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Regression Modelling of the Tensile Characteristics of 304l and 316l Stainless Steel Welded Joints

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Abstract

In the present work, plates made from 316L and 304L stainless steels (SS) were joined using gas tungsten arc welding (GTAW) to form similar and dissimilar welded joints. The welding process were conducted using ER308L filler rods and constant welding parameters, typically, welding voltage, welding current, and welding speed. Regression modelling was used to corelate the tensile characteristics of the 316L and 314L similar and dissimilar welded SS joints with or without elevated temperature. The results revealed that regression models for ultimate tensile strength (UTS), yield strength (YS) and ductility (elongation, E%) exhibited R-square values of 0.95, 0.91 and 0.74, respectively. The developed regression models can roughly predict the tensile characteristics of similar and dissimilar 304L and 316L SS welded joints.

Key words: Stainless Steels, Gas Tungsten Arc Welding (GTAW), Tensile Characteristics, Regression Modelling, Elevated Temperatures.

1. Introduction

Stainless steel (SS) is a steel alloy that consist of 10.5% or more of Cr and more than 50% of Fe. Stainless steels (SSs) alloys can be classified according to their microstructure into three main types, namely, austenitic, ferritic, and martensitic SSs. Austenitic stainless steel (ASS) contains a maximum of 0.15% C, a minimum of 16% Cr, and sufficient Ni and/or Mn to retain an austenitic structure at all temperatures from the cryogenic temperature to the melting point of the alloy [1-3]. ASS induces great combination of mechanical characteristics, good formability, good toughness, and weldability. Typical applications for ASS include cooking utensils, chemical and pharmaceutical equipment, pipework in the food industry, storage vessels, pipes and tanks for corrosive liquids [4].

Gas tungsten arc welding (GTAW) or tungsten inert gas (TIG) is an inert gas shielded arc welding process using a non-consumable electrode [5]. The arc is created by the transfer of current through a conductive ionized inert gas. This gas provides the protection from exposure to atmospheric contamination of the electrode, molten weld pool and solidifying weld metal. The GTAW process can be apply using metal rods with or without adding filler metal. It is used to join nearly all metals and alloys in a wide variety of thicknesses [6].

Regression modelling was used extensively to predict the characteristics of welded joints [7-12]. For instance, *Hamid* and *Farhad* [7] used regression modelling to predict the welding defects and bead shape factor. The results revealed that the developed models are quite accurate in predicting the actual welding process in terms of the weld quality indices. The model can be used to adjust the input parameters in such a way that the desired bead geometry is obtained while the welding defects are minimized. *Boriwal* et al. [8] investigated the effect of the input process parameters on the strength of the ASS welded joint of dissimilar material. Tensile strength is predicted through the developed model, which was validated by test, and percentage error for both responses was quiet less. *Anand* et al. [9] used multiple regression analysis (MRA) to predict the weld strength of copper-to-copper joints produced by ultrasonic metal welding process. The process parameters of the models include weld pressure, weld time and amplitude of vibration, whereas the output parameter is weld strength. Correlation coefficient is used to find out the adequacy of these models for predicting the weld strength. *Rajmohan* el al. [11] used regression modeling to predict the tensile strength and hardness of friction stir welded aluminum alloys. The results showed that predicted values by regression modeling have been found close to the experimental values. *Joseph* and *Martins* [12] used experimental methods to obtain the Bead Height (BH), Ultimate Tensile Strength (UTS) and Brinell Hardness Number (BHN) of mild steel welded joints. Regression analysis method was applied to predict the corresponding values of the BH, UTS, and BHN. The results showed that the regression analysis method predicted the properties with a good accuracy.

According to the literature review, it can be concluded that there is a shortage in the investigations regarding the modelling of the mechanical characteristics of SS welded joints to predict their behavior at elevated temperatures. Therefore, the present investigation aims to use regression modelling to develop formula which are capable to predict the tensile characteristics of 316L and 304L stainless steel similar and dissimilar welded joints.

