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The Influence of Post-Weld Tempering on the Mechanical and Microstructural Behaviour of AISI 1040 Carbon Steel Weld

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Abstract

This research examines the impact of post-weld tempering (PWT) on the mechanical and microstructural behavior of AISI 1040 carbon steel welds. To evaluate the effect of post-weld tempering on the mechanical properties of the welded joint, tensile and micro hardness tests have been performed. Also scanning electron microscopy(SEM) was used to study the surface morphology of tempered steel weld samples. The findings revealed that the PWT samples exhibited greater ductility, whereas the sample tempered at PWT-5500C exhibited superior tensile strength (approximately 17% greater) than the other post-tempered and as-welded samples. The As-welded samples were found to have the highest hardness; this is as a result of the rich carbide precipitation at the grain boundaries caused by the welding process. The result further showed that the ductility and toughness properties of AISI 1040 carbon steel welds can be improved by post-weld tempering. The SEM study revealed that the degree of lath marten site formation increases with the tempering temperature. In addition, the studies further revealed that tempering AISI 1040 carbon steel welds at a temperature of 700°C produces the optimal equilibrium of mechanical properties for industrial applications.

1. Introduction

Carbon steel weld is a welded joint between two carbon steel parts. Welding is a technique that employs heat or pressure to join metal components. Carbon steel is an excellent material for welding due to its durability and strength. It plays a crucial role in the production of vast applications in the manufacturing industry [1]. Mechanical joining includes adhesive bonding, welding, brazing, and soldering [2]. While welding is applicable for joining metals, the act of joining steel is deemed more crucial. Steel, a crucial component of industrial and infrastructure development, is frequently viewed as an indicator of advancement. Welding is a fundamental process in the manufacturing and construction industries, playing a pivotal role in joining various materials to create structures and components with diverse applications. One of the key concerns in welding is the alteration of the material's microstructure and, consequently, its mechanical properties in the heat-affected zone (HAZ). In the realm of welding, AISI 1040 carbon steel is a commonly used material due to its excellent weld ability and mechanical properties. The mechanical behavior of AISI 1040 carbon steel welds is critically dependent on factors such as welding parameters and post-weld heat treatments. Understanding the intricate relationship between post-weld tempering and the mechanical properties of AISI carbon steel welds is pivotal for achieving welds that meet or exceed the required specifications in terms of strength, ductility, and toughness. Through a comprehensive analysis of microstructural changes, hardness variations, and mechanical testing, the main focus of this research is to investigate the influence of post-weld tempering, a heat treatment process, on the mechanical behavior of AISI carbon steel welds. Tempering, a controlled reheating process, is known to have a profound impact on the microstructure and mechanical properties of welds. By examining the effects of tempering on AISI carbon steel welds, this research also seeks to provide valuable insights into optimizing welding processes and enhancing the performance and reliability of welded components in various engineering applications and also to provide a foundation for informed decision-making in the field of welding technology, ultimately contributing to safer and more robust structures. Post-weld tempering (PWT) is a thermal treatment used on welded steel structures. Its main goals are to reduce residual stresses and brittle fracture. Following thermal treatment, the quantity of residual stress and deformation in the weld is drastically reduced. Post-weld heat treatment (PWHT) refers to any heat treatment that is administered to a welded joint after welding [3, 4]. The post-weld thermal treatment of carbon steel welds, which modifies their mechanical and microstructural properties, is one of the most crucial production steps [5]. Welding's significance to modern industrialization has led to its pervasive application in the industrial process. Several studies have demonstrated that, with the proper heat treatment procedure, welded steel constructions can attain the required mechanical properties [6 - 27]. The focus of this study is to determine the influence of post-weld tempering on the mechanical characteristics of the studied carbon steel weld.

