International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 11 Issue 1 ǁ January 2023 ǁ PP. 20-27

Effect of Welding Process on the Hardness Characteristics of Welded and Heat-treated 304L: Statistical Approach

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Abstract
The present study is to investigate the effect of welding processes on the hardness characteristics of welded and heat-treated 304L. The Austenitic Stainless Steel (Type 3040L) plate was cut to the desired Square-Butt joint specification, and wire brushed before and after welding using the different stated welding processes. Thereafter, samples of the welded specimen were heat treated at 700 ^{0}C (973K). The as-received, welded, and heat-treated samples were purged to prevent atmospheric contamination using argon gas. Hardness testing of the weld zone and edge zone was done using a digital Vicker Hardness (Hv) tester. Results showed hardest weld produced without heat treatment and within the core area was made using MMA with a hardness value of 190.5, and values for TIG and MIG are 173.4 and 174.4 correspondingly. After heat treatment, the values obtained with MMA and MIG both decreased to 150.5 each, while the value for TIG increased to 178.4. In particular, alloy 304L welded by MMA has a hardness value of 187.2 before the application of the heat treatment operation to the edge area, and 176.8 and 169.8 for the sample welded with TIG and MIG processes respectively. Typically, following heat treatment, the hardness value obtained using MMA is 164.4, while the hardness values realized using the MMA and TIG are 162.6 and 132.3 respectively. Evidently, the hardness values decreased in the edge area. The implemented software and generated models have a performance accuracy of 95.04%, which is very good.

Keywords:_Hardness Characteristics, AISI 304L, Manual Metal Arc Welding (MMA), Tungsten Inert Gas Welding (TIG), Metal Inert Gas Welding (MIG)_

Date of Submission: 24-12-2022 Date of acceptance: 04-01-2023

I. INTRODUCTION

Alloy 304L is an austenitic stainless steel with excellent strength and good ductility at high temperatures[1]. Its typical applications include aero-engine hot section components, miscellaneous hardware, tooling, and liquid rocket components involving cryogenic temperature [2-3] Alloy 304L can be joined using a variety of welding processes.The type 304L Austenitic Stainless Steel (ASS) is a versatile material whose engineering properties have been well-acknowledged in various applications requiring welding [4]. It is the most weldable of all the 304 series [5], and this has underscored its successful use as structural steel parts in chemical, mechanical, automobile, metallurgical and nuclear, and cryogenic applications such as the handling of Liquefied Natural Gases (LNG). Welding as a local melting-freezing process is known to create thermal gradients in the metal around the weld [6-7]

The alloy 304 stainless steel is extensively used in industry due to its superior low-temperature toughness and corrosion resistance. The use of stainless steel has been growing steadily and new areas of application, often in demanding service environments, are constantly being developed. The serviceability of stainless steel in many of these applications is determined by the material properties of the steel and how they perform when exposed to different service environments. So, it is used in manufacturing of food processing equipment, chemical containers and heat exchangers. The type 304L austenitic stainless steel is an extra low-carbon variation of type 304 with a 0.03% maximum carbon content that eliminates carbide precipitation due to welding. As a result, it can be used in severe corrosive conditions.

Type 304L is generally considered to be the most common alloy of this stainless class. When a weld filler is a need, AWS E/ER 308, 308L, 304L, or 347 are most often specified. Stainless steels can be welded using several different processes such as shielded metal arc welding, gas tungsten arc welding, gas metal arc welding, etc. These steels are slightly more difficult to weld than mild carbon steels. The physical properties of stainless steel are different from those of mild steel and this makes it weld differently. These differences are lower melting temperature, lower coefficient of thermal conductivity, higher coefficient of thermal expansion, and higher electrical resistance, corrosion resistance, and high strength.

The properties are not the same for all stainless steels, but they are similar for those having the same microstructure. Regarding this, stainless steels from the same metallurgical class have similar welding characteristics and are grouped according to the metallurgical structure with respect to composition and welding. Shielded metal arc welding (SMAW) - also known as "stick welding", uses an electrode that has flux, the protectant for the puddle, around it. The electrode holder holds the electrode as it slowly melts away. Slag protects the weld puddle from atmospheric contamination. The SMAW is the arc welding process known to even a layman and can be considered a roadside welding process [8-9]

