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Thermal induced residual stress and microstructural constituents of dissimilar S690QT high-strength steels and 316L austenitic stainless steel weld joints

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Abstract

The effect of thermal cycle on the residual stress, microstructural constituents, and alloying elements composition of dissimilar S690QT and 316L austenite stainless steel was studied. Finite element model (FEM) using ANSYS 19.1 software and an experimental investigation using gas metal arc welding (GMAW) process with fully austenite filler wire were applied to developed thermal cycle and evaluate residual stress in the heat-affected zone of both materials. The experimental data were recorded using a thermal-cycle sensor (TCS) and x-ray diffraction technique. A microstructural investigation was done using Scanning electron microscopy (SEM) and Energy-Dispersive x-ray Spectroscopy (EDS). The thermal cycle showed the maximum temperature ($T_{\text{max}}$) in the HAZ of 316L side ($850^\circ$C) at a distance of 7 mm away from the centreline of the weld compare to S690QT side. The magnitude of tensile residual stresses in the 316L side decreased as welding heat input increased. The maximum residual stresses were observed on the S690QT side (700 MPa). Microstructural investigations revealed the formation of Bainite, and some retained of austenite at the temperature of 800 $^\circ$C in the coarse grain heat-affected zone (CGHAZ) of S690QT. On 316L side, some grain boundary austenite (GBA), intragranular austenite (IGA), and carbides were observed in the CGHAZ. Compared to the initial microstructure of both materials, a slightly increase of Mn, Cr, and Si were observed at the respective values of 1.90%, 1.25%, and 0.40% on the S690QT side compared to the BM. For 316L side, it indicated an increase of Cr (26%), Mo (5.69%), and Ni (17%) in the alloying element composition compared to the BM. Applying 10 kJ cm$^{-1}$ of heat input produced an excellent mechanical property and reduced the formation of carbide, inter-granular corrosion in the microstructure of 316L side.

1. Introduction

Dissimilar welding in ferrous materials offer advantages, notably in optimizing the strength/weight ratio. Applications where dissimilar welding is used is diverse, remarkably in the field of piping systems, nuclear power plants, car manufacturing, cookware, food, and beverage equipment, etc [1–3].

High-strength steel (HSS) with low alloying carbon steel has an advantage in terms of tensile strength and elongation function of the area that it will be used. It is very important to know about the allowing element composition of the base materials that will be objected to the dissimilar welds [4–6]. S690QT steel has a peculiarity based on the production process, which combines hot-rolling with air-cooling and reheating above the transformation temperature and water quenching [7]. The consequence of welding HSS can be the result of strong hardening with total deformation, causing in a high energy absorption capacity [8]. The first area that is exposed to the higher temperature is the coarse grain heat affected zone (CGHAZ). By increasing heat input, it can develop hot crack; the consequence of developing from ductile to brittle morphology in the heat-affected...
zone (HAZ). On the other hand, the decrease of the heat input has a lot of consequences in the structure of the HAZ causing some cold cracking (hydrogen crack), lack of fusion, incomplete penetration, porosity, and reducing the strength of the welded joint [9–14]. One of the major issues when welding HSS is to control the influence of cooling rate on the microstructure constituents and mechanical properties.

With austenitic stainless steel, which is the leading group of stainless steel having the particularity of a wide range of applications. The content of chromium (>17%) and Nickel (>10%) improved structure stability and corrosion resistance [15–18]. It is non-magnetic material and can resist environmental corrosion and improved mechanical properties [19–21]. A higher coefficient of thermal expansion in austenitic stainless steel is responsible for thermal distortion when increasing heat input during welding [22–25]. Due to its good combination of strength, ductility, and corrosion resistance, this grade can be used in a wide range of applications [26]. The issue that can cause is the higher thermal coefficient expansion, which is responsible for distortion as a result of the relatively high heat input introduced during the welding process. The use of an appropriate filler metal (chemical composition and mechanical properties) and the control of heat input can produce good weldability of materials.

The dissimilar welding includes materials of different chemical, thermomechanical properties, which have different reactions during the operation [27–29]. Today, Welding Operations are diverse and are of paramount importance in the performance of a welded joints. Additional difficulties of welding dissimilar metals are the characteristics based on the non-linear change of properties because of the difference in values of thermal conductivities, electrochemical potential as well as the formation of intermetallic compounds [30]. It is recommended to pay attention to these specific domains such as the choice of the weld metal, the geometry of the weld joint, the heat input parameter, welding steep’. These procedures are carried by ensuring that the different materials are preheated or allowed in their ambient temperature state.