2. Materials and Methods

2.1 Materials

The chemical composition of the AISI 1040 carbon steel plate was determined by X-ray fluorescence spectroscopy, which is a technique that uses the interaction of X-rays with a sample to identify the elements present and determine their concentrations [36]. The composition of the steel is summarized in Table 1. An E6013 electrode, which is a low-hydrogen mild steel electrode, was used for the welding process as prescribed in the study [26]. This electrode is suitable for welding carbon steels.

Table 1 *1040 Carbon steel composition*

Element	Composition (%)
C	0.39
Mn	0.69
P	0.03
S	0.04
Si	0.2
Fe	98.65

2.1 Sample preparation

The as-received AISI 1040 carbon steel plate with a thickness of 5 mm was mechanically cut into eight sections measuring 75 mm in length and 7 mm in width. Before welding the samples, two of the 75mm samples were arranged to create a single-butt junction between the two samples.

2.2 Welding Techniques

75mm by 7mm carbon steel samples were welded with electric arc welding. Wire brushes were used to remove dirt and other surface impurities. To create a proper joint, we also aligned and squared off the edges of the base metal. E6013 electrodes were used in the welding process to weld the pair samples in a butt weld setting based on the literature studies [28, 29].

2.3 Post Weld Tempering Process

Following the completion of the welding process, the samples were then heated to temperatures of 550^{0}C, 650^{0}C, and 700^{0}C respectively. An industrial muffle furnace with a heating specification of 12000C was employed for the thermal heat treatment process.

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2.4 Mechanical properties

The mechanical properties, such as tensile and hardness, were measured on the AISI 1040 carbon steel weld.

2.4.1 Tensile Test

The Instron Universal Testing Machine was used to conduct the tests. The tensile characteristics of a material are measured using this destructive method. The standard test technique for tensile characteristics of carbon steel under an axial load is ASTM A370, thus a specimen of standard shape and dimensions is prepared in accordance with this standard.The electro-mechanical test mechanism in the tensile testing equipment applies uniform uniaxial loading to test specimens. The system impacts forces between 10 and 100 kilo newton (KN), holds specimens, and analyzes the forces (stresses) and deformations (strains) that occur in order to conduct load against elongation (stress against strain) test. The stresses and strains are measured with highly accurate load and strain transducers that generate an electrical signal proportional to the stress or strain exerted. Stress(σ), strain(Ɛ), and other computed material characteristics were determined, analyzed, and reported. The material's stress and strain were calculated using the following equations [30]. Below is the schematic diagram of the tested samples.

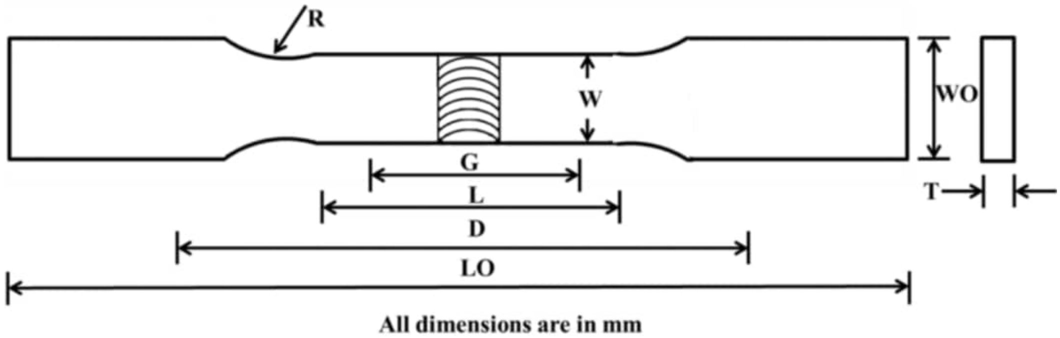

Fig.1 *Schematic diagram of the welded sample*

Where,
W- Width of the narrow section =14
WO - Width overall = 7
T- Thickness = 5
R - Radius of fillet = 72
G- Gage length = 55
L = Length of the narrow = 52
D = Distance between the grip =110
LO = Length overall = 150

$$\sigma = \frac{F}{A} \quad (1)$$

$$\varepsilon = \frac{L - L_0}{L_0} \quad (2)$$

Where,
F = Applied force (N)
A= Cross-sectional area (mm^2)
L= Instantaneous length of the specimen (mm)
L_0 = initial length of the specimen (mm)

Figure 2 shows the setup for the tensile test process used for the experimental process.

