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Effect of voltage variation on the properties of gas tungsten arc welded low carbon steel

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Abstract

This research was necessary as only limited work had been carried out on the effects of arc voltage on the mechanical properties of welded low-carbon steel using Gas Tungsten Arc Welding (GTAW). Even though it is pretty expensive compared to other welding types due to the required shielding gas, GTAW processes have the advantage of being automated with continuous feeding of the electrode into the weld and avoiding the production of fused flux or slag layer. It becomes imperative to determine the effect of welding parameters on the microstructure and mechanical properties of welded joints using GTAW at a fixed current (115A) but with varying voltage. The low carbon steel specimen employed has a thickness of 5 mm, while the electrode used was the E6013 electrode with a tungsten size of 2.4 mm and a filler rod size of 3.2 mm. The effects of voltage variations at different levels, specifically 200V, 205V, 210V, 215V, 220V, and 225V, on the microstructure and mechanical properties of GTAW weldments were investigated. Adjusting voltage levels while maintaining a constant current of 115A increased hardness values and decreased tensile strength and impact toughness compared to the unwelded sample. The increase in hardness of the welded steel can be attributed to the formation of a fine grain structure and intermetallic phase, as observed in the micrographs. Also, the ultimate tensile strength, ductility, and Young's modulus decrease as the voltage increases from 200V to 210V, followed by an increase as the voltage rises from 215V to 225V compared to the unwelded sample. The observed variances in the properties of the material were attributed to the high concentrations of sulfur (0.07%), manganese (1.48%), and phosphorus (0.22%) present in both the base metal and electrode utilized.

Keywords: Hardness; Low carbon steel; Microstructure; Tensile; Voltage; Welding

1. Introduction

Steel is widely used in several applications, including construction, infrastructure development (such as bridges), tool fabrication, equipment production, machinery assembly, shipbuilding, vehicle component manufacturing, and weapons production. Low-carbon steel is a metallic material characterized by its relatively low carbon content, often less than 0.25 weight percent, and the inclusion of various alloying elements [1]. Due to its relatively low carbon content, this type of steel is generally characterized by enhanced malleability compared to other steel varieties. Consequently, it can be shaped into thin layers, facilitating its application in various components such as automobile body panels. Additionally, it may be utilized as a low-carbon steel pipe, facilitating the transportation of multiple fluids [2]. In conventional practice, the assembly of mechanical components has commonly involved the utilization of fasteners, rivet joints, and similar methods. However, welding is frequently employed to expedite the process, reduce overall weight, and enhance the mechanical properties of the components [3]. A wide range of welding methods are currently obtainable, enabling the comprehensive utilization of welding as a fabrication method to join materials with distinct compositions, sizes, and shapes. The welding technique is considered vital due to its capacity to achieve high joint efficiency, simple setup, durability, flexibility, and potential to lower fabrication expenses [4]. The Gas Tungsten Arc Welding (GTAW), also known as the Tungsten Inert Gas (TIG) welding method, is crucial in numerous industrial applications. It is a viable method for welding both non-ferrous and ferrous materials. The weldability of different plate thicknesses is dependent on the amperage employed. The GTAW method is applicable for welding materials ranging from those with substantial thickness to those more delicate, resulting in superior-quality welds [5]. Welded joints are increasingly being utilized in essential parts where the consequences of failures are catastrophic. Therefore, there is a growing emphasis on inspection procedures and compliance with established standards. The welding process encompasses various factors, including but not limited to time, pulse frequency, temperature, power input, electrode, and welding speeds. These factors influence the ultimate characteristics of the weld metal [6]. The selection of appropriate welding parameters is crucial to ensure optimal weld quality for a specific operation. The strength of a welded joint is influenced by both metal composition and careful selection of optimal weld process parameters, as well as the shape of the weld bead. A high-quality welded joint is contingent upon appropriately controlling weld process parameters to attain the desired weld bead geometry [7]. Implementing a control system in arc welding can significantly reduce the reliance on subjective estimation commonly practiced by welders when determining the appropriate welding parameters for a specific operation [8]. Hence, it is imperative to conduct experimental research to obtain empirical data that can inform the design of a welding control system capable of providing optimal qualities [9]. This research investigated the effect of arc voltage on the microstructure and mechanical characteristics of TIG-welded joints of low-carbon steel. The objective of the experiment was to determine how mechanical properties of welded steel sample are affected by varying voltage at fixed current.

