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Effect of Welding Electrodes and Post-weld Heat Treatment on Some Mechanical Properties and Microstructural Transformations of Mild Steel Weldment using Smaw Process

A. A. Musa[1,2]*, I. Abdullahi[2], A. D. Sani[3] and A. I. Jimoh[4]

[1]Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria, Nigeria
[2]Department of Materials Science and Engineering, African University of Science and Technology, Abuja.
*abdulrahman@abu.edu.ng

Research Article

Abstract

The current study investigates the effect of some welding electrodes and post¬¬-weld heat treatment (PWHT) on tensile strength, hardness, impact energy, and microstructural transformations of mild steel weldments, using the shielded metal arc welding (SMAW) technique. Four different electrode specifications were used in this study, these include cast iron (AG4700), mild steel (E6014), stainless steel (E308L-16), and mild steel (E6013) electrodes. Eight (8) samples of mild steel plate of length 100mm and 5mm thickness were first sectioned and welded across the width using the four electrodes (2 samples per each). Following the welding operations, a post-weld heat treatment (Normalizing) at a temperature of 8000C was applied to four of the welded plates with each of the four distinct electrode materials, soaked for 50 minutes, and then allowed to cool naturally in the open air. Both the heat-treated and the as-welded samples were then subjected to various mechanical tests. The result obtained showed that the welds with mild steel electrodes (E6013 and E6014) possess higher tensile strength for both the heat-treated and untreated welds, while the AG4700 electrode gave the highest impact energy after thermal treatment as compared to other welds. The hardness values of the welds with the four electrode materials were generally found to decrease after post-weld heat treatment. The microstructural results revealed the growth of the original fine grain structures in the as-welded condition into coarser structures after heat treatment for all the weldments, which appears to account for the lower hardness obtained in the post-treated steel welds. Based on the results obtained, it can be concluded that some electrode materials impart adequate mechanical properties in the as-welded condition, while some, depending on the type of mechanical properties to be improved, require post-weld heat treatment on the weldment.

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Keywords
Electrode materials, post-weld heat treatment, mechanical properties, microstructures, SMAW process.

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1. Introduction

Steels represent the most important group of engineering materials as they have the widest diversity of applications among other materials (Tisza and Czinege, 2018; Kim *et al.*, 2018). Despite the introduction of composites in recent years, steels remain important raw material due to its high strength, stiffness, toughness, and tolerance at high temperatures (Zhang and Yang 2019; Vijendra, 2007). Mild steel is one of the important materials due to its unique mechanical properties. Mild steels have a low percentage of carbon generally between 0.16% and 0.30% (Zhang *et al.*, 2019; Emeriewen and Kalilu, 2018). It is widely applicable for the design and fabrication of most engineering materials such as structural design, process equipment, piping, and shipbuilding due to its economic sustainability and excellent weldability when compared with other steel alloys (Chopra *et al*., 2022; Taşdemir & Nohut, 2021).
Welding is a permanent and popular means of fabricating industrial materials. It is one of the most reliable methods available to engineers in their effort to reduce production and maintenance costs (Vijendra, 2007). It is the process of uniting two pieces of similar or dissimilar metals or alloys by fusion through the application of heat to the parts to be joined (Akinlabi and Mahamood, 2020; Messler, 2008). The two components to be joined are securely clamped and heat is applied to the joint, causing a liquid pool to form. This pool solidifies upon cooling, resulting in a durable and permanent bond between the two components (Manik *et al*., 2013). Moreover, many variables should be properly monitored when performing welding and thermal cutting operations because of the rapid heating and cooling at the welded joint that may cause distortion and poor mechanical properties of the weldment (Babu *et al.*, 2019). The mechanical properties of weldment determine the behavior of the welded structure in service (Kumar *et al.*, 2022). Hence, engineers and researchers continuously strive to produce weld joints with better mechanical properties to meet increasingly challenging service conditions (El-Batahgy *et al*., 2021).

One of the important variables that are normally considered during welding is the selection of the proper electrode materials that are chemically compatible with the parent materials for adequate weld joint properties (Cevik, 2021). Most weldments do not necessitate heat treatments as the condition in which they are welded offers enough strength and other characteristics to fulfill the intended service requirements. However, depending on the parent and electrode materials, certain fusion weldments may require post-weld heat treatment to improve some specific characteristics of the weld joints (Masoumi et al., 2022; Kumar *et al.,* 2021)

Therefore, this study investigates the effect of both the electrode materials and post-weld thermal treatment on some mechanical properties and microstructural transformation of mild steel weldment produced by the shielded metal arc welding process.

