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Original Research Article

Enhancement of Mechanical Integrity in Arc-Welded AISI 1035 Steel Through Post-Weld Tempering for Oil and Gas Applications

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Abstract

The use of welded medium-carbon steels is increasing within the oil and gas industry, which requires these materials to resist corrosive environments, extreme temperatures and cyclic loading. This investigation analyzes the effects of Post Weld Heat Treatment (PWHT) upon the mechanical performance of manually arc-welded AISI 1035 (UNS G10350) steel. Rectangular test pieces were machined from carbon-steel piping that had been manually arc-welded using electrode type E6013. These samples were preheated to a temperature of 100 °C, then subsequently heat treated at 300 °C, 450 °C and 650 °C for 1 hour prior to cooling in still air. Mechanical performance of each specimen was assessed via tensile testing utilizing a Testometric machine and hardness assessment using Rockwell testing in accordance with ASTM E18. The results indicated an increase in tensile strength with increasing temperature during heat treatment and maximum tensile strength at 650°C; this was due to the formation of precipitated carbides and stabilization of the weld structure through heat treatment. The stress-strain plots illustrated an increase in flow stress that corresponded to a reduction in the elongation to failure for PWHT specimens; a trend indicative of a strength-ductility trade off. Decreases in Rockwell hardness relative to the as-welded condition were exhibited across all heat-treated conditions; this reflected both relief of residual stresses present within the heat affected zone and tempering of martensitic microstructures within this zone. Overall, the results indicate that heat-treatment parameters may be selected to decrease hardness (and therefore associated SSC/HIC risks), while simultaneously increasing strength for load bearing applications within oil and gas fabrication and/or repair operations involving AISI 1035 components. The relationship between PWHT parameters and material properties will aid in establishing practical guidelines for specification of PWHT within oil and gas fabrication and/or repair operations involving AISI 1035 components.

Keywords: AISI 1035, post-weld heat treatment, tempering, tensile properties, hardness, hydrogen damage, sulfide stress cracking, oil and gas.

1. INTRODUCTION

The growing demand for energy has pushed the oil and gas industry into increasingly severe operating environments characterized by extreme temperatures, corrosive media, and cyclic loading. To operate efficiently, safely, and with minimal environmental impact, all equipment used in oil and gas production must be designed and fabricated to withstand these conditions. Arc welding is the most common method for fabricating and repairing critical equipment in this sector. Among the steels used, AISI 1035 is frequently selected because it offers a favorable balance of strength, toughness, and cost compared with many alternatives [1–10].

Arc welding, however, alters the microstructure of the base material. The intense heat input followed by rapid cooling creates a heterogeneous weldment with distinct regions and steep property gradients. In medium-carbon steels such as AISI 1035, portions of the heat-affected zone (HAZ) can transform to untempered martensite. Relative to the base metal, this phase is harder but less ductile and less tough, increasing the likelihood of crack initiation and propagation. In service, welded joints may also face critical failure modes, including sulfide stress cracking (SSC) in sour environments, hydrogen-induced cracking (HIC), and fatigue under dynamic loads [14, 15].

Post-weld heat treatment (PWHT), particularly tempering, is widely used to mitigate these issues [16, 17]. PWHT involves heating the weldment to a subcritical temperature to temper the brittle martensite in the HAZ into a more stable, ductile microstructure (e.g., tempered martensite) [18]. Tempering also reduces residual stresses and enhances toughness both essential for components operating in the harsh conditions typical of oil and gas service [19]. Although the benefits of PWHT are well recognized, a clearer, quantitative understanding of how tempering temperature and time affect the final mechanical properties of arc-welded AISI 1035 steel is needed to optimize design and fabrication practices for critical equipment [20].

2. MATERIALS AND METHODS

2.1 Materials

The materials used in this study were selected based on local availability. The carbon steel pipe and E6013 electrodes were procured from Chemz Limited, Warri, Delta State, Nigeria. Additional equipment and consumables included an electronic balance, a muffle furnace, tongs, a grinding machine, distilled water, ethanol, acetone, beakers, and emery papers. The chemical compositions of the steel and the electrode are presented in Table 1

Table 1: Chemical Composition of UNS G10350 carbon steel and electrode

Element	**C**	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Cu**	**Mo**	**Fe**
carbon Steel	0.342	0.61	0.0010	0.0029	0.233	0.144	0.178	0.075	0.050	98.36
E6013 Electrode	C	Mn	Si	S	P					
	≤0.12	0.3-0.6	≤0.35	≤0.35	≤0.040					