The results of the research developed by Tasalloti et al [31], which investigated the microstructure characterisation of dissimilar S960QC/UNSS32205 stainless steel. The results indicated the effect of increasing heat input, which had a beneficial effect on the structural integrity of the dissimilar welded joint. In their analysis, they did not perform a mechanical test to analyse the heat input effect in the mechanical properties of the welded joints.

To analyse residual stress in the weld joint of dissimilar pipe of Ferrite steel/austenitic stainless steel, Dean Deng et al [32] included cladding, buttering, and post-weld heat treatment (PWHT) in their experimental process. The authors observed the influence of the Cladding zone after PWHT on the residual stress of the welded joint. In this analysis, they were no microstructural characterisation in the HAZ, which could help explain in detail the microstructural phenomena occurring in the HAZ of dissimilar welded joints after PWHT.

In the same area, A Joseph et al [33] showed that when welding a dissimilar 2.25CrMo Ferritic /316L Stainless steel using Inconel – 82 buttering layer decreased residual stress in the HAZ. Another element that must be taken into consideration when welding dissimilar high strength and austenitic stainless steel is the evaluation of corrosion resistance in the welded joint. Cherish et al [34] applied the Potentiodynamic model to evaluate the corrosion resistance of the welded joint of dissimilar Monel 400/316L austenite stainless steel. Their results showed a higher corrosion resistance in the 316L austenite stainless steel side than on the Monel 400 side. The mechanical properties and microstructural characterisation of dissimilar stainless steel-carbon steel were analysed after heat treatment by Ramdan et al [24]. Based on the hardness test (Mechanical properties), Scanning Electron Microscope (SEM), and energy dispersive spectroscopy (EDS), the authors observed a sensitisation in the HAZ of stainless steel of all input variation compared to the carbon steel. The cause of the sensitisation in the stainless steel could be the formation of chromium carbide at the coarse grain HAZ [35].

In this work, dissimilar welding of high-strength steel (S690QT) and 316L austenite stainless steel were welded using gas metal arc welding (GMAW). The gas applied in the analysis was shielding gas 98% Ar + 2% CO2, and an automatic robot system welding equipment. The main objective of this work is to develop a good understanding between thermal cycle residual stress and the detailed analysis of microstructure and chemical composition when welding dissimilar S690QT/316L austenite stainless steel. The residual stress distribution is investigated using numerical and experimental methods. The microstructural characterisation in the heat-affected zone (HAZ) of the different samples is also analysed. Finally, a detailed analysis of chemical composition in the coarse grain heat-affected zone (CGHAZ) of welded joints is developed. The results from this analysis will help to proposed an optimum heat input which develops better mechanical properties and microstructural constituent in the HAZ of dissimilar S696QT/316L austenite stainless steel. The results are also useful for welding companies and material design laboratories.
2. Material and method

Two dissimilar plates of steel S690QT and 316L (X2CrNiMo17-12) plates each size 350 \( \times \) 200 \( \times \) 8 mm were butt joints using GMA welding. The samples were machined to have a V groove of 2 mm gap and an angle of 60°. The mechanical properties of that base material in Table 1 and the chemical composition of both base materials and filler wire are listed in Table 2. To determine a thermal-cycle during the welding processes a thermal cycle sensor (TCS) was installed behind the welding torch-alloying to record a cooling time during the solidification phase of the welded joints. Figure 1 shows a workstation composed of a power source, an automatic robot, a thermal cycle sensor, a workpiece, and data acquisition equipment. MAG welding robots name was an ABB IRC5 M2004.

The measurement location was given by the measurement range of TCS ranging from 600 to 1,350 °C which restrains its position. The conception of the device was made to minimize the effect of welding spatters on a thermal cycle of data analysis. The thermal cycles were recorded in S690QT and 316L sides at a distance of 7 mm away from the centreline of the weld. This is the distance to the fusion boundary (±0.1 mm from the fusion boundary). The thermal and stress analysis were conducted across the weld samples using ANSYS 19.1 software. The results of the thermomechanical analysis are shown by applying UY = 0. To ensure safe and reliable operations at critical temperatures, welded joints especially in the CGHAZ were examined. Scanning electron microscopy (SEM), and an energy dispersive spectroscopy (EDS) x-ray spectrum were applied using Hitachi SU3500 (Hitachi High-Technologies America, Chicago, IL, USA) equipment. SEM test includes the identification of microstructural constituents formed in the CGHAZ [31]. EDS analysis includes the alloying element composition in the CGHAZ. To performs the test, the specimens were etched on a 4% solution of HNO\(_3\) and ethanol to ensure any impurities were removed.

