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Investigation of Influence Heat Treatment on Mechanical Properties of Welded Joints

دراسة تأثير المعالجة الحرارية على الخواص الميكانيكية للوصلات الملحومة

Wannees A Shabeesh[#1], Muftah. O Elfetory[#2], Mohamed RG. Rahuma[#3]

[1,2]Mechanical Engineering Department, High institute of Engineering, Technology Zliten, Libya
[3]Libyan Center for Plasma Research affiliated with the Libyan Authority for Scientific Research Tripoli, Libya.

Email: wanissh@yahoo.com

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1. ABSTRACT:

This research investigates the impact of post-weld heat treatment (PWHT) on the mechanical properties of butt- welded low carbon steel joints. Welding processes can induce thermal stresses and microstructural changes that negatively affect mechanical performance. The study utilized Shielded Metal Arc Welding (SMAW) with controlled parameters and an E10-60 electrode. Non-destructive testing (NDT) methods, including Dye Penetrant Testing, UV Inspection, and Magnetic Field Detection, were applied to assess weld quality before and after welding. Subsequent heat treatment, specifically tempering at 550°C for 20 minutes followed by slow air cooling, was performed to balance hardness and toughness. Microstructural analysis and microhardness testing were conducted to evaluate the effects of the heat treatment on the welded joints. The results indicate that tempering significantly reduces hardness, particularly in the Heat-Affected Zone (HAZ), and enhances toughness and ductility, which are crucial for preventing cracking and failure in welded joints.

KEYWORDS: Welding, Low Carbon Steel, (PWHT), (NDT), Microhardness, Microstructure.

2. INTRODUCTION:

Welding is a foundational process in modern manufacturing and construction, critical for ensuring structural integrity and performance of conjoined components. In particular, low-carbon steels are widely favored because of their balanced mechanical properties and cost-effectiveness. However, the high thermal cycles inherent in welding lead to pronounced microstructural transformations and residual stresses, which can degrade toughness, introduce brittleness, or create nonuniform hardness distributions across the weld region [1].

To mitigate these adverse effects, post-weld heat treatment (PWHT) is commonly employed. PWHT can temper martensitic or bainitic microstructures, reduce residual stress, and promote microstructural homogenization, thereby improving ductility and toughness while controlling hardness gradients [2, 3]. For instance, studies have shown that applying PWHT to welded low- carbon steel joints can yield increases in tensile strength, yield strength, and elongation compared to the as-welded state [4]. Moreover, in thicker weldments, PWHT at optimized conditions has been demonstrated to significantly enhance impact toughness without excessively reducing hardness [5].

Despite its advantages, PWHT must be judiciously applied: if temperature or holding time are too high, there is a risk of grain growth, carbide coarsening, or over tempering, which may reduce strength or hardness and degrade performance [6]. The cooling strategy after PWHT (e.g., furnace cooling, air cooling, quenching) further influences the resulting microstructure and mechanical balance [7].

In this research, butt welds on low-carbon steel are fabricated under controlled welding parameters (electrode type, current type, groove angle, and root gap). Non-destructive testing methods are applied to assess weld quality prior to heat treatment. Thereafter, PWHT is conducted under selected regimes, and the resulting changes in microstructure, microhardness, toughness, and other mechanical properties are systematically evaluated. The objectives are: (i) to elucidate how PWHT influences the balance between hardness and toughness in welded joints, (ii) to map microstructural evolution before and after treatment, and (iii) to recommend optimal PWHT conditions for low-carbon steel butt welds.

3. METHODOLOGY:

3.1. Chemical Composition: The table (2.1) shows the percentage of carbon in the steel sample used.

Table (2.1): Chemical Composition.

Element	Fe	C	Si	Mn	P	S	Cr
Percentage	0.798	0.159	0.0259	0.430	0.0212	0.0438	0.106

Advantages of This Composition are Excellent weldability, High ductility and formability, Cost-effective, Ideal for general-purpose applications [10].

2.2 Preparation of Butt Weld: Single V-Groove Butt Joint, this is most suitable for material thicknesses between 6 mm and 20 mm. The figure (2.1) shows the method of preparing the sample before the welding process [11].

