cannot be ignored without a significant loss in the results accuracy. The material model is rigid-viscoplastic, temperature and strain rate dependent. Tabular data were used on the basis of the commercial code database and experimental data [21]; in particular, a maximum temperature of 1300°C, a maximum strain value of 10 and a maximum strain rate value of 63 [1/sec] were used to characterize the material. It is important to notice that while the temperature and strain rate values calculated during the simulations are within the given ranges, the calculated strain values, on the contrary, exceed the range and the corresponding flow stress is obtained by extrapolation procedures. This aspect is, at the moment, the main limitation of the model. In order to synthetically represent the material flow rule a regression has been made using the following equation:

\[
\sigma = (A + B\dot{\varepsilon}^n)(1+C\ln\dot{\varepsilon})(1 - T^m) \quad (1)
\]
where \( T^* = \frac{T - T_{\text{ROOM}}}{T_{\text{MELT}} - T_{\text{ROOM}}} \)

and the other material constants, determined by a numerical regression based on experimental data [21], are reported in table 1.

<table>
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<th>A</th>
<th>B</th>
<th>C</th>
<th>n</th>
<th>m</th>
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<th>Tmelt</th>
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<td>0.0183</td>
<td>0.6968</td>
<td>20</td>
<td>1500</td>
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Table 1 - Material constants for the utilized AISI 304

A constant interface heat exchange coefficient of 11 [N(mm s °C)-1] was utilized for the tool sheet contact surface.

The FSW of two sheets, 1 mm in thickness, was simulated. The overlapping between the sheets was 50 mm, and, as described above, one simulation object was utilized for the two sheets. The joint was meshed with about 10,000 tetrahedral elements with single edges of about 0.25 mm; in this way about four elements were placed along the sheet thickness. A non-uniform mesh with adaptive re-meshing was adopted with smaller elements close to the tool and a re-meshing referring volume was identified all along the tool feed movement. A cylindrical pin tool was adopted, characterized by a shoulder diameter equal to 10 mm, a pin height of 1.6 mm. The tool material is W25Re, an ultra-resistant alloy able to resist to the significant mechanical solicitations exerted by the material on the tool itself during the process. This aspect is critical, particularly during the sinking stage when the material is cold and its reaction can cause a severe pin deformation. The tool was modeled as rigid body and meshed, for the thermal analysis, with about 5,000 tetrahedral elements. Figure 1 shows a sketch of the model at the beginning of the sinking stage. The “steps” taking into account the overlapping geometry of the joint are highlighted.

Experience in previous FEM simulations shows that a coarser mesh leads to incorrect results and a finer mesh results in unaffordable computation time without significant improvement of simulation results. A constant shear friction factor of 0.1 is used for tool-sheet interface on the basis of the model validation performed in [19].

Three different combinations of process parameters were selected and simulated based on the results of a preliminary experimental campaign. In particular three levels of Specific Thermal Contribution (STC) were obtained at the varying of the tool rotational speed and feed rate: Low (300 rpm and 200 mm/min), Medium (500 rpm and 100 mm/min) and High (700 rpm and 50 mm/min).

3 RESULTS AND DISCUSSION

From the experimental point of view it is found that the set of process parameters defining the Low case study resulted in a poor weld. The STC was insufficient and visible flow defects are observed on the top surface of the joint: the material did not “closed” behind the tool and a crack is found all along the seam weld (Figure 2b). The developed numerical model was able to detect such poor welding conditions. In figure 2a and 2c is shown the way the defect is predicted by the FEM model.

Figure 1 - Sketch of the model at the beginning of the simulation.

Figure 2 - Low case study: simulated (a) and experimental (b) top view of the joint and 3D view of the simulated process (c)
As it can be seen a big crack is left by the tool on the Advancing Side (A.S.) of the joint, i.e. where the material closes behind the tool, indicating an insufficient material flow.

Temperature distribution on the top surface of the joint can explain the reasons for such behaviour. In Figure 3 a 3D view of the joints is shown after about 13mm of weld length. It is worthy notice that this distance, corresponding to different process times due to the different feed rates, can be considered as the weld length after which the process reaches the steady state.

