Nascimento, Filipe; Santos Vilaca da Silva, Pedro; Pires, Francisco M. Andrade; Fernandes, João C. S.; Quintino, Luísa

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Development of parameters for FSW of AZ31 Mg alloy with analysis of mechanical and corrosion properties

F. Nascimento¹, P. Vilaça², F.M. Andrade Pires³, J. C. S. Fernandes¹, L. Quintino¹

¹Instituto Superior Técnico, Universidade Técnica de Lisboa, Av. Rovisco Pais, 1,1049-001 Lisboa, Portugal
²Department of Engineering Design and Production, School of Engineering, Aalto University P.O. Box 1420, FI-00076 Aalto, Finland
³Faculdade de Engenharia da universidade do Porto, Rua Doutor Roberto Frias s/n, 4200-465 Porto, Portugal

Abstract
The expansion of the industrial application of magnesium alloys is affected by its weldability, namely in ground and air transportations where large size, complex welded components are required.

The solid state processing advantages of Friction Stir Welding (FSW), namely reduction of heat input and oxygen contamination when compared with the more widely used fusion welding processes represent a good opportunity for increasing the application of this family of high performance materials in engineering applications. In the present work, the FSW is applied to AZ31 plates with thickness of 2mm and the welding lobe is established for the most relevant FSW process parameters and the mechanisms of defective conditions are assessed.

For the set of parameters presenting technological feasibility, the mechanical efficiency under static and fatigue loading, the hardness distribution and the corrosion resistance are established. Features resulting from the FSW process are investigated, namely: extension of the lack of penetration at the root, heat input and the as-welded finishing conditions of the top surface of the weld beads. The mechanical properties under tensile loads are in-line with results from other authors but the analysis of efficiency under bending and the corrosion features are innovative contributions for the state-of-the-art. The mechanical properties considered for the characterization of the mechanical efficiency are more extensive than the ones available in literature. The results show that the best technological conditions present an overall efficiency of 65 % for static loading, maximum loss of hardness of 82 % a fatigue limit similar to the base material behavior. The polarization curves enabled a corrosion rate prevision for the welded zone of 34 % higher than for base material.

Keywords:
Friction stir welding; Magnesium alloy; Welding lobe; Mechanical properties; Corrosion test.
1 - Introduction

The use of magnesium brings several benefits for the weight reduction of different applications due to its low density and good mechanical properties. The Mg alloys are very promising and can efficiently decrease the weight of many engineering components and Friction Stir Welding (FSW) can be a good solution to overcome the typical low weldability of these alloys by fusion welding techniques. This solid state joining technique can weld these materials with low heat input and no susceptibility of introduction of hydrogen in the joint [1]. Some studies on the application of the FSW process to Mg alloys already exist, namely Xunhong and Kuaish [2] observed that with correct processing parameters it was possible to obtain a tensile strength of the welded joint very similar to the base material (93%) associated with grain refinement and homogenization in the nugget area. Yu et al. [3] verified the same behavior for the AZ31 alloys with an addition of cerium and also verified a large drop in ductility of the welded samples. Xie et al. [4] have verified that the properties the welded samples were lower than the base material however the application of an ageing treatment would improve its properties. It was also observed that the second phase particles in these alloys were broken and dissolved in the welded area of the Mg matrix. All these effects have been confirmed by Wen et al. [5] who also verified that the grain size decreased with multiples passes in the same area. Srinivasan et al. [6] has observed that the corrosion behavior of welded samples and base material are similar in the AZ61 magnesium alloy even though the surface treatment is very effective to decrease the corrosion rate of both material conditions. It was also verified that welded samples have a higher potential of stress corrosion cracking in the nugget of the welded sample. Zeng et al. [7] has verified that in the AM50 magnesium alloy the corrosion rate varies along the different areas of the welded sample being higher in the base material and lower in the welded area. Most corrosion studies have focused in other alloys than the alloy presented for this study that is usually pointed out has a suitable solution for automotive industry. Other studies have focused on the effect of the FSW process parameters on the properties of the welded alloys. Zhou et al. [8] studied the influence of the rotational speed on the properties of the joint and verified that for the lowest and highest welding travel speeds some defects occurred related to insufficient or excessive heat input and plastic flow. Zhang et al. [9] verified that for AZ31 magnesium alloy the obtained defects were due to insufficient heat input in these alloys. Cao and Jahazi [10] verified that while the yield strength of the butt welded alloys increased with the welding travel speed the ultimate strength would eventually reach a limit at a certain welding travel speed. Another study from the same authors [11] also addressed the influence of the rotational speeds in lap-joints and verified that the tensile shear load increases with the increasing rotational speed however from a certain point it starts to decrease which can be related to the higher heat input from the tool. Garacheh et al. [12] studied the influence of the weld pitch ratio: rotational/travel
speed, on the mechanical properties and verified that for higher values of this factor there is a larger weld nugget due the higher material flow and with the reduction of this factor increases the probability of presenting a defect at the root. Chowdhury et al. [13] observed the influence of the weld pitch verifying that for higher weld pitch the mechanical properties were better. The influence of the axial force was shown by Rose et al. [14] to be determinant in the formation of defects and in the nugget size and hardness.