2. Experimental Procedures

In the present investigation, the 316L and 304L SS were used as base materials. The 316L has a chemical composition (wt.-%) of 17.54% Cr, 2.05% Mn, 11.89% Ni, 1.02% Si, 0.026% C, 2.25% Mo, 0.018% S, 0.045% P, and 65.161% Fe. The 304L has a chemical composition (wt.-%) of 10.65% Ni, 18.91% Cr, 0.028% C, 2.01% Mn, 1.1% Si, 0.03% S, 0.04% P, and 67.232% Fe. The joint has a single V-groove with an angle of 60^{o} see Fig. (1). The ER308L rods were used as a filler material. The rods have diameter of 2.4 mm. The rods have chemical compositions (wt.-%) of 19.8% Cr, 1.9% Mn, 9.8% Ni, 0.4% Si, 0.02% C, 0.05% N, 0.15% Cu, and 68.24% Fe.

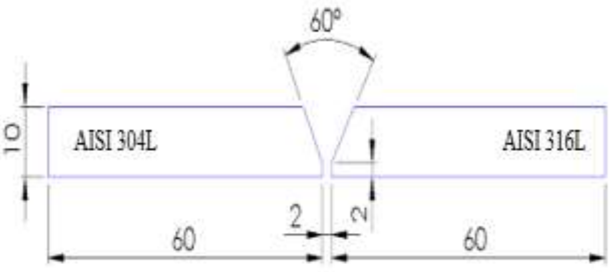


Fig. (1) The joint configurations (dimensions are in mm)

The welding of the 316L and 304L plates [(60 mm(width) x600 mm(length) x10 mm (thickness)] were performed using manual GTAW process. The welding process was conducted using four passes at constant voltage of 38 V, current of 210 A, and speed of 11 mm/sec. Several types of joints, typically, 304L-304L and 316L-316L similar joints as well as 316L-304L dissimilar joints. After welding, the joints were machined to form tensile specimens with the dimensions shown in Fig. 2. The specimen was designed so that minimum diameter is located at the center of welded region. The tensile tests of the 304L-304L and 316L-316L similar and 316L-304L dissimilar welded joints were performed at ambient, 100, 200 and 300 ^{o}C temperatures. At each temperature, three tensile specimens were tested. The tensile tests were carried out using *Shimadzu* universal testing machine having a maximum capacity of 200 kN. The elevated temperatures were performed using an electrical resistance furnace installed in the universal testing machine as shown in Fig. 3. Before tensile testing, the specimen was heated to the desired temperature for about 30 min to ensure that the temperature distribution in the heating chamber is homogenous. The tensile tests were conducted at constant crosshead speed of 1 mm/min. From each test, three replicates were performed and the ultimate tensile strength (UTS), yield strength (YS) and elongation (%) were determined.

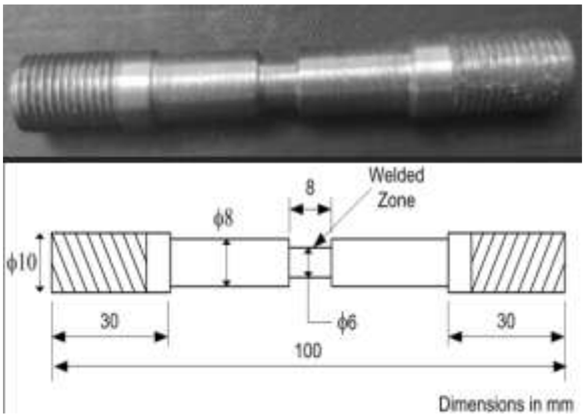


Fig. (2) Photograph and schematic illustration of the welded tensile specimens


(a) (b)