The finite element model with dimensions weld specimen of 150 \( \times \) 50 \( \times \) 8 and a 2 mm square gap is used (figures 2(a), (b)). The heat sources, temperature-dependent thermal properties, and heat loss due to the convection and radiation are taken into account and are applied on all surfaces of the plate except on the HAZ. The heat conduction equation for transient non-linear is giving as follows [7, 10, 11]:

\[
\lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{Q} = \rho c \frac{\partial T}{\partial t}
\]

(1)

Where \( T, \lambda, \dot{Q}, \rho, \) and \( c \) are respectively temperature distribution, thermal conductivity, internal heat generation, density, and specific heat.

The convection model is developed as follows (2):

\[
q_a = -h_s (T_s - T_a)
\]

(2)

With \( q_a \) the heat flux due to air cooling, \( h_s \) the heat transfer coefficient, \( T_s \) the ambient temperature (25 °C), and \( T_a \) the surface temperature of the welded joints. The convection is applied on all the surfaces of the plate except on the heat-affected area. The heat loss \( (\dot{q}_r) \) due to the radiation is considered using Stefan-Boltzmann law (3):

\[
\dot{q}_r = -\varepsilon \sigma (T_s^4 + 273)^4 - (T_a + 273)^4
\]

(3)

Where \( \varepsilon \) (0.8) is the emissivity, and \( \sigma \) is Stefan-Boltzmann constant.

The same mesh is used in both the thermal and stress analysis. The geometry has been divided into two parts with the following characteristics: The weld plate is made of two materials (S690QT and 316L), with a total of 148147, 30300 respective values of nodes and elements. The second part is that of the weld bead composed of 41055, 7800 respective nodes and elements giving a general total of 189202 and 38100 respectively nodes and elements. Figure 3(a) shows the thermal conductivity and the specific heat of stainless steel 316L as a function of the temperature distribution, values obtained in the literature [31]. Moreover, figures 3(b) and (c) respectively show JMat Software used to obtain the thermal conductivity and the specific heat as a function of the temperature of the high-strength steel S690QT and their values. This Software is used to obtain the remaining thermos-mechanical material properties. Table 1 shows the mechanical properties of the different base material.

| Table 1. Mechanical properties of S690QT (EN 10025-6) and 316L austenitic stainless steel. |
|-----------------------------------------------|
|        | S690QT | 316L | Filler wire |
| Yield strength (MPa) | 793 | 317 | 350 |
| Tensile strength (MPa) | 835 | 603 | 520 |
| Compression strength in x (MPa) | 55 | 65 | 38 |
| Elongation (%) | 16.3 | 56 | 30 |
| Hardness HV5 | 270 | 182 | — |
Table 2. Chemical composition of 316L (X2 CRNIMON22-5-3) and S690QT (EN 10025-4).

|   | C    | P    | S    | Mn  | Si   | Al   | Cr  | Ni  | Mo  | Nb  | V   |
|---|------|------|------|-----|------|------|-----|-----|-----|-----|-----|
| 316L | 0.018 | 0.038 | 0.036 | —   | —    | —    | 17.1| 10  | 2.04| —   | —   |
| 316L | 0.018 | 0.038 | 0.036 | —   | —    | —    | 17.0| 10  | 2.01| —   | —   |
| S690QT | 0.137 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | —   | —   | —   | —   |
| Filler | 0.015 | 1.70  | 0.016 | —   | —    | —    | —   | —   | —   | —   | —   |

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The process of numerical simulation presented in figure 4, starts with the design of the geometry of the two materials on SOLIDWORKS with the thermo mechanical characteristics of the respective materials. Later, this geometry was uploaded to ANSYS software (19.1, ANSYS, Inc., Canonsburg, PA, USA), and the process of meshing the materials was achieved. From the model, it is evident that the mesh lines are closer to the edges of the melting zone. Subsequently, the boundary conditions were defined according to thermal convection, radiation, and thermal conduction. The radiation was applied to the longitudinal ends of the two materials. At the same time, the same conditions were applied for the structural analysis of the welded joints (Stress analysis) thermal characteristics. The based materials were fixed to the workbench by mechanical supports to avoid the
movements during the welding and evaluation of mechanical properties. Subsequently, the problem was solved by the software, and the results generated were then analysed.