Shielded metal arc welding is widely used because of its versatility, portability, and comparatively simple and inexpensive equipment. In addition, it does not require auxiliary gas shielding or granular flux [10]. Welders can use the shielded metal arc welding process for making welds in any position they can reach with an electrode. Electrodes can be bent so they can be used to weld blind areas. Long leads can be used to weld in many locations at great distances from the power source. Shielded metal arc welding can be used in the field because the equipment is relatively light and portable. This process is also less sensitive to wind and draft than gas-shielded arc welding processes. Shielded metal arc welding can be used to weld a wide variety of metal thicknesses. This process is more useful than other welding processes for welding complex structural assemblies because it is easier to use in difficult locations and for multi-position welding [11]. Shielded metal arc welding is also a popular process for pipe welding because it can create weld joints with high quality and strength. However, the shielded metal arc welding process has several limitations. Operator duty cycle and overall deposition rates for covered electrodes are usually less than those of a continuous electrode process. This is because electrodes have a fixed length and welding must stop after each electrode has been consumed to discard the remaining portion of the used electrode clamped into the holder and reapply another. Another limitation is that the slag must be removed from the weld after every pass. Finally, the shielded metal arc welding process cannot be used to weld some of the non-ferrous metals [12].

Gas tungsten arc welding (GTAW) - also known as TIG (tungsten, inert gas), uses a non-consumable tungsten electrode to produce the weld [10]. The weld area is protected from atmospheric contamination by an inert shielding gas such as Argon or Helium [8, 13].

GTAW welding generally produces welds far superior to those produced by metallic arc welding electrodes. Especially useful for welding aluminium, and it is quite useful for welding many other types of metals as well. The GTAW process is most effective for joining metals up to 1/8 inch thick, although you can use it to weld thicker material with appropriate preheating.

Gas tungsten arc welding has many advantages over most other types of welding processes. The outstanding features are the following: It makes high-quality welds in almost all metals; there is no slag, so very little, if any, post-weld cleaning is required; there is no filler metal carried across the arc, so there is little or no spatter; welding can be performed in all positions; filler metal is not always required; pulsing may be used to reduce the heat input; the arc and weld pool are clearly visible to the welder; because the filler metal does not cross the arc, the amount added is not dependent on the weld current level [8, 11].

The limitations of the gas tungsten arc welding process include the following: The welding speed is relatively slow, the electrode is easily contaminated, it is not very efficient for welding thick sections because deposition rates are low, the arc requires protection from wind drafts that can blow the stream of shielding gas away from the arc.

Gas metal arc welding (GMAW) - commonly termed MIG (metal, inert gas), uses a wire-feeding gun that feeds wire at an adjustable speed and flows an argon-based shielding gas or a mix of argon and carbon-dioxide (CO2) over the weld puddle to protect it from atmospheric contamination [14-15]. The gas metal-arc welding process (GMAW) has revolutionized arc welding. In this process, a consumable electrode (in the form of wire) is fed from a spool through the torch (welding gun) at a pre-set controlled speed [16-17]. As the wire passes through the contact tube of the gun, it picks up the welding current. The consumable wire electrode serves two functions: it maintains the arc and provides filler metal to the joint. The method of delivery of the filler metal allows GMAW welding to be basically a one-handed operation which does not require the same degree of skill as Gas Tungsten Arc Welding (GTAW) [8,15]. The gas metal arc welding process has many advantages over most of the other arc welding processes. These advantages make the process particularly well suited to high production and automated welding applications. Gas metal arc welding has been the process choice for robotic applications. Some of the advantages to gas metal arc welding are the following: It is the only consumable electrode process that can be used to weld most all commercial metals and alloys, ferrous and non-ferrous; a relatively small amount of spatter is produced; the filler metal is fed continuously, so very little time is spent on changing electrodes; it can be used easily in all positions; the arc and weld pool are clearly visible; little or no slag is produced, resulting in minimal post weld cleaning; a relatively small diameter electrode is used, which gives high current densities; a high percentage of the filler metal is deposited in the weld; travel speeds and deposition rates are significantly higher than those obtained with shielded metal arc welding and gas tungsten arc welding; lightweight power sources can be hand carried to the job site; when spray transfer is used, deeper penetration is possible than with shielded metal arc welding, which may permit the use of smaller size fillet welds for equivalent strengths [8,18].

Some limitations of the process are the following: The equipment is more complex, more costly, and less portable than that for shielded metal arc welding; the arc requires protection from wind drafts, which can blow the stream of shielding gas away from the arc; the larger welding gun must be close to the work to ensure proper shielding, and it is less adaptable to welding in difficult to reach areas than shielded metal arc welding; relatively high levels of radiated heat and arc intensity can result in operator resistance to the process.