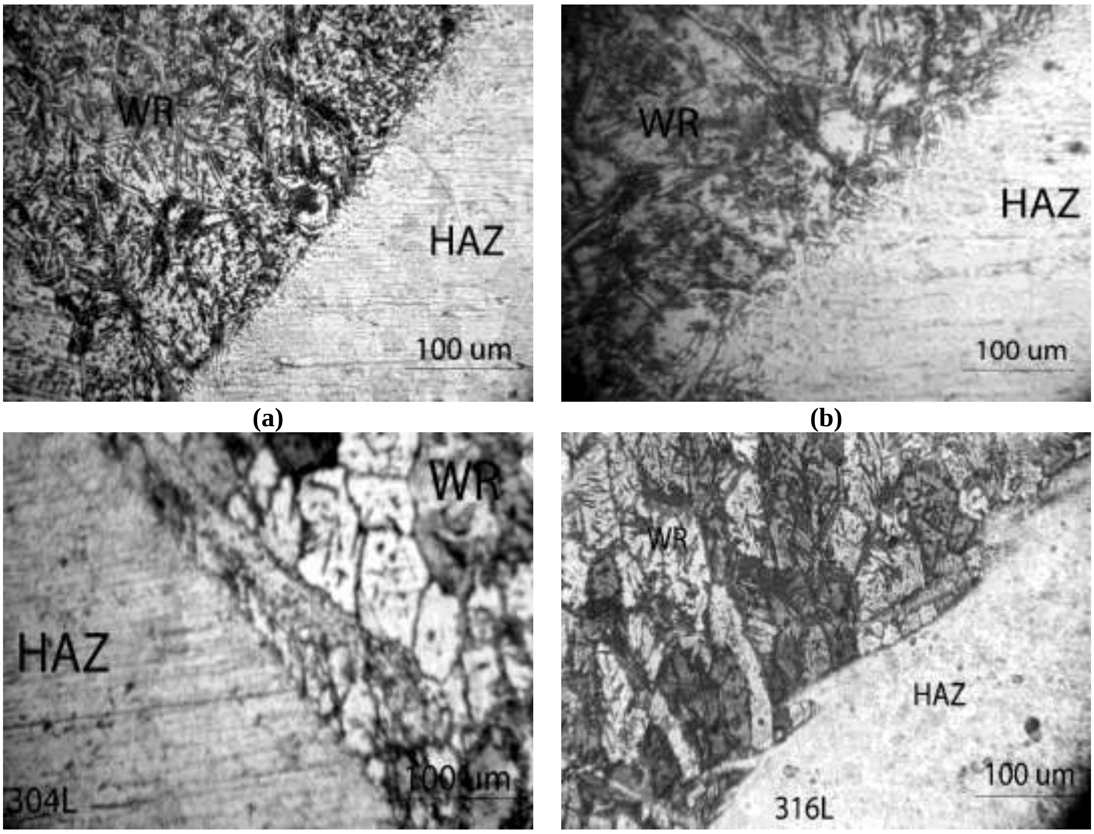
Fig. (3) Photographs show the experimental setup (a) and the furnace (b) used for tensile testing at elevated temperature.

The regression modelling was used to correlate the tensile characteristics of the welded joints with temperature. The calculations were carried out using TableCurve 2D automatic curve fitting software. TableCurve 2D has a wide database of linear as well as nonlinear regression formulas. It is used widely for modelling of complex research problems. The welded specimens were subjected to microstructural investigations using optical metallurgical microscope. They were ground and polished using the standard metallographic preparation techniques. After that, the specimens were etched in a solution consists of 33% HNO_3, 33% HCl acids and 34% H_2O for 1 minute.

3. Results and Discussion

3.1. Microstructure of the welded joints

Figures 4 shows typical microstructure of the welded region (WR) for the 304L and 316L similar and dissimilar joints. The results showed that, at the heat affected zone (HAZ), the grains were slightly bigger than the grains of the base metal. The grain growth occurred in the HAZ may attribute to the thermal cycles occurred during GTAW. The closer to the fusion zone boundary, the higher the peak temperature as well as the longer time the alloy remains at higher temperatures [13,14]. The weld metal showed needle-like growth. The growth is oriented in the direction of the weld. The 304L weld metal showed larger size of grains as compared with the 316L weld metal. The microstructure of the 304L-316L dissimilar welded region showed the nearly equiaxed austenite grains with discontinuous network of pedate (γ)-ferrite structure in the austenitic matrix. For the dissimilar 304L-316L, the fusion zone showed microstructures which is a combination of lacy ferritic and acicular growth of ferrite in the austenitic matrix.