3. Results and discussion

3.1. Thermal cycle variations

Figure 5 shows a numerical and experimental comparison of thermal cycle of dissimilar S690QT/316L welded joints. The heat inputs applied to the investigation were 16, 10, and 7 kJ cm$^{-1}$. The first weld pass (10 kJ cm$^{-1}$) was constant for whole samples. A total of 1,590 measurement points were recorded for each numerical and experimental investigation it is important to note that the measurements were taken at a temperature $T_1$ and $T_2$ at a distance of 7 mm away from the centreline of the welded joints (See figure 1).

From figures 5(a), (b), it is found that when the heat input of 16 kJ cm$^{-1}$ was applied, the numerical results indicated the maximum calculated temperature in the S690QT steel and 316L austenite stainless steel were approximately 1,585°C ($T_1$) and 1,885°C ($T_2$). From the same figures, an experimental result shows the decrease in the maximum temperature on both sides of the welded joint. The temperatures of 1,300°C and 1,680°C respectively for S690QT and 316L austenite stainless steels. When the heat input of 10 kJ cm$^{-1}$ (figures 5(c), (d)) was applied, the numerical results showed a

![Figure 3](image-url)

Table 3. Welding parameters used for the weld samples: arc current ($I$), arc voltage ($U$), welding speed ($v$), wire feed speed (WFS), arc energy ($E$), heat input ($Q$), torch angle ($^\circ$C), and shielding gas.

| $I$ (A) | $U$ (V) | $v$ (m/min) | WFS (m/min) | $E$ (kJ m$^{-1}$) | $Q$ (kJ m$^{-1}$) | Torch angle ($^\circ$C) | Shielding gas | Flow rate |
|--------|--------|-------------|-------------|------------------|------------------|------------------------|---------------|----------|
| 215    | 29.8   | 0.30        | 0.28        | 0.17             | 0.16             | 15                     | 98% Ar + 2% CO$_2$ | 151 min$^{-1}$ |
| 211    | 25.3   | 0.40        | 0.40        | 0.11             | 0.10             | 15                     | 151 min$^{-1}$ |
| 206    | 25.5   | 0.60        | 0.55        | 0.09             | 0.07             | 15                     | 151 min$^{-1}$ |
maximum calculated temperature in the S690QT steel and 316L austenite stainless steel of approximately 1,202 °C \( (T_1) \) and 1,490 °C \( (T_2) \).

The experimental measurements showed a recorded temperature of 1,000 °C \( (T_1) \) and 1,201 °C \( (T_2) \) respectively for S690QT steel and 316L austenite stainless steel. From different results (numerical and experimental), it was observed that there is a considerable gap between numerical and experimental data of thermal cycle. The average standard deviation between numerical and experimental was estimated at 10%. The highest temperature was observed in 316L austenite stainless steel. The outcome of the results was to reduce the gap between both methods. The results of thermal cycle of dissimilar S690QT/316L presented an efficiency of temperature distribution when the heat input of 10 kJ cm\(^{-1}\) is applied. The same values were recommended by Tassaloti et al [31], which had approximately the same thermal cycle values. The only difference was because they used the dissimilar S960QC/316L instead of S690QT/316L. In the fusion line (especially in the CGHAZ), they were a significant difference between both materials. A higher peak temperature was observed in the 316L part. This is always because of the amount of carbon, Mn, Ni, or Cr contains in the microstructural composition.

3.2. Stresses analysis

The model was based on single dissimilar materials with unit length \( L = 150 \) mm. A numerical study based on the Von Mises relation allowed us to evaluate the high-temperature effects due to the welding operations of the GMAW on the mechanical properties of the welded joints. The base metals to be welded were installed on 4 fixing points (figure 6(a)), during the welding operation, it was observed in figure 6(b), there is a distribution of the equivalent stress of the welding zone to the base metal. Figure 6(c) shows the normal distribution of stress along the X-axis where we can observe a high concentration of stress distribution in the 316L this is due to the low thermal conductivity of the materials, as well as that of figure 6(d), the transverse stress distribution along the Z-axis, and the same results are observed.

