Assessment of joint configuration and welding parameters for the dissimilar joining of AISI 304L and AISI 410S stainless steels by the friction stir welding

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Research Article

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Abstract

The FSW process parameters for dissimilar welding of AISI 410S and 304L steels were varied to provide a combination of good surface finish, no voids, and complete tool penetration. These findings have practical implications, as they can guide the welding industry in achieving optimal results. Preliminary tests were performed to analyse the proper position of the steels between the advancing and retreating sides. In welding, axial forces from 25 to 40 kN were applied, keeping the rotational speed constant at 450 rpm and the welding speed at 1 mm/s. Due to the differences between the physical and chemical properties of welded steels, a reduction in flash production and void formation along the stir zone is observed with the positioning of ferritic stainless steel AISI 410S on the advancing side. As the axial force increases, there is an increase in flash production, being more intense on the advancing side than on the retreating side. However, this increase in axial force decreases the material insertions’ size and nullifies the joints’ root flaws. It is possible to produce dissimilar joints between AISI 410S / 304L steels by the FSW process with a good surface finish and no defects in the stir zone.

1. Introduction

Stainless steels are Fe-based alloys with a chromium content of 11 to 30% and may contain Mo, Nb, and Ti additions, among others. Their chemical composition may result in different microstructures, giving rise to their classification, as shown by Folkhard [1] and Kotecki [2]. Austenitic stainless steels have a crystalline face-centred cubic (FCC) structure, are the most commercially used due to their high mechanical and corrosion resistance, and have a predominantly austenitic microstructure at room temperature. On the other hand, ferritic stainless steels are characterised by having an essentially ferritic microstructure with a body-centred cubic structure (BCC). Smith [3] has noted that ferritic stainless steels supply approximately the same corrosion resistance but have lower ductility, toughness, and weldability when equated to austenitic stainless steels. However, Lippold and Kotecki [4] have shown that ferritic stainless steels can be used in various applications where resistance to pitting and stress corrosion cracking is more critical than mechanical strength. Another benefit of ferritic stainless steel is that it usually does not contain nickel in its composition, as nickel is one of the costliest alloying elements and considerably increases the price of austenitic stainless steels over ferritic stainless steels as reported by Silva et al. [5].

The lower application of ferritic stainless steels in the industry is related to the metallurgical problems arising from these steels’ fusion welding. When subjected to welding thermal cycles, these materials undergo metallurgical changes, compromising their weldability and the mechanical and corrosion response of welds. The toughness is significantly affected as it is directly related to grain growth in the heat-affected zone and melting zone for autogenous welds, as shown by Silva et al. [6]. Besides, some secondary phases may be formed in the weld, affecting corrosion resistance. Silva et al. [7] evaluated the changes in the HAZ of the AISI 410S ferritic stainless steel submitted to different heat input levels in a fusion welding process. The authors have reported that there were zones with excessive grain growth in addition to martensite formation, which causes a compromise of mechanical strength and toughness. Another problem was the precipitation of chromium nitrides and finely dispersed carbides in the HAZ, which caused embrittlement and intergranular corrosion.
In recent decades, Friction Welding (FSW), a solid-state welding process developed by Thomas et al. [8] at The Welding Institute (TWI) in Cambridge, England, has revolutionised the joining of materials considered of low weldability. Mishra and Ma [9] reported that this process uses a non-consumable tool that rotates and penetrates the joint, resulting in intense plastic deformation of the materials to be joined and dynamic recrystallisation. Benefits commonly attributed to the FSW process include good weld strength and ductility, minimal residual stress and distortion, absence of melt-related defects, and fine-grained microstructure that increases resistance to traction and fatigue life as proposed by Bilgin and Meran [10], Debroy and Bhadeshia [11], and Sathiya et al. [12]. Liu et al. [13] report that FSW steel welding has significant advantages compared to traditional fusion welding because of the efficient control of welding temperature and cooling rate. This control avoids unfavourable phase transformation that usually occurs during traditional welding, and favourable phase fractions can be kept in the weld zone, thus preventing the degradation of typical properties associated with fusion welding.