(a) **(b)**

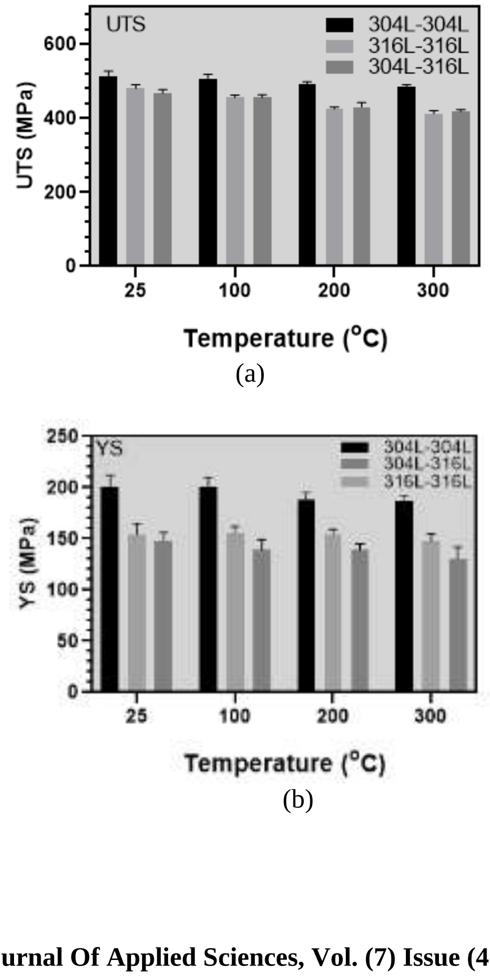
(c) **(d)**

Fig. (4) Microstructure of the welded regions for the (a) 316L, (b) 304L and (c,d) 304L-316L SS; (c) represents 304L and (d) 316L (d) sides, respectively

3.2. Tensile properties of welded joints

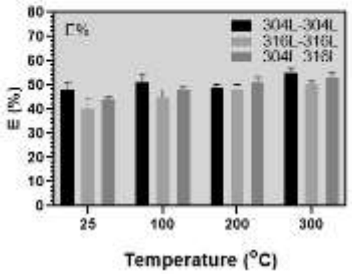
At ambient temperature, the average UTS for the 316L and 304L SS base-metals were about 482±6 MPa and 498±5 MPa, respectively. While the average YS of the 316L and 304L SS base-metals were about 170±6 MPa and 200±8 MPa, respectively. The variation of the UTS and YS of the SS weldments with temperature is illustrated in Figure 5. At ambient temperature, the average UTS of the similar 304L SS welded joints was about 512±15 MPa, which is higher than the 304L base metal. However, the average UTS of the 316L SS welded joints was about (480±10 MPa), which is practically the same as for the 316L base metal. The 304L-316L SS weldments shows UTS of about 467+10 MPa, which is slightly lower than the two base metals. The 304L SS weldments exhibited average YS of about 212±12 MPa, which is higher than the average YS of the base metal.

However, the 316L SS weldments exhibited average YS of about 165±11 MPa, which is lower than the average YS of the base metal. Similarly, the 304L-316L SS weldments shows YS of about 156±8 MPa, which is slightly lower than the two base metals. The ambient E% for the 316L and 304L SS base-metals were about 41±2% and 45±3%, respectively. While the similar 304L and 316L SS weldments exhibited average E%, at ambient temperature, of about 48±5% and 40±4%, respectively. The 304L-316L dissimilar weldments exhibited average E% of about 44±3%.



(a)

(b)



(c)

Fig. (5) Variation of the tensile properties of the SS welded joints with temperature: (a) UTS, (b) YS and (c) E%.