2. Materials and Methods

2.1 Materials

The materials used in this research include a mild steel plate of 5mm thickness, cast iron electrode (AG4700), mild steel electrodes (E6013 and E6014), stainless steel electrode (E308L-16), SiC grit papers and etchants solutions.

The chemical compositions of the mild steel plate used are shown in Table 1.

Table1. Chemical Composition of the Base Metal (Mild steel)

Element	C	Si	Mn	P	S	Al	Mo	Ni	Fe
%Composition	0.25	0.4	0.8	0.04	0.04	0.06	0.002	0.04	Bal.

2.2 Experimental procedures

The mild steel plate of thickness 5mm was cut into 8 equal pieces with a length of 100mm and 10mm in width using an electrical power saw. Each piece was then divided equally along the width, beveled to the angle of 30° to the horizontal, then butt welded with the four electrode materials, two plates per each electrode. After welding, four of the welded plates with each of the four different electrode materials were then subjected to the normalizing thermal treatment. The process involves heating the plates to a temperature of 8000C, maintaining them at this temperature for 50 minutes, and then allow to cool down naturally in an unconfined atmosphere. The welded samples (Both the heat-treated and untreated) were then cut and prepared in accordance with the standard specifications for each of the mechanical tests to be conducted, including tensile strength, hardness, and impact using a universal tensile testing machine, Rockwell hardness testing, and Charpy impact testing respectively. A metallographic sample preparation method was also used to carefully prepare the specimens for the microstructural analysis.

2.3 Microstructural examination

The microstructural examination was performed on the prepared samples using an optical microscope to reveal the microstructural transformations due to alternative heating and cooling process during welding. After welding, the samples for microstructural investigation were prepared according to metallographic sample procedures. The samples were first mounted in moulds with epoxy resin for easy handling during grinding and polishing operations. The mounted samples were then passed through a grinding operation using different grit papers, starting from the rough (160 grit) to the finer grit (800 grit) so that all scratches from cutting/sectioning can be properly removed. It was then polished and etched before viewing the structures in the microscope. The etchants used are 2% Nital and 2% Picral for the untreated and heat-treated samples respectively.

2.4 Mechanical test

2.4.1 Tensile test

The tensile test was performed on the welded samples using a WDW 100KN universal tensile testing machine. The total length of the test specimen is 100mm and the gauge length of 70mm. The specimen was clamped within the jaws of the upper and lower crossheads, aligned with the center of the testing machine and the direction of the tensile force, and the value of the applied force was measured from the already calibrated load cell. The extensometer attached to the lower moving crossheads measured the magnitude of the elongations as the force is gradually applied at a constant rate until fracture occurred. Both the applied force and the corresponding elongation were read directly from the machine at intervals of 5KN increases in force. This process was repeated for all the specimens, and the tensile strengths for each of the specimens after failure were then recorded.

2.4.2 Impact test

All the welded specimens (both thermally treated and untreated) were subjected to impact tests using the Charpy impact testing method. The dimension of the test specimen was 100mm in length and 5mm in thickness, with a 3mm depth of notch at the middle. The notch at the middle of the specimen serves as the stress concentrator. The specimen was then clamped one after the order to the vice on the Charpy impact testing machine, the pendulum was raised to a certain height and the gauge was set at zero before it was released. The energy absorbed in breaking the specimen was then read and recorded.

2.4.3 Hardness test

The surfaces of the test samples for hardness testing were first cleaned, grind, and slightly polished to obtain a smooth surface. Rockwell hardness scale A (HRA) was employed for the experiment and the samples were carefully mounted on the sample stage of the machine. A minor load of 10kg was first applied to the specimen followed by a major load of 60kg. Diamond cone indenter was used and the whole process lasted for 10-15 seconds. The difference between the penetration caused by the minor and the major loads is the Rockwell hardness value which is taken automatically from the machine. Each specimen was indented at three different places to take the average value and this was repeated for all the specimens tested.