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Table 1: Average chemical composition of low carbon steel (wt. %)

Fe	C	Si	Mn	P	S	Cr	Ni	Cu
99.13	0.0640	0.0183	0.2808	>0.219	0.0739	0.280	0.0267	0.0341

Table 2: Chemical composition of E6013 electrode (wt. %)

C	Si	Mn	Cr	Ni	Mo	V	Cu	Fe
0.20	1.00	1.20	0.20	0.30	0.30	0.0267	0.08	96.72

2. Materials and methods

A hot-rolled low-carbon steel plate, 1400 mm x 200 mm x 5 mm, was obtained from Owode-Onirin in Lagos, Nigeria. The steel plate specimens were appropriately sectioned into the prescribed dimensions and prepared for the welding operation. E6013 electrodes with a tungsten size of 2.4 mm, filler rod size of 3.2 mm, torch cup size of 8m, and argon shield gas were selected for the GTAW. The welding process was conducted at an inclination of 45 degrees, with a constant welding current of 115A. On the other hand, the voltage was adjusted at different levels, specifically 200V, 205V, 210V, 215V, 220V, and 225V. The direct effect of voltage on heat input necessitated the choice, while the narrow range of voltage selected was because not many studies have been carried out on it in the literature. Each welding operation lasted for 20 minutes, completing one specimen. The specimens underwent surface preparation, subsequent metallographic examination, and various mechanical tests. Table 1 shows the results of the chemical composition of the low-carbon steel, while Table 2 shows the chemical composition of the E6013 electrode. From the chemical composition of the control sample, it is observed that the sulfur content (0.074 wt. %) is high compared to the maximum requirement in low-carbon steel, and this may have a considerable effect on the ultimate tensile strength, ductility, and hardness properties of the welded material. Various factors, including the carbon content and the inclusion of other elements such as sulfur, manganese, or phosphorus, influence the microstructures and mechanical properties of welded steel. Low-carbon steels, characterized by a carbon content of less than 0.25%, exhibit favorable welding capabilities due to their ability to be welded without the need for cautionary measures using a wide range of available welding methods. Carbon is the main element responsible for the hardening of steel. Consequently, the presence of carbon determines the level of hardness that the steel can withstand when subjected to high-voltage welding. The Carbon Equivalent (CE) of the steel sample was calculated based on the International Institute of Welding and was found to be 0.17085. The carbon equivalent is employed to evaluate the impact of various alloying elements present in steel on the weldability of such steel. This value indicates that the steel has good weldability, however, with moderately high hardness at the weld joint. The high hardness of the weld joint could be attributed to the electrode used, which has a high CE of 0.525.

2.1. Experimental procedure

Two test specimens were produced, each measuring 200 × 50 × 5 mm. Before the butt-welding process, the edges of the samples were meticulously prepared by grinding and cleaning them with an iron brush. This meticulous preparation was undertaken to ensure that the edges to be welded possessed smooth and clean surfaces. The two components were joined through welding to create a finalized test plate measuring 200 × 100 × 5 mm, including a weld running along its center, as depicted in Fig. 1. Alignment of the edges was ensured during the welding process.

Figure 1: Finished welded test plates with 200 × 100 × 5 mm dimensions.

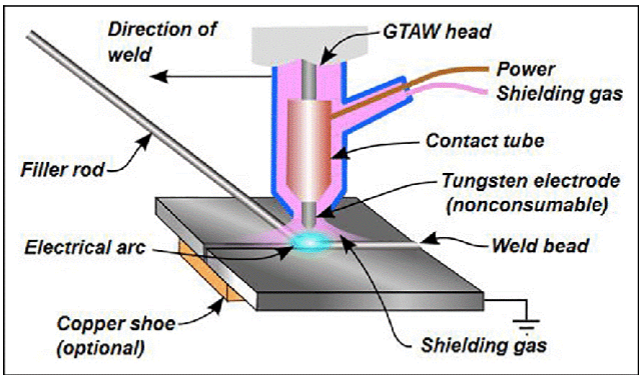

Figure 2: Illustration of Gas Tungsten Arc Welding Process [10].

