Numerical investigation of dissimilar friction stir welding of AISI 304L and 410S stainless steels

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Abstract

Friction stir welding (FSW) has been successfully used to join dissimilar materials with advantages such as incipient chemical mixing and positive recrystallization of the microstructure. However, to understand how welding parameters affect the thermal cycle and the material flow around the tool is essential to produce joints without defects. In this work, a numerical simulation of dissimilar joints of AISI 304L austenitic stainless steel with AISI 410S ferritic stainless steel using the FSW technique was performed. The equations of the model were discretized by the finite volume method (FVM), and the mixture between the materials was modeled by the volume of fluid method (VOF) using the ANSYS-fluent simulator. The results predicted the temperatures during the welding for different conditions and viscosity changes successfully. Furthermore, they predicted a better combination of welding parameters in relation to flash formation. The VOF method predicted the mixture of the materials. Furthermore, the results indicated the location of each material and thus avoided unnecessary experimental tests.

Keywords FSW · Dissimilar welding · 304L · 410S · Steel · VOF

1 Introduction

Dissimilar welding techniques optimize the use of each material according to its specific properties for each usage or condition, as discussed in the studies of Fang et al. [1] and Hosseini et al. [2]. Traditionally, dissimilar welding has been performed by different fusion welding processes with some success. However, such procedures have some limitations, especially regarding the metallurgical phenomenon during the solidification and cooling stages.

An example where dissimilar welding is feasible is the manufacturing of ferritic stainless steel (FSS) joints. Although FSSs are a class of alloys with some limitations for fusion welding, their lower cost compared with other classes of stainless steels has been recognized as an
advantage. They experience a monophasic solidification process, which results in ferrite as the only solid phase. This causes coarse grains in the fusion zone (FZ) and in the heat-affected zone (HAZ) and consequently impairs their properties, as reported by Silva et al. [3]. Pickering [4] highlighted that the grain growth in the FZ and HAZ is due to the absence of phase transformation. In these cases, Silva et al. [5] suggested the use of other types of stainless steels such as austenitic steels as the filler material. Also, some low Cr ferritic stainless steels, like 409 and 410S, may be subject to martensitic transformation, as reported by Mola and De Cooman [6] and Silva et al. [7]. This behavior occurs because the ferrite that is partially converted into austenite at high temperatures can be converted into martensite during fast cooling as explained by Pistorius and van Rooyen [8] and van Warmelo et al. [9].

Ferritic stainless steels can also experience a drop in their properties due to some harmful effects caused by carbide/nitride precipitations and intermetallic phases. Silva et al. [3] reported the formation of different kinds of precipitates in the HAZ of 444 steel, such as CrN, Cr7C3, Cr23C6, sigma, chi, and Fe2Nb Laves phase. Kuzucu et al. [10] reported the formation of M23C6, NbC, and sigma, in ferritic stainless steel containing 18–18 wt.% Cr under heat treatment, and they also observed a decrease in toughness. Sello and Stumpf [11] also investigated the Laves phase formation in ferritic stainless steels and highlighted that this phase plays a significant role in toughness. These metallurgical changes may impair critical metallurgical changes such as mechanical strength, toughness, and corrosion resistance. On the other hand, austenitic stainless steels have a remarkable toughness and weldability, as pointed out by Folkhard [12]. Nonetheless, they are prone to sensitization due to chromium depletion caused by the precipitation of Cr23C6 carbides, as highlighted by Dayal et al. [13].

Advances in manufacturing processes such as the solid-state welding process called friction stir welding (FSW) that was developed by The Welding Institute (TWI) in the 1990s [14] have opened up new perspectives for joining materials. Recently, studies on the friction stir welding (FSW) process have demonstrated that FSW is a promising joining method to avoid some of the problems related to fusion and solidification because the joining occurs in a solid state (at a temperature of 80% of the melting point, as cited by Mishra and Ma [15], or close to 90% of the melting point, as claimed by Qian et al. [16]). Besides this lower temperature peak reached during the process, the plastic deformation produced by the movement of the tool can promote the dynamic recrystallization phenomenon, as highlighted by Nandan et al. [17], and this phenomenon strongly affects the microstructure and mechanical properties. Although the FSW process has several advantages, parameter adjustment is a key issue to employ the FSW technique successfully.