Edge Preparation Details (as per ISO 9692-1): Step-by-Step Preparation:

1- Marking and Cutting: Use a band saw, oxy-fuel, or plasma cutter to shape the plate edges.

2- Beveling: Create a 30° bevel on each side using a beveling machine or angle grinder.

3- Cleaning the Edges: Remove any rust, oil, or scale using a wire brush or grinder.

4- Adjusting Root Gap: Ensure a root gap of 2–3 mm using spacers or clamps.

5- Tack Welding: Apply temporary tack welds to hold alignment before full welding.

6- Inspection: Use gauges and straight edges to verify angle, root gap, and alignment [11].

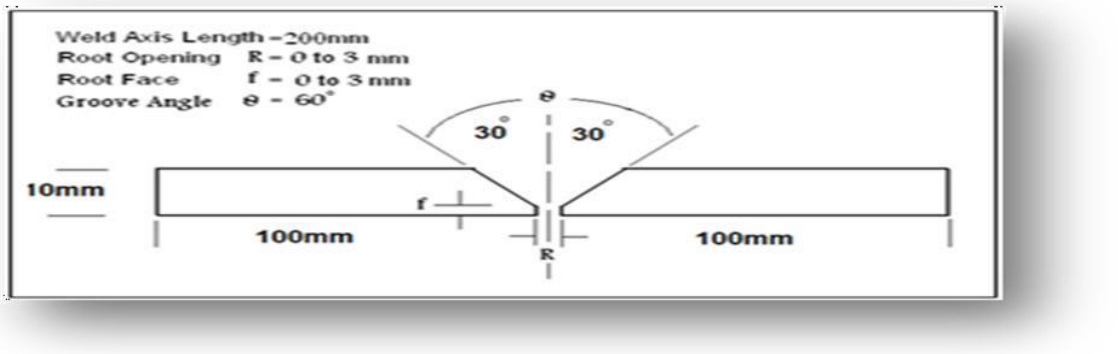

Figure (2.1): Single V-Groove Butt Joint.

2.3. Welding Process:

The figure (2.2) shows the equipment used in the SMAW welding process.

1. Butt welding using E10-60 electrode with AC arc.
2. Minimum groove angle: 60°.
3. Material: low carbon steel, thickness 10 mm.
4. Welding performed on one side only with a clearance and a minimum gap of 2 mm.
5. Electrode Negative (DCEN).

2.3.1. **DCEN stands for:** Direct Current Electrode Negative.

This means the electrode is connected to the negative (−) terminal, and the workpiece (base metal) is connected to the positive (+) terminal.

Figure (2.2): SMAW Welding.

2.3.2 **SMAW (Shielded Metal Arc Welding) / Stick Welding:**

SMAW, or stick welding, is a manual arc welding process using a consumable electrode coated in flux to create the arc and shield the weld from contamination. The figure (2.3) shows the sample after the welding process [9].

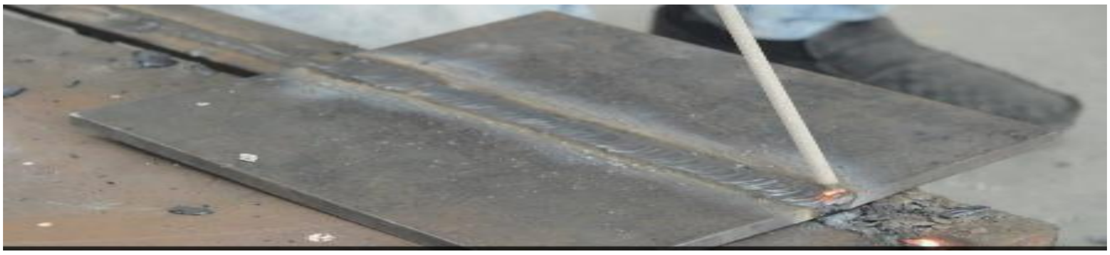

Figure (2.3): Sample Welding.