Stress analysis was applied using different heat input values (16, 10, and 8 kJ cm\(^{-1}\)). In the distribution of plastic stresses calculated according to the Von Mises criterion, it was observed that most of the stresses occurred...
in the weld metal region. The results showed the stress values taken from the weld metal vertical axis and weld start, middle, and endpoints. For the whole tested samples, the higher stress value is concentrated in the weld metal area and the fusion line between the weld metal and the coarse grain heat-affected zone. By comparing ANSYS modelling with an experimental analysis based on the heat input variations, a different result was obtained. It was found that with the increase of heat input, the heat-affected zone of S690QT also increased, causing an increase of stress in the HAZ. At the end of the welding process, the residual plastic strain increased in the area. The total strain increased following the increase in the melting temperature. On the 316L side, there were no major changes in the length of the HAZ. The total strain was increased slightly. An increase of elastic stresses during the welding process was noticed (figure 7). After the welding process (cooling temperature), it is observed that the elastic stresses were replaced by the equivalent stress. The major changes were observed when heat input of 16 kJ cm\(^{-1}\) was applied. The maximum equivalent stress was 700 MPa during welding, and 500 MPa after welding (S690QT). For the 316L side, the maximum equivalent stress was 400 MPa during welding and 300 MPa after welding (figures 7(a), (a1)). By applying the heat input of 10 kJ cm\(^{-1}\), the equivalent stress value was decreased on the S690QT side. The measured value was 400 MPa during welding and 375 MPa after welding process. For the 316L side, the measured value was 250 MPa during welding and 195 MPa after welding (figures 7(b), (b1)). The heat input of 8 kJ cm\(^{-1}\) developed the equivalent stress of 450 MPa (S90QT) during
welding process and 390 MPa after welding. The equivalent stress measured for 316L was 250 MPa during welding and 192 MPa after welding processes (Figures (c), (c1)). The results showed that a higher stress concentration was observed in the fusion line between the weld metal and base materials. The measurements were taken from the starting area, in the middle, and at the end of the welded area. It is important to note that when the heat input is lower, the maximum temperature developed in the melting area decreased. The decrease of melting temperature caused a reduction of permanent residual stress in the HAZ after welding.

3.3. Microstructure constituents of S690QT

SEM micrograph pictures were analysed on both sides of the welded joints. The typical microstructural constituent of S690QT is the composition mainly of bainite and martensite. To analyse the microstructural constituent in the CGHAZ of the different welded samples, the measurements were taken in the CGHAZ. Figure 8 shows the SEM images in the CGHAZ of the S690QT side using 3 different heat input values (16, 10, and 7 kJ cm⁻¹). Figure 8(a) presented the microstructural constituent composed of tempered martensite some trace of carbide, bainite, and retained of austenite at the maximum temperature of 720 °C. The heat input used for the sample was 16 kJ cm⁻¹. The bainitic transformation occurs at a higher temperature compared to the martensitic transformation. When applied the heat input of 10 kJ cm⁻¹ (figure 8(b)), a large transforming grain broke down to developed fine grains at a temperature of around 680 °C. The microstructural constituent in the CGHAZ was the composition of more bainite and some trace of martensite. By decreasing the heat input (10 kJ cm⁻¹), the decrease of carbide contains in the microstructure of CGHAZ was observed. The same results were reported in another study, which were analysed dissimilar high strength and ultra-high-strength steel [3]. The microstructure in that zone was changed depending on the previous austenite grain size. Figure 8(c), which used the heat input of 7 kJ/cm had in the microstructure the composition of mainly tempered martensite and some
retained austenite. It can be noticed also the presence of bainite formation in the microstructure. The result of combining heat input and microstructural constituent leads to having an approximate heat input value that will produce an appropriate microstructural constituent in the CGHAZ.

The alloying element composition in the CGHAZ of the S690QT side was evaluated. Using the heat input of $10 \text{ kJ cm}^{-1}$, the EDS spectrum was performed which was much preferable to analyse. Figure 9 shows an SEM micrograph of sample 2 and EDS spectra from CGHAZ position near the fusion line between weld metal and base metal. Figure 9(b) indicated an increase of Mn (1.90%), Cr (1.25%), C (3.20%), and Si (0.40%). The increase of Mn than base metal developed brittle failure mainly in martensite microstructural constituents (tempered martensite). The increase of carbon (C) was observed when using the EDS spectrum to evaluate the alloying element composition. The main reason can be the equipment that was used to carry out the measurement and the preparation of the material. That is why in the analysis it is not important to discuss the increase of carbon compared to the base metal.

