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Microstructure and Mechanical Characteristics of Welded AISI 1020 Low Carbon Steel Based on the Influence of Weld Joint Design and Shielded Metal Arc Welding Process

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Welding process, weld joint design, welding parameters, heat-input, mechanical properties

Abstract

This study examines the impact of joint design on the microstructure and mechanical properties of welded AISI 1020 low carbon steel using Shielded Metal Arc Welding (SMAW) with E6013 electrodes. Bevel, butt, and half-lap joints were welded under identical conditions and assessed for mechanical and microstructural performance. The bevel joint exhibited the best overall performance, with improved tensile strength (188.39 MPa), yield strength (113.98 MPa), and impact strength (34.54 J/mm^2) compared to butt and half-lap joints due to better weld penetration and load distribution. Microstructural analysis using optical microscope confirmed the presence of distinct ferrite morphologies, including ferrite, Widmanstätten ferrite, and acicular ferrite in the weld metal. The uniform distribution of phases and minimal welding defects in the weld metal zones of the bevel joint further support its mechanical superiority. These results highlight the importance of joint design in optimizing welded steel structures, with the bevel joint proving most suitable for high-strength applications. Hence, the research contributes to the understanding of the effects of joint geometry on welded steel properties and provides practical insights for industrial welding applications.

1. Introduction

Every manufacturing sector depends on combining different materials to produce larger components necessary for providing a variety of services. Methods utilized for material joining encompasses brazing, soldering, riveting, fasteners, welding, among others. Welding, specifically, is notable for its capacity to form robust, long-lasting, and seamless connections that can endure intense pressure and environmental conditions. This renders welding essential in sectors like construction, automotive, aerospace, and shipbuilding, where the strength and trustworthiness of joints are crucial. Heat, energy, pressure, or a combination of these can be used in the welding process, which is carried out on the junction of two surfaces with or without a substance known as the filler material [1, 2]. There are many types of welding such as Electric arc welding, Metal Inert Gas welding (MIG welding), oxy acetylene welding; Tungsten Inert Gas welding (TIG welding), laser welding, submerged arc welding (SAW) and friction welding, among others [3, 4].

Among the several welding techniques, electric arcs are by far the most often utilized heat source in commercial welding practice. The earliest of these techniques is called the shielded metal arc welding (SMAW) [5] which is the type of welding technique that is considered in this research. Shielded Metal Arc Welding (SMAW) is a process that melts and joins metals by heating them with an arc established between a stick-like covered electrode and the work piece. It is one of the most widely used welding processes due to its versatility and simplicity [6]. Also known as Manual Metal Arc Welding (MMAW), stick welding, and flux shielded arc welding, SMAW is simpler compared to other arc welding processes. The equipment is portable, inexpensive, and easy to transport, making it suitable for a variety of environments, including fieldwork [7]. As stated by Asibeluo & Emifoniye [4] according to the American Welding Society, common applications of SMAW include construction, pipelines, machinery structures, shipbuilding, job shop fabrication, and repair work [2]. The process employs a consumable electrode, electrode holder, power source (AC or DC), and a welding machine. The electrode is coated with flux, which produces a shielding gas and slag to protect the weld pool from atmospheric contamination [1,8]. In Shielded Metal Arc Welding (SMAW), various welding parameters must be considered to produce a high-quality weld with desirable properties suitable for the specific area of application [1]. These parameters include electrode type, current setting, arc length, travel speed, and electrode angle [8, 9]. Proper selection and control of these parameters influence the strength, appearance, and integrity of the weld, ensuring it meets the required standards for applications in construction, pipeline installation, shipbuilding, and repair work.

Another crucial aspect to consider is the kind of weld joint that will be employed, as the type of weld joint utilized for any welding project can have a significant impact on the weld's quality and strength, labor costs, and the performance of the weld joint while in use. As welding is the process of creating a lasting connection between different components, selecting the appropriate weld joint design is essential to ensure successful fabrication with mechanical properties that are at least comparable to those of the base metal. Moreover, it is important to carefully assess the attributes of the different types of joints utilized. Inadequate joint design can nullify even the ideal welding conditions. Hence, a key aspect in weld joint design, particularly in arc welding, is to ensure sufficient accessibility and room for the welding electrode or filler metal to move effectively and produce a proper weld bead [5, 10]. There are various types of weld joints available, each with its own unique strengths and applications, making it crucial to select the appropriate one for the specific task at hand [11]. When connecting two metal pieces together at their ends, a butt weld joint is commonly used, especially when a seamless finish is required. Butt joints find frequent use in applications such as pressure vessels, piping, and tanks which are used in welding metallic sheets, plates and even pipe work with different variations depicted in Fig.1 [2, 5]. In addition to the butt joint, this study also examined various other joint types, such as the half lap and bevel joints. Within the half-lap joint, some material is extracted from both members, resulting in a joint thickness equal to the thickest part, enabling welding with looser fit-up tolerances [10]. On the other hand, the bevel joint requires the shaping of metal edges before welding to create a strong and even joint. These grooves or shapes can be straight, slanted, or V-shaped, with angles ranging from 8 to 50 degrees, depending on the specific requirements of the task.