There are some studies in the literature devoted to FSS welding by FSW. Cho et al. [18] investigated the welding of 409 FSS by FSW and demonstrated that it was possible to produce a high-quality defect-free welded joint. Lakshminarayanan and Balasubramanian [19] using a welding speed of 50 mm/min and rotation speed of 1000 rpm successfully welded a 409 FSS by FSW that resulted in joints free of volumetric defects. Caetano et al. [20] investigated the relationship between rotation speed and axial force in the formation of defects in AISI 410S ferritic stainless steels welded by FSW. These authors reported that the production of joints without root flaws is achieved through the correct balance between the axial force and the rotation speed, allowing a greater immersion of the tool probe into the joint.

Nonetheless, a greater understanding of the parameters that affect the heat generation and the material flow is extremely important to optimize the FSW process. Advances in computational tools enable the modeling of the aforementioned conditions, providing reliable and useful data that can clarify the stirring mechanism based on the visco-elastoplastic behavior of these materials at high temperatures and therefore problems that could occur during the FSW welding can be predicted. Frigaard et al. [21] were the first to propose a model to describe the heat generated in aluminum by FSW. Later on, Seidel and Reynolds [22] proposed a model to describe the material flow around the tool, based on a 2D fluid flow that took into account the contribution of the plastic deformation on the heat generation. Sheppard and Wright [23] developed a viscosity model as a function of the temperature and the strain rate. Subsequent studies applied this same approach to evaluate the heat generation and material flow for specific materials such as mild steel, as proposed by Nandan et al. [24]; austenitic steel, as pointed out by Zhu and Chao [25]; and for ferritic steel, as reported by Cho et al. [26]. Silva et al. [27] performed a FSW simulation of AISI 304L stainless steel using the finite volume method for a range of welding parameters. These simulations were able to predict defects, as well as flashes and holes for some welding parameters.

Despite advances in numerical simulations of the FSW process, few studies have addressed the modeling of dissimilar welding in which a non-uniform heat generation and strain rate must occur. The differences of the chemical and physical properties of the welded materials result in a complex behavior of material flow in the stir zone. A literature survey has shown limited information regarding simulation of dissimilar materials such as Al to Mg alloys, as reported by Patel et al. [28] who evaluated the horizontal material flow from the advancing side to the retreating side and the vertical material flow from top to bottom in FSW, with good agreement with their experimental data. In another study, Yang et al. [29] evaluated the material mixing and distribution for Al-Cu dissimilar welds, introducing a local turbulent
flow below the tool pin, which has been considered a pivotal factor to describe the mixing zone formation. Hernández et al. [30] used the FLUENT computational fluid dynamics package to study the transient and steady-state models for the dissimilar welding of two different carbon steels with different carbon contents and concluded that the distribution of the spatial materials due to the stirring was dependent on the rotation and welding speed. Pankaj et al. [31] also simulated an FSW dissimilar weld based on the combination of low-carbon and high-strength steels, using the finite element method (FE). The numerical model was able to predict the temperature peak successfully. Another advance includes the simulation of Al to steel in underwater welding conditions, as reported by Eyvazian et al. [32]. However, to the best of our knowledge, no numerical investigation of the FSW process using dissimilar ferritic to austenitic stainless steels has been performed.

The main objective of this work is to develop a reliable numerical simulation to predict the heat generation, material flow, and the tendency to form volumetric defects in dissimilar welds between AISI 410S ferritic stainless steels and AISI 304L austenitic stainless steels. In order to do this, the position of the materials and some welding parameters such as rotation speed and axial force were varied. Furthermore, the numerical data were validated against a set of experimental tests.

### 2 Materials and experimental data

In this work, two 200 x 500 x 4 mm stainless steel plates: AISI 410S and AISI 304L, were used. The total length of the weld was 500 mm. All welds were made using the HZG Gantry System at the Helmholtz-Zentrum Geesthacht (HZG) GmbH, in Germany. The position of the steel plates and the simulated parameters used in this study are shown in Table 1.