In order to develop the best FSW parameters, the relation between the relevant properties and technological conditions need to be established. Different methods can be used for this goal and are found in the literature namely for aluminum alloys Two interesting examples point out that the Taguchi method was able to observe different relationships of the parameters and their influence in the properties of aluminium alloy as outlined by Vidal et al. [15] and Padmanaban and Balasubramanian [16] studied the influence of the tool properties in the welded samples properties and verified that the threaded probe profile promotes a better flow of material promoting better weld properties with the best ratio of shoulder/probe diameter around 2.5.

The present study will focus on the establishment of a set of FSW parameters presenting technological feasibility. The welding lobe limits are defined and characterized. The technological conditions are developed based on the mechanical efficiency, under static and fatigue loading, hardness distribution and corrosion resistance.

The main motivation for the present study is the application of the AZ31 Mg alloy as structural material for car seats. The car seats can account up to 11% of the total car weight as stated by Carvalho et al. [17]. Based on the standard FMVSS 209 [18], the same authors simulated the replacement of steel by other materials such as aluminium, carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP) and magnesium. The results from simulation show that the replacement of steel with magnesium can have weight decreases of about 20% to have the same performance as the steel seat but reductions up to 60% are possible still complying with the standard.

2 - Experimental procedure

The tested base material is 2mm thickness Mg alloy plates of AZ31 with chemical composition of 3.0 wt% Al, 1.0 wt% Zn, 0.2 (min) wt% Mn, 0.1 (max) wt% Si, 0.05 (max) wt% Cu, 0.005 (max) wt% Fe, 0.4 (max) wt% Ca, remaining wt% Mg. These plates were welded by FSW along the rolling direction using a tool with a scrolled shoulder and a threaded conic probe as represented in Figure 1.
Different process variables were investigated in order to identify the best conditions. The Taguchi method was used for combining the following process variables: travel speed (V), vertical force (F) and probe length. Table 1 resumes the variable parameters that were implemented.

Table 1 – Test parameters with Taguchi N9 matrix

<table>
<thead>
<tr>
<th>Trial</th>
<th>V [mm/min]</th>
<th>F [Kg]</th>
<th>Probe Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>100</td>
<td>400</td>
<td>2.10</td>
</tr>
<tr>
<td>E2</td>
<td>100</td>
<td>450</td>
<td>2.18</td>
</tr>
<tr>
<td>E3</td>
<td>100</td>
<td>500</td>
<td>2.26</td>
</tr>
<tr>
<td>E4</td>
<td>200</td>
<td>400</td>
<td>2.18</td>
</tr>
<tr>
<td>E5</td>
<td>200</td>
<td>450</td>
<td>2.26</td>
</tr>
<tr>
<td>E6</td>
<td>200</td>
<td>500</td>
<td>2.10</td>
</tr>
<tr>
<td>E7</td>
<td>400</td>
<td>400</td>
<td>2.26</td>
</tr>
<tr>
<td>E8</td>
<td>400</td>
<td>450</td>
<td>2.10</td>
</tr>
<tr>
<td>E9</td>
<td>400</td>
<td>500</td>
<td>2.18</td>
</tr>
</tbody>
</table>

