Post Weld Quenching Impact on Microstructure and Mechanical Properties (Tensile, Impact, Hardness) of High Strength Low Alloy Steel

Impacto del temple posterior a la soldadura en la microestructura y las propiedades mecánicas del acero de baja aleación y alta resistencia

Impacto da têmpera pós-soldagem na microestrutura e nas propriedades mecânicas de aços de alta resistência e baixa liga

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Summary. - Shielded Metal Arc Welding (SMAW) is the most widely used welding technique in engineering industries. Compared to other arc welding techniques like TIG, SMAW is less heat-concentrating. However, welding thick jobs using SMAW can result in serious issues such as structural distortion due to non-uniform input heat distribution. High thermal stresses and distortions can degrade mechanical properties, similar to high input heat. Fast heat removal may prevent such defects, and different quenching media like sand, water, and oil were used to investigate variations in mechanical properties. High-strength low-alloy steel was selected due to its good weldability and easy availability, which makes it suitable for many industrial applications, such as in the space and defense industries. The tensile testing results showed that oil quenching was superior to other quenching techniques because oil-cooled joints had the highest tensile strength and ductility. However, water-cooled joints showed the highest yield strength, but oil-quenched joints had the highest welding efficiency. The hardness of water-cooled joints in the heat-affected zone and weld zone was greater due to rapid cooling in water. The impact energy of oil-cooled joints in the heat-affected zone was superior to that of other joints. Overall, the mechanical properties of oil-cooled joints were superior and showed better geometric configuration, such as minimal distortions.

Keywords: Tensile strength; hardness; Impact strength; SMAW; High strength low alloy steel; quenching media.

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Resumen. - *La soldadura por arco metálico protegido (SMAW) es la técnica de soldadura más utilizada en las industrias de ingeniería. En comparación con otras técnicas de soldadura por arco como TIG, SMAW concentra menos calor. Sin embargo, soldar trabajos gruesos utilizando SMAW puede provocar problemas graves, como distorsión estructural debido a una distribución no uniforme del calor de entrada. Las altas tensiones y distorsiones térmicas pueden degradar las propiedades mecánicas, de forma similar al calor de entrada elevado. La eliminación rápida del calor puede prevenir tales defectos, y se utilizaron diferentes medios de enfriamiento como arena, agua y aceite para investigar las variaciones en las propiedades mecánicas. Se seleccionó acero de alta resistencia y baja aleación debido a su buena soldabilidad y fácil disponibilidad, lo que lo hace adecuado para muchas aplicaciones industriales, como en las industrias espacial y de defensa. Los resultados de las pruebas de tracción mostraron que el enfriamiento con aceite fue superior a otras técnicas de enfriamiento porque las juntas enfriadas por aceite tenían la mayor resistencia a la tracción y ductilidad. Sin embargo, las uniones enfriadas por agua mostraron el límite elástico más alto, pero las uniones enfriadas con aceite tuvieron la mayor eficiencia de soldadura. La dureza de las uniones enfriadas por agua en la zona afectada por el calor y en la zona de soldadura fue mayor debido al rápido enfriamiento en agua. La energía de impacto de las juntas enfriadas por aceite en la zona afectada por el calor fue superior a la de otras juntas. En general, las propiedades mecánicas de las juntas enfriadas por aceite fueron superiores y mostraron una mejor configuración geométrica, como distorsiones mínimas.*

Palabras clave: *Resistencia a la tracción; dureza; Fuerza de impacto; SMAW; Acero de baja aleación de alta resistencia; medios de enfriamiento.*

Resumo. **-** *A soldagem por arco metálico blindado (SMAW) é a técnica de soldagem mais amplamente utilizada nas indústrias de engenharia. Em comparação com outras técnicas de soldagem a arco, como TIG, o SMAW concentra menos calor. No entanto, a soldagem de trabalhos espessos usando SMAW pode resultar em problemas sérios, como distorção estrutural devido à distribuição não uniforme do calor de entrada. Altas tensões e distorções térmicas podem degradar as propriedades mecânicas, semelhante à alta entrada de calor. A rápida remoção de calor pode prevenir tais defeitos, e diferentes meios de têmpera como areia, água e óleo foram usados para investigar variações nas propriedades mecânicas. O aço de alta resistência e baixa liga foi selecionado devido à sua boa soldabilidade e fácil disponibilidade, o que o torna adequado para muitas aplicações industriais, como nas indústrias espacial e de defesa. Os resultados dos testes de tração mostraram que a têmpera em óleo foi superior a outras técnicas de têmpera porque as juntas resfriadas a óleo apresentaram maior resistência à tração e ductilidade. No entanto, as juntas resfriadas a água apresentaram o maior limite de escoamento, mas as juntas temperadas a óleo tiveram a maior eficiência de soldagem. A dureza das juntas resfriadas a água na zona afetada pelo calor e na zona de solda foi maior devido ao rápido resfriamento em água. A energia de impacto das juntas resfriadas a óleo na zona afetada pelo calor foi superior à das outras juntas. No geral, as propriedades mecânicas das juntas resfriadas a óleo foram superiores e apresentaram melhor configuração geométrica, como distorções mínimas.*