The applications of the FSW process in similar austenitic stainless steel welds show that although the formation of deleterious phases is expected in the stir zone, as proved by Kokawa et al. [14] and Park et al. [15], an essential aspect for the success of the welds produced is the intense grain refining resulting from dynamic recrystallisation, as observed by Wang et al. [16]. However, Çam [17] mentions that in applying the FSW process in ferritic stainless steels, there is some difficulty in recrystallisation and grain refining, although studies show promising applications from the point of view of mechanical properties. However, the combination of these aspects in dissimilar FSW welding between ferritic and austenitic stainless steel is still developing. More detailed information about the influence of process parameters and the phenomena involved in producing faultless and good-quality welds becomes a subject of scientific solid and technological appeal.

In the FSW process, rotational speed and axial force are the two main parameters directly related to heat generation, as shown by Caetano et al. [18], and Mishra & Ma [9]. A proper combination of welding speed, axial force, and rotational speed is critical in achieving a balanced set of welding parameters. Correct adjustment of these parameters allows the joining of metals, especially those with lower weldability when other welding processes are applied, as noticed by Silva et al. [6]. Low heat input and high welding speed are recommended for ferritic stainless steels to minimise ferritic grain growth and form a refined microstructure. Caetano et al. [19], and Bilgin and Meran [10] showed that such characteristics could be achieved using the FSW process.

Different industrial segments use dissimilar welding joints of other metals to bring together different properties, seek to minimise costs, and maximise the performance of equipment and machinery with varying processes of welding. Silva et al. [20] point out that joining different stainless steels in dissimilar joints in the petroleum distillation towers in the gas and petroleum industries through fusion welding processes is promising. Mukherjee and Pal [21] claim that the dissimilar joints between ferritic and austenitic stainless steels efficiently prolong metals’ service life due to improved toughness, mechanical strength, and corrosion resistance.

Chen et al. [22] show that developing and improving the FSW process parameters for different metal alloys made it possible to apply them to dissimilar joints. The obtaining of promising results range from the union of various aluminium alloys, as shown by Murr [23], to the joining of aluminium alloys with copper and
magnesium alloys, as studied by Carlone et al. [24] and Abdollahzadeh et al. [25]. Thus, recent studies by Li et al. [26] show satisfactory results for applying the FSW process in the dissimilar joining between Mg/Ti alloys. Mishra et al. [27] have successfully joined Ti alloys to stainless steel through friction stir spot welding (FSSW), a variant of the FSW process. The authors found that dwell time is a crucial parameter that, when optimised, can result in high shear strength.

Among the FSW process parameters evaluated over time and which were necessary for the progress of the dissimilar joining of these materials, stands out the influence of plate position, tool offset and tool rotational speed, as noted by Sahu et al. [28], as well as the behaviour of the material flow and stir zone consolidation with the rotation speed, observed by Gerlich et al. [29], and the influence of axial force on heat generation.

However, since the analyses carried out by Watanabe et al. [30], in the dissimilar joining between aluminium alloys and steels by the FSW process, studies with the exploration of process parameters required the dissimilar joining of different steels, such as those carried out by Wang et al. [31], are still incipient, requiring a more detailed exploration of the impact of these parameters on the origin and defects formation. Thus, this work aims to evaluate the effect of joint configuration and welding parameters, such as axial force, on the production of FSW dissimilar joints between austenitic stainless steel AISI 304L and ferritic stainless steel AISI 410S with excellent surface appearance and no defects.

2. Materials and Methods

The welds were made using 4-mm-thick plates of AISI 410S ferritic stainless steel and AISI 304L austenitic stainless. The material’s chemical composition was determined by optical emission spectroscopy (Shimadzu model PA7000 Japan) and is presented in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>410S</td>
<td>0.025</td>
</tr>
<tr>
<td>304L</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Source: The author.