Fig. 2 *Tensile test set-up*

2.4.2 Hardness Test

The ASTM E-18 standard test method is used to produce standard-sized and shaped specimens for evaluating the hardness of carbon steel. The samples were thoroughly cleaned and polished using abrasive paper with particle sizes of 240 and 600. Successful clamping and loading of AISI 1040 carbon steel weld samples was achieved. In the initial stage of each test, an indenter, typically a diamond cone or steel ball, is lightly pressed into the surface of the investigated material. After the primary load has been applied for a while, the secondary load will remain in place.Three replicate indentations were made on the sample at various points within the centre of the carbon steel surface and a mean value for the hardness were further obtained. Equation 3 was used to estimate the hardness value.

$$\mathrm{HRC} = \mathrm{N} - \frac{\mathrm{d}}{\mathrm{s}} \quad (3)$$

Where
N and s = scale factors; and d = penetration depth measured from the zero point (in mm).

2.5 Surface Morphology

To perform a morphological study on the samples, the JEOL JSM 7600F scanning electron microscope (SEM) was used. Prior to the examination, the samples were prepared to fit in the specimen chamber and were then mounted securely on a specimen stub. The samples were further coated with a thin layer of platinum, which is an electrically conductive material deposited on the sample using low-vacuum sputter coating. The platinum coating helps to eliminate electrostatic charging and improve the image quality.

3. Results and Discussion

3.1 Tensile Properties

Tensile features such as tensile strength (TS), elongation, and stress vs. strain curves, are determined and presented in Figures 1,2 and 3. As observed in Figure 1 the Tensile Strength increased with tempering temperature, and the highest tensile strength (3000 N/mm^2) was obtained at 550 °C. Beyond 550 °C,the tensile strength tends to decrease. The behavior trend is attributed to the carbide precipitate at the grain boundaries [31]. A similar phenomenon was reported in the study carried out by Fasogbon et al.[32].

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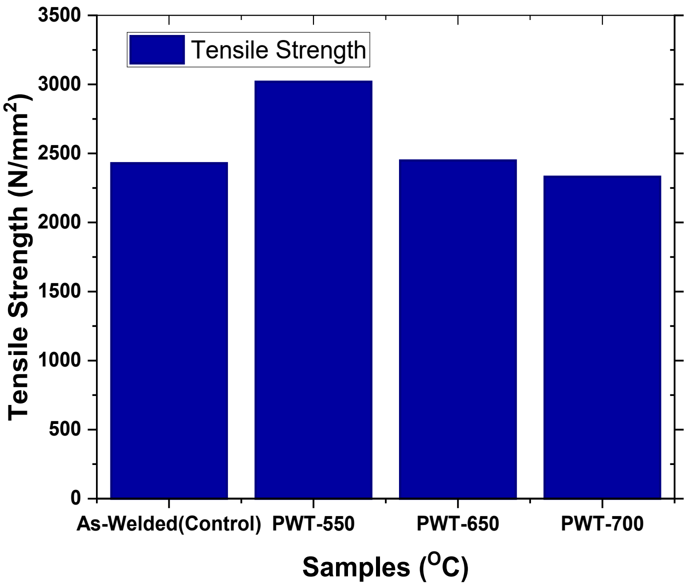


Fig. 2 *Plot of tensile strength of test samples*

A comparison of the elongation of as-welded and PWT samples is shown in Figure 3. The elongation increased as a result of the post-welding thermal treatment process. As a result, the plasticity of the PWT samples increased [32]. To improve the mechanical properties of the material, effective post-weld tempering is required.