The present work is aimed at examining the effect of various welding processes (GTAW, GMAW, and SMAW) on the hardness characteristics of welded and heat-treated 304L.

Specification Table

Subject area	Engineering & Technology
Compound	AISI 304L stainless steel plate, shielding gas (Argon gas), bare wire electrode (ER 309), Tungsten electrode, filler rod (ER 309 stainless steel), hand gloves, welding shield, stainless steel wire brush, Clamp and Tong
Data category	Vicker hardness measurement, Design expert softare
Data acquisition format	Tables, Software
Data type	Filtered, Raw, Analyzed
Procedure	An Austenitic Stainless Steel plate was cut to the desired Square-Butt joint specification according to the American Society for Testing and Materials (ASTM), 1990, and wire brushed before and after welding. Thereafter, samples of the welded specimen were heat treated for the purpose of stress relieving at 700 ^{0}C (973K).
Data accessibility	Manuscript

II. Experimental

2.1. Materials and methods

The materials used for the work are 70mm x 50mm x 3mm AISI 304L stainless steel plate, shielding gas (Argon gas), bare wire electrode (ER 309), Tungsten electrode, filler rod (ER 309 stainless steel), hand gloves, welding shield, stainless steel wire brush, Clamp and Tong.

The Austenitic Stainless Steel (Type 3040L) plate was cut to the desired Square-Butt joint specification according to the American Society for Testing and Materials [19], and wire brushed before and after welding using the different stated welding processes. Thereafter, samples of the welded specimen were heat treated for the purpose of stress relieving at 700 ^{0}C (973K). The as-received, welded and heat-treated samples were purged to prevent atmospheric contamination using Argon gas: an inert gas.

Hardness testing of weldments using a digital Vicker Hardness (Hv) tester was carried out. The hardness measurement was carried out in duplicate at two different locations for each specimen and the average values were calculated [20].

III. RESULT AND DISCUSSION

The hardness distribution in the different regions of the un-heat-treated and heat-treated samples are shown in Figures 1 and 2. The results showed that the hardness increased from the welded zone (WZ) also called the Core Area, heat affected zone (HAZ) also called the Edge Area to the parent metal (PM) or the Control for all the welding processes investigated.

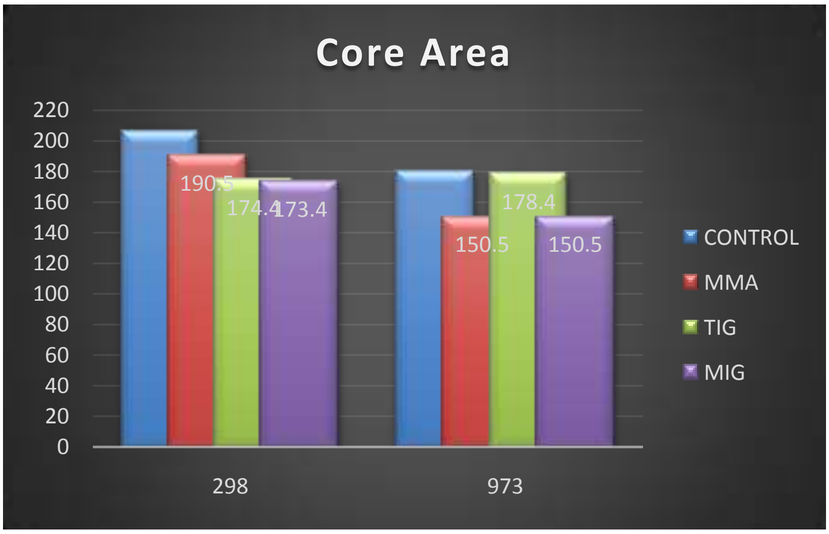

Figure 1: Hardness Distribution of the un-heat treated and heat-treated samples within the Core Area Using the Different Welding Processes