2.3.2.1. Main Components:

1. Welding machine (AC or DC).
2. Electrode (flux-coated rod).

2.3.2.2. Applications:

1. Structural steel construction.
2. Pipeline and shipbuilding.
3. Maintenance and repair work.

4. NON-DESTRUCTIVE TESTING:

4.1. UV Inspection Lamp: EV6000 UV Inspection Lamp, High-intensity LED UV-A lamp used in Penetration welding, Portable and efficient, ideal for industrial NDT environments.

4.2. Dye Penetrant Inspection: To identify external surface defects invisible to the naked eye.

Liquid Penetrant Testing (LPT): Purpose: To detect surface-breaking defects such as fine cracks, porosity, and weld-related discontinuities that are invisible to the naked eye, especially after single-sided welding where the root and face may develop defects.

4.2.1. Inspection Process:

1- Surface Cleaning: Remove oil, dirt, rust, paint, and contaminants using appropriate cleaners, Ensures the penetrant flows properly into any flaws.

2- Application of Penetrant: Apply a visible dye (red) or fluorescent dye (UV- reactive) penetrant to the weld surface, Penetrant seeps into any open surface flaws by capillary action.

3- Dwell Time: Allow penetrant to remain on the surface for 5–30 minutes depending on material and flaw size, Ensures sufficient penetration into defects.

4.2.2. **Excess Penetrant Removal**: Gently clean the surface to remove penetrant without flushing it from the flaws.

Figure (2.4): Dye Penetrant Inspection.

4.2.3. **Developer Application**: Apply a developer (usually white powder or spray), It draws the penetrant out of the flaws, creating visible indications.

4.2.3.1. **Visual Inspection**: Inspect the weld under white light (for visible dye) or UV light (for fluorescent dye), Flaws will appear as red lines/spots or glowing green/yellow marks.

4.2.3.2. post-Cleaning: Clean the part to remove chemicals used during the test.

4.3. Magnetic Field Detection:

Magnetic Field Detection: Utilizing magnetic fields and filings (black and gray colors) to reveal both internal and external flaws. The figure (2.4) shows the device used in this process.

4.3.1. Magnetic Particle Inspection (MPI) for Butt Welds:

To detect surface and near-surface discontinuities—such as cracks, lack of fusion, and porosity—in ferromagnetic materials like low carbon steel. This is especially crucial for single-sided welds where internal defects may propagate to the surface.

Figure (2.4): Magnetic Particle Inspection.

4.3.2. Inspection Process:

1- Surface Preparation: Clean the weld area to remove oil, rust, paint, and other contaminants.

2- Magnetization: Apply a magnetic field using an electromagnetic yoke or bench unit. The magnetic field should be oriented perpendicular to the expected defect direction.

3- Application of Magnetic Particles: Introduce magnetic particles either dry powder or suspended in a liquid carrier—onto the magnetized area.

4- Observation: Inspect the area under appropriate lighting. For fluorescent particles, use UV light to detect indications where particles accumulate Demagnetization and Cleaning: After inspection, demagnetize the part and clean off residual particles.

5. HEAT TREATMENT:

Samples heated in a furnace to a temperature below the recrystallization point (550 c), Held at temperature for 20 minutes, Slow cooling in still air.

***4.1* Tempering**: (more specifically in welding: Post-Weld Tempering or Stress Relief Heat Treatment and prevent cracking), Explanation:

1- Samples heated to a temperature below the recrystallization point(550c) [15].

2- Held at temperature for 20 minutes.

3- Slow cooling in still air.

The Table (2.1) shows the temperatures for the processing process used.

Tempering Temperatures Chart

Colour	Hardest	Approximate Temperature (°C)	Uses
Pale Straw		230	Lathe tools, Scrapers, Scribers
Straw		240	Drills, Milling Cutters
Dark Straw		250	Taps & Dies, Punches, Reamers
Brown		260	Plane Blades, Shears, Lathe Centres
Brown/Purple		270	Scissors, Press Tools, Knives
Purple		280	Cold Chisels, Axes, Saws
Dark Purple		290	Screwdrivers, Chuck Keys
Blue	Toughest	300	Springs, Spanners, Needles

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4.1.1. **Purpose of Tempering**: Tempering (or stress-relief annealing) may be applied after welding to reduce internal stresses and prevent cracking.

