A COMPARISON OF DIFFERENT NUMERICAL APPROACHES FOR FSW WELDS OF API 5L - X80 STEEL

UMA COMPARAÇÃO DE DIFERENTES ABORDAGENS NUMÉRICAS PARA JUNTAS DO AÇO API - X80 SOLDADAS POR FSW

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Abstract: This contribution offers a study for two numerical approaches of FSW joints for the API 5L-X80 steel. The first one, a pure thermal model, takes into consideration the preponderant frictional force of the tool being in contact with the workpiece. The second model is a computational fluid dynamic approach, which involves determining experimental values for physical constants and observing its influence in viscous dissipation and strain rates of the material. Temperature and thermal history from the FSW processing were recorded and analyzed. The acquired data was provided from two different heat input conditions. In cases of previewing tool or workpiece local temperature, the pure thermal model is a sufficient suitable approach. Conversely, the CFD model frequently requires huge amounts of information, regarding physical constants and experimental variables, becoming a delicate task for its construction. The pure thermal model was able to offer unequivocal temperature results without the need for large experimental data acquisition. This approach was considered to be finer employed when one aims to forecast temperatures in regions proximate to the welding line. The natural complexity associated with FSW processing suggests there are enormous quantities of experimental factors to be considered for the numerical modeling of high-temperature materials. Also, the CFD approach offers distinct results, which might be crucial for understanding the full aspects of experimental variables. A coupled numerical approach with both models is suggested to fully represent the thermophysical aspects of FSW processing.

Keywords: Computational models. FSW joints. X80 steel. Pure thermal model. CFD model.

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Resumo: Este trabalho oferece um estudo para duas abordagens numéricas de juntas FSW para o aço API 5L-X80. O primeiro, um modelo puramente térmico, leva em consideração a força de atrito preponderante da ferramenta em contato com a peça. O segundo modelo é uma abordagem de dinâmica de fluidos computacional, que envolve determinar valores experimentais para constantes físicas e observar sua influência na dissipação de viscosidade e taxas de deformação do material. A temperatura e o histórico térmico do processamento do FSW foram registrados e analisados. Os dados adquiridos foram fornecidos a partir de duas condições diferentes de entrada de calor. Em casos de visualização da temperatura local da ferramenta ou da peça, o modelo térmico puro é uma abordagem adequada e suficiente. Por outro lado, o modelo CFD frequentemente requer um grande número de informações, tanto a respeito das constantes físicas quanto das variáveis experimentais, tornando-se uma tarefa delicada para sua construção. O modelo térmico puro foi capaz de oferecer resultados inequívocos de temperatura sem a necessidade de grandes aquisições de dados experimentais. Esta abordagem foi considerada mais refinada quando se visa a previsão de temperaturas em regiões próximas à linha de soldagem. A complexidade natural associada ao processamento de FSW sugere que existem enormes quantidades de fatores experimentais a serem considerados para a modelagem numérica de materiais de alta temperatura. Além disso, a abordagem CFD oferece resultados distinto, o que pode ser crucial para a compreensão de muitos aspectos das variáveis experimentais. Uma abordagem numérica acoplada com ambos os modelos é sugerida para representar totalmente os aspectos termofísicos do processamento FSW.

Palavras-chave: Modelos numéricos. Juntas em FSW. Aço X80. Modelo térmico puro. Modelo em CFD.
INTRODUCTION

Friction stir welding (FSW) is a manufacturing welding process developed by The Welding Institute in 1991, initially proposed to weld aluminum and other light-weight alloys. FSW has been known to provide welding joints with enhanced mechanical properties when compared to arc welded joints. Besides the superior mechanical properties of FSWed joints, the solid-state nature of this process avoids typical fusion welding problems, such as element depletion and liquation cracks (WITEK, 2015). The advantages of employing FSW, among others, are: joints with superior mechanical properties due to dynamic recrystallization, less harmful manufacturing process and the consolidated union of the welded joint, maintains the chemical composition of the welded joint, offers minimal environmental risks, produces little machining waste and requires little or no surface cleaning (WITEK, 2015). These features inspired the application of FSW in high-temperature alloys such as stainless steels, duplex stainless steels, titanium and nickel alloys, and High Strength Low Alloy (HRLA) steels (SANTOS et al., 2010; ABBASI; NELSON; SORENSEN, 2013; AVILA et al., 2016).