3. Results and Discussions

3.1 Microstructural Examination Results

From the microstructural examination, it was generally observed that the grain sizes of all the heat-treated steel welds are coarser as compared to untreated welds. In addition to the increase in the grain sizes, Plate 1a primarily consists of ferrite and pearlite structures, while Plate 1b (heat-treated) shows some nodules of cast iron along the grain boundaries of the transformed austenite structures, thereby making it softer with higher impact energy and lower hardness value as revealed in Figures 2 and 3 respectively. This finding aligns with the investigation carried out by Winiczenko et al., (2018). Plate 2 showed the micrographs of the heat-treated weldment and the one without heat treatment by utilizing stainless steel electrode. Plate 2a contains a mixture of fine distribution of ferrite and pearlite phases, whereas, in Plate 2b, certain carbide structures were observed to form along the grain boundaries of the weld owing to the chemical reaction between chromium in the stainless steel and carbon during the process of thermal treatment. Plates 3 and 4 consist of randomly distributed fine ferrite structures within the pearlite matrix in the as-welded condition which slightly becomes coarser after thermal treatment. The pearlite structures become more obvious in Plate 3b and 4b as indicated by the darker portion of the structures. This is because most of the austenite structures that have been consumed during the welding operation will transform back into a small number of pearlites due to slow cooling (Fujii *et al.*, 2006).

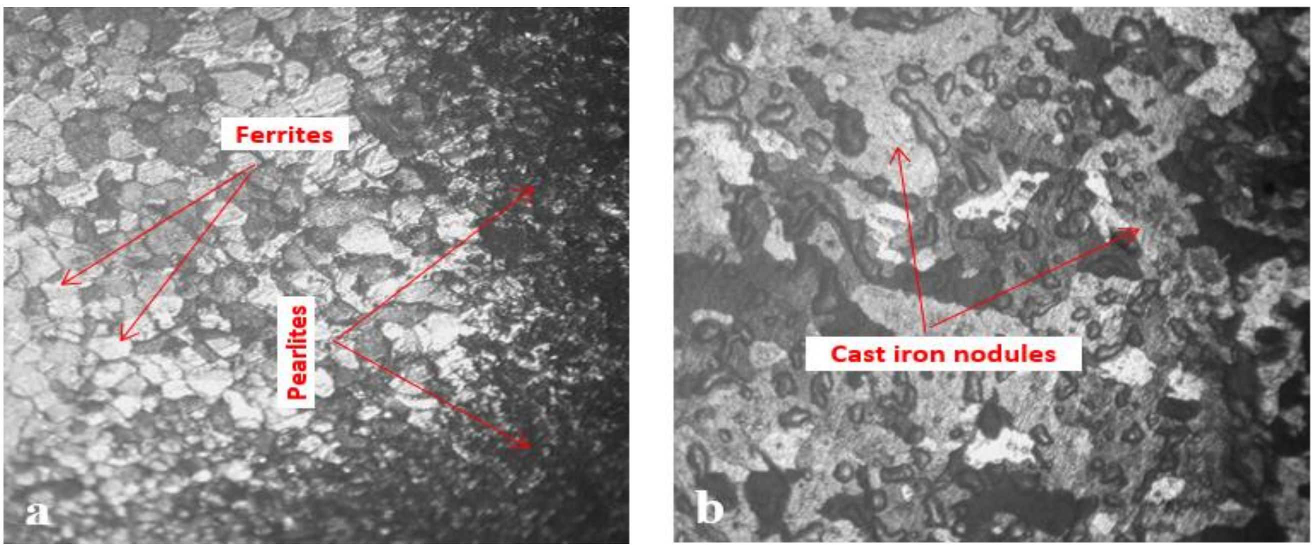


Plate 1: Microstructure of Mild Steel Weldment (x100) using AG4700 Electrode (a) Untreated (as-welded) (b) Heat Treated