The tool used in the experimental and simulated tests was made of polycrystalline cubic boron nitride (PCBN), and argon was used as the shield gas. The chemical compositions of the AISI 410S and the AISI 304L stainless steels are given in Table 2, and the thermal properties of the tool and the steel are shown in Tables 3 and 4.

### 3 Physical model

In this study, the beginning and ending of the welding line were not analyzed, since these regions are not a representative part of the weld. Therefore, the results will focus on the intermediate section of the welding line, which has a constant heat generation and the cross section has similar properties, geometry, and structure. The aforementioned features indicate that intermediate region can be modeled by a steady-state regime as commented by Song et al. [35].

The steady simulation of the intermediate section of the workpiece was assumed to be in fully contact with the tool as shown in Fig. 1. Throughout the welding period, pressure, rotation, and welding speed were kept constant and $\tau = \sigma_{yield} / \sqrt{3}$, where $\sigma_{yield}$ was evaluated using the distortion energy theory considering a plane stress.

The simulations were performed using a non-uniform mesh composed of hexahedrons that were generated by the ICEM-Mesh software. The material properties used in the simulations are presented in Tables 3 and 4. We employed the viscosity model described in Silva et al. [36], which constants were modified to mismatch the physical properties of the two investigated materials. Figure 2 shows the viscosity profiles as a function of strain rate and temperature.

### Table 1 FSW welding parameters

| Test | Advancing Side | Retreating Side | Axial Force (kN) | Rotational Speed (rpm) | Weld Speed (m/s) |
|------|----------------|-----------------|------------------|------------------------|-----------------|
| 1    | AISI 410S      | AISI 304L       | 40               | 450                    | 1               |
| 2    | AISI 304L      | AISI 410S       | 40               | 450                    | 1               |
| 3    | AISI 410S      | AISI 304L       | 40               | 650                    | 1               |
| 4    | AISI 304L      | AISI 410S       | 40               | 650                    | 1               |
| 5    | AISI 410S      | AISI 304L       | 30               | 450                    | 1               |
| 6    | AISI 304L      | AISI 410S       | 30               | 450                    | 1               |

### Table 2 Chemical composition of AISI 304L stainless steel (% mass)

| Material | Fe  | C    | Cr  | Mn  | Ni  | P    | Si   | S    | Mo  |
|----------|-----|------|-----|-----|-----|------|------|------|-----|
| 410S     | Bal | 0.025| 12.8| 0.3 | 0.21| 0.023| 0.37 | <0.010| 0.014|
| 304L     | Bal | 0.026| 18.5| 1.21| 7.94| 0.029| 0.32 | <0.010| 0.29|
The volume of fluid (VOF) was used to obtain the volume of each phase in the mixed zone of the dissimilar weld region as defined by ANSYS [37]. In this method, the interface between the phases is solved by a continuity equation for one or more phases, as given by

$$ \frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \mathbf{v}_q) \right] = \sum_{p=1}^{n} (\dot{m}_{pq} - \dot{m}_{qp}) $$

where $\dot{m}_{pq}$ is the mass transfer between phase $p$ and phase $q$, $\rho$ refers to the density of each phase, and $\alpha$ represents the phase fraction.

### 3.1 Governing equations

Using the aforementioned approaches, the continuity equation is given by:

$$ \frac{\partial u_i}{\partial x_j} = 0 ; \ i = 1, ..., 3 $$

where $u_i$ denotes the Cartesian components of the velocity field in $x$, $y$, and $z$ directions. Equation (2) states that the volume variation is null. Adopting a coordinate system attached to tool, the momentum equation is given by

$$ \frac{\partial \rho u_i}{\partial t} + u_i \frac{\partial \rho}{\partial x_j} + \frac{\partial (\rho \mu u_i)}{\partial x_j} = -\rho \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \frac{\partial \mu u_i}{\partial x_j} \right) - \rho U \frac{\partial u_j}{\partial x_j} + S_t $$

where $\rho$, $U$, $P$ and $\mu$ are the density, the weld velocity, the pressure, and the non-Newtonian viscosity of the material, respectively. The viscosity model ($\mu$) used for both materials (AISI stainless steel 410S and AISI stainless steel 304L) is described in [36], which the AISI stainless steel 410S used the same model of Ti–6Al–4V alloy, with appropriate changes in material properties. The energy equation is given by:

$$ \frac{\partial (\rho C_P T)}{\partial t} + u_i \frac{\partial (\rho C_P u_i T)}{\partial x_j} = -\rho C_P U_j \frac{\partial T}{\partial x_i} + \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} \right) + S_t $$

where $C_P$ and $k$ represents the specific heat and thermal conductivity, respectively. The simulation was performed in a steady-state regime. However, the transient terms were kept in Eqs. (1), (3), and (4) in order to reach the steady-state regime through a distorted transient. $S_t$ is a total source term, which is composed of two components: one is the energy dissipated by friction between tool and workpiece ($S_f$) and the other is the energy generated by plastic deformation ($S_p$).

### Table 4 Thermal properties of tool material and AISI 304L stainless steel [33, 34]

| Material       | Density ($kg/m^3$) | Thermal Conductivity ($W/m \cdot K$) | Specific Heat ($J/kg \cdot K$) |
|----------------|--------------------|-------------------------------------|-------------------------------|
| 304L           | $7.97 \cdot 10^3 - 6.01 \cdot 10^{-2} \cdot T$ | $19.36 - 0.02960 \cdot T$ | $431.73 + 0.2879 \cdot T$ |
|                | $-1.12 \cdot 10^{-3} \cdot T^2$                | $+6.525 \cdot 10^{-3} \cdot T^2$ | $-0.000131237 \cdot T^2$ |
|                | $+6.16 \cdot 10^{-0.7} \cdot T^3$              | $-2.88 \cdot 10^{-8} \cdot T^3$ | $+3.85 \cdot 10^{-9} \cdot T^3$ |
| PCBN           | 3120                                           | 130                                 | 1966                          |

### Fig. 1 Schematic diagram of the FSW simulation. (a) velocity boundary conditions and (b) top view of the tool
3.2 Source terms and boundary conditions

The heat sources were added to the FLUENT commercial software by means of a UDF (user-defined function). The $S_i$ source term is defined in FLUENT as the heat flux and is defined by

$$S_i = q_1 \frac{A_r}{V}$$  \hspace{1cm} (5)

where $A_r$ is the contact area between the tool and workpiece and $V$ is the volume enclosing $A_r$. $q_1$ [W/m$^2$] is the heat generated by the contact between the shoulder of the tool and the workpiece, which is defined by

$$q_1 = [\delta \eta \tau + (1 - \delta)\mu \rho P] (\omega r - U_1 \sin \theta)$$  \hspace{1cm} (6)

In the above equations, $P$ indicates the normal pressure of the tool during welding, $\omega$ is the angular velocity, $U_1$ is the welding speed, $\eta$ is the thermal efficiency, and the term composed by $(\omega r - U_1 \sin \theta)$ represents the relative velocity between the tool and the workpiece. $\sin \theta$ is defined by

$$\sin \theta = \frac{V}{r}$$  \hspace{1cm} (7)

$$\cos \theta = -\frac{x}{r}$$  \hspace{1cm} (8)

$$r = \sqrt{x^2 + y^2}$$  \hspace{1cm} (9)

where $r$ is the radius of the global axis fixed at the center of the tool.

In Eq. (4), the term $S_b$ indicates the source term by generated by plastic deformation. $S_b$ has been calculated as $f_m \mu \Phi$, where $\mu$ designates the viscosity, and $f_m$ is an arbitrary constant that indicates the extension of atomic mixing in the system. In this study, a value of 0.04 was used for $f_m$, defined by Cho et al. [26] and $\Phi$ is given by

$$\Phi = 2 \left( \frac{\partial u_1}{\partial x_1} \right)^2 + \left( \frac{\partial u_2}{\partial x_2} \right)^2 + \left( \frac{\partial u_3}{\partial x_3} \right)^2 + \left( \frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} \right)^2$$

$$\hspace{4cm} + \left( \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} \right)^2 + \left( \frac{\partial u_1}{\partial x_1} + \frac{\partial u_3}{\partial x_3} \right)^2 + \left( \frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} \right)^2 \right)$$  \hspace{1cm} (10)