![Figure 3 - 3D view of the temperature distributions: Low (a), Medium (b) and High (c) case studies.](image)

As it can be seen from the figure the temperature observed in the welding area of the Low case study is about 550°C, reaching a maximum of about 600°C only around the tool. This value is about the 40% of the melting temperature of the considered alloy (about 1440°C). In literature it is known that effective FS welds are obtained for temperatures within 50%-90% of the melting temperature of the material to be welded [10]. As the Medium process conditions are adopted, this value increases to about 750°C, representing about 52% of the melting temperature of AISI304. In this case an effective weld is obtained. As temperature increases further, i.e. when the High case study is selected, a maximum temperature of about 900°C is found.

Further information can be gained from the accumulated strain profiles. Transverse sections have been taken after a tool weld length of 13mm right behind the tool pin, i.e. when the material has “closed” at the advancing side. In Figure 4 the obtained profiles are shown.

![Figure 4 - Transverse sections showing the strain distributions: Low (a), Medium (b) and High (c) case studies.](image)

As it can be seen from the figure the material fails to close behind the tool pin at the advancing side for the Low case study. The insufficient temperature reached, as highlighted in the previous Figure 3, result in a too “hard” material. The so called “soft” state cannot be reached and material particles cannot flow around the pin. In this way an insufficient deformation is found, leading to the crack shown visible in Figure 4a. It is worthy notice that the defect present in the experimental specimen (see again Figure 2b) is not only on the surface, but it is observed through the joint thickness, in a similar way with what numerically calculated. As far as the other two case studies are regarded, an increasing deformation is observed at the increasing of the STC. This is due to the simultaneous increase in the rotational speed and decrease in the feed rate. In this way a single particle around the pin will rotate more times around the tool itself before laying at the advancing side. The process mechanics above described is reported in [1-3, 5, 10] and confirmed by the location of the maximum strain calculated by the model.

The welding tool has a key role in FSW of hard materials as it undergoes significant thermo-mechanical solicitations. In Figure 5 the temperature distribution on the utilized W25Re tool are reported at the varying of the considered case study. It is observed that the maximum temperature is reached around the tool pin. For the High case study this value is about 900°C. At this temperature the sheet are in a “soft” state, being the flow stress dramatically reduced with respect to the room temperature conditions. On the contrary, the tool material presents still good mechanical properties.
being its tensile strength equal to 3800 Mpa at room temperature and decaying to 330 MPa only at 1500°C.

Figure 5 - Tool temperature distributions: Low (a), Medium (b) and High (c) case studies.

Finally the reaction force on the welding tool has been analysed. It is known in literature that the component perpendicular to the sheet plane (Z axis in Figure 1) is the largest, being the one in the direction of the weld line about one order of magnitude smaller [10]. In Figure 6 the evolution of the Z load with time is presented.

Figure 6 - Tool temperature distributions: Low (a), Medium (b) and High (c) case studies.

As it can be seen two similar trends are observed for the Medium and High case studies. As expected, before reaching a steady state, a decreasing trend is observed due to the progressive heating of the sheets to be welded. Larger forces are calculated for the Medium case study due to the lower temperature resulting in harder material conditions. On the other hand, a totally different behaviour is found for the Low case study. A value that is almost constant with time is calculated. As a matter of fact, the actual process never starts: at the beginning of the weld the contact area between the tool and the sheets is not the entire area of the tool shoulder as the material is nearly "milled" by the tool itself. In this way the force, which was supposed to be the largest of the three, is the lowest. These conditions never change during the process resulting in a nearly stable force.

4 CONCLUSIONS

In the paper the results coming from a numerical analysis on FSW of AISI 304 stainless steel lap joints are presented.

The utilized model, initially created for aluminium alloys and subsequently effectively utilized for AISI 304 butt joints, is lagrangian thermo-mechanically coupled. From the obtained results the following conclusions can be drawn:

Lap joints of stainless steels can be successfully obtained by FSW. However, the Specific Thermal Contribution given to the joint and governed by the main process parameters, must allow for a temperature in the stirring area in excess of about 50% of the welded material melting temperature. When these conditions are not reached, a rough surface is obtained material does not close behind the tool pin.

Large deformation values are needed in order to get effective welds, with maximum values that are found at the advancing side close to the lateral surface of the pin.

Significant thermo-mechanical solicitations are observed on the welding tool. In particular the vertical reaction force has a decreasing trend form the beginning of the process and till the latter reaches the steady state. After this point it will maintain about constant. The above described behaviour does not maintain true when insufficient temperature is found and defective welds are obtained.

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6 REFERENCES


7 BIOGRAPHY

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