2.2. Welding of the joints using the gas tungsten arc

A typical gas tungsten arc welding operation is shown in Fig. 2. Each pair of steel samples was aligned on an anvil using an angular Iron, and the welding was set up. The samples were welded using a voltage of 200V, 205V, 210V, 215V, 220V, and 225V with a fixed welding current of 115 Amperes. The welding voltage was varied using a dual-voltage device.

2.3. Hardness test

The hardness tests were performed using a Brinell Testing Machine, following the ASTM A370-14 standard. Before conducting the hardness tests, the surfaces of the samples were meticulously filed, ground, and polished to ensure that the diameter of the indentations was discernible, hence providing precise measurement. Throughout the experiment, a constant weight of 3000 kg was exerted by a hardened steel ball-shaped indenter measuring 10 mm in diameter. This load was applied to the smooth surface of every sample. The diameter of the retracted indenter was measured. The hardness tests were performed thrice, and the mean values were recorded. The experiments were also carried out within the fusion zone of the weld metal.

2.4. Tensile test

The tensile tests were conducted following the ASTM A370-15 standard. The experiment was conducted on a welded steel sample with a hydraulic tensile testing machine using a 24.7 × 4.24 × 4.67 mm machined specimen. Before the tests, the samples underwent machining processes on the lathe machine to achieve the required dimensions. Longitudinal tensile tests were carried out, in which the specimens were taken along the weld and consisted entirely of weld metal. The gauge length measurements and the cross-sectional area calculation perpendicular to the load direction were performed on the tensile test samples. The tensile test was conducted by subjecting the standard tensile samples to a continuous application of longitudinal or axial load at a specified extension rate until failure ensued. The applied tensile load and corresponding extension measurements were recorded during the experiment to calculate stress and strain values. The values for ultimate tensile strength and ductility were determined.

2.5. Impact test

Impact testing was conducted on V-notched weldments following the ASTM E23 standard. This experiment was conducted by utilizing the Avery-Dennison Impact-testing machine. Each experiment was performed three times, and the mean values were recorded. Longitudinal impact tests were carried out, in which the specimens were taken along the weld and consisted entirely of weld metal. The prepared specimen was positioned on the anvil with a V-notch gauge. The Pendulum was initially adjusted to a specified energy level of 298.642 J and, after that, released to impact and fracture the specimen that had been carefully positioned. The reading of the energy impacted was recorded. This test measures the toughness of the specimen, which is its ability to absorb energy. The Avery Impact Testing Machine comprises a pendulum of 875 mm in length. This pendulum carries the striking head, also known as the hammer, and is connected to the drive arm. The drive arm is responsible for pushing the pointer along the scale. The information and scale measure the amount of energy absorbed during the release of the pendulum from the brake lever as it strikes the Charpy test specimen that is securely positioned on the anvil along the vertical axis of the notch.

2.6. Metallography and preparation of samples

The microstructural analysis was conducted utilizing an optical microscope to enhance the visibility of the characteristics of the weld metals under investigation. The magnitude or dimensions of these features can be assessed and quantified, enabling a comparison with established standards of acceptability. Failure analysis frequently employs these investigations to identify the material's composition and ascertain whether it underwent appropriate processing treatments.

The microstructure test was carried out on various welded fusion zones of the metal using the optical microscope to observe the microstructure characteristics of the welded joints. Before the metallography, the samples were ground and polished until a mirror-like surface was achieved. To reveal the crystal structure of the specimen, a suitable etchant called Nital (2%) was employed.

3. Results and discussion

3.1. Microstructural analysis

Fig. 3 and Fig. 4 show the optical micrographs of the unwelded steel sample. The observed microstructure of the sheet metal (base metal) exhibits a characteristic composition consisting primarily of ferrite, with localized patches of pearlite (αFe+Fe_3C) observed at the grain boundaries, edges, and corners of the grain structure. Additionally, a decrease in the size of the pearlitic grains is observed from the base metal to the Heat Affected Zone (HAZ), resulting in a more dispersed distribution, as depicted in Fig. 5.