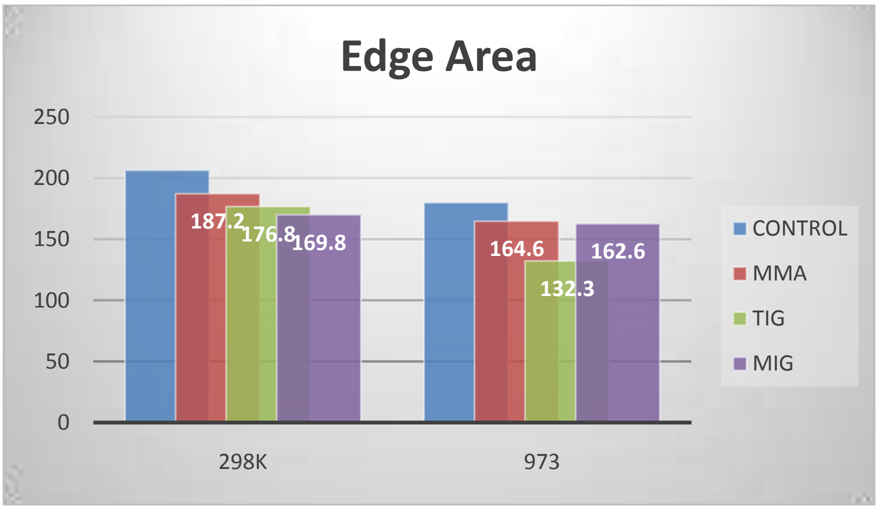

Figure 2: Hardness Distribution of the un-heat treated and heat-treated samples within the Edge Area Using the Different Welding Processes

It is observed that the different welding processes had a profound effect on the hardness characteristics of the AISI 304L. A cursory look at the results shown in Figures 1 and 2 above reveals that after welding the different samples using the different welding processes, without heat treating and within the core area, it was noticed that the weldment samples attained using MMA showed the highest hardness value of 190.5, followed by TIG with a hardness value of 174.4 while the hardness value obtained using the MIG is 173.4. Whereas after heat treatment, there was a conspicuous alteration in the hardness properties of the AISI 304L welded with the various welding processes. Typically, the hardness values achieved from using both MMA and MIG reduced to 150.5 each while the hardness value gotten from TIG got increased to 178.4 after heat treatment.

Similarly, there were variations in the hardness characteristics of the investigated alloy 304L joined with the different welding processes with respect to the edge area. Specifically, before the application of the heat treatment operation to the edge area, the hardness value of the AISI 304L welded using MMA is 187.2, and 176.8 for the sample welded with the TIG process while for the sample welded using MIG process, the value of the hardness is 169.8. However, after the application of the heat treatment operation, obvious changes occurred in the hardness characteristics of the AISI 304L welded with the various welding processes. Characteristically, the hardness figures realized from using MMA as a welding process are 164.4 and 132.3 for using the TIG welding process, while 162.6 is the hardness value obtained from using MIG as a welding process. Evidently, within the edge area, the hardness values decreased after heat treatment.

According to authors [21-22], the foregoing observations could be attributed to the differences in cooling rate across the samples. Generally, with the edge area, the cooling rate is slower in the HAZ due to the interaction between the PM and WZ. The slag coating in the MMA help makes it absorb more heat and hence, a slower cooling rate than in the TIG and MIG due to the presence of the slag. TIG responds to heat input more rapidly and therefore allows for deeper heat penetration than other methods, and consequently, possesses a faster cooling rate.

Also worthy of note is the fact that the MMA welding process deposits more carbon in the process due to flux coating. This suggests that there is a compositional variation which could be another factor responsible for the variation noticed in the hardness properties of alloy 304L.

It is also pertinent to state that the welded metal was observed to have the lowest hardness value compared to the control sample (parent/base metal). This observation, which concurs with [23], may be attributable to the loss of quenching components from the weld zone (WZ), their coarse structure [24], as well as grain growth [25]. Another explanation for the presence of coarse grain size in the welded zone (WZ) is the heat cycle, a low dislocation density, and precipitation dissolution [26].

3.1 Statistical Analysis of the Hardness Characteristics of Welded and Heat treated AISI 304L using RSM

Mathematical model of the effect of the welding process on the hardness characteristics of welded and heat-treated 304L as a function of the considered factors are expressed in the final equation in relation to both the coded and actual factors as shown below:

For the Final Equation in Terms of Coded Factors, Hardness value = +184.29 – 8.43A + 17.66B

Final Equation in Terms of Actual Factors, Hardness values = + 162.18570 – 0.024963 *Temperature + 0.182988 * Welding Process.

In terms of the coded variables, the model predicted the response the for each factor at different levels considered. The coded model showed the relative importance of the variables while the equation in terms of actual factors can be used to make predictions about the response for given levels of each factor.