Palavras-chave: *Resistência à tracção; dureza; Resistência ao impacto; SMAW; Aço de baixa liga de alta resistência; meios de extinção.*

1. Introduction. - Shielded Metal Arc Welding (SMAW) is widely used in various industries due to its affordability and availability. It has a higher power density than gas fusion welding, but lower than Tungsten Inert Gas (TIG) welding. However, extensive distortions can occur during SMAW due to the low concentration of flame. Skilled welders can be easily sourced locally. High Strength Low Alloy Steel, known for its durability and strength, is utilized in upper atmosphere research, power production, and defense industries [1,2]. High Strength Low Alloy Steel is widely used in various industries due to its exceptional strength to weight ratio, enhanced toughness, ductility, and weldability. However, welding joints of low alloy high strength steel can experience a degradation of strength in the joined material. Welded joints exhibit reduced hardness and impact strength, and their ductility is also mitigated. These changes in mechanical properties are caused by the high heat input during welding, which results in alterations to both the microstructure and macrostructure of the welded samples [3,4].

Srinivasan et al. conducted a research study and revealed that the impact of heat on the mechanical properties of TIG welded joints made from High Strength Low Alloy (HSLA) steel. The study found that the strength of the welded joints decreased to 55% of the strength of the base material due to the welding process [5,6]. To address this issue, the samples were subjected to heat treatment, which resulted in an increase in strength. However, while other mechanical properties such as hardness were improved, the ductility of the welded samples was found to be lower than that of the base metal [7,8]. Sapthagiri et al. conducted a study on the impact of filler wire variation on the mechanical properties of welded joints made from low alloy high strength steel. The study found that using copper-coated filler wire resulted in an improvement in both yield strength and percent elongation [9].

Arc welding is more likely to produce defects such as angular and linear distortions compared to advanced techniques like laser and electron beam welding. Rami et al. investigated the impact of different welding clamps used in gas metal arc welding on the mechanical properties of the welded joints. The study found that using a heat treatment clamping technique resulted in achieving welding efficiency of over 80% [10]. Srivastava et al. conducted a study on the penetration depth of filler material in welding. The findings showed that changes in input heat and welding speed had a negative impact on the penetration depth, which, in turn, affected the joint efficiency [11].

Li et al. studied the effect of changes in welding input heat on the mechanical properties of low carbon steel and found that different microstructural phases were generated due to aberrations in cooling rate [12]. Eroglu et al. investigated the microstructural variations in High Strength Low Alloy Steel caused by changes in input heat energy. They observed that the hardness property in the weld region and heat-affected zone was reduced due to increased input heat. While martensite was produced as a result of lower heat input, hardness property decreased beyond a certain point with further increase in heat input [13]. Bijaya et al. conducted a study comparing the mechanical properties of mild steel joints that were welded using GMAW and SMAW methods. The rapid cooling rate after welding resulted in the development of bainite and martensite structures, which led to an increase in the hardness and tensile strength of the joints. However, the impact strength was found to have been reduced [14]. Ruming et al. investigated the enhancement of mechanical properties of welding joints through the addition of Cerium. The results revealed an improvement in toughness attributed to the surplus of crack-free energy. Additionally, the tensile strength of low alloy steel was enhanced due to the refined grain structure, resulting in a noticeable increase in welding efficiency upon the addition of Ce [15].

Narwadkar et al. conducted a study on the production of angular distortions in different types of welded joints. The results indicated that the bevel groove joint was more susceptible to angular distortions than single and double V groove joints, which were found to have lower angular distortions [16]. In another study, Adamczuk et al. investigated the correlation between the number of welds passes and angular distortion. It was found that there was a direct relationship between the number of passes and the angular distortions, with a greater shrinkage power resulting from the welding of thicker plates due to the direct effect of increasing the amount of weld metal on angular distortions [17]. Wei et al. studied the impact of distortions on the performance of welding joints and revealed that distortions have a direct effect on joint strength and dimensional accuracy [18]. Despite significant advancements in arc welding technology, distortion induced by welding remains one of the most noticeable challenges in the production industry for ensuring higher weld efficiency. Anis et al. investigated the impact of weld thickness and position on the residual stress generated during welding due to the contraction and expansion of the welding joint [19,20]. Residual stresses generated during welding hindered the joint efficiency increment, hence M Islam et al. performed a research work to evaluate joint mechanical properties after different post welding treatments. Pre-bending and pre-heating are some techniques utilized to control distortions [21,22].