The FSW process joined the samples at Helmholtz-Zentrum Geesthacht (HZG) in Germany. All welds were made using the HZG Gantry System with a butt joint configuration, as shown in Fig. 1. An inert gas (Ar) injection system was used to protect the material during the process at temperatures above 535°C; these stainless steels react with the atmosphere. Welds were performed in load control mode with an integrated system to record process data such as penetration depth, rotational speed, torque, tool forces, and tool position over time.
The welds were made with a polycrystalline cubic boron nitride (PCBN) tool. The tool had a conical diameter of 25 mm, a conical pin of 9.2 mm diameter, and a length of 3.7 mm. The pin had a conical surface with negative recesses, which were in the form of a spiral concerning the tool's axis of symmetry.

Preliminary tests were performed to evaluate the behaviour of steels to the effects of different phenomena between the advancing side, where the direction of travel is the same as the direction of rotation of the tool, and the retreating side with these opposite directions in the FSW welding. For these tests, Caetano et al. [18] found the best parameter settings on the FSW similar welding for AISI 410S ferritic stainless steel. Thus, in the preliminary tests, the rotational speed was kept constant at 450 rpm, the welding speed at 1 mm/s and the tool inclination angle at 0°, varying the axial force between 25 kN and 30 kN and concerning to the position of the AISI 304L and AISI 410S steels between the advancing and retreating sides, as shown in Table 2.

### Table 2. Parameters Test for Dissimilar FSW Butt Welding of AISI 410S/304L Steels.

<table>
<thead>
<tr>
<th>Test</th>
<th>Rotation Speed (rpm)</th>
<th>Axial Force (kN)</th>
<th>Advancing Side</th>
<th>Retreating Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>450</td>
<td>25</td>
<td>304L</td>
<td>410S</td>
</tr>
<tr>
<td>2</td>
<td>450</td>
<td>30</td>
<td>304L</td>
<td>410S</td>
</tr>
<tr>
<td>3</td>
<td>450</td>
<td>25</td>
<td>410S</td>
<td>304L</td>
</tr>
<tr>
<td>4</td>
<td>450</td>
<td>30</td>
<td>410S</td>
<td>304L</td>
</tr>
</tbody>
</table>

After choosing the appropriate steel for the FSW joint's advancing and retreating side, four welding conditions were analysed to evaluate the influence of process parameters on heat generation and defect formation. Under these conditions, the axial force was varied from 25 to 40 kN, maintaining the rotational speed at 450 rpm, the tool angle at 0°, and the welding speed at 1 mm/s, as shown in Table 3.

### Table 3

Welding Parameters for Dissimilar FSW Butt Welding of AISI 410S/304L Steels

<table>
<thead>
<tr>
<th>Condition</th>
<th>Rotation Speed (rpm)</th>
<th>Axial Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>450</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>450</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>450</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>450</td>
<td>40</td>
</tr>
</tbody>
</table>

These parameters were related to the heat input generated during FSW welding. Eq. 1 shows the equivalent heat input total required for the joint consolidation among the different ways to calculate the heat generated during the FSW process. The coefficient of friction of the material, the pressure exerted by the tool, the rotational speed, and the geometry of the tool used in welding are the inputs needed to determine that heat input. They are calculated according to the equation formulated by Deqing et al. [32]:

\[ \vec{E} = \pi \mu \cdot \vec{P} \cdot \vec{V} \cdot \frac{\vec{D} + \vec{d} + \vec{D} + \vec{d}}{45. (\vec{D} + \vec{d})} \]
Where $E_t$ is the equivalent total heat input (kJ/mm), $\mu$ is the coefficient of friction of the material, $P_s$ is the pressure exerted by the tool on the material (Pa), $V_r$ is the speed of rotation (rad/s), $D$ is the shoulder diameter and $d$ is the pin diameter (m). Another way to calculate the heat input to the FSW process is by using Eq. 2 to determine the equivalent heat input per unit length per second, proposed by Lienert et al. [33]:

$$E_{el} = \eta \cdot \frac{T \cdot V_r}{V_s}$$

Where $E_l$ is the heat input per unit length (kJ/mm), $\eta$ is the efficiency of the FSW process for steels, $T$ the Torque (Nm), $V_r$ the rotational speed (rad/s), and $V_s$ the welding speed (mm/s).