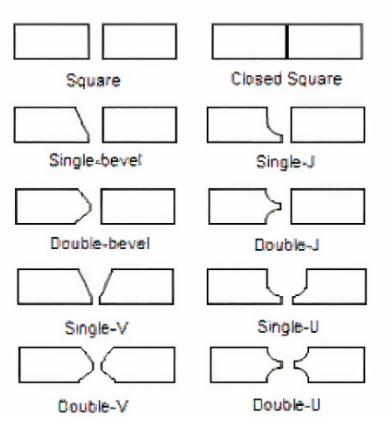


Fig. 1 *Butt joint geometry [2]*

This research focused on low carbon steel as the base metal. Low carbon steels, containing up to 0.3% carbon, are typically the easiest steels to weld at room temperature. They offer good formability and relatively low strength, which is largely influenced by their carbon content. Due to their low carbon percentage, these steels exhibit excellent weldability and can generally be welded without special precautions using most available processes [3, 6, 12-13]. Several studies have examined the welding of low carbon steel using the SMAW method, putting either the welding parameters or the joint types into consideration. For instance, Singh et al. [2] investigated the effects of joint geometries on welding of mild steel by shielded metal arc welding (SMAW). Mild steel plates, IS 2062: E250, were utilized as specimens in the research. Welding was carried out on various butt-joint configurations, such as square butt-joint, single V-joint, double V-joint, and single J-joint, while maintaining consistency in all other welding parameters like current, voltage, and welding speed. Mechanical examinations and microscopic studies were performed to assess alterations in the mechanical and microstructural properties of the welded metal. The outcome indicated that the double V-joint displayed superior mechanical characteristics in comparison to the other joints. Despite the satisfactory performance of the single V-joint, it exhibited a broader heat-affected zone (HAZ), increasing the risk of welding flaws and constraining its potential applications. The single J-joint also delivered acceptable results, but the presence of martensite in its microstructure raised its hardness, leading to fragility and, hence restricting its usage. The square joint was deemed unsuitable for thicker plates, as in the present investigation. Overall, the study offered a comparative evaluation of the findings, enriching the comprehension of welding procedures. In another study where the welding characteristics of weldment with respect to different types of weld design and welding current was investigated by Jha & Jha [5]. In the study, 6 mm mild steel plates were welded using various joint configurations, including Single V, Double V, and Flat surfaces through Shielded Metal Arc Welding. The findings revealed that the Single V joint design exhibited the highest UTS compared to other joints, and the weld properties improved to a certain extent up to a specific current level, beyond which the strength decreased. Additionally, the welding speed was also influenced by the welding current. In another research Husaini et al. [14] aimed to evaluate the effects of welding on the microstructure and mechanical characteristics of welded joints. Low carbon steel was welded using the Shielded Metal Arc Welding (SMAW) method with a 2.6 mm diameter E7016 electrode. A single V-notch with a 70° angle was used, and the welding position was 1G. The results indicated that the highest impact toughness in the weld metal area was 251 joules/mm^2, while the lowest in the HAZ was 119 joules/mm^2. Hardness values were approximately 87.6 HRB for the weld metal, 73.9 HRB for the HAZ, and 67.1 HRB for the base metal. The microstructure analysis revealed that the weld metal zone, HAZ, and base metal comprised ferrite and pearlite, observed using an optical microscope, in low carbon steel AISI 1010.