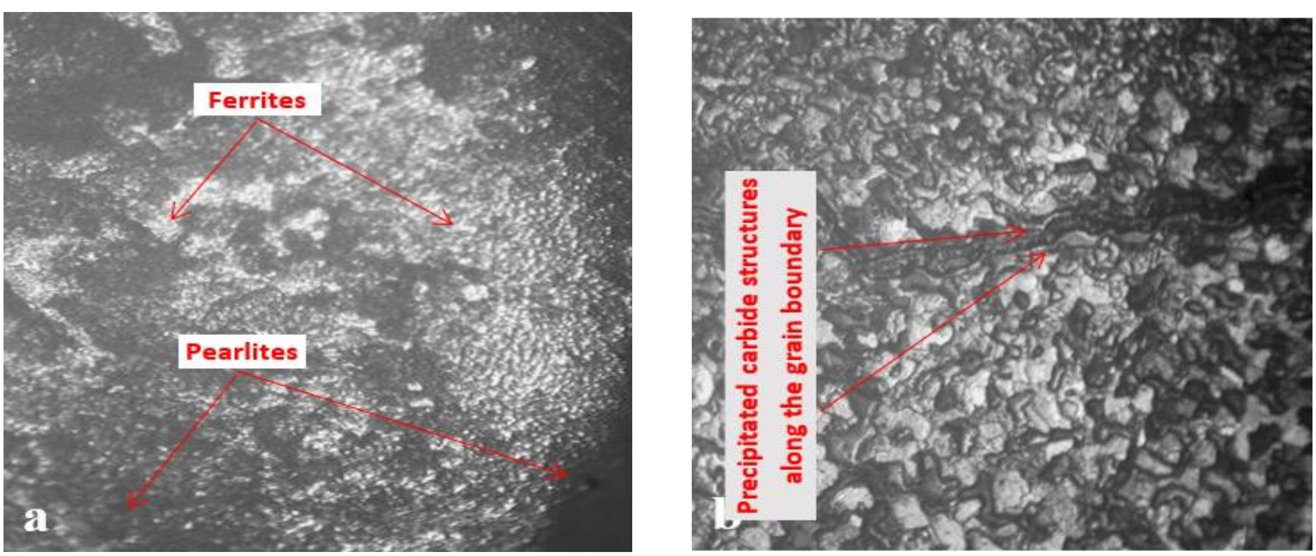
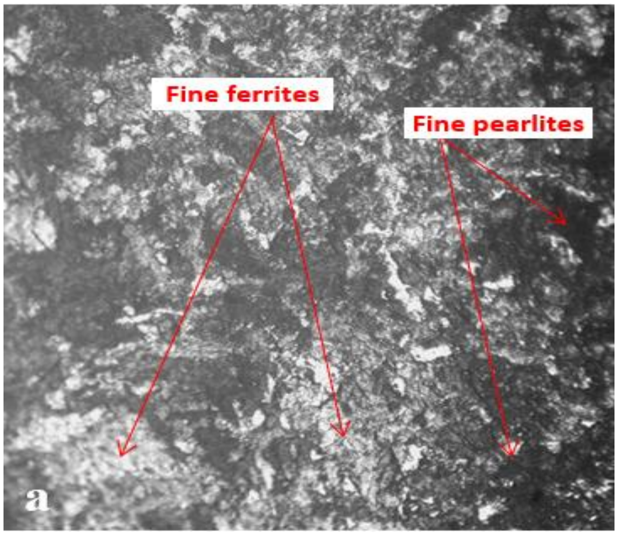


Plate 2: Microstructure of Mild Steel Weldment (x100) using E308L-16 Electrode (a) Untreated (as-welded) (b) Heat Treated



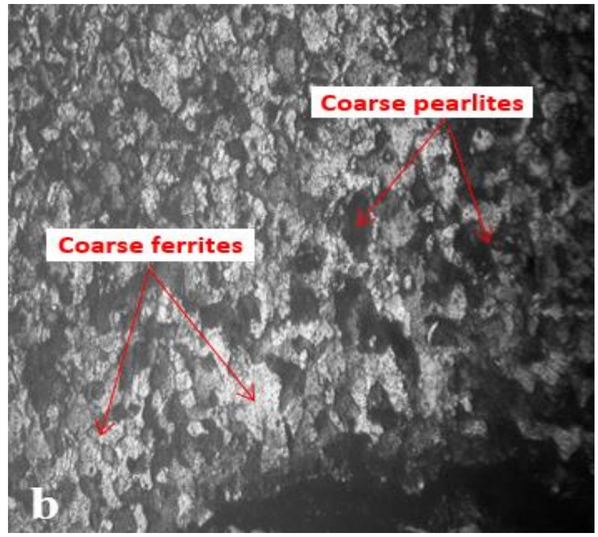
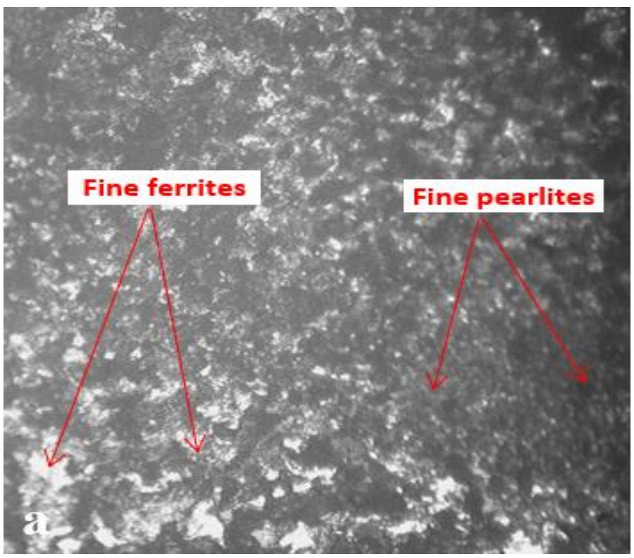


