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Mechanical Characterization of Post weld quenched Al 6082-T6 TIG welded Joints

Caracterización mecánica de uniones soldadas TIG Al 6082-T6 templadas después de la soldadura

Caracterização mecânica de juntas soldadas TIG Al 6082-T6 pós-soldagem temperada

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Summary. - This research aims to enhance the efficiency of weld joints through a cost-effective methodology. Aluminium 6082-T6 is the chosen material due to its frequent use in applications that require intermediate strength with low weight. Welding operations typically lead to a weakening of material strength by up to 50% due to the high input heat. Therefore, the focus of this study is to improve the strength by employing quenching techniques with different media, such as sand, water, and hydraulic oil. A comparative analysis of the mechanical properties is performed based on the quenching of weld joints using these various media. Additionally, microstructure examination is conducted to facilitate this comparative study. The mechanical properties investigated include hardness, tensile strength, yield strength, and toughness, with the goal of understanding the impact of different quenching media. The research reveals that water-cooled joints exhibit higher yield strength, while oil-cooled joints demonstrate superior tensile strength compared to other joints. Furthermore, the ductility of oil-cooled joints is notably higher, as measured by % elongation. Water cooling leads to noteworthy hardness in both the Weld Zone (WZ) and Heat-Affected Zone (HAZ) due to rapid cooling. In contrast, the hardness of oil-cooled joints is not significantly different from that of water-cooled welded joints. Regarding toughness, oil-cooled joints show greater impact energy in the HAZ compared to those quenched with water, sand, and air. However, in the WZ, air-cooled joints exhibit superior impact energy, which directly indicates better toughness properties. Therefore, oil-cooled joints display higher toughness in the HAZ, while air-cooled joints are tougher in the WZ. Overall, the mechanical properties of oil-cooled joints are significantly enhanced, leading to an improved weld efficiency from 55% to 72%.

Keywords: TIG welding; mechanical properties; Al 6082-T6; quenching media.

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Resumen. - *Esta investigación busca mejorar la eficiencia de las uniones soldadas mediante una metodología rentable. El aluminio 6082-T6 es el material elegido debido a su uso frecuente en aplicaciones que requieren resistencia intermedia con bajo peso. Las operaciones de soldadura suelen provocar una reducción de la resistencia del material de hasta un 50 % debido al elevado calor de entrada. Por lo tanto, este estudio se centra en mejorar la resistencia mediante técnicas de temple con diferentes medios, como arena, agua y aceite hidráulico. Se realiza un análisis comparativo de las propiedades mecánicas basado en el temple de las uniones soldadas con estos diversos medios. Además, se realiza un examen de la microestructura para facilitar este estudio comparativo. Las propiedades mecánicas investigadas incluyen dureza, resistencia a la tracción, límite elástico y tenacidad, con el objetivo de comprender el impacto de los diferentes medios de temple. La investigación revela que las uniones refrigeradas por agua presentan un mayor límite elástico, mientras que las refrigeradas por aceite demuestran una resistencia a la tracción superior en comparación con otras uniones. Además, la ductilidad de las uniones refrigeradas por aceite es notablemente mayor, medida mediante el porcentaje de elongación. El enfriamiento por agua produce una dureza notable tanto en la zona de soldadura (ZS) como en la zona afectada por el calor (ZAC) debido al rápido enfriamiento. Por el contrario, la dureza de las uniones enfriadas con aceite no es significativamente diferente de la de las uniones soldadas enfriadas con agua. Con respecto a la tenacidad, las uniones enfriadas con aceite muestran una mayor energía de impacto en la ZAC en comparación con las templadas con agua, arena y aire. Sin embargo, en la ZS, las uniones enfriadas con aire exhiben una energía de impacto superior, lo que indica directamente mejores propiedades de tenacidad. Por lo tanto, las uniones enfriadas con aceite muestran una mayor tenacidad en la ZAC, mientras que las uniones enfriadas con aire son más tenaces en la ZS. En general, las propiedades mecánicas de las uniones enfriadas con aceite mejoran significativamente, lo que lleva a una mejora en la eficiencia de la soldadura del 55% al 72%.*