Figure 1 is an illustration of the FSW process, in which two workpiece plates are joined by a rotating tool.

Figure 1: Illustration of FSW process, showing typical sequential steps.

(a) (b) (c) (d)

Source: Adapted from (SANTOS; IDAGAWA; RAMIREZ, 2014).

The FSW process frequently generates three microstructural distinct regions, also referred to as zones. The stir zone (SZ), in which material mixing takes place; the thermo-mechanically affected zone (TMAZ), where the material is under the influence of high temperature and stress; and the heat-affected zone (HAZ), in which the material is metallurgically transformed. This last region is next to the unaltered base metal (BM). FSW joints also have the distinctive nature of being asymmetrical due to different translational and rotational motion of the tool.

This manufacturing process is especially suitable for high demanding mechanical components such as gasoducts and chemical storage vessels.
HRLA steels, such as the API 5L-X80, are more suitable for pipeline and offshore construction due to a combination of microstructure and mechanical strength (Witek, 2015). These steels can be recognizable by low carbon content and alloying elements, such as boron, vanadium, titanium, chromium, nickel, molybdenum, and niobium, which microstructurally results in a HAZ with greater tenacity (Janovec et al., 2000).

This work was motivated by the increasing necessity for an FSW computational model, to provide an understanding of the thermal phenomena of X80 welding joints manufactured by this process. Especially for FSW, a suitable microstructure, which allows high structural commitment, depends on welding thermal cycles whichever the process, but especially friction stir welding that combines a high degree of deformation and elevated temperature. Due to this fact, this work focuses on comparing two computational models, a pure thermal model and another with a computational fluid dynamics (CFD) approach. Both models are proposed to preview temperature distribution and thermal cycles in the advancing side of API 5L-X80 steel welds. Computational models are some of the straightforward approaches to preview thermal cycles in FSW (Schmidt; Hatte, 2005). In this work, the advancing side of the weld was chosen due to a major concern regarding the SZ integrity (Santos et al., 2010).

The first approach, the pure thermal model, considers the X80 steel as rigid solid, neglecting fluidity effects, such as viscous dissipation and convective effects. The second approach, conversely, is to consider the fluidity effects of the material such as viscosity, peripheral velocity around the tool, and strain rates.
2 MATERIALS AND METHODS

Experimental and data acquisition were like those presented by HERMENEGILDO et al. (2018) and SOUSA et al. (2019). FSW was carried out following a set of parameters leading to a minor heat input of 1.69 kJ/mm (Joint #1), and greater heat input of 1.91 kJ/mm (Joint #2). The tool’s translational speed \((u)\), rotational speed \((\omega)\), and input torque \((M)\) were calculated and acquired by experimental data and can be viewed in Table 1.

Table 1: Input parameters for both welding conditions.

| Weld Joint | Heat Input [kJ/mm] | \(u\) - Welding Speed [m/s] | \(\omega\) - Rotational Speed [rpm] | \(F\) - Axial Force [kN] |
|------------|-------------------|---------------------------|---------------------------------|---------------------|
| Joint #1   | 1.91              | 1.67                      | 500                             | 35.8                |
| Joint #2   | 1.69              | 2.00                      | 300                             | 29.8                |

Source: Adapted from (SANTOS; IDAGAWA; RAMIREZ, 2014).

2.1 Thermal History and Friction Stir Welding

Sound joints of 380 mm length were produced by FSWelding two X80 plates of dimensions 110 × 400 × 12 mm. FSW manufacturing processes were conducted with a PCBN ceramic tool pin of 5.7 mm length. Due to the dimensional limitations of the tool, the joints were manufactured by two welding passes, one on each side of the plate. Thermal history at specific locations was measured by eight K-type thermocouples situated at 2 mm below the workpiece’s surface, with distances of 6, 8, 10, and 12 mm from the welding centerline.