4.2. Microscopic Examination (Metallography)

Microscopic examination is used to evaluate the microstructure of metals to detect defects, verify treatment processes, or assess material quality.

4.2.1. Sample Sectioning: Purpose: To cut a representative portion of the specimen without altering its microstructure, A precision abrasive cutting machine is used, Coolant is applied to avoid heat-affected zones.

Sample Mounting: Purpose: To embed the sample in a resin block to ease handling and protect edges during preparation, Types: Hot Mounting: Using thermosetting resins under pressure and heat, Cold Mounting: Using liquid resins (e.g., epoxy or acrylic) at room temperature.

4.2.2. **Grinding and Polishing**: Purpose: To create a flat, smooth surface free of scratches and deformation.

Steps: Grinding: Done using abrasive papers in stages (coarse to fine). Polishing: Done with cloth wheels and diamond/alumina suspensions for mirror finish.

4.2.3. **Microscopic Examination**: Purpose: To observe and analyze the sample's microstructure (grain size, phases, inclusions, defects). Process: Often preceded by etching (chemical treatment) to reveal grain boundaries, Optical microscopes or scanning electron microscopes (SEM) are used depending on magnification required.

4.2.4. **Main Observations**:

1- Grain size and shape.

2- Microcracks, porosity, inclusions.

3- Heat treatment effects and weld integrity.

4.3. **Microscopic Examination**: Samples cut, mounted, polished (with sandpaper), and inspected under a microscope, Microstructural analysis conducted to observe the effects of heat treatment.

5.1. Importance of the Figure (5.1):

This visual helps:

1- Understand where and how hardness measurements are taken.

2- Relate hardness values to specific metallurgical zones.

3- Maintain consistent methodology across different samples.

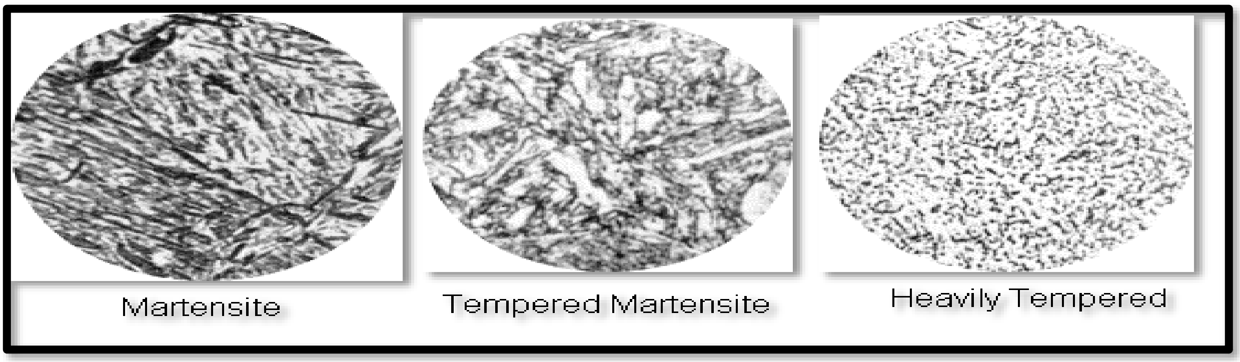

Figure (5.1): Sample Preparation before Microhardness Testing.

Microhardness refers to hardness testing methods that measure a material's resistance to localized plastic deformation using very low loads. It is ideal for

assessing small, thin, or surface-treated areas, such as coatings or heat-affected

zones (HAZ) in welding. Figure (5.1) showing sample preparation before the operation.