From the analysis of variance, ANOVA, **(**Table 2) the Model F-value of 7.26 implies the model is significant. There is only a 3.32% chance that an F-value this large could occur due to noise.

P-value**s** less than 0.0500 indicate model terms are significant. In this case B is a significant model term. Values greater than 0.1000 indicate the model terms are not significant.

Adequate Precision describes the ratio of signal to noise. Usually, it is preferable to have a ratio of more than 4. Thus, the ratio of 6.982 attained from the study of the effect of the welding process on the hardness characteristics of welded and heat-treated alloy304Lsuggests the adequacy of the signal. Hence, the model is useful for navigating the design space.

More so, the results of Tables Table 1showed the effect of the welding process on the hardness characteristics of welded and heat-treated alloy 304L. The plot of the predicted versus actual hardness value **(**Figures 3) is a straight-line graph, depicting that the regression models is able to forecast the hardness value of the alloy under consideration within the operating conditions.

Table 1: Experimental Design Matrix for the RSM Results of the Effect of Welding Process on the Hardness Characteristics of Welded and Heat-treated 304L

Run	Factor 1 A: Temperature K	Factor 2 B: Welding Process #	Response 1 Hardness Value HV/0.2
1	298	304	206.4
2	973	111	150.5
3	298	141	174.4
4	298	131	173.4
5	973	304	197.9
6	973	141	178.4
7	298	111	190.5
8	973	131	150.5

It is pertinent to note that for the purpose of this research, the as received Austenitic Stainless Steel was coded as 304 according to AISI while the welding processes employed were coded according to EN 111 for Manual Metal Arc welding also called Shielded Metal Arc Welding (SMAW), 131 for Gas Metal Arc Welding (GMAW) GMIG, and 141 for Gas Tungsten Arc Welding (GTAW) or TIG.

Table 2: ANOVA for Linear model Obtained for the Hardness Value

Source	Sum of Squares	df	Mean Square	F-value	p-value

Model	2160.83	2	1080.42	7.26	0.0332	significant
A-Temperature	567.85	1	567.85	3.81	0.1082	
B-Welding Process	1592.99	1	1592.99	10.70	0.0222	
Residual	744.27	5	148.85			
Cor Total	2905.10	7				

Factor coding is **Coded**.
Sum of squares is **Type III - Partial**

The 3-D surface plots **(**Figure 4) clarifies that there is relation between the hardness value and the factors under investigation. The nature of the three-dimensional surface plots suggests that the welding process, temperature and the resulting hardness values do interact.

3.1.1 Comparative Analysis Between the Actual and Predicted Hardness Values

The comparison between the calculated (actual/experimental) hardness values and regression model based predicted hardness values are shown in **Table 3**. From the **Table 3**, it is observed that there were changes in the hardness values of the hardness characteristics of the welded and heat-treated alloy 304L due to the various welding processes and operating temperature. ThePercentage error is calculated as:

$$\text{Percentage error} = \frac{\text{Actual Value} - \text{Predicted Value}}{\text{Actual Value}} \times 100$$

A percentage very close to zero means we are approaching the targeted value which is good. It is always necessary to understand the causes of the error, such as whether it is due to the imprecision of the Design