The tool rotation speed, $\Omega = 1200$ rpm, the plunge speed 0.1 mm/s and the dwell time of 6 s were kept constant. The tested parameters are the most relevant in influencing the properties of the welded samples. Samples were taken from all acceptable welds and were metallurgically characterized using a reagent composed by 10 mL acetic acid, 4.2 g picric acid, 10 mL $\text{H}_2\text{O}$, 70 mL ethanol (95%). The samples were observed under optical and scanning electron microscopy (SEM) and submitted to tensile testing according to ISO 10002 and the strain rate enforced was 5mm/min. The results were analyzed using the Global Efficiency to Tensile strength (1). The GET assesses the tensile strength efficiency of the welded joint against the base material (BM) properties. This coefficient was introduced by Vilaça [19] and is established in (1) where: $E$ is the Young Modulus, $\sigma_y$ is the yield stress, $\sigma_{UTS}$ is the ultimate tensile stress, $A$ is the elongation and $U_T$ is the toughness. Considering the intended application the coefficients considered in (1) are established in in Table 2.
GET = C_E \cdot \left( \frac{E}{E_{BM}} \right) + C_{\sigma_Y} \cdot \left( \frac{\sigma_Y}{\sigma_{Y_{MB}}} \right) + C_{\sigma_{UTS}} \cdot \left( \frac{\sigma_{UTS}}{\sigma_{UTS_{MB}}} \right) + C_A \cdot \left( \frac{A}{A_{BM}} \right) + C_{UT} \cdot \left( \frac{UT}{UT_{BM}} \right) \quad (1)

<table>
<thead>
<tr>
<th>C_E</th>
<th>C_{\sigma_Y}</th>
<th>C_{\sigma_{UTS}}</th>
<th>C_A</th>
<th>C_{UT}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.3</td>
<td>0.3</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 2 – Coefficients for GET efficiency calculation

The established coefficients take into account an application in automotive industry where there is a need for the seat to for the material to work in its elastic limit guaranteeing safety for the users. For this goal it was established that a yield and tensile strength similar to the base material should be preferred over the others (Table 2). The other considered attributes were considered to have the same significance although the young modulus has a lower contribution for this goal.

The samples for 3-point bending testing were produced with a width of 20 mm and these samples were tested with the root side on the tensile side, using a test speed of 6 mm/min.

Similarly to GETS also an efficiency coefficient named GEB was created to evaluate the bending properties (2) versus the BM properties, where \( F \) is the maximum load, \( d \) is the displacement at maximum load and \( U_B \) is the energy consumed until maximum load. Considering the intended application the coefficients considered in (2), are established in in Table 3.

\[
GEB = C_F \cdot \left( \frac{F}{F_{MB}} \right) + C_d \cdot \left( \frac{d}{d_{MB}} \right) + C_{UB} \cdot \left( \frac{U_B}{U_{BM}} \right) \quad (2)
\]

<table>
<thead>
<tr>
<th>C_F</th>
<th>C_d</th>
<th>C_{UB}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.25</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 3 – Coefficients for GEB efficiency calculation

The choice of these coefficients (Table 3) enables the promotion of a better resistance in the bending behavior. Therefore there is a focus on the energy consumed until maximum load. The higher value in this coefficient promotes a better bending behavior. The other two values have been considered to have the same weight overall.

Vickers hardness test with a force of 0.5 kg was applied to each sample with 21 indentations along the mid-thickness of transversal section to the weld joints and centered at the center of the nugget. A hardness drop ratio was developed to compare the lowest hardness values of the welded sample with the average hardness of the base material (3).

\[
HARD = \frac{H_{min}}{\overline{H}_{MB}} \quad (3)
\]

\[
\%Weld = C_{GET} \cdot GET + C_{GEB} \cdot GEB + C_{HARD} \cdot HARD \quad (4)
\]

<table>
<thead>
<tr>
<th>C_{GET}</th>
<th>C_{GEB}</th>
<th>C_{HARD}</th>
</tr>
</thead>
</table>

Table 4 – Coefficients of the weld efficiency calculation
The weld efficiency (4) is a weighted average from the previous 3 parameters. The coefficients considered (4) are given in Table 4. These coefficients were established for the welded material to have a good performance to both tensile and bending loads. However, the bending behavior is more important for the overall analysis. The HARD factor was deemed not to have a big influence in the overall performance therefore there was a decrease in its coefficient value. The fatigue testing samples were prepared according to standard ASTM E 466-96 and tests were performed at a frequency of 15 Hz and with a force ratio, $R = 0.1$. The establishment of the maximum force applied during the fatigue testing was made taking into account the calculated yield strength for both base material and welded samples.