Figure 5 depicts the microstructures observed in the various zones. The composition of the steel includes ferrite and bands of pearlite. It is widely acknowledged that several solid-state phase transformations, including but not limited to recrystallization, grain growth, phase transitions, annealing, and tempering, take place within the Heat Affected Zone (HAZ) of steel welds. The observed trend in Fig. 5 indicates a general increase in the size of grains near the HAZ as the welding voltage increased from 200V to 225V. The observed phenomenon can be attributed to the rise in

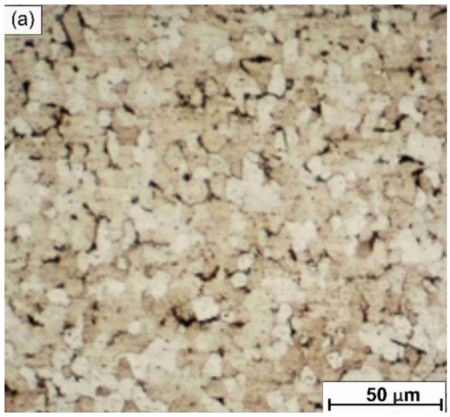

Figure 3: Optical micrographs of the unwelded low-carbon steel sample at lower magnification

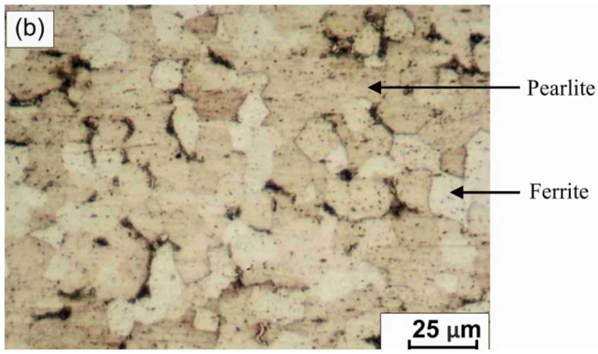

Figure 4: Optical micrographs of the unwelded low-carbon steel sample at higher magnification

the heat input, wherein the heat input (H) exhibits a direct correlation with both the voltage (V) and current (I) while demonstrating an inverse relationship with the welding speed (v). The electrical current utilized in this investigation is maintained at a constant value of 115A. The primary cause for the observed rise in hardness value can be attributed to the process of grain structure recrystallization. During welding, the temperature at the weld center increases, forming a finer grain structure. Furthermore, the primary cause for the observed increase in hardness can be attributed to the existence of hard and brittle intermetallic compounds. The heat input can induce changes in the mechanical properties of the welded region.

The grains close to the fusion zone are generally smaller and behave as the origin of nucleation. As solidification proceeds, the grains tend to have columnar growth. The fusion zone has a uniform microstructure, as shown in Fig. 6, and the heat of the welding process influences the grain size of the welded region. Also, the increase in hardness can be mainly attributed to hard and brittle intermetallic compounds. During welding, intermetallics refer to the rigid steel particles that become separated from the parent metal. A rise in hardness levels is associated with a decrease in the tensile strength of the weld joint.

3.2. Mechanical analysis

3.2.1. Tensile test result

The effect of welding voltage on the ultimate tensile strength, ductility, and young modulus of the welded steel are shown in Fig. 7, 8, and 9, respectively. These figures show that the ultimate tensile strength, ductility, and young modulus decrease as the voltage increases from 200V to 210V, followed by an increase as the voltage rises from 215V to 225V compared to the unwelded (control) sample. The highest ultimate tensile strength of 371.56MPa