### 3. Results and Discussions

#### 3.1 Setting the joint configuration based on the position of the steel.

Due to the physical and chemical properties differences between AISI 410S and AISI 304L steels, preliminary testing was required to choose the most suitable steel for the FSW joint's advancing and retreating side. In previous work, Muthukumaran and Mukherjee [34] observed that metal flow in FSW welds is caused by metal extrusion around the tool pin and the frictional heat generated between the tool shoulder and the sample. Sinha et al. [35] showed that as the friction intensity between the tool shoulder and the workpiece is one of the main factors responsible for defect elimination. Thus, parameters such as axial force and speed of rotation directly affect this metallic flow.

In this study, such as thermal conductivity and elastic modulus are different between welded steels, an asymmetry in heat input, deformation, and flow of materials were observed between the advancing side and retreating side. Through the Fig. 2, it can be seen that in Tests 1 and 2, in which the AISI 410S ferritic stainless steel was placed on the retreating side, with the tool travel direction opposite to the tool rotation direction, a large production of flash was observed, which were more intense for Test 2, which was welded with greater axial force. However, in Tests 3 and 4, where AISI 304L austenitic stainless steel was placed on the retreating side, a better surface finish was found with a considerable decrease in flash production.

Analysing the cross-sectional macrographs of the dissimilar stainless steel welded joints produced by the FSW process, it is possible to observe that besides the higher flash production in Tests 1 and 2, the presence of voids and a smaller stir between the steels is noticeable. In the other tests, in which the AISI 410S ferritic stainless steel is positioned on the advancing side, the tool travel direction is the same direction of rotation and the highest temperatures are reached; the best results were achieved. The joint configuration of Test 3 and 4, which were welded with the low-strength metal on the advancing side, provided a more massive flow of elastoplastic material from the advancing side directed to the retreating side, generating more significant participation of the AISI 410S steel in the formation of the stir zone. This behaviour avoids the formation of voids and the consequent instabilities responsible for excessive flash production, as shown in Fig. 3.
Wang et al. [31], analysing welded dissimilar joints of AISI 304 austenitic stainless steel and low carbon steel by FSW process, also proved beneficial effects positioning the low-strength steel on the advancing side. In this joint configuration, the authors reached material flow sufficient to fill up the cavities and other defects, getting good results. Cruz da Silva et al. [36] simulating numerically the dissimilar welding between 304L and 410S stainless steel, found that when the AISI 304L stainless steel is placed on the advancing side, the viscosity profile is less homogeneous, which can be indicative of inefficient mixing. The authors also verified that a tendency of uniform movement was observed by inverting the positioning and placing the AISI 410S stainless steel on the advancing side. According to Jafarzadegan et al. [37], austenitic stainless steels have relatively high elevated temperature flow stress and low thermal diffusivity compared to carbon steels, compromising an adequate material flow when this steel is positioned on the advancing side in the FSW process.

Thus, based on these results, it was demonstrated that improvements in surface finish and elimination of voids in the stir zone were achieved when the AISI 410S ferritic stainless steel was placed on the advancing side, and the AISI 304L austenitic stainless steel was on the retreating side of the butt joint. After this set of experiments, four different conditions following the parameters indicated in Table 3 were additionally tested. These conditions were welded to evaluate further the interference of rotation speed, axial force, and torque on surface finish and defect formation.

### 3.2 Axial Force

The axial force considerably influences the distribution and flow of material along the welded joint and its participation in heat generation during welding. According to Kim et al. [38], an appropriate rotation and forward speed for each applied axial force results in defect-free welds. It is possible to observe through the analysis of the axial force over the welding time that significant interference was not observed after stabilisation, and its application in none of the welded conditions resulted in the instability of the process, as shown in Fig. 4. Kim et al. [38] reported in their study that the instability in the application of axial force results in a lack of forging necessary to ensure the consolidation of the welded joint and, consequently, leads to the formation of volumetric defects.