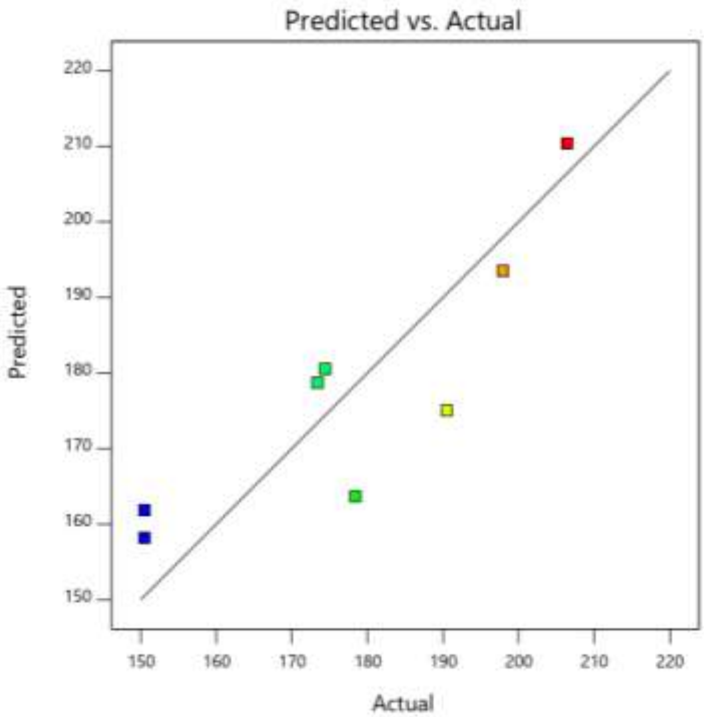

Figure 3: Plot of the predicted versus actual hardness value

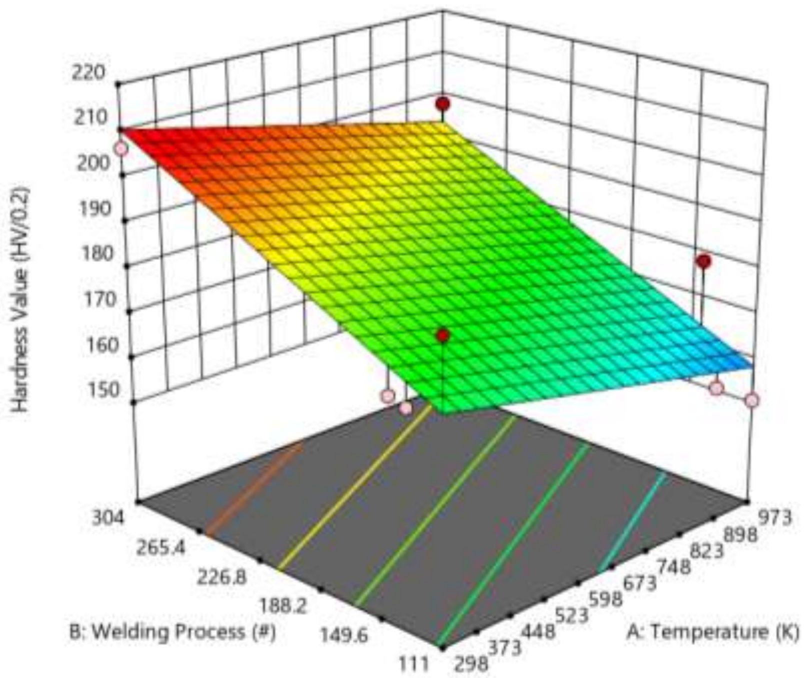

Figure 4: 3-D surface plots

Table 3: Showing theComparative Analysis Between the Actual and Predicted Hardness Values

Run Order	**Actual Value**	**Predicted Value**	**|Residual|**	$\frac{\text{\|Residual\|}}{\text{Actual Value}}$	**Percentage error (%)**
1	206.40	210.38	3.98	0.019	1.9
2	150.50	158.21	7.71	0.051	5.1
3	174.40	180.55	6.15	0.035	3.5
4	173.40	178.72	5.32	0.031	3.1
5	197.90	193.53	4.37	0.022	2.2
6	178.40	163.70	14.70	0.082	8.2
7	190.50	175.06	15.44	0.081	8.1
8	150.50	161.87	11.37	0.076	7.6

Expert software or irregularities with the welding processes and its associated operating conditions. Average percentage error (% error) is the summation of percentage error, divided by the total number n where n = 8

That is, Average percentage error = $\frac{\text{Summation of percentage error}}{n}$

Therefore, Average percentage error = $\frac{39.7\ \%}{8}$ = 4.96 %

Hence, the implemented software and the models generated have a performance accuracy of 95.04 % which is very satisfactory.

IV. CONCLUSION

In this study, three different welding processes (MMA, MIG and TIG) were used to weld alloy AISI 304L. The specimens were welded and heat treated at 700 ^{0}C. It was observed that both the welding processes and heat treatment temperature have significant influence on the hardness characteristics of the 304L Austenitic Stainless Steel. The hardness values decreased across the welding processes investigated after the application of the heat treatment operation. Also, variations in hardness characteristics of the steel were noticed in parent metal, core area and edge zone with respect to the employed welding process and temperature of heat treatment.

Specifically, in terms of hardness as a property and with respect to the core area, the optimal and best welding process that gave the best hardness value is TIG while MMA is best suited with respect to the edge zone.

ACKNOWLEDGEMENT

The authors, Ochuko Goodluck Utu (Principal Researcher) and Okiemute Dickson Ofuyekpone (Co-Researcher) gratefully acknowledge the financial support granted by the Tertiary Education Trust Fund (TETFund), Nigeria through the Institution Based Research (IBR) Interventions for the research.

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