Corrosion testing was performed according to the ASTM B117:11. The samples were immersed in a saline environment for 350h. Both the front and back of the welded samples were tested. These samples were compared with the base material that was also included in the same batch. Weight measurements were performed to the tested samples prior and after the testing allowing the calculation of the material loss.

4 – Presentation and analysis of the results

Welding lobe

The implementation of the trials according to the Taguchi method enabled to establish the limit conditions and thus the welding lobe, as depicted in Figure 2. These limit conditions for weld joint feasibility are mainly governed by the weld pitch ratio: rotational/travel speed of the tool and vertical forging force (F), i.e., the probe length did not play a significant role. It was observed that for the lower travel speeds with a higher force (trials E2 and E3), the volume of base material undergoing viscoplasticity in the vicinity of the tool was excessive and the tool penetration was too high, resulting in abundant continuous flash (Figure 3). This local softening mechanism is more intense in FSW of Mg than for other typical materials welded by FSW, such as, Al and Cu, because Mg has a lower thermal conductivity (resulting in high heat near the tool) and a significant loss of mechanical resistance at relatively low temperatures. The other extreme limit condition corresponds to the higher travel speeds with a lower force (trial E7), where the heat input is not enough to bring the base material in contact with the tool to the minimum viscoplasticity level necessary for the base material to flow around the probe, leading to the is plow out of the base materials at the leading edge of the tool (Figure 4). The crystalline arrangement of HCP of the Mg alloys also contributes for a lower flow stress, when compared with the FCC structure of Al and Cu alloys.
Figure 2 – Welding lobe showing defective zones with continuous flash (top-left) and material detachment (low-right). Trials E1, E4, E5, E6, E8 and E9 produced feasible joints.

Figure 3 – Defective conditions of trials E2 and E3 where the large plasticized volume exceeds the shoulder’s diameter resulting in the plunging of the tool within the base materials.

Figure 4 – Defective condition of trial E7 due to insufficient viscoplasticity removing the base material from the joint at the leading edge of the tool.

**Weld efficiency**

Hardness testing has been performed to identify the relative loss of mechanical properties in the weld joint zone. The best results were obtained for the colder FSW conditions, i.e., higher advancing travel speeds, or equivalently, weld pitch ratios. Moreover, the weld pitch ratio plays a more important role than the vertical forging force and probe length. This better performance of the colder welds (E8 and E9) is related to the lower heat released with the higher advancing
speeds. The heat released affects the heat treatment of the grain size and promotes the coalescence of the grain size which results in the decrease of hardness. Figure 5 shows this trend and it can be verified that the trials with the same advancing speed (E4, E5, E6 and E8, E9) the changes in applied forces and pin size are not relevant in the measured hardness with small differences in their efficiency.

Figure 5 – Hardness profiles for the feasible trials and correspondent HARD efficiencies.

The mechanical properties obtained from the tensile tests enabled to establish the joint efficiency via the GET parameter. The results are presented in Figure 6. The GET parameter shows that the trial 5 is the one with best overall performance. The loss of hardness in the HAZ and defects at the root of the welds (Figure 7) play the most relevant role. Both trial E4, E8 and E9 present root defects which is related to the decrease in the tensile properties of this material. Trial E5 is defect free (Figure 6) and therefore presents better ductility and toughness properties when compared to the other trials (Figure 7). The trial E1 did not present any root defect, the lower tensile properties of this trial is mainly related to the changes in the material properties due to the heat released by the process, as described before.
Figure 6 – Mechanical resistance properties obtained from the tensile tests of the feasible joints. Overall joint efficiencies established with the GET parameter.