The four axial force curves over time initially displayed similar behaviour. During the initial stage of the process, a pressure gradient emerged along the penetration channel. This variation occurs due to the different levels of contact between the tool and the joint surface and, consequently, the area's variation at the force application. Increased pressure is counterbalanced by increased axial force. The pressure gradient decreases to a stable state after the tool reaches the desired penetration depth. After reaching equilibrium, any new sudden changes in the axial force versus time curve characterise a non-uniformity in applying force, compromising the material flow and resulting in defect formation. However, in the welded conditions tested in this study, after the equilibrium was established, no changes were observed in the application of axial force, resulting in adequate material flow, as observed by Caetano et al. [19] in similar welding of AISI 410S steel plates.

### 3.3 Torque

An analysis of the parameters for the dissimilar welding of AISI 410S/304L stainless steels by the FSW process shows that the torque exerted by the tool increases with increasing axial force. Figure 5 shows that
the torque for condition 4, with an axial force of 40 kN, is greater than that for condition 1, with an axial force of 25 kN. Therefore, the higher the force, the higher the tool pressure on the material, and the higher the torque required for tool rotation. In previous work, Buchibabu et al. [39] noted that in FSW welding, the torque is influenced by changes in axial force and increases with increasing welding speed for different rotational speeds. Rotational speed also causes torque changes due to the greater or lesser degree of plasticity of the base metal caused by changes in heat input. Thus, the rotational speed, the welding speed and the applied axial force determine factors for the torque evolution during the FSW process, as reported by Leitao et al. [40].

3.4 Heat Generation

The process parameters directly affect the heat input, which strongly influences the heating and cooling rates of the thermal cycle and, consequently, the resulting microstructure. However, the heat input calculated based on the process parameters corresponds to equivalent heat input and not precisely to the heat input produced during the process since there are losses that are not considered, being the main ones by conduction and convection in the weld region.

The rotational speed is the main parameter related to the friction force at the interface between the base metals and the tool. It is directly linked to heat generation during welding, as reported by Bilgin e Meran [10] and Lakshminarayanan and Balasubramanian [41]. Frictional coupling of the tool surface with the base metal governs the heating mechanism and tool rotation, thereby allowing the stirring and mixing of the material around the pin. Thus, the higher the rotational speed, the higher the process temperature, and this is due to increased friction heating, as proposed by Colegrove et al. [42], Shiri et al. [43], and Uday et al. [44].

The strong influence of the rotational speed on heat generation was observed among similar welds of AISI 410S ferritic stainless steel produced by FSW, as pointed out by Caetano et al. [19], which observed that the reduction in rotational speed from 800 to 450 rpm generates a drop-in equivalent heat input total and equivalent heat input per unit length around 0.4 kJ/mm, keeping the axial force constant. Observing the Fig. 6, for the FSW dissimilar welding between ferritic and austenitic stainless steels, when the constant rotational speed is maintained at 450 rpm and the axial force is changed from 25 kN to 40 kN, it can be inferred that the 5 kN force increase between conditions 1, 2, 3 and 4, also produce a more significant amount of heat in the process. Therefore, this increase in axial force will help raise the temperature and increase the material's softening degree. However, the axial force has less influence on the heat generation than other parameters, such as the rotation speed, due, among other factors, to its lower influence on the frictional heat generated during the FSW process.

3.5 Surface Finishing

In this work, surface analysis of the dissimilar joints for the AISI 410S/304L steels obtained by the FSW process shows that the flash produced is directly related to the axial force increase. As pointed out by Trueba et al. [45], increases in axial force cause an increase in heat input, thereby allowing higher FSW welding temperatures and causing a decrease in viscosity and displacement of a more considerable amount of material through the tool pin. However, as the material flow is enhanced, the plasticised material's contention by the shoulder of the tool becomes more difficult. When the metal's viscosity reaches such low values, which
are enough to allow the plasticised material displaced by the shoulder of the tool to flow out of the weld nugget, large flashes will be formed, as observed in Fig. 7.