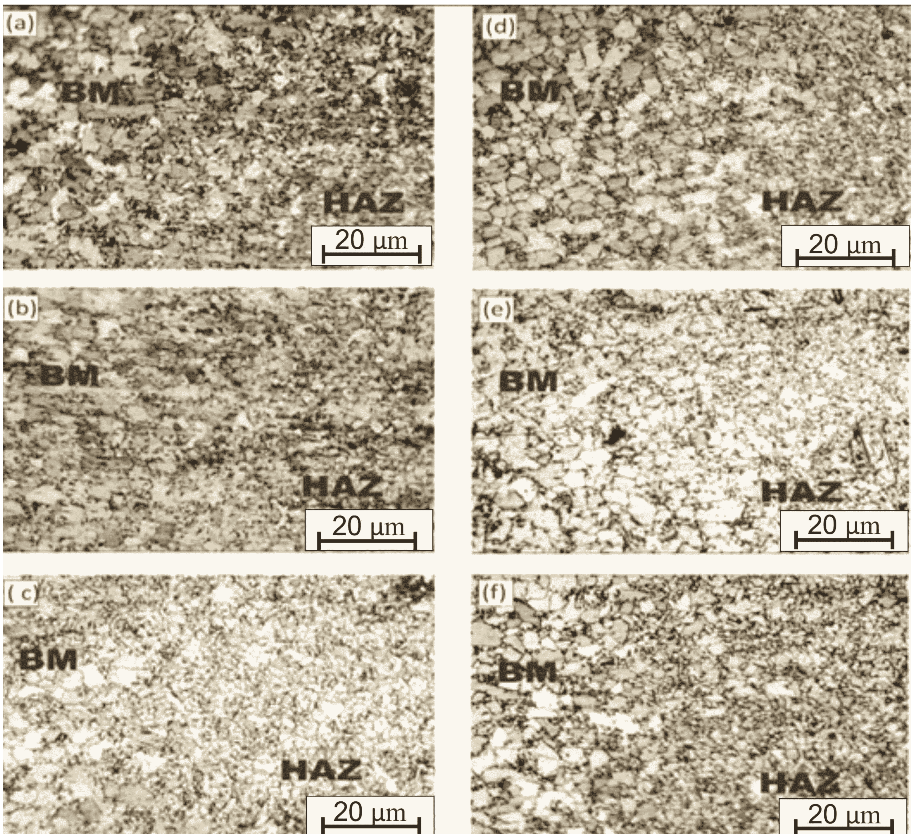

Figure 5: Optical Micrographs of Base Metal (BM) zone and Heat Affected Zone (HAZ) of specimen welded at voltages (a) 200V (b) 205V (c) 210V (d) 215V (e) 220V and (f) 225V.

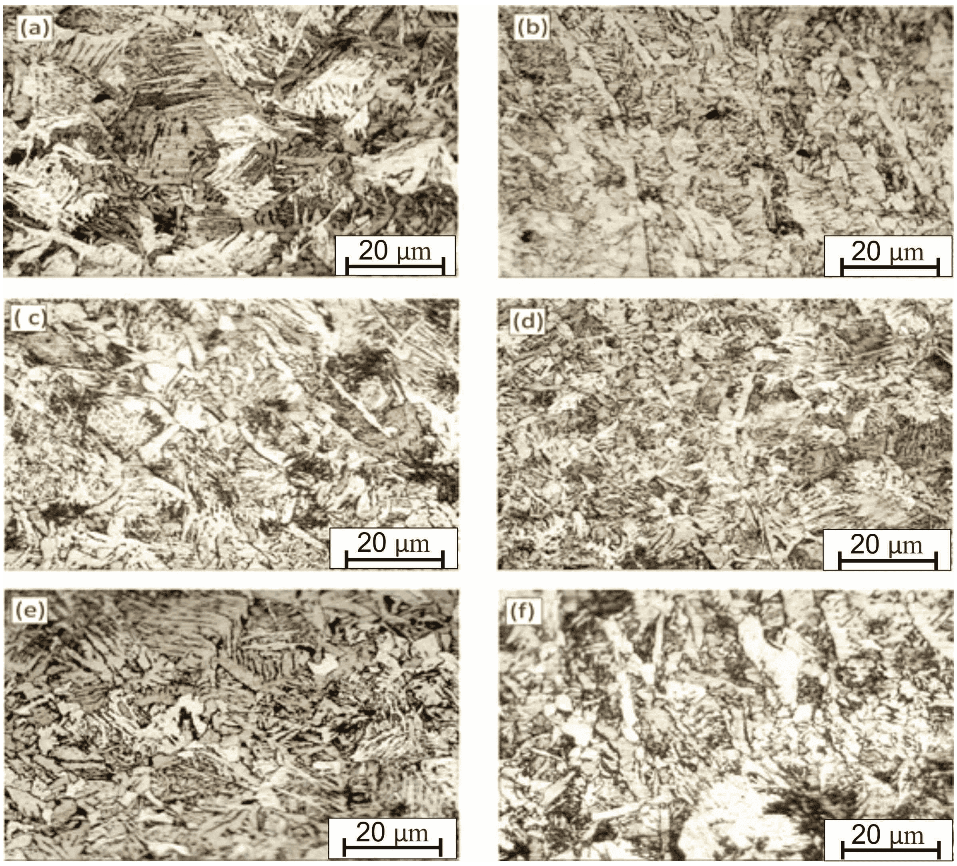

Figure 6: Optical micrographs of fusion zone of welded samples at voltages (a) 200V, (b) 205V, (c) 210V, (d) 215V, (e) 220V, and (f) 225V.