The originality of this study is rooted in its thorough scrutiny of various joint configurations within a unified inquiry, thereby furnishing a more holistic insight into their collective influence on weld performance. This study is therefore aimed at advancing the knowledge pertaining to the application of SMAW on low carbon steel, thereby facilitating the advancement of optimal methodologies that can be universally embraced within the welding sector to enhance the quality and cost-efficiency of welds. The outcomes of this examination are poised to provide invaluable perspectives for welding practitioners and scholars, aiding in the enhancement of SMAW practices for mild steel and potentially shaping the landscape of standards and protocols for welding procedures across diverse industrial and manufacturing domains.

2. Methods

2.1 Materials

Hot-rolled low-carbon steel (8 mm thick) sourced from a steel industry in Sango-Ota, Ogun State, Nigeria was used. The base metal, an AISI 1020 type, is renowned for its high ductility, good machinability, moderate strength, toughness, and excellent weldability. Also, E6013 mild steel welding electrode with a Nickle-potassium coating suitable for both AC and DC welding was used. This electrode is commonly applied to automobile bodies, truck frames, metal furniture, bridges, and storage tanks [6]. Detailed chemical compositions are provided in Tables 1 and 2.

Table1 *Chemical composition of steel (AISI 1020 type)*

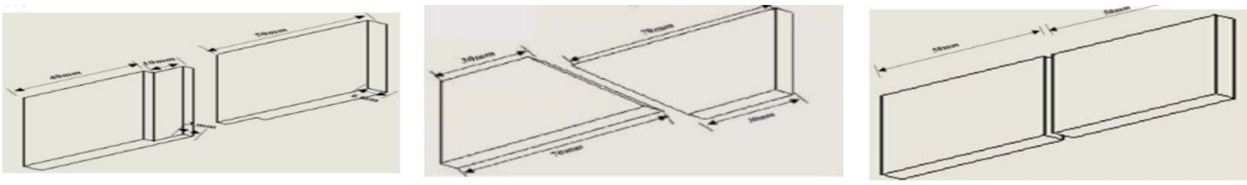
Elements	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Fe
Composition	0.199	0.212	0.522	0.0179	0.0096	0.0439	0.0029	0.0155	0.0407	98.98

Table 2 *Chemical composition of electrode (E6013)*

Elements	Fe	C	Mn	Si	P	Ni
Composition	99.155	0.12	0.3	0.35	0.04	0.035

2.2 Experimental Procedure

Low carbon steel sheets with an 8 mm thickness were cut into sizes according to the joint design specifications. The joint designs used were butt, half lap, and bevel joints as seen in Figure 2. The butt joint was created by cutting the material vertically (50 x 50 x 8 mm), the half lap joint was formed by machining a section of the material (50 x 50 x 4 mm), and the bevel joint was made by cutting at a 30° angle from the edge to the horizontal. The materials were smoothed and cleaned thoroughly to remove any impurities that could lead to inclusions and affect the weld quality, ensuring easy coupling during welding. The cut samples were paired and aligned on a table using an angular iron, and the welding circuit was set up before welding. Welding of the samples in a horizontal position was performed continuously using the SMAW method with constant welding parameters: current of 110 A, voltage of 23 V, and speed of 3.57 mm/s. The weld joints were brushed to ensure complete penetration. The welded joints were then ground with a wire brush to remove any spatter, resulting in a good surface finish.



(a) **(b)** **(c)**

Fig. 2 *Welding joints used; (a) Half lap joint sample; (b) Bevel joint sample; (c) Butt joint sample [10]*

2.3 Mechanical Evaluation and Microstructural Characterization

Universal Testing Machine was used to perform the tensile tests on the samples. The ends of the test samples were secured in grips connected to a straining device and a load measuring device. Upon fracturing the test sample, the results were generated by computer software.

The Izod impact test was conducted on the samples using a Honfield Balance Impact Testing Machine in accordance with ASTM E23. Prior to mounting on the machine, the test samples were notched to a depth of 2 mm with a V-shaped hand file. The notched test samples were then mounted on the impact testing machine, which applied a constant impact force. The amount of impact energy absorbed by the specimens before yielding was read from the calibrated scale on the impact testing machine.

The hardness of the base metal (BM), heat-affected zone (HAZ), and weld metal (WM) across the welded joint of the samples was measured using a digital Vickers micro-hardness tester, specifically an Indentec Hardness Testing Machine, according to ASTM E92-17 at 5 mm intervals from the WM.