The heat generated by the contact of the tool and the workpiece is split between them. The fraction that is inputed to the plate ($f$) is defined by:

$$f = \frac{J_w}{J_t + J_w}$$  \hspace{1cm} (11)

where $J_i$ is defined by the following equation:

$$J_i = \sqrt{\rho C_p k}$$  \hspace{1cm} (12)

In Eq. (12), $i = w$ or $t$ for the workpiece and the tool, respectively. A convection boundary condition was established on all faces of the plate. For the upper surface of the plate, the radiation flux between this face and surrounding as combined with the convection heat flux. Having established the above conditions, the heat loss conditions in the bottom, side, and top of the plate are, respectively, given by the following equations:

$$k \frac{\partial T}{\partial z} = h_b (T - T_e)$$  \hspace{1cm} (13)

$$\pm k \frac{\partial T}{\partial y} = h_s (T - T_e)$$  \hspace{1cm} (14)
where $h_b$, $h_s$, and $h_t$ are the heat convection coefficients for the bottom, side, and top of the workpiece, respectively, $T_a$ is the environmental temperature, and $k$ is thermal conductivity.

Under boundary conditions, the velocities generated on the materials by contact between the tool and workpiece were also prescribed. Previously, Silva et al. [27, 36] simulated the tool as a cylindrical without threads, which resulted in a difference of the location of some defects simulated and obtained in the real welding. In order to avoid possible defects caused by the simplification of the geometry of the tool, the simulations, in this work, were performed using the real tool with threads shown in Fig. 3. Also, the velocities given in Eqs. (16) to (18) were evaluated based on geometry presented in Fig. 3.

The threads in the tool cause two effects on the velocity field. First, a radial velocity in the opposite direction of radius growth, and second, a vertical velocity. Both effects cause a material flow toward the bottom of the workpiece. These threads are used to reduce the production of flashes. The effect of threads on the tool was included in the Fluent simulator using the UDF by the following equations:

$$u = (1 - \delta)(wr \sin \theta - U_1) \tag{16}$$

$$v = (1 - \delta)(wr \cos \theta) \tag{17}$$

$$w = -0.0254 \frac{tpi}{\omega} \tag{18}$$

where $R_p$ is the radius and tpi designates threads per inch.

### 4 Results

In this work, a hybrid mesh composed of hexahedron and prism elements was used as shown in Fig. 4. This mesh has 293,648 elements and 333,342 nodes. A mesh refinement
study was performed, and the mesh presented in Fig. 4 provided results in terms of welding cycles independent of the grid size. Therefore, this grid was chosen for all simulations shown in this work.

The welding cycles of Test 1 were compared with the experimental results measured by four thermocouples placed on the upper surface: two on each side (advancing side and retreating side). On each side, the thermocouples were positioned at a distance of 15 and 20 mm, respectively, from the center of the welding line. The diameter of the tool is 23.6 mm, and consequently the thermocouples are 3.2 and 8.2 mm from the edge of the shoulder, as shown in Fig. 5.

Figure 6, which presents the results for all positions mentioned above, shows that there is a good agreement between all the experimental and numerical cycles evaluated. Time, along the horizontal axis in Fig. 6, was calculated by dividing each position along the length of the plate by the welding speed. The simulated results showed the same temperature peaks as the experimental results but a small difference in the base of the welding cycle. These results demonstrate that the heat input of the experimental and simulated results is similar.

Temperature is an important factor that influences the results in welding. Figure 7 shows the cross section of the temperature field, for all tests, at the center of the pin and perpendicular to the welding velocity. As expected, the welding parameters directly influence the temperature. Figure 7 shows that the temperature increases when the axial force
and rotation increase. Based on the previous study of Silva et al. [27] using similar welding procedures with these materials such behavior was expected because the friction coefficient and slip rate were kept constant during the simulation. In addition to the former effects, in dissimilar welding, the temperature is also influenced by the order in which the dissimilar materials are placed (retreating and advancing sides). In addition to the natural asymmetry of the heat distribution that occurs between the advancing side and the retreating side, the asymmetry is accentuated by the use of different materials. All the tests presented in Fig. 7 show an increase in temperature when the AISI 304L stainless steel was placed on the advancing side. This occurs because the AISI 304L stainless steel has greater strength than the AISI 410S stainless steel, and consequently the tool slides more easily when the AISI 304L stainless steel is placed on the advancing side because the AISI 304L steel has a higher flow resistance. Therefore, more heat is generated by the friction, which also increases the temperature of the surface, as reported by Al-Badour et al. [38].