2. Research Objective and Novelty. - The degradation of strength caused by high heat input during welding is a primary factor contributing to joint failure under load. Uneven thermal distribution across the joint amplifies the effects of residual stresses and increases the size of the Heat Affected Zone (HAZ). This study aims to improve the mechanical properties of welded joints. Achieving this goal is challenging due to the fact that high input heat during welding can reduce the strength, ductility, hardness, and toughness of the welded structure by as much as 50% compared to the base metal. The density of input energy, or the concentration of heat, is a critical factor influencing the performance of welded joints. TIG welding is known for its high concentration of heat, whereas SMAW distributes the heat over a wider area, ultimately diminishing the mechanical and microstructural properties. Therefore, this study focuses on quenching the welded joints immediately after welding in various media to explore the impact on mechanical properties. Distortions that arise in welded structures are a major cause of strength degradation. Uneven temperature distribution across the welded joint causes distortions, ultimately weakening the structure. Consequently, enhancing the mechanical properties is vital to ensuring the reliability of welded joints. Ductility is especially important in large structures like pressure vessels. In this study, the quenching and cooling of welded joints immediately after welding are investigated to assess their impact on the mechanical properties of welded structures.

3. Experimental Methodology. - Quenching media were selected from local market due to easy availability. Normally welded joints are cooled in Air. Hence, to make direct comparative study welded joints after welding were cooled in Air, Water, Sand and old hydraulic oil (used) etc. Following experiments were performed after cooling in different media,

a. Tensile Testing
b. Impact testing
c. Hardness Testing
d. Microstructural characterization

High Strength Low Alloy Steel plate of 8mm thick was selected as base material and its chemical composition performed by spectroscopy and mechanical properties of base material was evaluated by using Universal Testing Machine (UTM) Tinius Olsen H150KV in material and metallurgy lab. Chemical composition of HSLA plate is represented in Table I and mechanical properties are represented in Table II.

Element	C	Si	Mn	Mo	V	Cr	S	P	Fe
Maximum	0.18	0.22	0.98	1.12	0.27	1.25	0.018	0.017	Remaining

Table I: Spectroscopy results of High Strength Low Alloy Steel

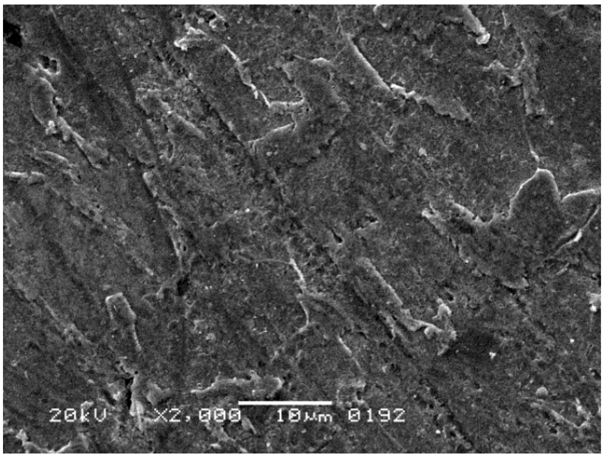
Material	Yield stress (MPa)	Ultimate strength (MPa)	Elongation %	Hardness (HV)
High Strength Low Alloy Steel	545	705	13	200

Table II: Tensile Strength and Hardness of Base metal (annealed state)

3x welded joints were tested in each testing category. Hardness testing and impact testing were performed to investigate effects of variations in cooling media. Hardness of base metal was checked by using Ernst hardness tester. Charpy Impact test was performed on machine of 300J capacity. Welding rod E-7018 was used for welding purpose, welding current of around 150Amp and welding speed of 200mm/min were used as welding parameters. Impact testing samples were prepared as per ASTM E23-18 standard. Charpy impact testing setup was utilized to evaluate toughness of welded joints. All quenching media were at standard atmospheric values of temperature and pressure before quenching.

4. Results and Discussions. -

4.1 Microstructural characterization. - The microstructural study was conducted to assess the impact of different quenching media on grain boundaries and grain sizes, which ultimately affect the mechanical properties. As shown in Figures Ia and Ib, the air-cooled samples primarily consisted of a ferrite phase. The slow cooling rate due to natural convection in air resulted in coarse ferrite grain boundaries and a minimal presence of pearlite, which was enveloped by a ferrite matrix. In contrast, Figures Ic and Id reveal finer grain boundaries due to rapid cooling in water. The spacing between lamellae of pearlite and ferrite was reduced as represented in Figure Id. This decrease is associated with enhanced strength but reduced ductility due to the rise in hardness.