3.4. Microstructural constituent of 316L austenitic stainless steel
In the base metal composition of 316L, the microstructure is mainlly parallel lamella austenite and ferrite [35, 36]. Figure 10 shows an SEM micrograph of 316L austenite stainless-steel side of sample 1 (16 kJ cm$^{-1}$). Sample 1 was the most affected with a higher heat input value. The microstructure constituent of 316L austenite stainless steel reveals the apparition of carbide around the austenite grain. The increase of carbide formation in the CGHAZ of 316L occurs also because of the permanent homogeneous structure in terms of chromium diffusion in the microstructure constitution. In the same microstructure, the appearance of ferrite constituents across the fusion line (fusion between weld metal and CGHAZ). According to the slow cooling time recorder when welding
sample 1, it was observed that the appearance of grain boundary austenite (GBA) and some intergranular austenite in the microstructural constituent of CGHAZ. Similar results have been reported for gas metal arc welding welded austenitic and ferrite stainless steel plate [37, 38].

EDS analyses presented in figure 11 evaluated the alloying element composition in some areas of the CGHAZ. The idea was to control the stability of Cr, Mo, and Ni in the alloying element composition of 316L austenite stainless steel. The results show an increase of Cr, Mo, and Ni of respectively 26%, 5.69%, and 17% more than the initial value. The cause could be the increase of cooling time which is subject to the resistance to solidification cracking as well as improving the ductility and fracture toughness of the weld [18]. The evaluation of carbon content C was excluded from the analysis. Figure 11 confirmed the important amount of carbide formation in the microstructure due to the higher heat input value applied for sample 1 and intergranular corrosion as well. It can be seen in the figure the way the amount of Cr, Mo, and Ni increased when they were measured. The results of increasing the amount of Cr, Mo, and Ni have been confirmed in many cases [29], and they were also some restrictions by others [39, 40].

4. Conclusions

The current study investigated the 3D non-linear (ANSYS 19.1) thermal cycle and residual stress with the finite element method using dissimilar welded joints of S690QT and 316L austenite stainless steels. An experimental analysis of thermal cycle and residual stress using a thermal cycle sensor (TCS). Microstructural constituents and characterisation of the chemical composition of both materials under the influence of heat inputs were analysed in detail using SEM/EDS images. Three heat inputs values were applied (16, 10, and 7 kJ cm⁻¹) and the analysis identified the following aspects:
Figure 9. SEM micrograph of sample 1 (S690QT) and EDS spectra from CGHAZ position near the fusion line, indicating chemical composition of different alloying elements.

Figure 10. SEM micrograph of 316L austenitic stainless-steel side of sample 1 (16 kJ cm$^{-1}$) indicating the microstructural constituents in the CGHAZ: (a) SEM micrograph using 100 $\mu$m of the resolution, (b) different morphologies of austenite formation namely, grain boundary austenite (GBA) and intragranular austenite (IGA) are indicated in the figure.
The different results of thermal cycle (numerical and experimental) showed a considerable gap and was estimated at around 10%. The maximum temperature was observed in the HAZ of 316L side. This temperature difference is made possible by the existing difference in thermal conductivity of both materials.

The maximum residual stress was obtained when the heat input of 16 kJ cm\(^{-1}\) (700 MPa) was applied in the HAZ of S690QT side after welding. On the 316L side, the maximum residual stress was around 400 MPa. The decrease of melting temperature caused the reduction of residual stress in both sides of HAZ after welding.

The results of welding dissimilar S690QT/316L using GMAW with the heat input of 10 kJ cm\(^{-1}\) produced an excellent mechanical property, reduced the carbide, and inter-granular corrosion formation in the microstructure.

When heat input of 16 kJ cm\(^{-1}\) was applied, the microstructural constituent of S690QT was mainly the composition of some carbide clusters, tempered martensite, and bainite. In the CGHAZ of 316L side, the microstructural constituent was the composition of the morphology of austenite formations, which were dominated by some grain boundary austenite (GBA), intragranular austenite (IGA), and some carbides.

The alloying elements composition in the CGHAZ of S690QT indicated an increase of Mn (1.90%), Cr (1.25%), Si (0.40%) more than the base metal (BM) composition. On the 316L side, the results showed a significant increase of Cr, Mo, and Ni of respectively 26, 5.69, and 17% more than the composition of the BM.

The appearance of carbide in the microstructure of 316L can be justified by the heat input applied which can lead to the formation of intergranular corrosion in the microstructure.

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Conflict of interest

None.