Palabras clave: *Soldadura TIG; propiedades mecánicas; Al 6082-T6; medios de enfriamiento.*

***Resumo**. -* *Esta pesquisa visa aumentar a eficiência de juntas soldadas por meio de uma metodologia econômica. O alumínio 6082-T6 é o material escolhido devido ao seu uso frequente em aplicações que exigem resistência intermediária com baixo peso. As operações de soldagem normalmente levam a um enfraquecimento da resistência do material em até 50% devido ao alto calor de entrada. Portanto, o foco deste estudo é melhorar a resistência empregando técnicas de têmpera com diferentes meios, como areia, água e óleo hidráulico. Uma análise comparativa das propriedades mecânicas é realizada com base na têmpera de juntas soldadas usando esses vários meios. Além disso, o exame da microestrutura é realizado para facilitar este estudo comparativo. As propriedades mecânicas investigadas incluem dureza, resistência à tração, resistência ao escoamento e tenacidade, com o objetivo de compreender o impacto de diferentes meios de têmpera. A pesquisa revela que juntas resfriadas a água apresentam maior resistência ao escoamento, enquanto juntas resfriadas a óleo demonstram resistência à tração superior em comparação com outras juntas. Além disso, a ductilidade das juntas resfriadas a óleo é notavelmente maior, medida pela % de alongamento. O resfriamento a água resulta em dureza notável tanto na Zona de Solda (ZS) quanto na Zona Afetada pelo Calor (ZAC) devido ao resfriamento rápido. Em contraste, a dureza das juntas resfriadas a óleo não é significativamente diferente daquela das juntas soldadas resfriadas a água. Em relação à tenacidade, as juntas resfriadas a óleo apresentam maior energia de impacto na ZAC em comparação àquelas temperadas com água, areia e ar. No entanto, na ZC, as juntas resfriadas a ar exibem energia de impacto superior, o que indica diretamente melhores propriedades de tenacidade. Portanto, as juntas resfriadas a óleo apresentam maior tenacidade na ZAC, enquanto as juntas resfriadas a ar são mais tenazes na ZC. No geral, as propriedades mecânicas das juntas resfriadas a óleo são significativamente aprimoradas, levando a uma eficiência de soldagem aprimorada de 55% para 72%.*

Palavras-chave: *Soldagem TIG; propriedades mecânicas; Al 6082-T6; meios de têmpera.*

1. Introduction. - Aluminium alloys are widely used in numerous applications due to their excellent strength-to-weight ratio. Among these alloys, Al 6082 is noted for its significant strength combined with a low weight. Additionally, this alloy exhibits remarkable resistance to rust and possesses good reusability properties [1]. Its application is especially prevalent in the automobile industry, where it is used in the manufacturing of suspension components. Al 6082 is primarily composed of Aluminium (Al), Magnesium (Mg), and Silicon (Si). To further enhance its mechanical properties such as tensile and yield strength, impact strength, and grain boundary size, Al 6082 undergoes heat treatment [2]. A hot forging process is commonly utilized by many industries to produce intricate parts in a single operation. However, this process results in a highly deformed microstructure with significant thermal and mechanical stresses. As a consequence, post-forging heat treatment is often employed to alleviate such defects [3][4].

Joining Al 6082 through welding helps to reduce residual mechanical and thermal stresses to some extent. However, a major drawback of welding is the reduction in joint strength. After welding, the tensile strength and hardness can be reduced by up to 50%, necessitating post-weld heat treatments to enhance joint strength. Unfortunately, these post-weld heat treatments can be expensive [5]. Forging is considered a cost-effective and efficient method for manufacturing small-sized parts; however, for large-sized parts, forging becomes cumbersome and expensive [6]. As a result, welding is commonly employed to join different parts and create giant structures. The choice of welding parameters is known to significantly impact the performance of welded joints, with the type of welding technique playing a crucial role [7]. Tungsten Inert Gas (TIG) welding is preferred in applications requiring concentrated heat, while Shielded Metal Arc Welding (SMAW) is not suitable for such tasks due to its wider heat-affected zone (HAZ) compared to TIG welding [8].