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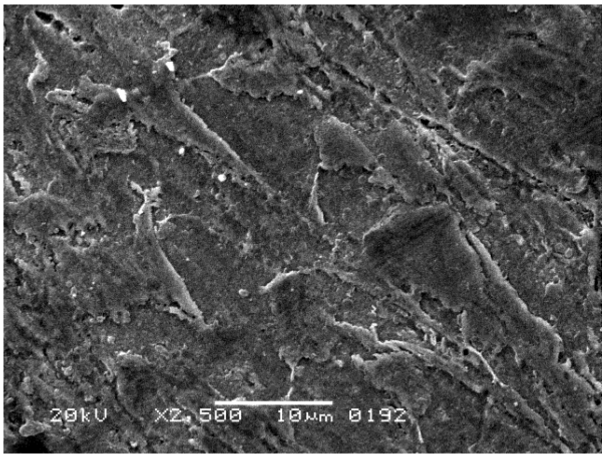

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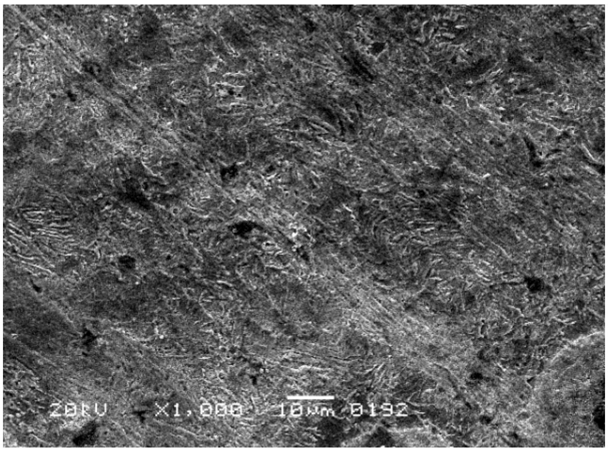

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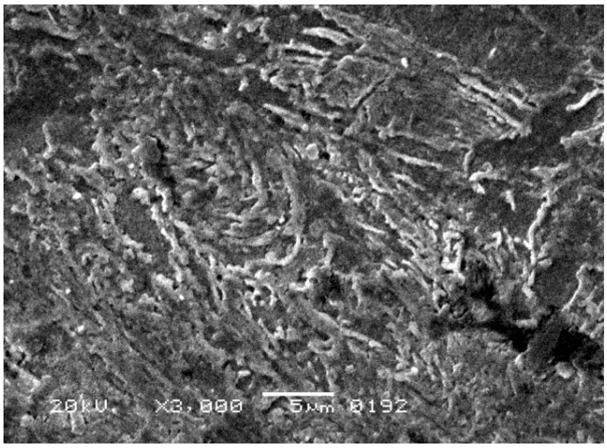

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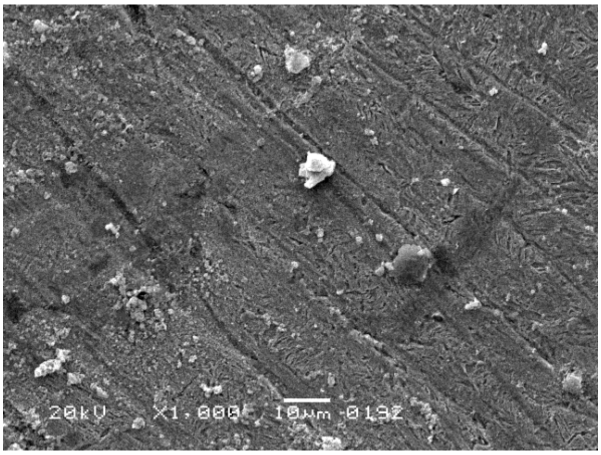

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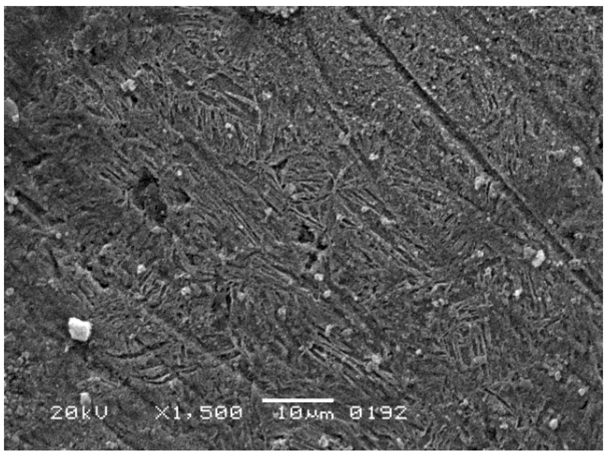