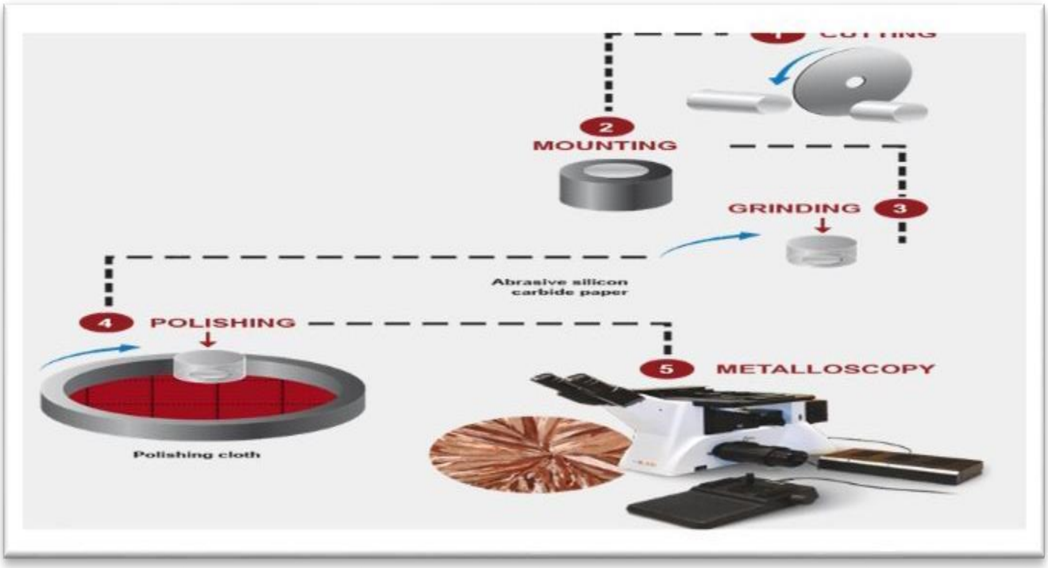

Figure (5.2): sample preparation.

5.2. Vickers Hardness Calculation:

Formula (load in gf):

$$HV = 0.0018544 \times \frac{F\ (\text{gf})}{d^2\ (\text{mm}^2)}$$

Figure (5.3): Formula Vickers Hardness Calculation.

5.3. Typical Applications:

1-Measuring hardness of thin films and surface treatments. 2-Microscopic Hardness Testing.

3-Hardness assessed under a microscope using a standard reference table.

4-Comparing treated vs untreated samples to observe grain size and hardness variations.

Table (5.1): Test Characteristics.

Property	Description
Load Range	Typically, 10 to 1000 grams
Equipment	Microhardness tester with a microscope and precise load control
Sample Surface	Smooth, polished surfaces required
Application Area	Small-scale regions like coatings, weld zones, microstructures

6. RESULTS AND DISCUSSION:

6.1. Illustrated in both Table (6.1), and Table (6.2):

Table (6.1): Changes in Weld Metal vs. Base Metal vs. HAZ.

Zone	Before Tempering	After Tempering	Change
Weld Metal (WM)	**Moderate**	**Slightly lower**	**Slight drop in hardness**
HAZ	**Highest**	**lower**	**Significant reduction in hardness and brittleness**
Base Metal (BM)	**Low**	**Slightly lower**	**Minimal change**

Table (6.2): Microstructure and Hardness for sample.

Zone	Thermal Effect	Final Microstructure	Hardness
Weld Metal	Fully melted & solidified	Ferrite + Pearlite (or partial Martensite)	Medium
Heat-Affected Zone	High heat, rapid cooling	Martensite / Ferrite + Pearlite + Martensite	**Highest**
Base Metal	Unaffected	Ferrite + Pearlite (unchanged)	Normal

6.2. Weld Metal vs. Base Metal vs. HAZ:

1. **Weld Metal:** Melts and solidifies often has controlled composition and may be softer after solidification and post-weld treatment.
2. **Base Metal:** Not affected much thermally keeps original hardness.
3. **HAZ:** Altered by heat, but not melted, and therefore most prone to hardness variation due to rapid cooling and phase changes. The figure (6.1) shows the hardness before and after the tempering process for the three areas.