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References

[1] Mvola B, Kah P, Martikainen I and Suoranta R 2016 Dissimilar high-strength steels: Fusion-welded joints, mismatches, and challenges Reviews on Advanced Materials Science 44 146–59
[2] Ranjanbodeh E, Serajzadeh S and Kokabi A 2011 Effect of welding parameters on residual stresses in a dissimilar joint of stainless steel to carbon steel Journal of Material Science 46 3225–32
[3] Bayock N, Kah P, Layus P and Karkhin V 2019 Numerical and experimental investigation of the heat input effect on the mechanical properties and microstructure of dissimilar weld joints of 690-MPa QT and TMCP steels Metals 9 1–20
[4] Zhang Y, Shi G, Sun R, Gou K, Zhang C and Wang Q 2019 Effect of Si content on the microstructure and the impact properties in the coarse-grained heat-affected zone (CGHAZ) of typical weathering steel Mater. Sci. Eng. 762 1–10
[5] Das R, Bhattacharjee K and Rao S 2017 Welding heat transfer analysis using element free Galerkin method Advanced Material Research 410 298–301
[6] Little G and Kamtekar A G 1998 The effect of thermal properties and weld efficiency and transient temperatures during welding Comput. Struct. 68 157–65
[7] Bayock N, Kah P, Salminen A, Mvola B and Yang X 2020 Feasibility study of welding dissimilar advanced and ultra high-strength steels Reviews on Advanced Materials Science 59 57–66
[8] Panciakiewicz K, Hucko P, Turniadowicz M and Świerczynska A 2020 Laser dissimilar welding of AISI 430F and AISI 304 stainless steels Materials 13 1–15
[9] Zhou M, Xu G, Hu H, Yuan Q and Tian J 2017 The effect of large stress on bainitic transformation at different temperatures Steel Res. Int. 88 1–7
[10] Goldak J, Chakravarti C and Bibby M 1984 A new finite element model for welding heat sources Metallurgy transition B 15B 299–305
[11] Karkhin V, Vesselin M and Petrov P 2016 Principles of welding (St Petersburg: Saint Petersburg Polytechnic University)
[12] Kiyoshima S, Deng D and Ogawa K 2009 Influences of heat source model on welding residual stress and distortion of multi-pass J-groove joints Computers Material Science 46 987–95
[13] Alkhiami S, Dabiri M, Piili H and Bjork T 2021 Effect of manufacturing parameters and mechanical post-processing on stainless steel 316 processed by laser powder bed fusion Mater. Sci. Eng. A 802 140660
[14] Rottger A, Boes J, Theisen W, Thiele M, Eisen C, Edelmann A and Hellmann R 2020 Microstructure and mechanical properties of 316L austenite stainless steel processed by different SLM device Int. J. Adv. Manuf. Technol. 108 789–83
[15] Świerczynska A, Fidyrdysh D, Landowski M, Rogalski G and Labanowski J 2020 Hydrogen embrittlement of X2CRNiMoCuN25-6-2 super duplex stainless steel welded joints under cathodic protection Construction Building Materials 238 117697
[16] Varbai B and Maljinger K 2019 Optimal stitching sequence for austenite to ferrite ratio evaluation of two lean duplex stainless steel weldments Measurement 147 106832
[17] Ouali N, Khenfer K, Belkessa B, Fajout J, Cheniti B, Idir B and Branchu S 2019 Effect of heat input on the mechanical properties, residual stress, and corrosion resistance of UNS 32101 lean duplex stainless steel weld joints Journal of Material Engineering Performance 28 4252–64
[18] Daha G, Nassef I, Abdallah P and Abousseda H 2012 Three-dimensional thermal finite element modelling for keyhole plasma arc welding of 2025 duplex stainless steel plates International Journal of Engineering and Technology 2 720–8
[19] Sadeghan M, Shanmani M, Shafiei A, Branislav H and Milani D 2014 Effect of heat on microstructure and mechanical properties of dissimilar joints between super duplex stainless steel and high strength low alloy steel Material Design 60 678–84
[20] Parvathavarthini N, Dayal R, Hhattak H, Shankar V and Shannmugum V 2006 Sensitisation behaviour of modified 316N and 316L stainless steel weld metals after complex annealing and stress relieving cycles J. Nucl. Mater. 355 68–82
[21] Palanichamy P, Vasudevan M and Jayakumar T 2009 Measurement of residual stresses in austenitic stainless steel weld joints using ultrasonic technique Science Technoloby Weld Joint 14 166–71