Plate 3: Microstructure of Mild Steel Weldment (x100) using E6013 Electrode (a) Untreated (as-welded) (b) Heat



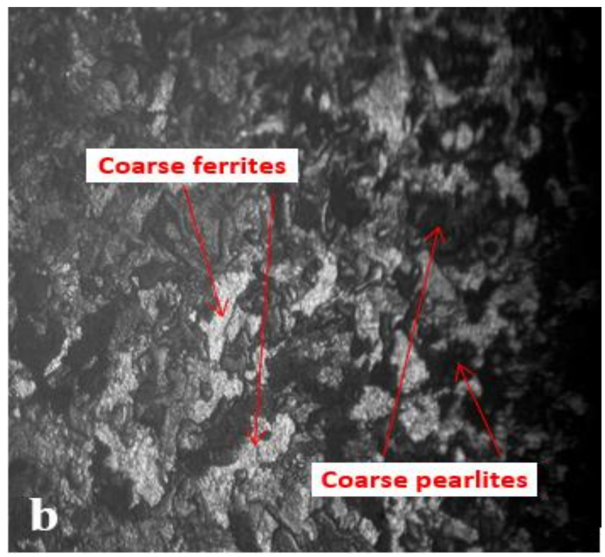


Plate 4: Microstructure of Mild steel weldment (x100) using E6014 electrode (a) Untreated (as-welded) (b) Teat Treated

3.2 Tensile Strength Results

Figure 1 presents the tensile strengths of the welds with the four electrode materials for both the thermally treated and the untreated weldments. It can be seen from the result that welding of mild steel using mild steel electrodes does not require post-weld treatment as the two mild steel electrodes (E6013 and E6014) gave the highest tensile strength in the as-welded condition. This might be due to the chemical compatibility between the electrode materials and the parent metal (Bodude and Momohjimoh, 2015; Pita and Maumela, 2021). The tensile strength of the welds with AG4700 and E308L-16 slightly increased after heat treatment but was considerably lower compared to that of the welds with mild steel electrodes for both the treated and untreated conditions. This slight increment can be attributed to the relieving of some stored residual stresses in the weldments and the transformation of ferrite and pearlite to martensite structures after thermal treatment (Dodo *et al*., 2016).

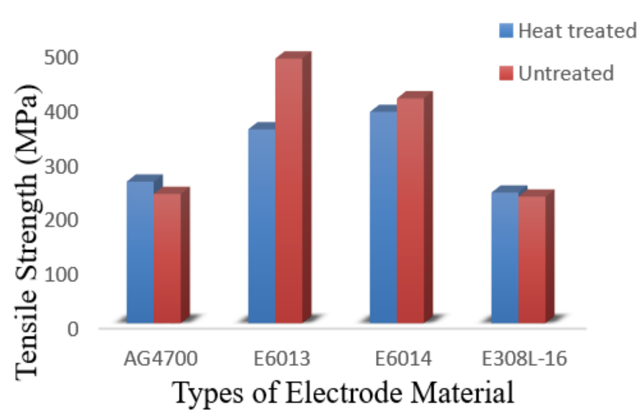


Figure 1: Tensile Strength Variation of Both the Heat-Treated and Untreated Samples with Different Electrode Materials

3.3 Impact Energy Results

Figure 2 shows the results of the impact energies of the welds with the different electrode materials in the treated and untreated conditions. It can be seen that post-weld heat treatment has a great influence on the impact energies of the welds with AG4700 and E308L-16 electrodes. The weldments become tougher after heat treatment due to the increase in their grain sizes as well as the formation of other structures such as cast-iron nodules along the grain boundaries, as in the case of the cast iron electrode, which leads to the improvement in the impact energy of the weldments (Winiczenko et al., 2018). Under the as-welded conditions, the electrode materials made of mild steel still exhibited satisfactory impact properties, thereby demonstrating their appropriateness for welding the original material. A similar finding was previously reported by Jamaludin et al., (2013).