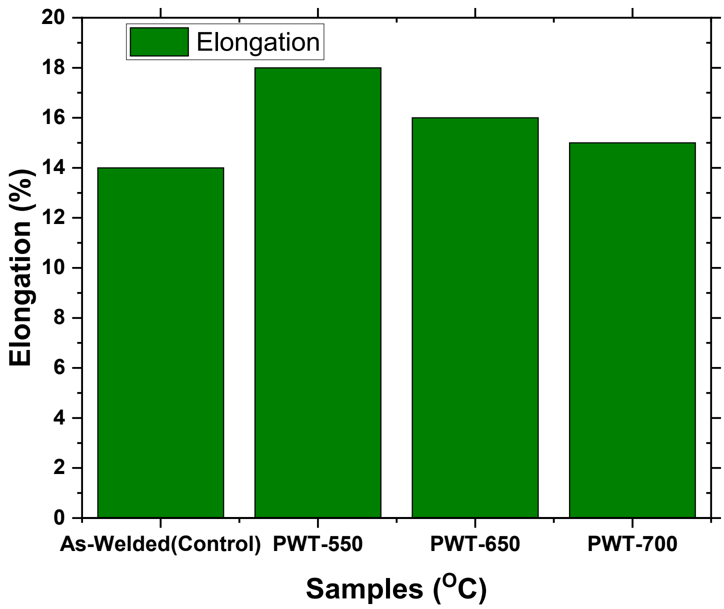


Fig. 3 *Plot of elongation of tested samples*

The curves of stress versus strain are also shown in Figure 4. Observations from the plot showed that the flow stress increased as the elongation to fracture decreased in post-weld-tempered samples. Post-weld samples exhibit a superior mechanical behaviour due to their high strength and minimal plastic deformation.

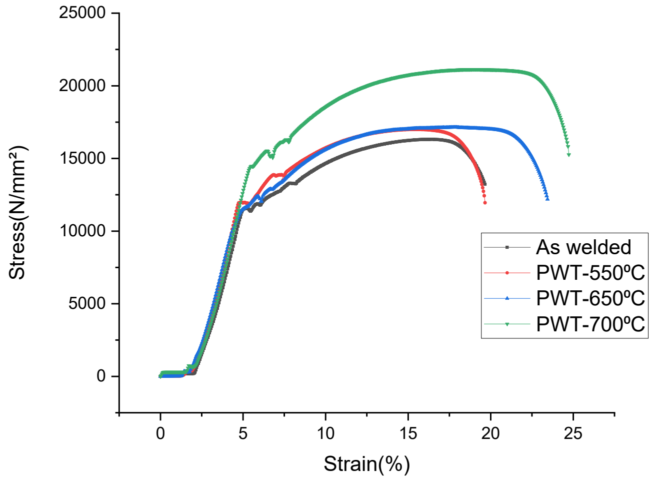


Fig. 4 *Plot of stress-strain of tested samples*

3.2 Hardness Properties

The Rockwell hardness (HRC) test was conducted on each of the samples. Figure 5 depicts the hardness values of the as-welded and post weld tempered samples. As observed, the as-welded samples were shown to have a greater hardness value than post-welded tempered samples. This shows that post-weld tempering processes have decreased the residual stresses created in the welded steel during welding and have contributed to the overall drop in hardness value. Reducing the amount of carbide in the samples by a tempering operation after welding might also facilitate the homogeneous dispersion of carbon atoms [33, 34]. This result is in agreement with the study conducted by Mishra et al. [35] on tempered high-strength steel; it has been shown that increasing the tempering temperature causes a greater reduction in hardness value.