TIG welded joints of Al 6082 have been found to exhibit superior strength compared to Metal Inert Gas (MIG) welded joints. This improvement in strength is attributed to the presence of equally sized grain boundaries after TIG welding, resulting in a very fine spacing between adjacent grains [9]. Furthermore, the hardness of the joints has been shown to be influenced by the speed of the tungsten electrode, with higher speeds contributing to the softening of the joint area. The impact of subzero temperature conditions has been observed to strongly affect the mechanical properties of Al 6082, and thick plate coalescence using arc welding has led to the occurrence of various defects such as cracks and pores [10]. These findings highlight the importance of selecting appropriate welding techniques and parameters to ensure the desired mechanical properties and structural integrity in welded joints, especially when dealing with large-sized structures.

A parametric study to evaluate key influencing factors in TIG welding of Aluminium alloys is considered very essential. An increment in welding current has been found to negatively affect the tensile strength and hardness of the welded joints. However, optimal results have been achieved with a welding current of 150A and a welding speed of 200 mm/min, leading to improved tensile strength and hardness properties [11]. The heat treatment of Al 6082-T6 alloy has produced a serious effect on hardness. Artificial aging at 175°C has significantly enhanced the hardness, whereas performing solution heat treatment before age hardening has led to a degradation in hardness. The development of the Mg2Si phase during artificial aging has increased the brittleness of Al 6082, consequently contributing to its increased hardness [12].

Exploration of input heat influence on the precipitation hardening of Al 6082 during TIG welding has affirmed that the concentrated arc generated during TIG welding allows for directed heat flow to the fusion areas, quickly achieving the desired fusion temperature. Additionally, TIG welding is considered a welding technique with minimal defects, especially when compared to other fusion techniques. The distortions resulting from temperature distribution on welded joints are known to be more severe in other fusion techniques than in TIG welding [13][14]. Severe residual stresses due to non-uniform thermal loading are known to negatively impact the corrosion behaviour of aluminium alloys. The elevated temperatures experienced during welding induce thermal stresses, leading to stress corrosion cracking, precipitation, and subsequent pitting corrosion. These factors ultimately compromise the strength of welded joints [15]. Moreover, the anodic and cathodic behaviour of aluminium alloy precipitates influence the corrosion phenomenon. The research has demonstrated that magnesium dissolution exhibits an anodic behavior and contributes to the enhanced occurrence of pitting corrosion [16].

1.1 Research Motivation. - The strength and hardness of Al 6082-T6 significantly deteriorate due to the high heat input generated during the welding process. A comprehensive literature review reveals that this degradation primarily results from substantial microstructural alterations induced by welding. Given the high thermal conductivity of aluminium, heat is rapidly conducted, leading to an expanded HAZ and subsequent microstructural disruptions, which frequently contribute to joint failure. Moreover, the ductility of welded joints is considerably reduced due to microstructural distortion and reinforcement through the incorporation of additional filler metal. This study explores the potential enhancement of the mechanical properties of Al 6082-T6 weld joints through post-weld quenching using various cooling media following TIG welding. The HAZ width in samples cooled under ambient air conditions is relatively larger due to the slower heat dissipation, which negatively impacts tensile strength, impact resistance, and hardness. Minimizing the HAZ width is crucial for improving the mechanical performance of welded joints. Therefore, rapid dissipation of post-welding heat is essential to mitigate mechanical property degradation. This investigation evaluates the effect of different cooling media on the mechanical behaviour of Al 6082-T6, recognizing that each cooling medium exhibits distinct heat transfer characteristics, leading to variations in the resulting mechanical properties of the weld joints.