The specimens were ground using various grades of emery paper (220, 320, 500, 600, 800, and 1000), followed by polishing and etching procedures. In accordance with ASTM E407-3, the polished surfaces were etched with Keller's reagent (2 mL HNO_3 + 3 mL HCl + 5 mL HF + 150 mL H_2O) for approximately 18 seconds. Micrographs of the samples were obtained using a Nikon Optiphot metallurgical microscope and a Nikon D70 digital camera at magnifications of 100x and 400x. The examination of the microstructures in the weld zone (WZ), heat-affected zone (HAZ), and parent metal (PM) was conducted using optical microscopy.

3. Results and Discussion

3.1 Tensile Properties

The tensile results reveal a nuanced relationship between welded joint design and the resulting mechanical properties (tensile strength and yield strength) of low carbon steel (AISI 1020) welded with E6013 mild steel electrodes using Shielded Metal Arc Welding (SMAW). As seen in Fig. 3, the base metal exhibited the highest ultimate tensile strength (UTS) of 190.16 MPa. This serves as a baseline for comparison, representing the material's inherent strength in its unaltered state. The uniform microstructure of low carbon steel, characterized by ferrite grains and a small amount of pearlite, contributes to its relatively high ductility and toughness, as seen in Fig. 7. Among the welded joint types, the bevel joint, with a 30° angle, demonstrated a UTS of 188.39 Mpa, remarkably close to the base metal, and had the highest tensile strength when compared to the remaining joint types (butt and half-lap). This can be attributed to the angled configuration of the bevel joint, which allows for a more gradual stress distribution across the welded area. This minimizes stress concentrations, which are known to initiate failure in welded joints. Additionally, the bevel joint geometry facilitates deeper penetration of the weld metal, ensuring thorough fusion of the base metal plates. This creates a larger effective cross-sectional area, contributing to the joint's high tensile strength. The butt joint, which involves welding two pieces of metal along their edges in a straight line without any gap, had a tensile strength of 164.35 Mpa, which was lower than that of the bevel joint. This reduced strength could be attributed to factors such as incomplete fusion and lack of penetration, which can lead to weaker interfacial bonds between the base metals, reducing the overall strength of the joint. The presence of weld defects like porosity or Inclusions could also contribute to the decrease in strength. Furthermore, the half-lap joint displayed the lowest tensile strength (158.03 Mpa) among the three joints. This can be due to the overlapping configuration of a half-lap joint, which subjects the weld to eccentric loading, inducing bending stresses in addition to tensile stresses. This complex stress state makes the joint inherently weaker compared to butt or bevel joints under pure tensile loading. The edges of the overlap in a half-lap joint act as stress raisers, further compromising the joint's integrity under tensile load.

In the same vein, as seen in Fig. 4, which represents the yield strength of each joint and the control sample, a similar trend was observed as in Fig. 3. The base metal (control) had the highest yield strength of 164.60 Mpa, representing the stress at which the material begins to deform plastically, and serves as a reference point for evaluating the welded joints. The bevel joint also had the highest yield strength (113.98 Mpa) among the welded joints but was lower than the base metal. This reduction can be attributed to welding-induced residual stress due to localized heating and cooling. These stresses, often tensile in nature, can interact with applied loads and effectively reduce the yield strength of the joint. The butt joint showed a further decrease in yield strength (107.83 Mpa) but was still higher than the half-lap joint (98.52 Mpa), which had the lowest yield strength. This further decrease in both joints can be attributed to similar reasons given for the tensile strength above. In general, among these joints, the bevel welded joint is the most suitable choice for industrial and manufacturing applications based on the tensile and yield strength data. It offers the best combination of high strength and reliable performance, making it ideal for high-load-bearing structures and components. The bevel joint design ensures better weld quality through improved penetration and fusion, which contributes to its superior mechanical properties.