The estimated heat input \((HI)\), based on the work by KYFFIN (2007), was calculated by:

\[
HI = \left( \frac{\omega \cdot M}{1000 \cdot u_{welding}} \right) \cdot \eta.
\] (1)

2.2 Computational Modeling

Numerical models were developed using the COMSOL Multiphysics® software. The models were employed to preview temperature distribution and thermal history at positions around the welding line where is extremely difficult to measure temperature, owing to the physical presence of the FSW tool during the manufacturing process.

A symmetry condition was established along the welding line in order to reduce the computational time. Detailed geometry and assumptions can be seen in Figure 3.
The tool, acting as a heat source in both models, is dealt with a 90% efficiency ($\eta = 0.90$) following the work of CHO et al. (2013) with similar materials. The tool’s position, CAD modeling, and physical assumptions were based on multiple works (SONG; KOVACEVIC, 2003; SCHMIDT; HATTEL, 2005). A flat shoulder with 0°C tilt angle was used in order to provide maximum temperature during the welding process (SIMAR et al., 2006; CUI et al., 2018). The tool’s dimensions were incorporated according to its real size in the experimental setup. The tool has a conical pin with the following dimensions: $R_p = 5$ mm, $R_{tip} = 1.8$ mm and $H_p = 5.7$ mm being the pin’s radius, the pin’s tip radius and the pin’s height, respectively. The shoulder geometry was modelled as: $R_{shoulder-outer} = 12.0$ mm (shoulder outer radius) and $R_{shoulder-inner} = 5$ mm.

Thermophysical properties, such as thermal conductivity and specific heat, were considered as those provided by CHO et al. (2013) and ANTONINO et al. (2014) for both the workpiece and the tool, present in Figure 4.

Equation 2 defines the general heat flux during the FSW processing (NANDAN; DEBROY; BHADESHIA, 2008).

$$\nabla(-k \nabla T) = Q_{shoulder} + Q_{pin} + Q_{\nu} - \rho C_p u \nabla T,$$  

(2)
where $Q_{\text{shoulder}}$ is a superficial purely frictional heat flux and it can be expressed by:

$$Q_{\text{shoulder}} = (1 - f_{\text{pin}}) \cdot \omega \cdot r \cdot \mu \cdot \tau_{\text{friction}}, \quad \tau_{\text{friction}} = \frac{F_N}{A_s}, \quad (3)$$

In Eq. (3), $r$ is the radial distance from the tool’s center axis to the tool’s periphery, $\mu$ is the friction coefficient between the tool and the workpiece, $\tau_{\text{friction}}$ is the forging pressure related to the normal force being applied.

The $Q_{\text{pin}}$ term is the pin’s volumetric heat contribution which is defined in:

$$Q_{\text{pin}} = \left( f_{\text{pin}} \cdot M \cdot \omega \right) \cdot \frac{V_{\text{pin}}}{\eta}. \quad (4)$$

In both models, $f_{\text{pin}}$ is the numerical aspect related to the fraction of heat generated from the pin’s thermal contribution. It is estimated to be around 20%, according to (COLEGROVE et al., 2000).

### 2.3 Thermal Model

In this work we assume the contact condition ($T_{\text{friction}}$) being independent of temperature. As the material is treated as a rigid solid this model does not account for viscous dissipation so,
in this case, \( Q_\nu = 0 \). This leads to contact conditions being independent of temperature.

2.4 CFD Model

This numerical approach was designed to evaluate the material as a high viscosity fluid. In this approach, viscous heat dissipation is considered to occur in the material’s neighboring regions around the tool. The viscous dissipation term regarding heat generation (W/m\(^3\)) can be estimated by:

\[
Q_\nu = \beta \cdot \mu_{dv} \cdot \varphi,
\]

where \( \beta \) is the fraction of plastic strain dissipated as heat (for steels is around 0.5%), \( \mu_{dv} \) is the non-newtonian dynamic viscosity.