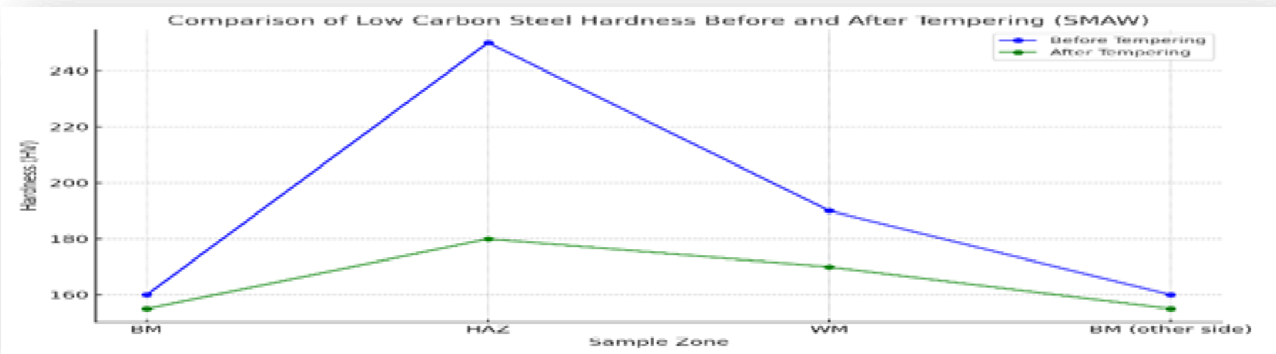

Figure (6.1): hardness before and after the tempering process.

The table (5.11) shows the average values of microscopic hardness taken practically for welded samples before and after the treatment process.

Table (5.11) showing the results of analysis of treated and untreated weld joints.

Average hardness of untreated samples	**45.05**
Average hardness of treated samples	**32.75**

The figure (6.4) shows the microscopic structure of the sample before and after the treatment process.

Image of the treated sample	*Image of the untreated sample*

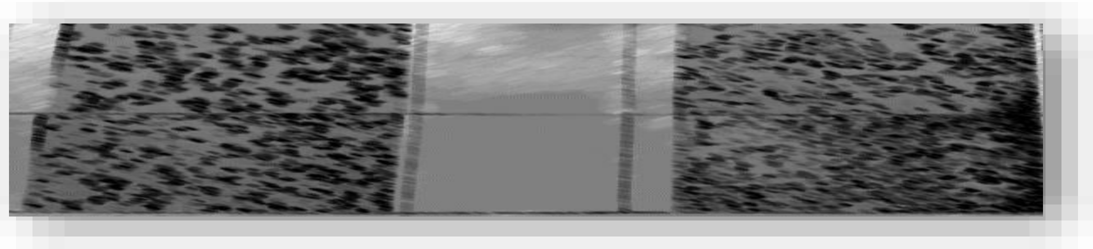

Figure (6.4): showing the results of analysis of treated and untreated weld joints

7. CONCLUSION:

The welding process applied to low-carbon steel using the Shielded Metal Arc Welding (SMAW) method demonstrated high penetration and produced welds of excellent quality. The implementation of non-destructive testing (NDT) proved to be highly effective in providing accurate assessments of the welded joints, enabling the detection of even minor internal and external defects within the samples. Furthermore, post-weld heat treatment (PWHT) was found to significantly enhance the mechanical performance of butt-welded joints in low-carbon steel. Among the various treatments applied, tempering yielded the most favorable balance between hardness and toughness. It effectively reduced hardness, particularly within the heat-affected zone (HAZ), while simultaneously improving toughness and ductility—properties that are crucial for preventing cracking and failure in welded structures. Additionally, microhardness testing played a vital role in evaluating the mechanical characteristics at microscopic levels, offering both precision and versatility. This method remains indispensable for industrial quality control, research, and the advancement of modern materials.

8. RECOMMENDATIONS

1- Further studies should include tensile and impact testing to comprehensively assess mechanical improvements.

2- Explore varying heat treatment parameters (e.g., different temperatures and soaking times) for optimization.

3- Apply similar studies on different types of steel and other alloys to generalize findings.

4- Use other types of electrodes and compare laboratory results.

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