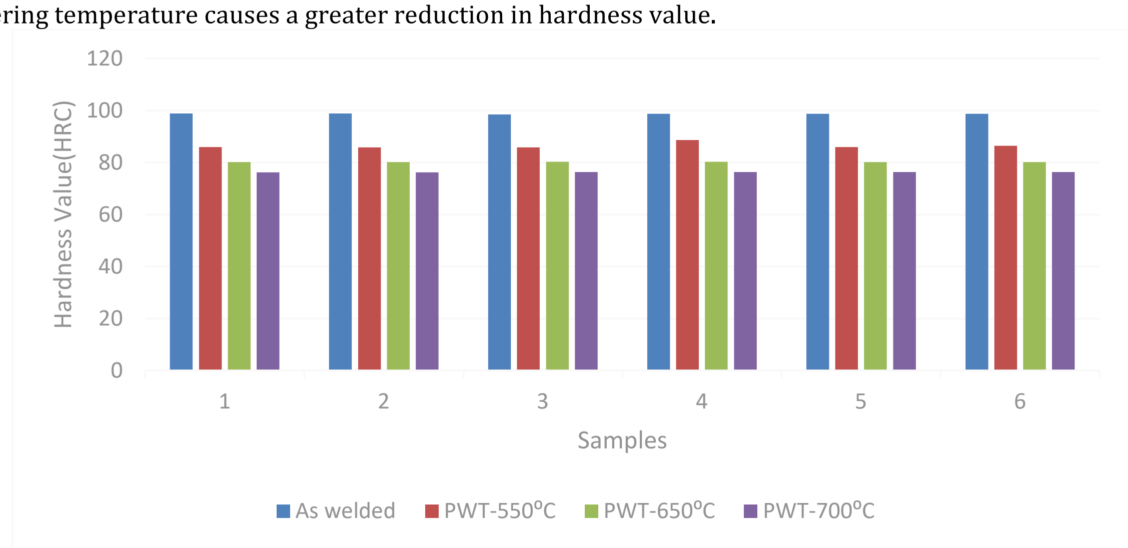
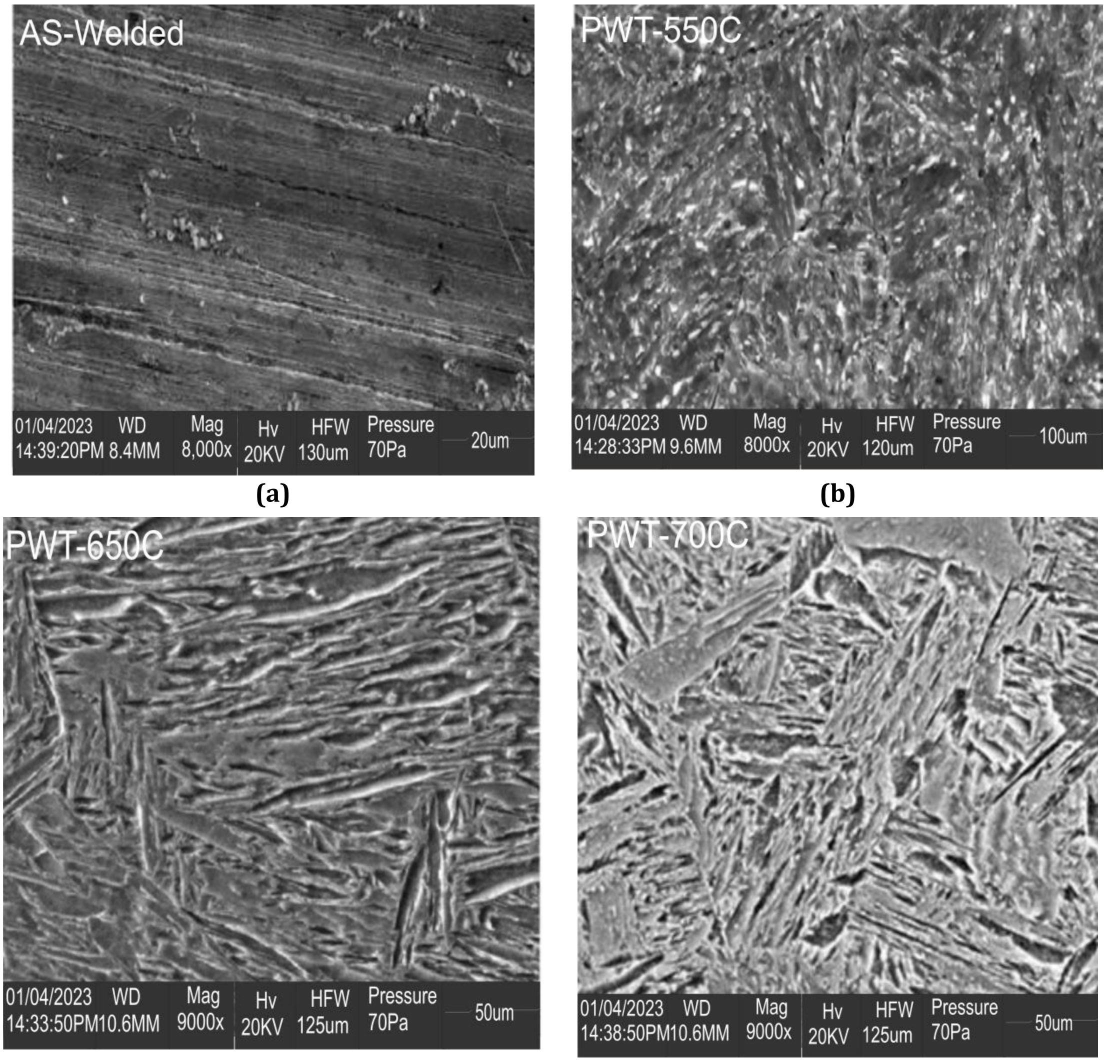