The non-newtonian dynamic viscosity can be estimated by the ratio in:

\[
\mu_{dv} = \frac{\sigma_E}{3\dot{\varepsilon}},
\]

where \( \sigma_E \) is the effective flow stress and \( \dot{\varepsilon} \) is the effective strain. Each part of this proportion being defined as follows (NANDAN; DEBROY; BHADESHIA, 2008):

\[
\dot{\varepsilon} = A [\sinh(\alpha\sigma)]^n \exp \left( -\frac{Q_{DEF}}{RT} \right),
\]

\[
\sigma_E = \frac{1}{\alpha} \sinh^{-1} \left[ \left( \frac{Z}{A} \right)^{\frac{1}{n}} \right].
\]

where \( Z \) is the Zenner-Holloman strain rate compensated by temperature, as follows:

\[
Z = \dot{\varepsilon} \exp \left( \frac{Q_{DEF}}{RT} \right),
\]

where \( Q_{DEF} \) is the activation energy of the dislocation’s movement in the material. Values of \( A, \alpha \) and \( n \) are found by fitting Eq. (8) and Eq. (10) to experimental data and previous works (CUI et al., 2018; AVILA et al., 2018).

Lastly, \( \varphi \) is the volumetric fraction of material displaced in the stir zone (SZ) and thermo-mechanically affected zone (TMAZ) during the welding, which accounts for a normal component and a shear component, defined by:

\[
\varphi = 2 \sum_{i=1}^{3} \left( \frac{\partial u_i}{\partial x_1} \right)^2 + \left( \frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} \right)^2 + \left( \frac{\partial u_3}{\partial x_2} + \frac{\partial u_2}{\partial x_3} \right)^2 + \left( \frac{\partial u_3}{\partial x_1} + \frac{\partial u_1}{\partial x_3} \right)^2.
\]
Being $\epsilon_{ij}$ the strain rate tensor, which is given by:

$$\dot{\epsilon}_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right).$$  \hfill (11)

Equation (12) is defined as a general outward heat flux that was implemented at the upside and downside of the workpiece, in which $\epsilon$ is the surface emissivity of the tool and the workpiece, $\sigma$ is the Stefan-Boltzmann constant. Additionally, $T_{env}$ is the ambient temperature (23°C) and $h$ refers to the convective coefficients linked to the workpiece surfaces present in the model and tool’s surface area. Values for both convective coefficients were similar to those used by COLEGROVE et al. (2000), CHO et al. (2013) and SOUSA et al. (2019).

$$q_{total\,loss} = \sigma \cdot \epsilon (T_{env}^4 - T^4) + h(T_{env} - T).$$ \hfill (12)

3 RESULTS AND DISCUSSION

Both models were verified and validated through comparative analysis. The thermal cycles simulated curves had a considerable agreement with the experimental values for maximum temperature values as well as cooling rates.

From Eq. (10) and Eq. (11) above, we observe that there is a certain degree of complexity associated with obtaining such values of $\varphi$. The challenge of estimating such values becomes extremely complex, not only because of the attempt to model the viscous plastic material around the tool, but also because these constituent relationships are characteristic of each welding parameter used (SIMAR et al., 2006; NANDAN; DEBROY; BHADRESHIA, 2008; SCHMIDT; HATTEL, 2008). Non-Newtonian viscosity, for example, may depend on the strain rate and activation energy (which in turn varies throughout the experiment). The latter, therefore, depends on internal factors such as hardening and softening of materials, both associated with microstructural evolution during the process.

For FSW of more ductile materials (with lower yield stress) such as Al, Cu, and Mg, the use of the CFD approach in the literature is quite common (NANDAN; DEBROY; BHADRESHIA, 2008). However, some authors have used this fashion to model high-temperature alloys. For example, CHO et al. (2013) used it for modeling FSW of a 403 ferritic stainless steel.