Figure 7 shows in detail that the number of flashes increases as the axial force increases from 25 to 40 kN, and these flashes are more critical for the advancing than the retreating side. According to Bogaard et al. [46] and Mandal et al. [47], austenitic stainless steel has relatively low thermal diffusivity and high flow stress in elevated temperatures concerning ferritic stainless steel. Thus, as the axial force increases and the temperature rises, there is a greater material flow in the elastoplastic state of AISI 410S steel on the advancing side. Thus, due to the lack of tool shoulder restraint, more steel is available to escape around the tool, generating larger flashes in this region. According to the analysis of defects in FSW welds performed by Threadgill [48], flash production can occur either by high heat input or by instabilities in the application of axial force, generating an irregular flow of material with the formation of voids and loss of plasticised material.

In the evaluated conditions, no surface cavities were observed despite the presence of superficial depressions due to the intense pressure exerted by the tool shoulder on the welded material under conditions 3 and 4, which were welded with the highest axial forces. These surface cavities are associated with a lack of heat or excess heat in the material during the welding process. Even under conditions with lower axial force and, consequently, lower heat input, the amount of heat generated in the region near the tool and shoulder was sufficient to give the material a suitable viscosity and plasticity. Despite the presence of dissimilar alloys in the joint formation, there was uniformity in the surface finish with onion rings patterns being formed, a fact not always achieved in dissimilar joints, as shown by Shankar et al. [49] regarding FSW welding between Al and Cu and by Kasai et al. [50] on the FSW dissimilar joining between steel and magnesium.

### 3.6 Defect Analysis

The cross-sectional analysis of AISI 410S/304L stainless steel dissimilar joints produced by the FSW process is shown in Fig. 8. It was verified that the joints' consolidation without internal voids for Conditions 2, 3, and 4, welded with axial forces of 30, 35, and 40 kN, respectively. It shows that the material flow reached an adequate plasticisation state due to the intensity of heat obtained by combining the parameters used. However, for Condition 1, welded with an axial force of 25 kN, the presence of small voids in the stir zone in a region closer to the weld root was observed.

This behaviour was noted by Tongne et al. [51], who attributed it to a lower interaction between the tool and material due to the low axial force. Consequently, a reduction in frictional force and insufficient heat is observed, making it difficult to reach a plasticiser state suitable for material flow during the FSW process. Second, Doude et al. [52], these voids in the stir zone in regions close to the weld root, as noted in Condition 1, indicate using parameters below the recommended ideal set to consolidate a defect-free FSW joint. It is due to the low rotation speed combined with a low axial force. Therefore, the combination of rotation speed at 450 rpm, axial force at 25 kN, and welding speed at 1 mm/s was inadequate, with low quality to dissimilar FSW joints between AISI 410S and AISI 304L steels.

In welds analysed as the axial force increases under conditions 2, 3, and 4, it is possible to observe a more significant contact between the two steels in the stir zone, with the formation of larger inserts of AISI 304L
austenitic stainless steel towards AISI 410S ferritic stainless steel and from this to AISI 304L austenitic stainless steel. While for Condition 1, only two large inserts of AISI 304L steel and one of AISI 410S steel were observed in the formation of the contact region between the two steels, in the stir zone for Condition 4, three AISI 304L steel inserts and three AISI 410S steel inserts were observed in the contact region. Therefore, it is possible to observe that applying a more intense axial force strongly influences the contact zone between the two steels.

The macrographs' evaluation, along with the cross-section of the FSW welds, also showed an increase in flash production as the axial force increased. The flash formation is higher on the advancing side than on the retreating side, as observed between Condition 2 and Condition 4. Keeping the rotational speed at 450 rpm and increasing the axial force from 30 to 40 kN clearly observed the occurrence of such effects, as can be seen in Fig. 9. Da Silva et al. [53] proposed an empirical parameter (Y parameter) to correlate friction coefficient (µf), pressure (P) (or axial force) and rotation speed (ω) to the tendency to form flashes in FSW welds. According to the study, pressure is the most significant welding parameters responsible for flash generation. The results shown that a gradual increase in welding speed slightly decrease the Y parameter, reducing flash tendency. However, when rotation speed or pressure (axial force) raise, the Y parameter increase, leading to a more pronounced flash formation. This behaviour agrees with the results obtained in this study.