3.3. Regression modelling of tensile properties of welded joints

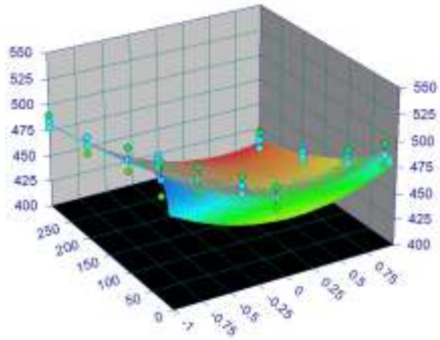
The regression modelling formulas that were developed to corelate the UTS, YS and E% with temperature for the 304L and 316L SS similar and dissimilar welded joints are listed in formulas (1), (2) and (3), respectively, as follows:

$$UTS = 387.06697 + 10.226118 \cdot x + 50.636182 \cdot \ln(t) + 28.125 \cdot x^2 - 7.936671 \cdot (\ln(t))^2 - 8.0422447 \cdot x \cdot \ln(t) \quad \ldots(1)$$

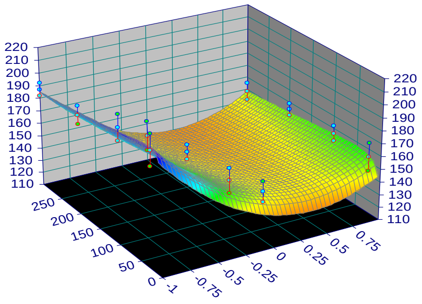
$$YS = 103.34022 - 0.8932135 \cdot x + 22.673831 \cdot \ln(t) + 34.375 \cdot x^2 - 3.0835331 \cdot (\ln(t))^2 + 1.9449157 \cdot x \cdot \ln(t) \ldots \quad \ldots(2)$$

$$E\% = 47.392877 - 7.0714948 \cdot x - 3.2111861 \cdot \ln(t) - 0.75 \cdot x^2 + 0.72561362 \cdot (\ln(t))^2 + 0.97130763 \cdot x \cdot \ln(t) \quad \ldots(3)$$

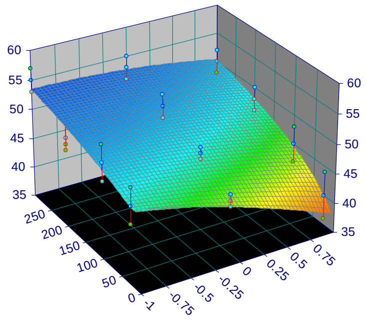
Where: *t* is the temperature in Celsius, *x* is the weld type and its equal to -1 for AISI 304L, +1 for AISI 316L, and 0 for AISI 316L-304L. Formulas (1), (2) and (3) have R-Square value of about 0.95, 0.91 and 0.74, respectively. Figure 6 shows the variation of the tensile properties with temperature and the joint type. The small circles shown in Fig. 6 represents the experimental data, while the 3D surface represents the predicted results



(a)



(b)



(c)

Fig. (6) Regression modelling results for the (a) UTS, (b) YS and (c) E% for 304L, 316L and 304L-316L SS welded joints; the y-axis is the temperature in Celsius and the x-axis is joint type (-1 for 304L, +1 for 316L, and 0 for 316L-304L).

4. Conclusion

Based on the results, the following conclusions can be drawn:

1. Increasing the temperature reduces the UTS and YS, but increases E%, of the 304L, 316L and 304L-316L SS welded joints.
2. At ambient and elevated temperatures, the 304L SS welded joints exhibited better mechanical characteristics when compared with the 316L and 304L-316L SS welded joints.
3. The developed non-linear regression models can predict the tensile characteristics, at several temperatures up to 300 °C, of the 304L, 316L and 304L-316L SS welded joints with an acceptable accuracy. The regression models for UTS, YS and E% showed R-square values of 0.95, 0.91 and 0.74, respectively.

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