Although some $Z$ values have been listed for low carbon steels, it is still necessary to point out that, in the case of X80, this value does not reflect the total strain rate dependence of temperature. Such results are influenced by complex phase transformations that occur in the material during the FSW process. These, in turn, depend on the chemical composition and
experimental conditions of each material. Some authors predict that the best application of $Z$ values will be in materials that do not undergo complex phase transformations, such as non-ferrous alloys and stainless steels (SIMAR et al., 2006; NANDAN; DEBROY; BHADRESHIA, 2008; SCHMIDT; HATTEL, 2008; CHO et al., 2013).

Figure 5: Isothermal contours for Joint #1 using the CFD approach.

For the CFD model, as expected, simulated temperatures in this region were higher for the condition with greater heat input than for the other condition. In Joint #1 and Joint #2 maximum temperatures were $1227^\circ C$ and $1169^\circ C$, as can be observed in Fig. 5 and Fig. 6, respectively.

In both models, thermal cycles represented in Fig. 7 and Fig. 8 it can be seen that the simulated data curve for 0, 2, and 4 mm thermocouple is slightly altered. This numerical alteration can be compared as an experimental impedance due to the tool’s dimensional size. The “spike-like” curve of those simulated temperatures can be justified due to temperature data acquisition from the tool’s edge, measuring temperatures coming from a transition zone (shoulder/workpiece) of the model.

Source: The Authors (2020).
Material deformation occurs considerably to regions closer to the welding tool, however, due to heating, the material yield stresses become smaller. In contrast, for portions of the material situated in more distant regions, the achieved deformations are smaller, but the yield stress of the material tends to be higher comparatively due to lower temperatures. In this case, this fact also reinforces that a pure thermal model deals exclusively with local variables, in a more localized way. That is, the region of analysis is shifted towards the tool’s proximities.

Concerning ferrous alloys, especially for X80, it can be expected that these viscosity values are even higher, and that the plastic material velocity values are even lower, according to the heat generation mechanisms proposed by NANDAN, DEBROY and BHADESHIA (2008). A more frictional contribution to this numerical simulation is precisely a consequence of the low viscosity during material processing. Apparently, the viscosity of the specimen in some of the more adjoining regions of the tool was high enough to have a low TMAZ volume fraction.

In fact, a pure thermal model can predict the non-uniform thermomechanical conditions in the peripheric region to only a certain accuracy. Furthermore, the assumption that an equilibrium of contact pressure and, thus, its temperature independence is occurring, does not account for the plastic heat dissipation ($Q_p = 0$), as proposed by SCHMIDT and HATTEL.
These differences concerning simulated and measured temperatures might also be due to simplifications of the current thermal model, which ignores the heat contribution by the material flow around the tool (SANTOS; IDAGAWA; RAMIREZ, 2014).

Similarly, as predicted by previous works of SANTOS, IDAGAWA and RAMIREZ (2014), AVILA et al. (2018) and SOUSA et al. (2019), temperatures simulated for the welding line are slightly lower for the cold joint, as shown in Fig. 8. This is due to a greater cooling rate imposed during welding for the C-joint. This result affects temperature prediction for external zones of the weld, as the thermal model is more suitable for predicting temperatures around neighboring regions of the tool.

For the thermal model, surface maximum temperature computed for both conditions can be viewed in Figs. 9 and 10. Convective coefficients also may alter the predicted temperature values. Greater values of these coefficients seem to lead to an underestimation of temperatures. This fact tends to occur mainly in the workpiece’s regions which are closer to the welding center line (SCHMIDT; HATTEL, 2008).

Source: Adapted from (SOUZA et al., 2019).
Figure 8: Comparative graphic showing simulated and experimental thermal cycles of FSW considering a Joint #2 - CFD model.

Source: Adapted from (SOUZA et al., 2019).

Figure 9: Thermal model simulation result of FSW considering a hot joint, showing the location of maximum temperature on the workpiece surface.