Figure 7 – Micrographs of the root of the cross-section of selected welded joints. a) Sample E5 with full penetration (no defect) and b) sample E9 with LOP (root defect)

Figure 8 presents the different bending properties of welded specimens compared to the base material. The level of penetration is the most influential parameter regarding the mechanical resistance under bend loading. The trials with smaller probe lengths (Trial E6 and E8), higher travel speeds and lower forging forces have the lowest results (Figure 8). Trial E1 has the best performance when compared to the other processes which can be related to higher heat input that has improved the local bending behavior of these samples. It was also identified that despite having a root defects trial E9 presents the second best bending efficiency. This means that this defect is not long enough to promote any damage in this sample leading to this higher bending efficiency.
Figure 8 – Mechanical resistance properties obtained from the bending tests of the feasible joints. Overall joint efficiencies established with the GEB parameter.

The global weld efficiency (3) is presented in Figure 9 and shows that trials E5 and E9 present the best results regarding the weld efficiency considering the mechanical resistance obtained via static loading tests and hardness. The trial E5 and E9 corresponds to the middle of the welding lobe, with the intermediate and longest probe length, respectively.

<table>
<thead>
<tr>
<th>[%]</th>
<th>E1</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
<th>E8</th>
<th>E9</th>
</tr>
</thead>
<tbody>
<tr>
<td>GET</td>
<td>51</td>
<td>61</td>
<td>66</td>
<td>57</td>
<td>61</td>
<td>61</td>
</tr>
<tr>
<td>GEB</td>
<td>64</td>
<td>55</td>
<td>61</td>
<td>60</td>
<td>54</td>
<td>63</td>
</tr>
<tr>
<td>HARD</td>
<td>76</td>
<td>80</td>
<td>82</td>
<td>81</td>
<td>86</td>
<td>89</td>
</tr>
<tr>
<td>GLOBAL</td>
<td>60.3</td>
<td>60.0</td>
<td>65.1</td>
<td>56.3</td>
<td>59.8</td>
<td>64.9</td>
</tr>
</tbody>
</table>

These results that these trials have a good efficiency mainly due to their longer probe length that gave good results in the bending behavior. The tensile behavior is also influenced by the probe length since the root defect promotes the cracking of the different parts. The fatigue testing will show these alloys and the importance of the defect on the welded sample properties.

**Metallurgical analysis**

From the SEM images presented in Figure 10 for the trial E1 it is possible to verify the significant grain refinement in the nugget zone and a small grain coalescence in the HAZ when
compared with the base material. But the main result is the significant coalescence of the AlMn particles in the HAZ. These particles can be found somewhat disseminated in the base material, and even in the nugget, but with much smaller dimension than in the HAZ. These AlMn particles will act as corrosion initiators in magnesium alloys microstructure. These particles will work as cathodes and will promote the pitting corrosion in the alloys. This analysis shows that the Mg welded sample will be more prone to suffer corrosion than the base material. The Figure 11 confirms the high level of density and size of the AlMn particles in the HAZ compared to the nugget zone. From the analysis of Figure 11b (trial E9) it is also possible to conclude that the thermomechanically affected zone (TMAZ) is small even for cold weld conditions with high vertical forging force.

![Figure 10 - SEM imaging of trial E1: a) Base material; b) Heat affected zone (HAZ); c) Nugget](image)

![Figure 11 – Optical microscopic analysis of E5 and E9: a) Detail of the transition of nugget to HAZ for trial E5 and b) Macrograph of the cross-section of trial E9.](image)

**Fatigue testing**

Fatigue testing has been performed in specimens from the trials in the middle of the welding lobe: E1, E5 and E9. Figure 12 shows that the base material reaches infinity life around 77.5% of the yield strength ($\sigma_{\text{yield,BM}} = 155$ MPa) while the trials with LOP defect only reach about 55% of their own yield strength, $\sigma_{\text{yield,E1}} = 95$ MPa; $\sigma_{\text{yield,E9}} = 140$ MPa, respectively. It was also observed that trials with no defects (E5) have similar behaviors to the base material although there is a decrease in the considered yield strength ($\sigma_{\text{yield,E5}} = 140$ MPa).
Figure 12 – Fatigue test analysis for trials E1, E5 and E9. The E5 samples had no LOP root defect detected however this defect has been observed in the E1 and E9 trials.