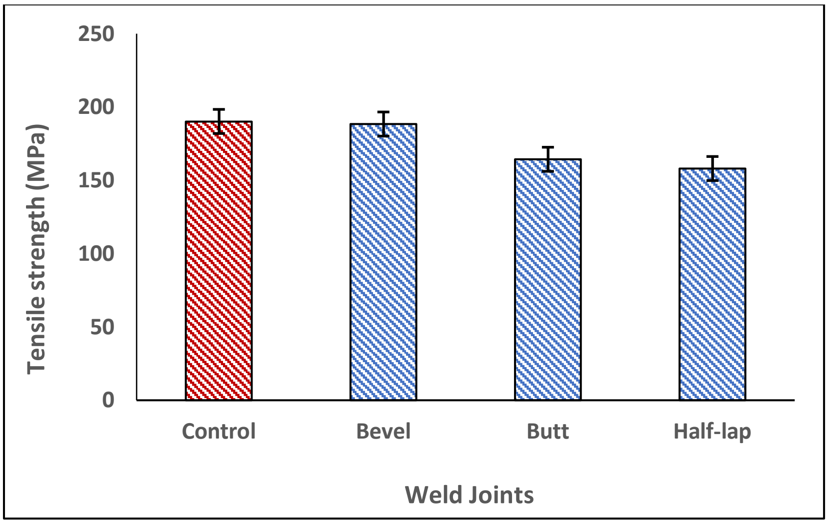


Fig. 3 *Tensile strength of weld joints and control*

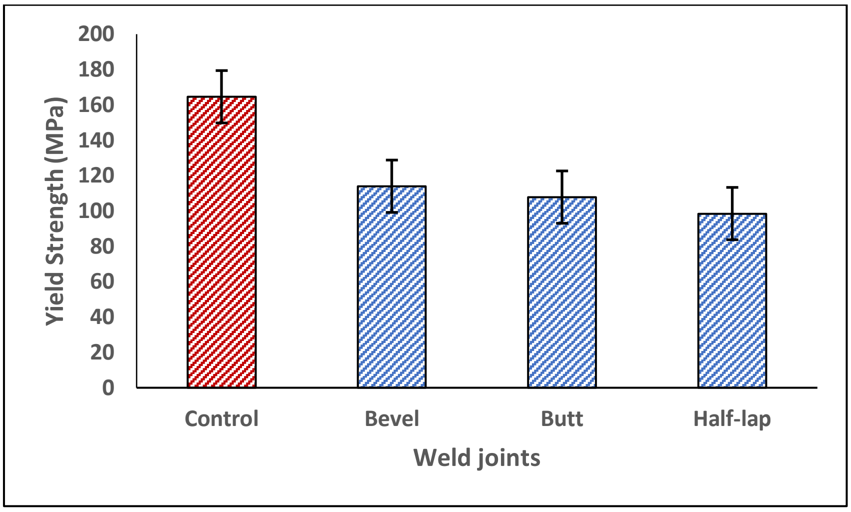


Fig. 4 *Yield strength of weld joints and control*

3.2 Impact Strength

The impact strength results, as seen in Fig. 5, highlight the critical influence of welded joint design on the fracture toughness of low carbon steel (AISI 1020) welded with E6013 mild steel electrodes using Shielded Metal Arc Welding (SMAW). The base metal exhibited the highest impact strength of 63.38 J/mm^2, serving as a reference point. After welding different joint designs, the impact strength decreased progressively from the bevel joint (34.54 J/mm^2) to the butt joint (15.23 J/mm^2) and finally to the half-lap joint (11.42 J/mm^2). The base metal's high impact strength signifies its ability to absorb energy and resist fracture under sudden loading due to its microstructure, consisting of ferrite and pearlite, which allows for plastic deformation and energy dissipation before fracture occurs. The bevel joint's reduced impact strength compared to the base metal can be attributed to heat-affected zone (HAZ) embrittlement, where rapid cooling rates lead to brittle martensite formation, and notch sensitivity at the weld toe and root regions that act as stress concentrators.

The butt joints further decreased impact strength is associated with weld defects like lack of fusion and undercut, which weaken the joint and serve as crack initiation sites, along with higher stress concentration due to the linear weld alignment. The half-lap joint exhibited the lowest impact strength due to significant stress raisers at the overlap edges and eccentric loading, which introduces bending stresses in addition to tensile stresses. Overall, the bevel welded joint is the most robust among the welded joints, offering a better balance of strength and toughness, making it more suitable for applications where resistance to sudden loads and impacts is critical. Despite the lower impact strength compared to the base metal, the bevel joint design ensures better stress distribution, deeper penetration, and more thorough fusion, contributing to its relatively higher impact strength.