Source: Adapted from (SOUZA et al., 2019).

Additionally, the thermal model provides a more suitable physical illustration of the FSW for this material in this welding conditions. The absence of TMAZ in both welding conditions
can be explained by the low viscous volumetric dissipation caused by the following factors: great material viscosity; by high yield stress; and because the main heat-generating mechanism is friction in the joint. Such a viscous dissipation term is related to the fact that the material transforms energy in the form of defects during plastic welding.

Figure 10: Thermal model simulation result of FSW considering a cold joint, showing the location of maximum temperature on the workpiece surface.

Thus, viscous heat dissipation becomes only sensitive for use in models that consider more ductile materials and which have their deformation and shear heat generation mechanisms. The current simulation becomes useful for not employing such calculations, compensating for the maximum temperature values obtained for each condition. As this is a more thermal approach to the FSW process, the current considerations and boundary conditions for the numerical scheme favor the obtaining of temperature distribution results.

The CFD model however may offer different insights as to superficial and volumetric shear rate results. Figure 11 shows shear rate values for the joint’s superior part, in direct contact with the tool’s shoulder.

These values are agreeing with previous works of COLEGROVE and SHERCLIFF (2005) and FAIRCHILD et al. (2009), which were previewed to range between \(10^3\) and \(10^4\). These shear rate values are might be observable in regions around the vicinity of the tool.

Figure 12 shows shear rate values for the joint as a whole. It can be perceived that, as Fig. 11, shear rate values are greater around the tool vicinity.

Source: Adapted from (SOUSA et al., 2019).
At the same time, according to FAIRCHILD et al. (2009), the advance side of the tool is more susceptible to the formation of defects compared to other regions of the bead. Welding speeds also influence the field of relative material speeds around the tool. Shifts in viscosity rates and strain rates generate a greater asymmetry between the forward and backward side, affecting the heat generation mechanisms for the CFD model.

Despite the advantage of obtaining shear rate values and temperature profile when using this model, CFD models still need experimental data that are onerous to estimate and acquire.
4 CONCLUSIONS

The current work is a fashion to preview temperatures and thermal cycles for different welding conditions of API 5L–X80 weld joints of FSW using two numerical models. Two computational models were compared in order to reach an agreement of the most suitable computational model. This happens due to physical and metallurgical principles, which manage how the heat input is distributed throughout the workpiece. The thermal model showed a practical and straightforward way of finding consistent temperature data regarding different positions of K thermocouples with the experimental values of temperature and with maximum temperatures predicted for the proximities of the welding line. Additionally, collecting data to be utilized in the CFD model has proved to be a long and laborious work, which seems to lead to similar predicted results. The intrinsic complexity associated with FSW is also a major task to be surpassed when one is seeking to model this process. Moreover, it suggests there is still a tremendous number of experimental factors to be considered for the numerical modeling of FSW.

In relation to the CFD module, rigorous validation of flow and temperature values is also challenging, as can be seen by the amount of information one has to own to implement in the model. These models are satisfactory to predict the material’s velocity around the tool region. As for the CFD models, values of maximum temperature for each welding condition were similar to the pure thermal model. This is a strong suggestion of the correct approach by the pure thermal model, in which the friction contribution is predominant over the sliding condition.

It is worth noting that this fact reduces the amount of crucial data collected and provides a more straightforward simulation approach for this material.

The CFD approach might be useful when is necessary to extract information about shear rates and viscosity values for different parameters. However, CFD numerical modeling can be more time-consuming to be processed as it requires some experimental data in order to achieve higher accuracy and significance for the physical aspects of FSW manufacturing. However, the authors suggest a fully coupled model, which takes into consideration both thermal aspects and fluidity characteristics of the material. This hybrid approach might be suitable due to the intrinsic complexity of FSW processing. Despite the results of this hybrid numerical model, computational time should increase greatly since the software needs to solve equations for both dynamic fluid behavior and thermophysical properties. Thus, this fact elucidates the advantage of using the proposed pure thermal model.
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