Corrosion testing

According to the Table 6, presenting the corrosion testing results for the trials in the middle of the welding lobe, the level of heat input is the most significant aspect in these alloys. The decreasing weld pitch ratio, from 12 (trial E1) to 3 (trial E9), reduced the susceptibility to corrosion. Moreover, the highest travel speed has the lowest loss of mass percentage and the values are very close to the ones of the base material.

Table 6 – Loss of mass by saline environment corrosion (350h) obtained for trials E1, E5 and E9.

<table>
<thead>
<tr>
<th>Sample [wt. %] Corrosion</th>
<th>MB</th>
<th>Travel speed [mm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Trial E1)</td>
</tr>
<tr>
<td>3.10%</td>
<td>9.26%</td>
<td>5.77%</td>
</tr>
</tbody>
</table>

The temperature plays a very important role in this property as it is the main characteristic that can influence this property. Polarization curves of different materials have been made to understand the mechanism involved in the corrosion for this alloy. The corrosion rate, \( CR \) (g/s) can be calculated through the Faraday’s law which is given by:

\[
CR (\text{cm/s}) = \frac{i (\text{EW})}{\rho \cdot F \cdot A} \quad \Rightarrow \quad CR (\text{mm/year}) = \frac{K_{\text{corr}} (\text{EW})}{\rho} \tag{5}
\]

Where: \( K \) is 3.27x10⁻³ (mm.g/(μA.cm.year)); \( \rho \) is the density (g/cm³), \( icor \) is the corrosion density (μA/cm²) and \( EW \) is the dimensionless equivalent weight of the corroding species. These calculations according the standard ASTM G 102 – 89 and are based on the polarization curves where the oxidation and reduction curves describe the material behavior for this alloy.
Based on Table 7, it is possible to conclude that with the optimum parameters (trial E5) an increase in the corrosion rate is observed. This increase translates into an increase of 34% compared to the possible rate in the base material. This calculation is based on the standard corrosion density of the magnesium alloys which is higher in welded samples (Figure 12 and Table 7). The cathodic curve of the base material is much steeper than the one obtained for the sample of trial E5 (Figure 13).

![Figure 13 – Polarization curves for base material (left) and welded trial E5 (right).](image)

**Table 7 – Corrosion rate calculation for base material and trial E5 based on Faraday’s law**

<table>
<thead>
<tr>
<th>Material</th>
<th>icor [μA/cm²]</th>
<th>Ecor [V]</th>
<th>EW</th>
<th>CR [mm/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31 BM</td>
<td>1.138</td>
<td>-1.597</td>
<td>12.15</td>
<td>2.58E-02</td>
</tr>
<tr>
<td>FSW Trial E5</td>
<td>1.518</td>
<td>-1.580</td>
<td>12.15</td>
<td>3.45E-02</td>
</tr>
</tbody>
</table>

Table 7 shows that the increase in corrosion in the welded sample using the parameters of trial E5 should have an increase in corrosion of about 34%. These measurements are not in aligned with the measurements of saline testing where the increase in corrosion is 86% higher (Table 6). The Faraday’s law assumes a linear corrosion rate however in the saline tested samples it was observed the pitting corrosion on their surface due to the existence of AlMn particles. The increase of these particles size with the heat released in the process promotes preferred corrosion sites that increase the corrosion rate and enables the difference between these corrosion rates.

**Conclusions**

Friction Stir Welding is a process with good potential for joining magnesium alloy AZ31. The present paper contributes to this goal by defining the weld lobe of the 2mm plates of AZ31 by FSW and the mechanisms of defective conditions which were presented considering the vertical forging force and the weld pitch ratio;
Determining the best FSW parameters were established for intermediate conditions (weld pitch ratio = 6) resulting in no LOP, reaching a GET = 66 %; GEB = 61 %; Hard Loss = 82 %, corresponding to an overall static efficiency of 65 %;

These best developed FSW conditions resulted in a fatigue limit of about 0.8 x \( \sigma_{\text{yield}} \) and similar to the base material behavior;

The corrosion tests in saline environment have shown that corrosion level increases from cold to hot welds and is mainly localized in the HAZ. The best set of parameters resulted in an increase of about 86% relative to base material. The root of the welds are also preferential location for corrosion activity;

The polarization curves enabled a corrosion rate prevision for the welded zone of about 35.4 mm/year, and 34% higher than for base material.

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