2.2 Methods

2.2.1. Welding Process

Rectangular specimens were machined from the carbon steel pipe to nominal dimensions of 170 × 15 mm (tensile testing), and 70 × 10 mm (hardness testing). All joints were produced by electric arc welding using E6013 electrodes. Prior to welding, the faying and adjacent surfaces were wire-brushed to bare metal to remove oxides, oil, and loose scale, minimizing the risk of porosity and lack of fusion. With each workpiece secured on a flat fixture, the electrode was held at a 60–80° travel angle in the holder. Following the procedures of Farhadi *et al.*,[21], a butt weld was deposited by striking the arc and traversing along the prepared edges. After welding, the specimens were cooled in still air to room temperature. Once solidified, slag and spatter were removed by chipping and wire brushing. Representative welded specimens are shown in Figures 1 and 2.

Fig. 1: Samples of UNS G10350 carbon steel pipe weld for tensile testing

Fig. 2: Samples of UNS G10350 carbon steel pipe weld for hardness testing

2.2.2 Post Weld Heat Treatment Process

The samples were preheated to 100 °C to promote sound, defect-free welds. Post-weld tempering was then performed at 300 °C, 450 °C, and 650 °C, each with a holding time of 1 hour, followed by cooling in still air. All heat treatments were carried out in an SX-4-10 muffle furnace at the specified temperatures.

2.2.3 Mechanical properties

The mechanical properties such as the tensile and hardness of the carbon steel weld were evaluated. The tensile test is a standard test which was conducted using the Testometric Testing machine. The yield and tensile strengths, the percentage elongation and the percentage reduction in area was determined. The tensile strength is given according to [22] as:

$$UTS = {}^{P_{max}}/_{A_0} \quad (1)$$

Where P_{max} = maximum load applied

A_o = Original Cross-sectional area.

The percentage elongation after fracture is given as

$$\varepsilon\% = l_u - l_o \times {}^{100}/_{l_o} \quad (2)$$

Where ℓ_o = the original gauge length

ℓ_u = the final gauge length.

The percentage reduction in area is also given as

$$RA = \frac{A_o - A_u}{A_o} \times 100 \quad (3)$$

Where A_o = the original cross-section area

A_u = the minimum cross-sectional after fracture.

The hardness of carbon steel pipe is measured using standard-sized and rectangular-shaped specimens fabricated in accordance with ASTM E-18. Rockwell hardness machine was used to carry out hardness test, on the carbon steel weld where each of the samples were, indented five times in five different regions of each of the surface using a diamond indenter. The results from Rockwell hardness machine were summed up and average calculated which represents the hardness value of each of the carbon steel weld

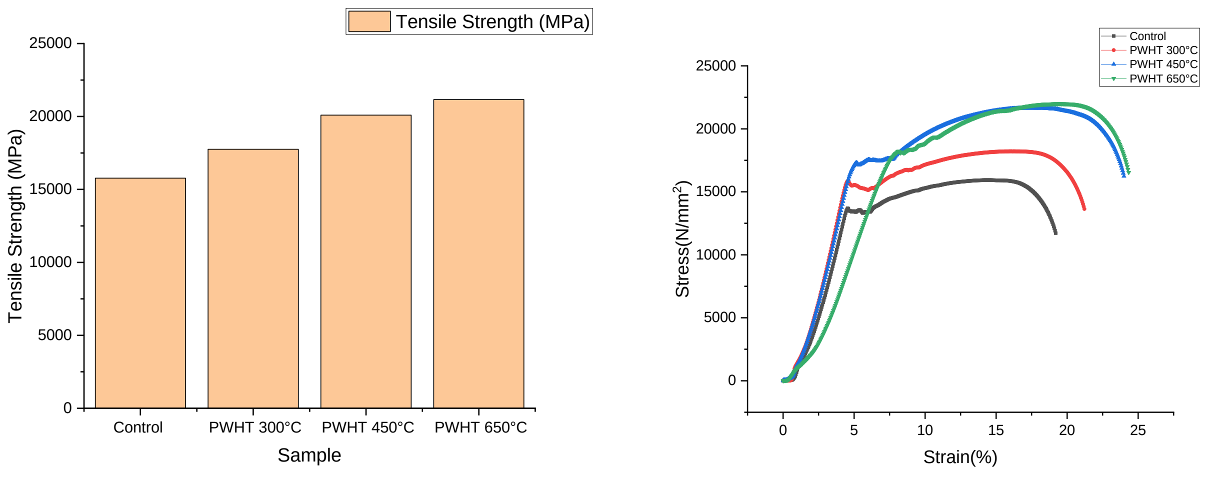
3. RESULTS AND DISCUSSION

3.1 Mechanical Properties Analysis

The mechanical properties, namely tensile and hardness tests, of the as-welded and post-welded heat treatment (PWHT) samples are determined and presented.