Table 3: Effect of Varied Welding Voltage on the Mechanical Properties of Low Carbon Steel

Voltage (V)	Ultimate Tensile Strength (MPa)	% Elongation	Young's Modulus (GPa)	Impact Energy (J)	Hardness (HBN)
Control Sample	331.36	35.13	16.94	69.89	95.5
200	240.41	7.08	16.6	11.04	111
205	182.18	5.83	16.44	14.71	131
210	77.85	2.63	13.59	23.91	143
215	294.75	11.03	14.2	34.95	146
220	334.56	29.4	14.32	42.3	150
225	371.56	30.44	17.27	53.34	156

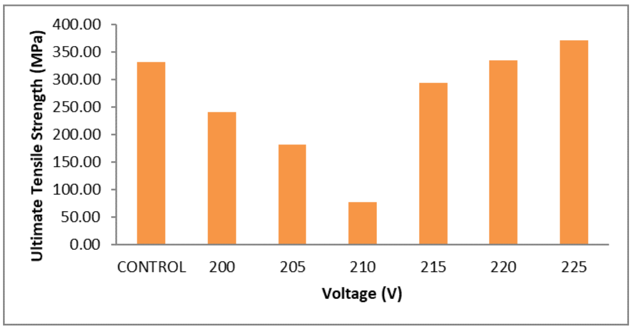

Figure 7: Effect of Welding Voltage on the Ultimate Tensile Strength of low carbon steel

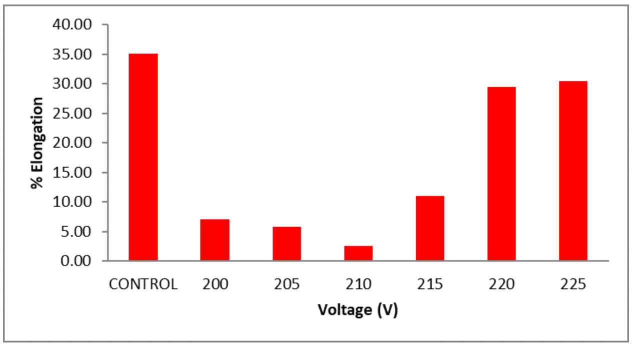

Figure 8: Effect of Welding Voltage on the Ductility of low carbon steel

and Young Modulus of 17.27GPa were achieved at 225V. Compared to the unwelded sample's ductility of 35.13%, the ductility of the welded sample at 225V was lower (by 30.44%). The lowest tensile properties were achieved when welded at 210V. The decrease in tensile strength could result from excessive grain growth or high sulfur, manganese, and phosphorus content in the base metal. It may also be associated with the presence of voids and other defects occurring as a result of increasing voltage. Excessive grain growth could also decrease the tensile properties, according to [11].

3.2.2. Impact test result

Fig. 10 shows the effect of welding voltage on the impact toughness of the welded joint made by GTAW. The impact toughness values of all the welded joints are lower than that of the unwelded sample, irrespective of the welding voltage. However, as the welding voltage increases, so do the impact toughness values. Also, the high concentrations of sulfur (0.07%) and phosphorus (0.22%) observed in the base metal exceed the recommended range of 0.03% to 0.05% for steel. When the sulfur and phosphorus contents of the steel are too high, the likelihood of brittleness increases, which reduces the ductility and impact toughness of the fusion zone.