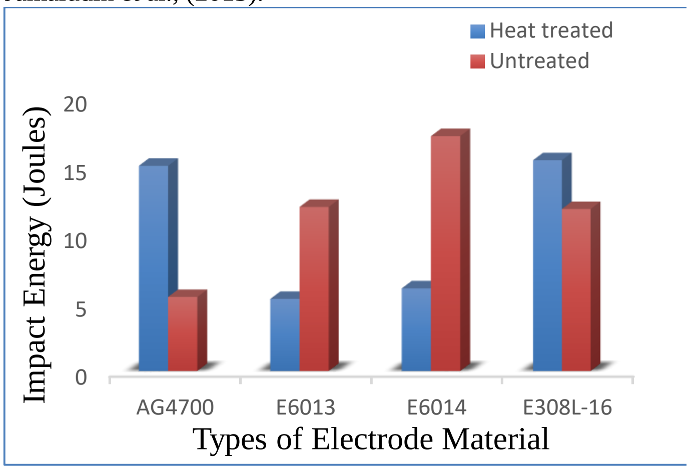


Figure 2: Impact Energy Variation of Both the Heat-Treated and Untreated Samples with Different Electrode Materials

3.4 Hardness Results

The hardness results shown in Figure 3 slightly differs from Figure 1 and 2 in the sense that the cast iron electrode (AG4700) and stainless steel (E308L-16) gave the highest hardness values in both the thermally treated and untreated conditions. However, the hardness of the welds decreases for all four electrode materials after heat treatment. The increase in the hardness value of the welds with cast iron electrode is due to the diffusion of the cast iron nodules into the austenite structure during welding which forms martensite and carbides at the weld interface while cooling (Pascual et al., 2008). The hardness is seen to have decreased after thermal treatment due to the transformation of the martensite and carbides back to austenite structures during the normalization process. Also, the high hardness value of the weldment with stainless steel electrode may be a result of the precipitation of chromium carbides within the weld joint and the heat-affected zone of the weldment (Monteiro et al., 2017).

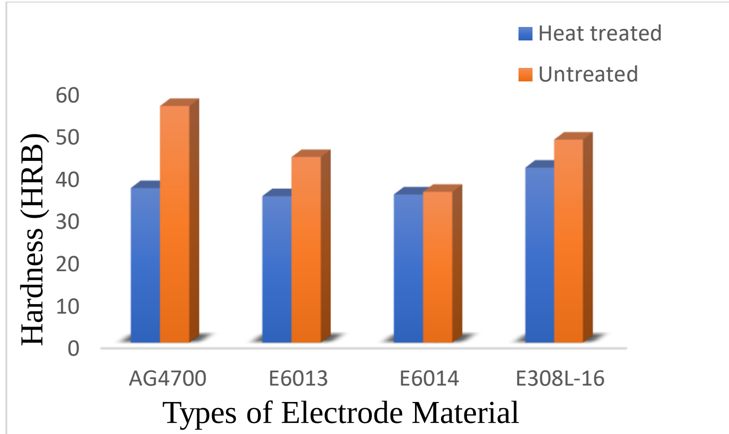


Figure 3: Hardness Variation of Both the Heat-Treated and Untreated Samples with Different Electrode Materials

4. Conclusion

Based on the outcome of the current investigation, the following conclusions were drawn

1. The types of welding electrodes and post-weld heat treatment have a great influence on the microstructural transformations as well as the mechanical properties of mild steel weld joints.
2. The microstructural examination results further explain the causes of variation in the properties of the weldment under the different welding conditions as clearly presented in Plates 1-4. The structures primarily consist of ferrite and pearlite phases in the as-weld condition. However, other phases such as nodules of cast iron and carbides were observed to form in addition to the ferrite and pearlite, especially in the case of welds with cast iron and stainless steel electrodes.
3. The tensile strength and impact energy results indicate that welding of a mild steel plate using mild steel electrodes does not require post-weld heat treatment as the untreated welds with E6013 and E6014 gave the highest tensile strength and impact energy, as compared to that of the heat-treated welds.
4. Cast iron (AG700) and stainless steel (E308L-16) electrodes produced weld joints with higher hardness values in both the thermally treated and untreated conditions as compared to that of the two mild steel electrodes.
5. It can also be concluded that post-weld heat treatment can be utilized to enhance the impact energy of mild steel weldment with either AG700 or E308L-16) electrodes

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