3.1.1 Tensile Properties

The tensile strength and stress vs. strain curves, are evaluated and presented in Figures (a-b), respectively. As depicted in Fig. 3a, the Tensile strength increased with increasing PHWT temperature, and the highest Tensile strength was obtained at 650 °C. The behavior trend is ascribed to the carbide precipitate at the grain boundaries [24]. A similar phenomenon was reported in the study carried out by Fasogbon *et al.*, (2016). Similarly, Figure 3b shows the stress vs. strain curves. As observed, the PWHT samples showed an increase in flow stress as the elongation to fracture decreased. The behaviour characteristic of the PWHT samples is as a result of their high strength and little plastic deformation.



(a) (b)

Fig. 3: Tensile characteristics (a)Tensile strength and (b) stress vs strain curves

3.1.2 Hardness Properties

The Rockwell hardness (HB) test was conducted on each of the samples. Figure 4 shows the hardness values of the as-welded (Control) and PWHT samples. As revealed, the as-welded samples were shown to have a greater hardness value than PHWT samples. This shows that PHWT 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 [24]. This result is in congruent with earlier study conducted by Mishra *et al.*,[25] on tempered high-strength steel, it was shown that increasing the tempering temperature causes a greater reduction in hardness value.

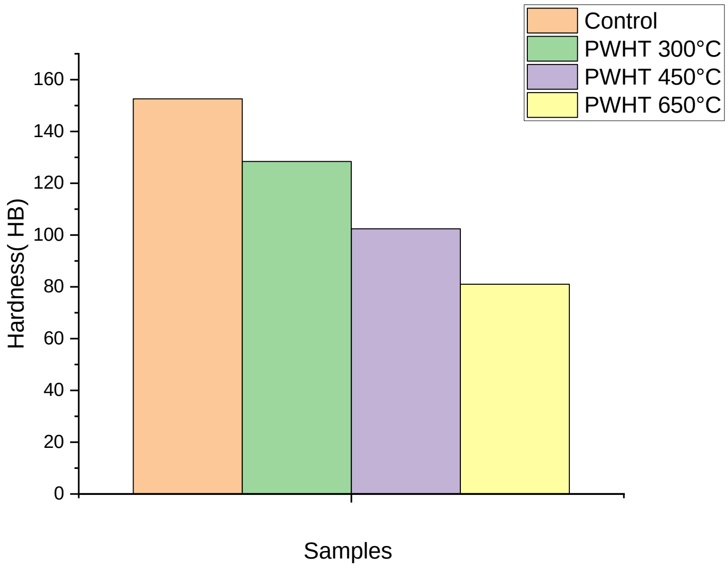


Fig. 4: Hardness measurement of Carbon steel welded pipe samples

CONCLUSIONS

The Oil & Gas industry is now reliant upon welded medium-carbon steels that are able to withstand corrosive media, thermal cycling and cyclic loading. This study investigated how post-weld tempering (PWHT) affected the mechanical integrity of manually welded AISI 1035 (UNS G10350) steels. Rectangular test specimens of AISI 1035 steel were produced from carbon-steel pipes via manual metal arc welding using an E6013 electrode. Samples were pre-heated to 100°C, followed by 1 hour of tempering at 300°C, 450°C, and 650°C with air cooling to ambient. Tensile properties of the samples were determined using a Testometric instrument, whereas hardness measurements were performed in accordance with ASTM E18 via Rockwell testing. Results demonstrated that, as expected, tempering enhanced tensile strength with increasing temperature and that the greatest strength occurred after tempering at 650°C, which is consistent with precipitation and stabilization of carbides present in the weld microstructure. The stress-strain curves of the PWHT samples indicated greater flow stresses than the non-PWHT samples, but lower elongations to failure, suggesting a trade-off between strength and ductility. The Rockwell hardness values obtained from all tempered conditions were significantly less than those for the as-welded control samples, indicating both residual-stress relief and tempering of martensite within the heat-affected zones (HAZ).

In addition to this, the results demonstrate that properly selected PWHT procedures may be used to decrease hardness (therefore reducing potential risks associated with SSC/HIC), while simultaneously increasing strength for use in load bearing applications. The trends in process-property behavior reported here will provide useful information for establishing guidelines for selecting appropriate PWHT procedures for fabrication and repair of AISI 1035 components used in Oil & Gas services.

Conflict of Interest: The author confirms that there is no conflict of interest to declare.

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