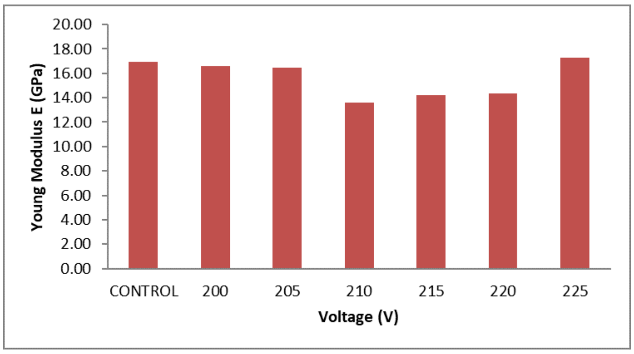

Figure 9: Effect of Welding Voltage on the Young Modulus of low carbon steel

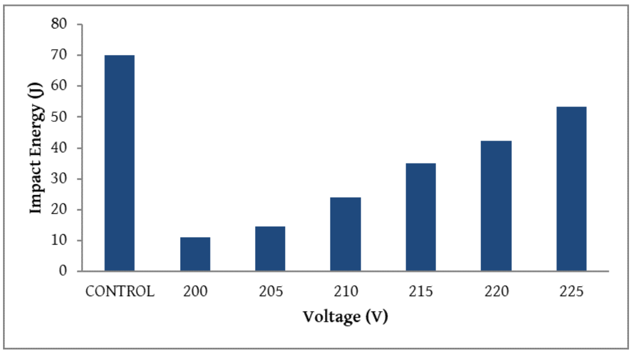

Figure 10: Effect of welding voltage on the impact toughness of low-carbon steel.

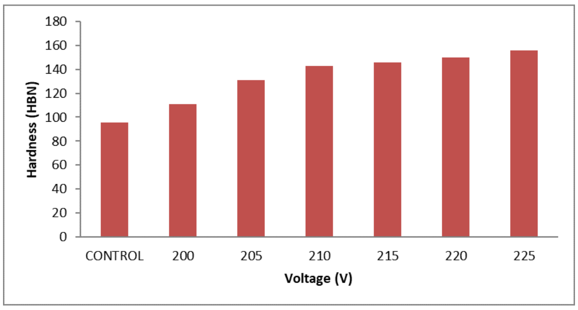

Figure 11: Effect of welding voltage on the microhardness of low-carbon steel.

3.2.3. Hardness test result

Fig. 11 shows the effect of welding voltage on the hardness value of the welded low-carbon steel. The hardness value generally increases with an increase in the welding voltage. The unwelded (control) sample has the least hardness value. The highest hardness value of 156 HBN was obtained at a welding voltage of 225V. This phenomenon can be attributed to the structural alterations in weld metal during the solidification process, which subsequently influence the likelihood of defects forming under different welding conditions. The increased hardness observed in the fusion zone can be ascribed to the development of the intermetallic phase.

The high concentration of manganese (1.48%) in both the base metal and the electrode significantly enhances the hardness of the welded sample. It also can reduce the critical cooling rate during the hardening process and diminish the ductility, thereby effectively improving the steel's hardenability compared to other alloying elements. Furthermore, the significant presence of high phosphorus concentrations contributes to increased strength and hardness; however, this comes at the cost of reduced ductility and impact toughness.

The phosphorus content of 0.22% in the base metal exceeds the recommended range of 0.03% to 0.05%, typically observed in most steel compositions. The presence of a significant amount of sulfur in the base metal, specifically at a concentration of 0.07%, had a detrimental effect on the ductility and notched impact toughness of the material, leading to increased brittleness. The typical concentration of sulfur in steel usually is limited to 0.05%. While an increase in strength and hardness is observed, there is a decrease in ductility and toughness. Higher hardness values suggest that the welded interface may exhibit increased susceptibility to brittleness compared to the base metal. Consequently, it is necessary to implement post-weld heat treatment to enhance the mechanical characteristics to their optimal levels [12]. These findings also reveal similarities to the work done by [13].

4. Conclusion

This study investigates the effect of varying welding voltages on the serviceability and performance of low-carbon steel samples welded using GTAW. The results show the selected welding voltage values significantly affect the microstructure and mechanical properties of the welded samples. A variation in the arc voltage (200V, 205V, 210V, 215V, 220V, and 225V) at a constant current 115A results in increased hardness values and decreased tensile strength and impact toughness compared to the unwelded base metal. The increase in hardness of the welded steel can be attributed to two factors observed in the micrographs: the refinement of the material's grains and the presence of intermetallic phase, as well as alloying elements such as manganese, phosphorus, and sulfur present in the material.

Furthermore, it is observed that the ultimate tensile strength, ductility, and Young's modulus decreased as the voltage increased from 200V to 210V, which may result from weld defects. Conversely, these properties were increased as the voltage was further increased from 215V to 225V compared to the unwelded (control) sample. Also, the impact toughness and hardness values increase as the welding voltage increases. The observed variances in the properties of the material were attributed to the high concentrations of sulfur (0.07%), manganese (1.48%), and phosphorus (0.22%) present in both the base metal and electrode utilized. Therefore, welded steel's final microstructures and mechanical properties are generally influenced by various parameters, including the presence of other elements such as sulfur, phosphorus, and manganese.

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