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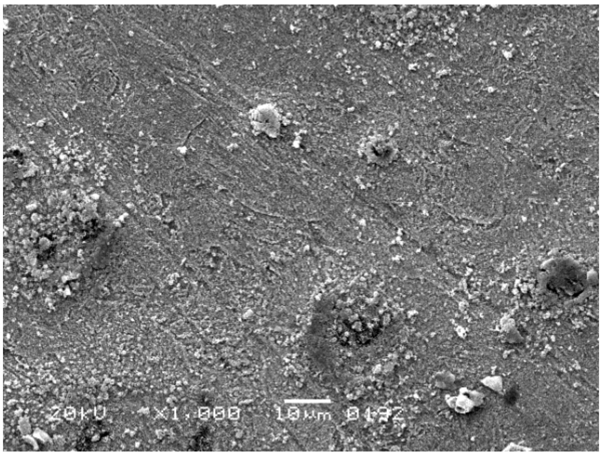

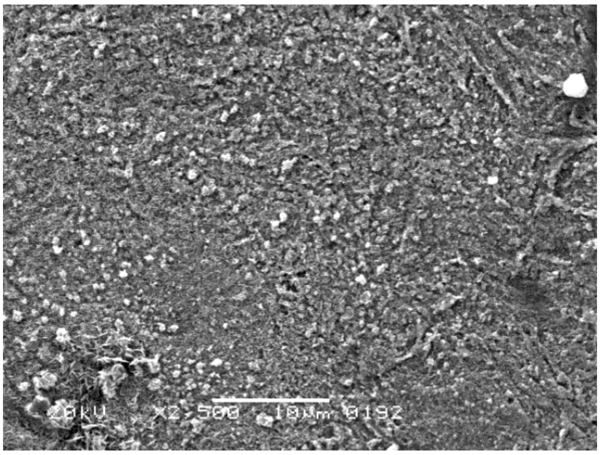

(g) (h)

Figure I: Microstructural Graphs (a) Air-cooled Samples (b) Water-cooled samples (c) Sand- cooled samples (d) Oil-cooled samples.

Sand cooling was relatively ineffective due to its slow cooling rate, attributed to the poor thermal conductivity of sand. As shown in Figures Ie and 1f, the microstructure exhibited coarse grain boundaries of ferrite and pearlite. Consequently, the mechanical properties are expected to be similar to those of air-cooled samples. In contrast, high-resolution micrographs of oil-cooled samples revealed a fine network of ferrite and pearlite, contributing to enhanced strength and hardness. The moderate cooling rate in oil facilitated precipitate diffusion along grain boundaries, as illustrated in Figures Ig and 1h, which could impede dislocation movement. Additionally, the grain boundaries in oil-cooled samples were larger compared to those in water-cooled samples, suggesting a potential improvement in ductility due to the balanced cooling effect of oil.

4.2 Hardness testing. - Welding reduces hardness of steel joint and base metal because high input heat deteriorates microstructure. Hardness of steel after welding mitigated to almost 60% of base metal hardness. Enhancement in hardness of welded joints was observed due to immediate quenching in water and oil. Water quenching significantly ameliorated hardness because of development of very fine and compact ferrite and pearlite lamellae in welding regions and heat affected regions. Results of comparison of WZ hardness are showed in Figure II, hardness 222HV was observed in WZ of water-cooled joints as compared to 140HV hardness of air-cooled joints. Air and sand cooled joints showed similar range of hardness because of slow cooling processes. Oil cooling represented significant enhancement as compared to normal air cooling after welding. Oil-cooled joints hardness was greater than air and sand cooled joint, however less than water-cooled joints because oil cooling are not as rapid as water cooling due high viscosity of oil.

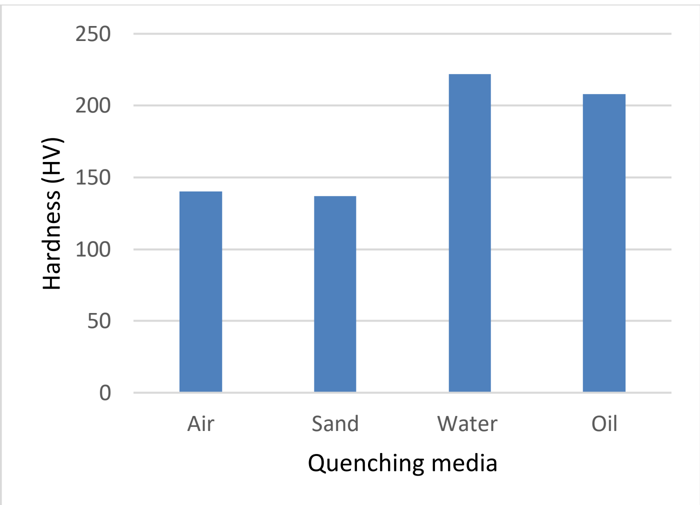

Figure II: WZ Hardness.