Fig. 5 *Hardness test of AISI 1040 carbon steel welded samples*

3.3 Morphological SEM Study

A scanning electron microscope (SEM) picture of 1040 carbon steel samples that have been welded and then tempered at various tempering temperatures is shown in Figure 6(a–d). The SEM images show the welded metal zones (WMZ). Figure 6(a) displays the SEM shape of the sample that has been welded. It has a ferrite-pearlite microstructure because of carbide precipitation. Figures 6(b-d) show the microstructures of the tempered samples, revealing that the degree of lath marten site formation increases with the tempering temperature.



(c) **(d)**

Fig. 6 *SEM image of the As-welded and tempered AISI 1040 carbon steel weld(a) As-welded; (b) Tempered at 550⁰ C; (c) Tempered at 650⁰ C; and (d) Tempered at 700 ⁰ C*

4. Conclusions

The effect of post-weld thermal treatments on the integrity of AISI 1040 carbon steel electric arc welds has been studied. The study revealed that tempering carbon steel at a higher temperature decreases both thermal deformation and residual stress, whereas welding causes deformation and induces residual stress and strain in the welded pair, thus altering the mechanical properties of the welded joint. The findings show that, as a result of the welding process the material's strength, toughness, and ductility decreases as evidence from the as-welded sample having the lowest tensile strength, elongation, and flow stress, but a modest increase in hardness and brittleness. All the post-tempered samples exhibited a higher ductility than the as-welded samples, but the PWT-550⁰C samples had approximately 17% greater tensile strength. Post-weld tempering reduces the hardness of AISI 1040 carbon steel and increases its toughness. This is likely because welding precipitates a great deal of carbide along the grain boundaries. It has also been demonstrated that post-weld tempering of AISI 1040 carbon steel welds increases their ductility and toughness properties. The SEM study revealed that the degree of lath marten site formation increases with the tempering temperature. In addition, the research revealed that AISI 1040 carbon steel welds reach the optimal balance of mechanical properties when tempered at 700 °C, making it suitable for a various industrial application.

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Conflict of Interests

The authors declare that there is no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

Author contributions

B.U.O *conceptualized the research,* ***B.U.O*** *and* ***S.O.O.*** *carried out the experiment. And* ***B.U.O*** *and* ***S.O.O.*** *drafted the manuscript and wrote the final manuscript. All authors reviewed the manuscript.*

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