2. Experimental Methodology. - TIG welding technique was utilized in this study for welding of Al 6082-T6 alloy of 8mm thickness, different quenching media were used immediately after welding process to alter mechanical properties and welding efficiency. Following parameters were studied:

a. Microstructural examination
b. Tensile testing
c. Hardness testing
d. Impact testing

To investigate variations in strength and ductility, the researchers conducted tensile testing. Tensile samples were prepared according to the ASTM E8M-16a standard, and a H150KV tensile testing machine (UTM) was employed for this research. The hardness of the samples was evaluated using an Ernst Vickers Hardness Tester. Four different quenching media air, sand, water, and hydraulic oil (Shell Morlina S2 BL 10) were selected for the purpose of cooling. To assess toughness after the cooling process of welded samples, Charpy V-notch impact testing was performed following the ASTM E23-18 standard for sample preparation. Microstructural examination of properly prepared metallurgical specimens/weldments was conducted using an Optical Metallurgical Microscope. The chemical composition of the material was determined using an optical emission spectrometer, and the weight percentages of constituent elements are presented in Table I. For comparison with the welded samples, the mechanical properties of the base material were tabulated in Table II. Based on a comprehensive review of the literature, suitable welding parameters were selected to achieve high-quality welded joints.

Element	Mg	Si	Mn	Cu	Cr	Zn	Ti	Fe	Al
Percentage	1	.7	.95	.13	.26	.21	.12	.48	Balance

Table I: Chemical composition of Al 6082-T6

Base material specimens were cut from 8 mm thick plate and tensile specimens were prepared as per ASTM E8M-16a standard.

Base metal	Yield strength (YS)	Tensile strength (UTS)	% Elongation	Hardness Vicker (HV)
Al 6082-T6	250MPa	300MPa	10%	90

Table II: Base material mechanical properties

For TIG welding, the welding parameters chosen were an electrode traveling speed of 200 mm/min and a current of 180 A. The welding process utilized a Precision TIG AC type machine, and a 3.2mm diameter filler wire AA4043 was selected. To prevent any interference with the mechanical properties, the dwell time after welding was kept to a minimum.

3. Results and Discussion. -

3.1 Microstructure Study. - Microstructural study was performed to evaluate the impact of different cooling media on HAZ of welding joints of Al 6082 T6. The microstructural examination presented in Figure I illustrates distinct grain boundaries within the HAZ. Coarse grain boundaries were observed in both Figure I(a) and Figure I(b),