In both Condition 1 and Condition 2, welded with axial forces of 25 and 30 kN, respectively, root flaws were found, as can be seen in Fig. 10a. These defects are observed in a line relative to the interface between the two plates of the butt joints and a lack of cohesion between the two steels forming a discontinuity in the root of the joint. Edwards and Ramulu [54] reported that this defect is associated with insufficient tool penetration. However, as the axial force increases to 35 and 40 kN, the remaining line of the interface between the butt joint materials is still noticeable. Still, without evidence of joint root recess, as can be seen in Fig. 10b. Kumar and Kailas [55] studied the material flow in dissimilar joints of aluminium alloys welded by the FSW process. The authors have also observed the formation of this remnant line in the weld root. Their results show that an attenuation regarding the defect formation has occurred due to the displacement of the tool to the advancing side. According to the authors, this uncentered configuration of the butt joint has intensified the plastic deformation. However, the same study also showed that the presence of the remaining line does not change the material's mechanical strength properties.

Caetano et al. [19] observed different root flaw morphologies. They attributed this behaviour to the distinct mechanisms of forming these defects. This defect can be formed by excess or lack of axial force. When an excessive axial force is applied, the tool pin will greatly penetrate the plate. Thus, it will promote an excess heat generated at the bottom of the plate, leading to the welding between the plate and the counter plate, therefore affecting the material flow in this region. However, the root flaws observed in Conditions 1 and 2 can be formed due to a reduction in axial force. In this case, the defects are attributed to a lesser interaction between the tool and the material, consequently reducing frictional force and heat generation, both necessary to achieve a proper state of plasticisation of the material flow. This improper plasticisation hinders material movement around the tool. This behaviour makes it challenging to consolidate the stir zone during the FSW process.
The occurrence of root flaws due to high and low penetration demonstrates that the production of FSW joints without root failures must be accomplished not only with an increase or decrease in axial force but also with an appropriate balance between axial force and tool angle, which allows a greater immersion of the pin in the joint, as reported by Shultz et al. [56]. The correct balance between tool angle and axial force is a way to consolidate FSW joints without defects in the root. This behaviour can also be achieved with the proper balance between axial force and rotational speed without having to vary the tool's angle, as occurred in Condition 4. For this condition, although the remaining line refers to the interface between the different butt joint materials, no discontinuities that characterise the formation of a root defect were observed.

Among the welded conditions, the macroscopic analysis confirmed the presence of small voids in AISI 410S steel in a region close to the interface with AISI 304L steel and close to the joint's root in the stir zone of Condition 1, as shown in Fig. 11. This lack of fill or tunnel defect consists of the weld joint's internal regions without material, forming voids along the weld length. According to Mishra and Ma [9], this defect is caused by the lack of heat produced by cold parameters, such as low rotational speeds and low axial forces, which generate less friction or shorter tool time residence in the material. Kumar and Kailas [57] state that, in addition to low heat, the lack of tool shoulder pressure on the material also unsettles the flow, precluding it from filling the entire weld region.

Therefore, the analysis of the different welded conditions shows that it is possible to produce dissimilar joints between AISI 410S ferritic stainless steel and AISI 304L austenitic stainless steel by the FSW process with a good surface finish and no stir zone defects. This behaviour is possible using parameters that ensure a suitable heat intensity to plasticise the material flow, which can be obtained by increasing the axial force to around 40 kN at the constant rotational speed at 450 rpm because, despite flash production, condition 4 is free of voids and root recesses that characterise the formation of joint root flaws.