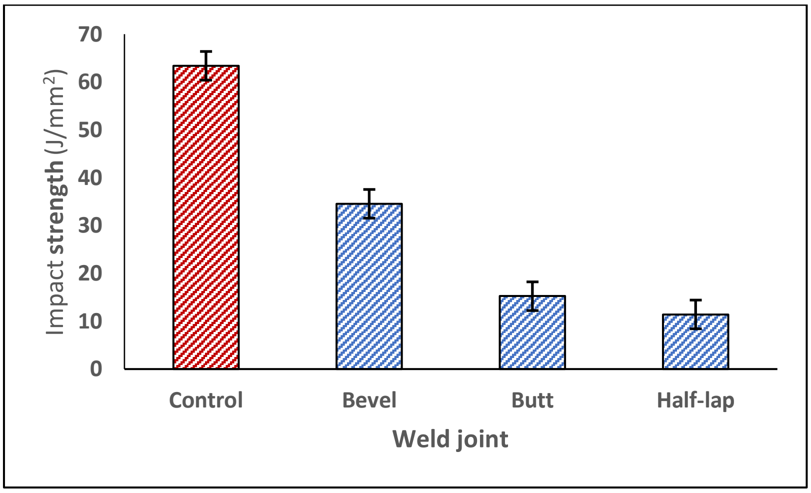


Fig. 5 *Impact strength of weld joints and control*

3.3 Hardness

The hardness, which is the resistance to surface indentation, is presented in Fig. 6 for different zones of each welded joint. The hardness values ranged between 63.5 HV and 74.5 HV across the zones of the welded samples. It was observed that the hardness of the base metal is 63.5 HV, while the measured hardness of the heat-affected zone (HAZ) and weld metal regions for each of the welded joints varies from 71 HV to 74.5 HV and 69.1 HV to 73.3 HV, respectively, depending on the grain size and phases sampled from each indentation. This indicates that the hardness of the HAZ region for all welded joints is greater than that of the weld metal and base metal. This is because the HAZ undergoes rapid heating and cooling cycles during welding, leading to the formation of martensite, a very hard and brittle phase of steel. The rapid cooling rate in the HAZ, especially near the fusion line, doesn't allow enough time for the softer ferrite and pearlite phases to form, resulting in a higher concentration of martensite. Additionally, the HAZ experiences grain refinement due to the rapid thermal cycles. While smaller grains can improve strength and toughness to some extent, they also contribute to increased hardness, especially when combined with martensite formation. The highest hardness value was found in the butt welded joint (74.5 HV) at the HAZ zone. This is because the butt joint configuration leads to more concentrated heat input and faster cooling rates compared to bevel and half-lap joints. The rapid cooling in the butt joint HAZ promotes a greater degree of martensite formation, resulting in higher hardness. In contrast, the bevel joint's HAZ showed slightly lower hardness (73.4 HV) due to its more gradual heat dissipation and slower cooling rate. Meanwhile, the half-lap joint, with its wider HAZ and even slower cooling, had the lowest hardness (73 HV) among the three joint types. Similar to this result was also observed in Boumerzoug et al.[15] .