Aval et al. [39] welded the alloys AA5086 and AA6061 by FSW, and these authors verified an increase in temperature when the material with greater resistance was placed on the advancing side. In the work published by Al-araji et al. [40], the simulation showed the opposite behavior, but the authors attributed this difference to a limitation of the software that did not calculate the heat generated by the friction, which is the main factor responsible to increase the temperature when the position of the dissimilar materials is changed.

The results of Tests 1 through 4 (Fig. 7a–d) show that the temperature increased up to or higher than 80% of the melting point. However, these extremely high temperatures are not observed in practice during the FSW processes. These temperatures are consequence of a limitation of the model used here that assumes a constant friction coefficient. Iordache et al. [41] developed a friction function using experimental tests, which it varies with temperature in range between $\mu_0 e^0$. Further experiments to develop a variable friction coefficient function of temperature are still required. Although this model predicted temperature levels outside the expected range for some rotations and axial forces, the model was successfully employed by Silva et al. [27] to predict defects such as flash formation and voids during the FSW of AISI 304L.

Based on simulations and experimental results, Silva et al. [27] observed that if the maximum temperature is above 80% of the melting point then drawbacks in the welded joint are expected. The ideal temperature for the FSW process is close to 80% of the melting point temperature of the metals being welded. The results of Tests 5 and 6 (Fig. 7e, f) present temperatures close to 80% of the melting point temperature, and they indicate better results with the lowest probability of flash formation.

The model presented in this work predicts the temperature of the material, but it is able to predict the voids and the formed phases. However, when the results are combined with thermodynamic simulations, it is possible to predict the formed phases. Also, injecting particles into the model it is possible to predict the voids. The former observations can be verified in previous studies of similar welding of 304L and 410S steels performed by Silva et al. [27, 42].

Figure 8 shows the cross section of the micrography results at the center of the pin for Tests 1 and 5. The simulated temperature field for Test 1 (Fig. 7a) shows that the maximum temperature was over 80% of the melting point (between 1499 k and 1649K), and consequently, flash
formation is favored as shown (in the experimental results) in Fig. 8a. However, Test 5 (Fig. 8b) shows a significant decrease in the number of flashes formed compared to Fig. 8a (Test 1). These differences demonstrate that when the temperature is greater than 80% of the melting point flashes are favored.

Figure 9 presents the cross section of the viscosity field at the center of the pin for all tests investigated; the minimum viscosity found was $1.55 \cdot 10^4$ kg/m.s and the maximum viscosity was defined in the code based on the analyze performed by Silva et al. [36]. When the AISI 304L stainless steel is on the advancing side, the viscosity profile is less homogeneous, as confirmed in Fig. 9b, f. These figures show regions with higher viscosity (light blue regions) within the stir zone (dark blue region), as pointed out by the arrows. In Fig. 9d, the change is not so evident, because the temperatures in these tests are considered too high for the parameters expected in FSW, which causes excessive softening of the entire simulated region.

As discussed below, the lack of homogeneity in the viscosity field can indicate an inefficient mixing of the different materials. The study developed by Chen et al. [43] showed a similar behavior to those presented in Fig. 9a, d, and e, in which the low viscosity around the tool is homogeneous and represents the stir zone. In contrast, the lack of homogeneity in the stir zone is an indication that problems can be expected in the weld joint.

Inefficient mixing due to inversion of material sides has also been shown in the literature. Jafarzadegan et al. [44] welded stainless steel 304 with st 37 steel with the latter, the low strength material, on the advancing side and they confirmed that the material flow was sufficient to fill up cavities and groove-like defects. This choice was based on the review carried out by Mishra and Ma [15], whose work showed the need to position the less resistant material on the forward side. A similar situation occurred in this study between 304L and 410S stainless steels.

As the position of the material influences the final material in the weld region, a cross section of the phase fraction of the two dissimilar materials positioned at 60 cm after the tool is shown in Fig. 10 for all tests.