4. Conclusions

Based on the experimental results of the FSW process parameters and their implications on the formation of defects for dissimilar welding between AISI 410S ferritic stainless steel and AISI 304L austenitic stainless steel, it was possible to conclude that:

1. With the right combination of welding parameters, a dissimilar joint can be successfully welded between AISI 410S ferritic stainless steel and AISI 304L austenitic stainless steel, producing a stable and defect-free joint.
2. Due to the differences in the steels' physical and chemical properties and the different phenomena that occur on the advancing and retreating sides, when AISI 410S ferritic stainless steel is placed on the advancing side, flash production and voids in the stir zone are reduced.
3. By analyzing axial force over the welding time, it is possible to observe that in none of the welded conditions, significant fluctuation in applying axial force was observed, allowing the formation of the stir zone without defects in some conditions.
4. The torque exerted by the tool increases with increasing applied force because the more significant the friction resulting from the force application, the higher the tool pressure on the material, and the higher the torque required to consolidate the tool rotation.
5. Flash production increases with increasing axial force, and it is larger on the advancing side. In this region, higher temperatures are found, allowing more material to be elastoplastic. The lack of restraint by the tool shoulder of this larger amount of material generates larger flash production on the advancing side.

6. The dissimilar joints' production between the AISI 410S/304L stainless steels welded by the FSW process without root flaws was achieved, keeping the rotational speed at 450 rpm and increasing the axial force to 40 kN, consolidating an appropriate balance between rotation speed, axial force, and tool angle.

Declarations

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References

4. LIPPOLD JC, KOTECKI DJ (2005a) Welding metallurgy and weldability of stainless steels. Wiley, New Jersey, USA


9. MISHRA RS, MA ZY Friction stir welding and processing. Materials Science and Engineering: R:, Reports (2005) [s.l.], v. 50, n. 1–2, pp. 1–78, 31 ago


42. COLEGROVE PA, SHERCLIFF HR, ZETTLER R Model for predicting heat generation and temperature in friction stir welding from the material properties. Science and Technology of Welding and Joining, [s.l.], v. 12, n. 4, pp. 284–297, 1 maio 2007
43. SHIRI SG, Technology et al (2013) [s.l.], v. 29, n. 11, p. 1091–1095, 1
46. BOGAARD RH et al Thermophysical properties of stainless steels. Thermochimica Acta, [s.l.], v. 218, pp. 373–393, 3 maio 1993
Figures

Figure 1

Dissimilar butt joint configuration between AISI 410S and AISI 304L steels [18].

Figure 2
Surface finishing of dissimilar welding tests of AISI 410S/304L steels by FSW process.

**Figure 3**

Cross-section macrograph of AISI 410S/304L dissimilar welding tests performed by the FSW process.

![Cross-section macrograph of AISI 410S/304L dissimilar welding tests performed by the FSW process.](image)

**Figure 4**

Axial force (kN) over time (s) for different welding conditions.
Axial force variation during the AISI 410S/304L steels dissimilar welding by the FSW process.

Figure 5

Torque variation during the AISI 410S/304L steels dissimilar welding by the FSW process.
Figure 6

Equivalent heat input per unit length and total heat input were calculated for the different conditions of AISI 410S/304L steels, and dissimilar welding was performed by the FSW process.
Figure 7

The surface finish of dissimilar welding of AISI 410S/304L steels by FSW process as a function of rotational speed and axial force applied.
Figure 8

Transverse macrographs of the different dissimilar welding conditions of AISI 410S/304L stainless steels by the FSW process.
Figure 9

Micrograph of the tool/steel contact boundary. (a) Small flash production on the retreating side of Condition 2. (100x) (b) Larger flash on the advancing side of Condition 2 (100x). (c) Larger flash production on the retreating side of Condition 4 relative to Condition 2. (100x) and (d). Flash production on the advancing side of Condition 4 is larger than on the retreating side. (100x)
Figure 10

(a) Root flaws due to lack of penetration in Condition 2. (200x) (b) No root flaws in Condition 4 (200x).

Figure 11

Voids are present in the stir zone in a region near the root. (a) (100x) (b) (500x).