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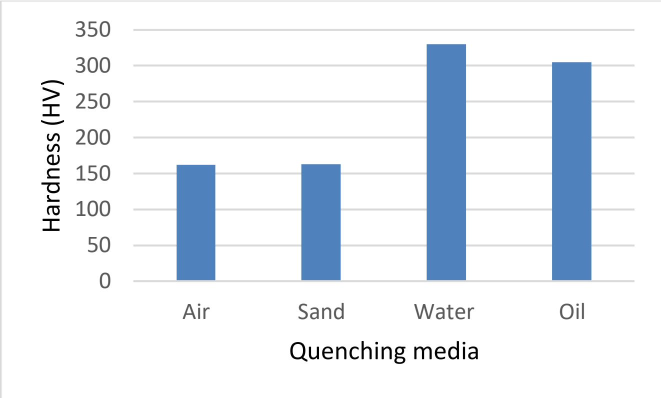

Figure III: HAZ Hardness.

Comparison of HAZ hardness between welded joints quenched in different media are represented in Figure III. Water cooling showed maximum hardness than others, 330HV hardness was attained after water cooling of welded joints. Fine grains development due to rapid cooling in HAZ because low concentrated heat input, dislocation motion was restrained, and internal stresses induced which causes brittleness. Oil cooling is a slow cooling process as compared to water cooling due to high viscosity of oil. 305HV hardness was observed in HAZ after oil cooling of welded joints and ultimately results in low internal stresses. Air and sand cooling, both are very slow cooling processes and imparted similar effects on welded joints with minimum variations. Welded joints are normally air cooled hence degradation of hardness from 200HV to 162HV in HAZ were observed. Enhancement in hardness was observed after quenching of welded structures in water and oil.

4.3 Tensile Testing. - Mechanical behavior of welding joints were investigated under tensile loading. Ultimate tensile strength (UTS), Yield strength (YS) and % elongation was evaluated to investigate the direct impact of cooling in different media on welding joints. Comparative study had been performed to appraise difference in strength properties of welded joints. Samples from welded joints were tested as per ASTM standard and samples after testing are represented in Figure IV.

Figure IV: Tensile Testing Samples.

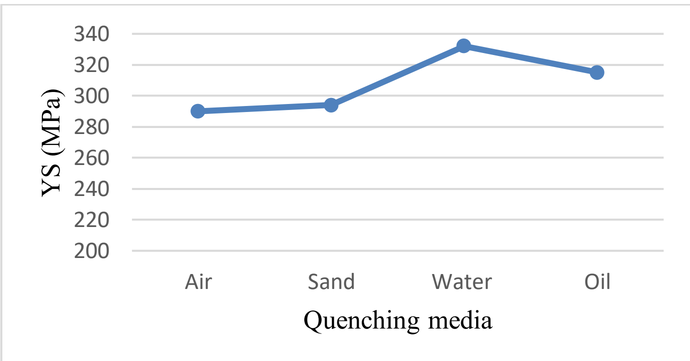

Figure V: Yield Strength Comparison.

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Results represented in Figure V manifest comparison of YS of welded joints, water cooled joints exhibited maximum yield strength of 332MPa. Water cooled joints were brittle in nature because rapid cooling promotes internal stresses in WZ and HAZ. Moreover, due to fine grain boundaries in WZ and HAZ areas enhanced yield strength and ultimately promoted brittleness. Oil cooling was comparatively slow process than water cooling but fast than air and sand cooling. Little internal stresses produced during oil cooling because of slow cooling in oil. Hence, higher yield strength was attained due to good heat sinking of oil and ultimately improved microstructure. Air and sand cooled joints didn't reveal any remarkable difference between strength properties because both are slow cooled processes.

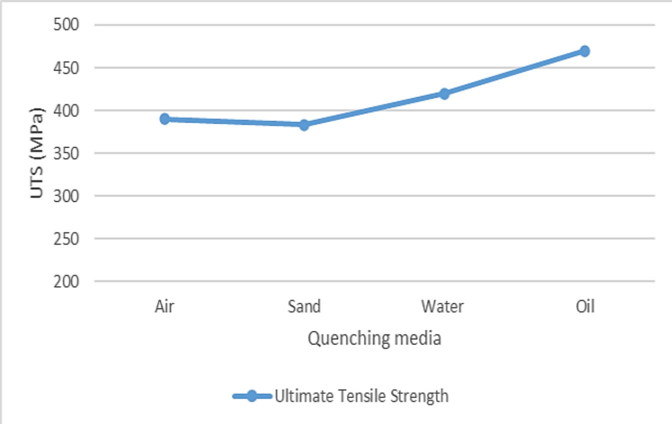

Figure VI: Ultimate Tensile Strength Comparison

Results represented in Figure VI delineate comparison of UTS of welding structures. It is normally observed that UTS dropped to 50% due to impact of high heat input, however oil cooled joints showed higher strength of 470MPa as compared to air cooled joints of 390MPa. Water cooled joints UTS was ameliorated as compared to air and sand cooled joints but not as significant as oil cooled joints. he cooling rate of water is higher than that of oil, making it more effective in rapidly reducing temperature. However, this higher cooling rate also induces internal stresses and increases brittleness due to the formation of harder phases. In the case of the welded samples, the 8mm thickness acted as a heat sink, affecting the overall cooling behaviour. However, in thicker sections, microstructural variations may not be as pronounced due to uneven heat dissipation, leading to less uniform phase transformation across the sample.