Figure 10b, d, and f show that in all situations where the AISI 304L stainless steel was placed on the advancing side, the mixture had misshapen issues. However, when the AISI 410S stainless steel was placed on the advancing side, it showed a tendency of movement at the base and the AISI 304L steel showed a movement yield at the top, as shown in Fig. 10a, c, and e. This behavior was observed in the study developed by Singh et al. [45], the authors welded magnesium with...
aluminum and the advancing side penetrates from below on the retreating side.

Al-Badour et al. [38] welded Al 6061 and Al 5083-O by the FSW process and found a similar behavior to that shown in Fig. 10. The authors showed that when the most resistant material (Al 6061) was placed on the advancing side, the penetration into the other material was inefficient. In this study, when the 304L steel was placed on the advancing side, the mixture did not present an efficient and homogeneous penetration (Fig. 10b, d, and f).

The behavior of the material flow observed above in the numerical simulation presented in Fig. 10 was compared to the experimental results in terms of macrography of the welding region. The experimental results showed the same trend observed in the simulated results. For instance, when the lowest-strength material was placed on the advancing side, the AISI 410S tends to penetrate through the base, and the material on the retreating side tends to penetrate through the top, as seen in Fig. 11.

The above numerical results show that the simulation was able to predict which material should be placed on the retreating and advancing sides. Figure 12 compares the macrography results of Tests 5 and 6. Although the maximum temperature for Tests 5 and 6 presented above did not exceed 80% of the melting point, inverting the materials had a great impact on the result. Figure 12b shows that when the AISI 304L stainless steel is placed on the advancing side several defects, such as flashes and voids are observed in the weld.

Figure 13 presents the macrography results of Test 1 as well as the simulated temperature, viscosity, and velocity fields. The low viscosity zone (Fig. 13c) demonstrates a similarity with the stir zone, represented by the black dotted line. The low viscosity zone has a small difference at the base of the pin and at the end of the shoulder. These differences are due to the limitations of the model, which does not consider the depression caused by the tool that extends the stir zone more than the simulation.

Another important aspect shown in Fig. 13 is the transition between the zone with the smallest viscosity (dark blue region in Fig. 13c) and high viscosity (red region in Fig. 13c). This region of transition has reduced viscosity and zero velocity. This behavior can be associated with the thermomechanically affected zone (TMAZ), in which
the material is submitted to deformation and heating. However, this region is smaller than the stir zone. This deformation occurs in the transition between the intense movement present in the stir zone and the lack of movement in the heat-affected zone, as shown in the study of Threadgill [46].

In addition to above-commented zones, another region was observed, where the viscosity was not altered during the welding and did not present any speed, which is defined as the heat-affected zone. Differing from the other regions, the microstructural changes results only from the temperature changes (region after blue dotted line).
5 Conclusions

This work presented an experimental and numerical investigation of dissimilar joints of AISI 304L austenitic stainless steel with AISI 410S ferritic stainless steel using the FSW process. The equations of the model were discretized by the finite volume method (FVM), and the mixing of the materials was modeled by the volume of fluid method (VOF) using the ANSYS-fluent simulator.

This investigation demonstrated that the temperatures predicted by the simulation were close to the experimental results. In addition, the temperature field can be used to predict possible defects when the simulated temperature reached values above 80% of the melting point of the materials.

The viscosity of the mixing zone became heterogeneous, when the materials were positioned in an inappropriate order. A heterogeneity of the stir zone can cause material flow problems, which can give rise to voids and failures in the mixing of materials.

At extreme temperatures, the viscosity field was not able to detect problems in the stir zone, but the VOF method was efficient in predicting an inefficient mixing of the materials.

The combination of the speed, viscosity, and temperature analyses resulted in excellent indications of the size of the materials.

Conclusions

The combination of the speed, viscosity, and temperature analyses resulted in excellent indications of the size of the thermomechanically calibrated zone, stir zone and heat-affected zone.

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Author contribution

Numerical simulation of the study was conducted by Silva, Y.C. and Oliveira Junior, F. Welding experiments were conducted by Andrade, T.C.. Review and discussion of the results were carried out by all authors.

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Availability of data and materials

Data and materials are available.

Declarations

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Conflict of interest

The authors declare no competing interests.

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