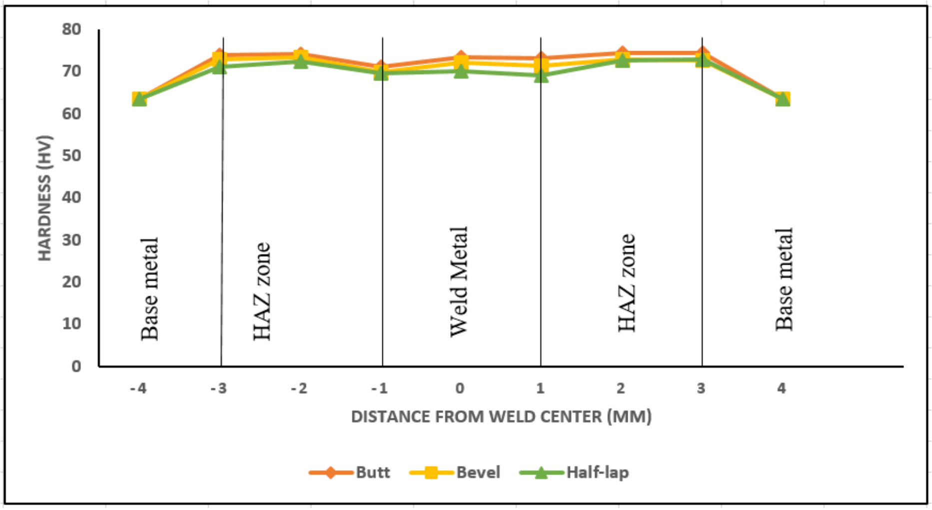


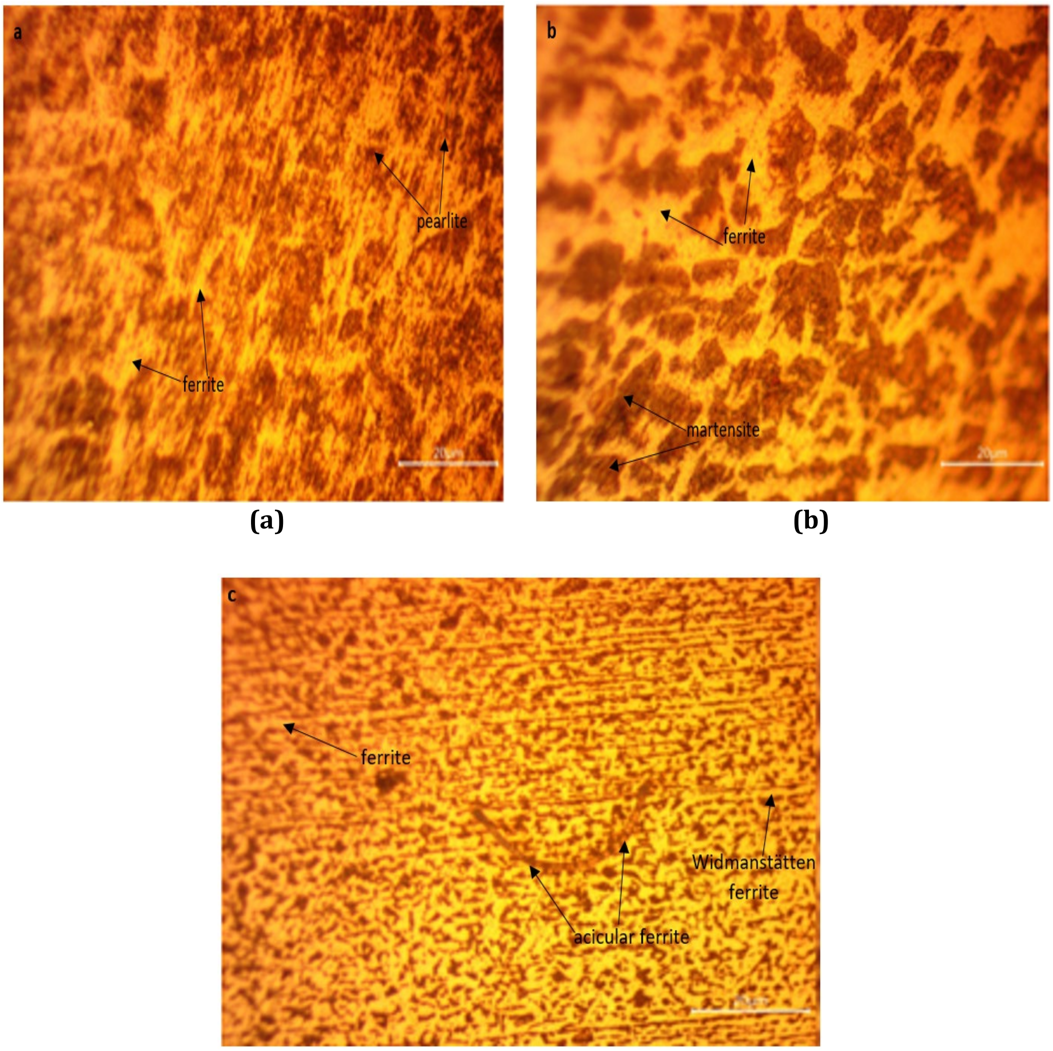
Fig. 6 *Hardness of welded samples across the zones*

3.4 Metallographic Microstructure Analysis

The analysis of the microstructure is apparent in the illustrations provided in Fig. 7 for bevel welded joints due to the optimum properties. Fig. 7a shows the micrograph of low carbon steel (AISI 1020) before welding (base metal), taken using a Nikon Optiphot metallurgical microscope and a Nikon D70 digital camera at 400x magnification, reveals a typical ferrite and pearlite microstructure. The image shows ferrite as the lighter regions and pearlite as the darker, more etched areas. Ferrite, with its body-centered cubic (BCC) structure, contributes to the steel's ductility, while pearlite, a lamellar mixture of ferrite and cementite (Fe_3C), enhances strength. The grains are relatively uniform and equiaxed, typical of rolled and annealed low carbon steel, and the visible grain boundaries indicate effective etching. This microstructure implies that the steel has good ductility and toughness, balanced by the strength provided by the pearlite. The fine pearlite colonies and uniform ferrite grains suggest controlled cooling from the austenite phase. The 20-micrometer scale bar helps to assess the grain size, confirming that the sample preparation, including etching and polishing, was done effectively. Overall, the microstructure indicates that steel possesses desirable mechanical properties for various applications.