Difference between core and surface microstructure which leads to some ductility due to austenite and ferrite. Already used hydraulic oil has moderate viscosity which provides greater cooling rate than critical cooling rate. Vapor blanket stage was not established because of moderate viscosity, hence higher UTS was achieved in oil cooling. It is conspicuous from results represented in Figure VII that ductility of HSLA degraded from 13% elongation (base metal) to 7.2% elongation (air-cooled joints). High input heat mitigated ductility by deteriorating materials microstructure. Water cooling was detrimental to ductility because rapid cooling constrained dislocation motion and developed internal stresses. Oil cooling enhanced ductility by increasing % elongation from 7.2% to 9% for oil cooled joints.

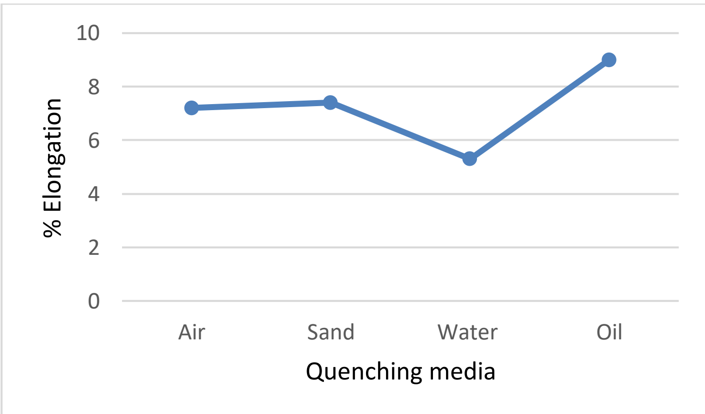

Figure VII: Percent Elongation Comparison

Oil cooling is comparatively slower than water cooling due to higher viscosity of oil. Air and sand cooled joints are not much distinguished in % elongation because both are slow cooling techniques. Statistical data analysis was conducted to assess the variations in mechanical properties, with the results presented in Table III. The analysis revealed the largest range in Ultimate Tensile Strength and Hardness, which can be directly linked to the influence of cooling rate. Statistical analysis plays a crucial role in identifying and quantifying the relationships between different variables, ensuring that the observed trends are reliable and representative.

		Mean	Median	Standard Deviation	Range
UTS		415.75	405	34.27	87
YS		307.7	304.5	16.9	42
% Elongation		7.225	7.3	1.4	3.7
Hardness	**WZ**	176.75	174	38.64	85
	HAZ	240	234	78	168
Impact Energy	**WZ**	48.25	50.5	6.98	18
	HAZ	94.125	95.75	14.6	41

Table III: Statistical Analysis

4.4 Welding Efficiency. - Welding efficiency of normal air-cooled joints is 50-55 %, tensile strength degrades after welding due to input heat. SMAW is a widely used technique, but joints are less efficient than TIG welding joints.