[22] Demmque R 2018 Evaluation of the thermal cycle on the characteristics of welded joints through the variation of the heat input of the austenitic AISI 316L steels by the GMAW process Science and Technology of Materials 30 51–9
[23] Radek D, Kariem A, Nesarv O, Wirawan F, Suratman B, Widayanto B and Wirawan R 2019 Mechanical properties and microstructure at stainless steel HAZ from dissimilar metal welding after heat treatment processes IOP Conf. Series: Materials Science and Engineering 553 012034
[24] Ramdan R D, Koswara A L, Surasno, Wirawan R, Widayanto B and Suratman R 2018 Metallurgy and mechanical properties variation with heat input, during dissimilar metal welding between stainless and carbon steel IOP Conf. Series: Materials Science and Engineering 308 012056
[25] Marques J, Ramasamy A, Batista C, Nobre P and Loureiro A 2015 Effect of heat treatment on microstructure and residual stress fields of a weld multimaterial austenitic steel-clad J. Mater. Process. Technol. 222 52–60
[26] Farzanek K, Khashayar R, Heidardarzadeh A and Reza T 2021 Effect of hydrogen on the tensile behavior of austenitic stainless steels 316L produced by laser- powder bed fusion Metals 11 1–12
[27] Kurt B 2007 The interface morphology of diffusion bonded dissimilar stainless steel and medium carbon steel couples Journal Material Processing Technology 190 138–41
[28] Shamsul B 2013 Mechanical properties of dissimilar welds between stainless steel and mild steel Advanced Materials Research 795 74–7
[29] Jun-Hyoung K, Amanov A, Myoung-Sung K, Hak-Doo K, Young-Sik P and Yoon-Suk C 2016 Microstructural characterization and mechanical properties of stainless steel inlay welded dissimilar materials Mater. Sci. Forum 879 932–7
[30] Shamsolhodaei A, Oliveira J, Schell N, Maawad E, Panton B and Zhou Y 2020 Controlling intermetallic compounds formation during laser welding of NITI to 316 stainless steel Intermetallics 116 106656
[31] Tasalloti H, Kah P and Martikainen Y 2017 Effect of heat input on dissimilar welds of ultra high-strength steel and duplex stainless steel: microstructural and compositional analysis Material and Characterization 123 29–41
[32] Deng D, Ogawa K, Kiyoshima S, Yanagida N and Saito K 2009 Prediction of residual stresses in a dissimilar metal welded pipe with considering cladding, buttering and post-weld heat treatment Comput. Mater. Sci. 47 398–408
[33] Joseph A, Sanjai K, Rai R, Jayakumar T and Murugan N 2005 Evaluation of residual stresses in dissimilar weld joints International Journal of Pressure Vessel and Pipe 5 82
[34] Cherish M, Karthikeyan R and Vicent S 2017 A study on corrosion resistance of dissimilar welds between Monel 400 and 316L austenitic stainless steel IOP Conf. Series: Materials Science and Engineering 346 012025
[35] Fernanda S, Wagner A, Monteiro S, Candido V and Alisson Clay R 2020 Mechanical properties and microstructural characterization of a novel 316L austenitic stainless steel coating on A516 Grade 70 carbon steel weld Journal of Materials Research and Technology 9 636–40
[36] Mani C, Karthikeyan R and Vincent S 2018 A study on corrosion resistance of dissimilar welds between Monel 400 and 316L austenitic steel IOP Conf. Series: Materials Science and Engineering 346 012025
[37] Şenol M and Cam G 2020 Microstructural and mechanical characterization of gas metal arc welded AISI 430 ferritic stainless steel joints Proc. of 4th Int. Conf. on Engineering Technology and Innovation (ICEIT2020) (November 4–8) (Skopje, N. Macedonia) 11–9
[38] Serindag H T and Cam G 2021 Microstructure and mechanical properties of gas metal arc welded AISI 430/AISI 304 dissimilar stainless steels butt joints Journal of Physics: Conference Series 1777 012047
[39] Jafarzadegan M, Feng H, Abdollah-Zadeh A, Saeid T, Shen J and Assadi H 2012 Microstructural characterisation in dissimilar friction stir welding between 304 stainless steel and st37 steel Materials Characterisation 74 28–41
[40] Schino A D and Kenny J M 2003 Grain refinement strengthening of a micro–crystalline high nitrogen austenitic stainless steel Material Letter 57 1830–4