Furthermore Fig. 7b shows the micrograph of the heat-affected zone (HAZ) in low carbon steel (AISI 1020) after welding, taken at 400x magnification. It provides crucial insights into the structural changes induced by the welding process. The image shows a more pronounced and coarser microstructure compared to the base metal, indicative of the transformations due to thermal cycles experienced during welding. The darker regions represent martensite formation, resulting from the rapid cooling rates in the HAZ. Martensite is a hard and brittle phase, which significantly increases the hardness of the HAZ. The ferrite regions, lighter in color, are less prominent due to grain refinement and transformation into martensite. The observed microstructure, with its mixed phases, highlights the increased brittleness and hardness in the HAZ compared to the unaffected base metal this can be linked to the hardness as seen in Fig. 6. This change can adversely affect the toughness of the material, making it more susceptible to fracture under stress. The scale bar indicates 20 micrometers, providing a sense of the grain size and the extent of phase transformation. This detailed microstructural view underscores the importance of controlled welding parameters to manage HAZ properties and ensure the integrity of the welded joint.

Fig. 7c shows the weld metal microstructure, captured at 400x magnification, which reveals a heterogeneous matrix composed primarily of ferrite, interspersed with Widmanstätten ferrite and acicular ferrite and no martensite formation. The presence of these distinct ferrite morphologies indicates a complex thermal history during the welding process, characterized by varying cooling rates. The predominant ferrite phase, with its relatively coarse grains, suggests moderate cooling rates, while the finer Widmanstätten and acicular ferrite structures are indicative of localized rapid cooling. This intricate microstructure significantly influences the weld metal's mechanical properties, contributing to a balance of strength, toughness, and ductility. The ferrite matrix provides the foundation for ductility, while the Widmanstätten and acicular ferrite enhance strength and hardness. However, the presence of Widmanstätten ferrite can also introduce some susceptibility to brittle fracture under certain loading conditions, which may be reflected in the observed impact strength results.



(a) (b)

(c)

Fig. 7 *Optical micrograph of bevel joint (a) Base metal of welded low carbon steel (x400); (b) HAZ of welded low carbon steel (x400); (c) Weld metal of welded low carbon steel (x400)*

4. Conclusion

In conclusion, this investigation into the effects of welded joint design on the mechanical properties and microstructure of low carbon steel (AISI 1020) using SMAW with E6013 electrodes successfully achieved its primary objectives as well as the aim stated in this research which is advancing the knowledge pertaining to the application of SMAW on low carbon steel, thereby facilitating the advancement of optimal methodologies that can be universally embraced within the welding sector to enhance the quality and cost-efficiency of welds . The study revealed a clear correlation between joint design, resulting microstructure, and mechanical performance, highlighting the superior tensile and impact strength of bevel joints compared to butt and half-lap joints.

The bevel joint, with its superior strength and toughness, emerges as the optimal choice for applications where structural integrity and impact resistance are paramount. Potential areas of application for this joint configuration include Construction: Load-bearing structures, bridges, and infrastructure components subject to dynamic loads. Manufacturing: Heavy machinery, pressure vessels, and equipment requiring high strength and durability. Automotive and Aerospace: Chassis components, structural elements, and parts subjected to vibrations and impact. By adopting bevel joints in these applications, engineers and manufacturers can enhance the safety, reliability, and longevity of welded structures, ultimately contributing to improved efficiency and cost-effectiveness in the welding sector. Furthermore, this study serves as a foundation for future research, which could explore the effects of varying bevel angles, welding parameters, and post-weld heat treatments on the mechanical properties and microstructure of welded joints. Such investigations would further refine the understanding of SMAW welding and facilitate the development of even more advanced welding techniques tailored to specific applications and materials.

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Conflict of Interest

No conflict of interest among all the authors.

Author Contribution

***Study conception, supervision and design**: Isiaka Oluwole Oladele.* ***Interpretation of results, drafting and editing of manuscript**: Samuel Olumide Falana, Ayodele Olawumi Adedeke, Collins Chidiebere Okoye.* ***Analysis and interpretation of results**: Peace Pamilerin Adara and Aladesuyi Kole Aladenika. All authors reviewed the results and approved the final version of the manuscript.*

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