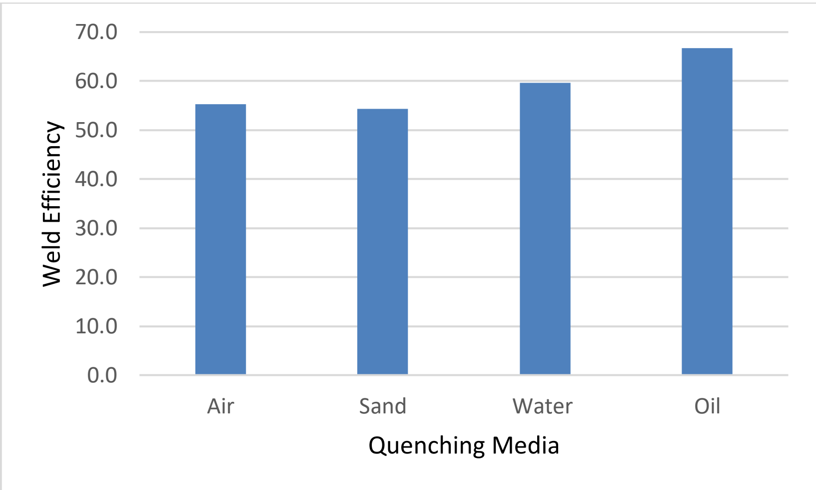

Figure VIII: Welding Efficiency Comparison

Input heat concentration is low, hence wider HAZ resulted which ultimately diminishes mechanical properties of joints. Thicker joints behave like heat sink, hence localized improvements in strength after welding was observed in normal air and sand cooled joints. Rapid cooling of welding joints in water reduced the width of HAZ and hinder the dislocation movements. Efficiency of welded joints quenched in water was less than efficiency of oil quenched welded joints as represented in Figure VIII. Severe internal stresses developed during water cooling was responsible of low UTS due to brittle behavior of joints. Almost 12% of UTS was enhanced due to oil cooling of welding joints. Improvements in weld efficiency of oil quenched weld joints were due to moderate viscosity of used hydraulic oil because no vapor blanket developed in moderately viscous oil. Air and sand cooled weld joints were equally efficient because slow cooling resulted in both processes.

4.5 Impact Testing. - Impact testing was performed to appraise toughness of welded joints after quenching in different media. Charpy impact tester was utilized, and sample was prepared having V notch of 2mm depth. Toughness property pertinent to ductility because high ductile materials have good toughness. Behavior of welding joints under sudden impact loading was evaluated and difference between toughness of WZ and HAZ is represented in Figure IX. Reduction in impact energy of WZ and HAZ of Normal air-cooled joints revealed degradation in toughness, welding mitigated impact energy from 200J of base metal to 55J in WZ of joint. Rapid cooling in water and oil produced severe effects on toughness in weld zone of joints by reducing impact energy. Rapid cooling in water promotes brittleness due to internal stresses at crystallographic planes, hence impact energy of water-cooled joints was minimum as compared to other joints. Remarkable improvements in Impact energy of oil cooled was observed as value of impact energy in HAZ was increased by 18J than air cooled joints. Moderate cooling rate in oil was attained due to moderate viscosity and responsible for fine grain boundaries. Brittle behavior of joints was negligible due to minimum internal stresses.

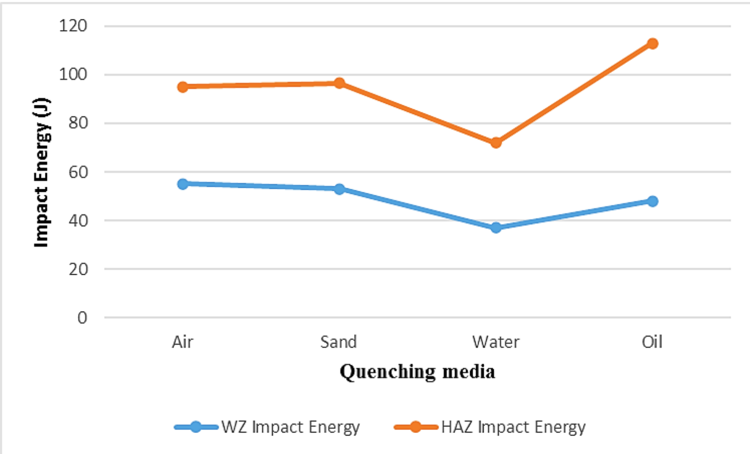

Figure IX: Impact Energy Comparison

5. Conclusion. - Considerable improvements were observed due to immediate quenching after welding of HSLA steel. Results of tensile testing revealed that maximum tensile strength was achieved due to oil quenching. Moreover, greater ductility was observed in form of enhanced % elongation after oil quenching. Water quenching degraded % elongation due to rapid cooling. Yield strength of water-cooled joints was greater because of narrow HAZ and constrained dislocation movement. Generation of internal stresses at crystallographic planes due to fast cooling promoted brittleness, hence UTS of water-cooled joints were less than oil cooled joints. Appreciable enhancement in welding efficiency was observed due to oil quenching. Oil quenched joints were 11% more efficient than normal air-cooled joints. Maximum hardness of 330HV was reported due to water quenching in HAZ and 222HV in WZ. Significant increase in impact energy was observed after oil quenching, water quenching mitigated toughness because impact energy of water-cooled joints was very low as compared to others. Overall performance of oil cooled joints under different mechanical loadings was noteworthy, hence oil quenching after welding would be performed for better mechanical properties of joints.

6. Future Recommendation. - To gain a deeper understanding of the long-term performance and durability of welded joints, it is recommended to incorporate fatigue testing into future studies. Creep testing under high temperature and constant load should be included in future research. Creep resistance is essential for welded joints in high-temperature environments, such as pressure vessels and steam pipes. While various quenching media have been evaluated in this study, it is suggested to explore additional or alternative cooling methods, such as cryogenic cooling or the use of hybrid quenching techniques.

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1. Conception and design of the study
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4. Discussion of the results
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