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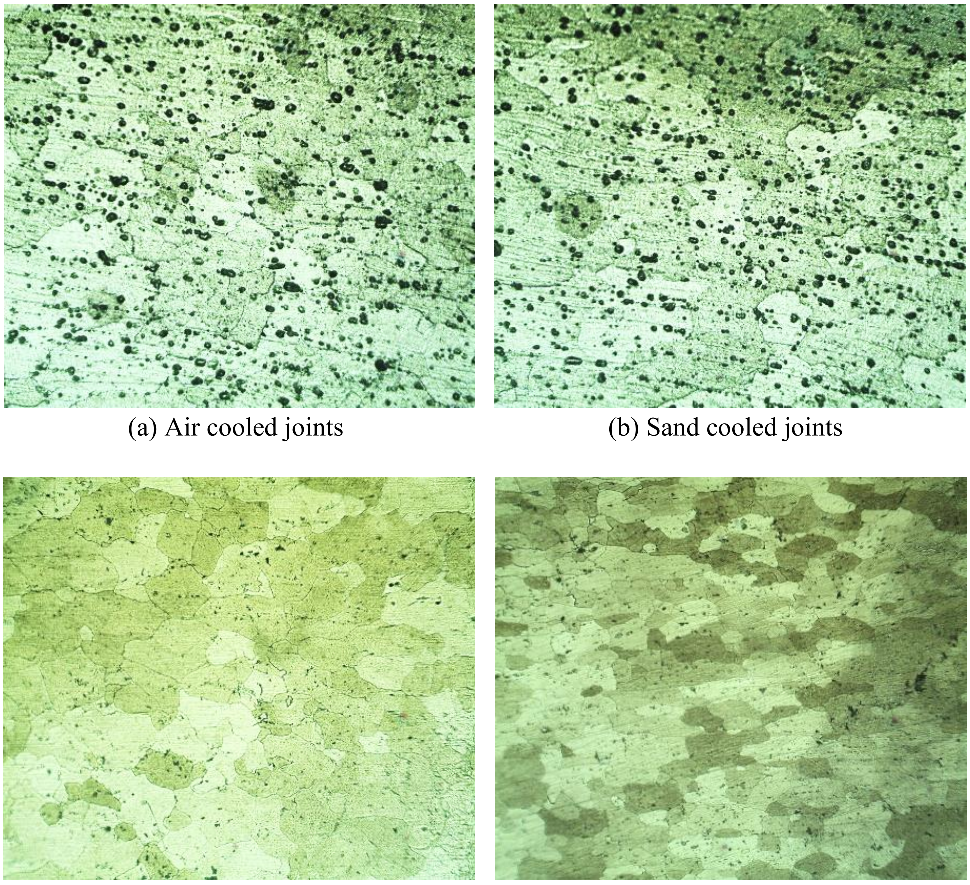
contributing to improved elongation percentage and ductility but reduced strength. Conversely, Figure I(c) and Figure I(d) depict fine grain boundaries resulting from the rapid cooling process involving water and oil. Notably, oil cooling leads to the formation of elongated grains, as evident in Figure I(d). In comparison, joints cooled with air and sand exhibit higher levels of porosity when compared to those cooled with water and oil. The presence of pores creates points of stress concentration, ultimately causing a degradation in the mechanical strength of the joints. Microstructural analysis of oil cooled joints reveals the presence of fine and equiaxed grains due to the moderate viscosity of the oil, which facilitates quick and uniform heat dissipation without the formation of a vapor shield.



(a) Air cooled joints (b) Sand cooled joints

(c) Water cooled joints (d) Hydraulic-oil cooled joints

Figure I: Microstructure of HAZ of Air, Sand, Water & Hydraulic-oil cooled joints.

Water-cooled joints exhibit fine yet irregular grains due to their rapid but non-uniform cooling process. The black spots observed in the HAZ of air-cooled and sand-cooled samples likely result from the formation of secondary phases, such as Mg_2Si precipitates or other intermetallic compounds, during cooling. The slower cooling rates in air and sand facilitated the diffusion of precipitates along coarse grain boundaries. These precipitates appear darker under optical microscopy due to their distinct optical properties compared to the aluminium matrix. In contrast, rapid cooling in water and oil quenching leaves less time for precipitate formation and growth. Instead, the rapid cooling rate traps solute atoms within the aluminium matrix, inhibiting the development of distinct precipitates. Consequently, black spots are smaller or less noticeable in these samples. Additionally, slower cooling rates may encourage the segregation of elements like Mg or Si at grain boundaries. Rapid cooling, on the other hand, promotes fine grain boundaries, enhancing mechanical strength while reducing the ductility of welded joints. The formation of precipitates restricts dislocation motion under loading, leading to increased strength. Rapid cooling seizes these precipitates along fine grain boundaries, potentially contributing to strength enhancement. This precipitation effect is counteracted by the presence of pores and coarse grain boundaries, meaning slow cooling may not significantly improve strength and hardness.

3.2 Tensile Testing Results. - The strength (both tensile and yield) of welded joints decreased by approximately 50% as a result of the weld heat input effects [5]. Figure II represents the outcomes of the comparison between the yield strength (YS) of welded joints that were quenched or cooled using different cooling methods. For each cooling treatment, three samples were chosen, and the comparison was based on the average values. The water-quenched welded samples exhibited a higher YS compared to the samples cooled in air, sand, and oil. This improvement in YS was achieved because the rapid cooling in water led to the formation of fine grain boundaries.

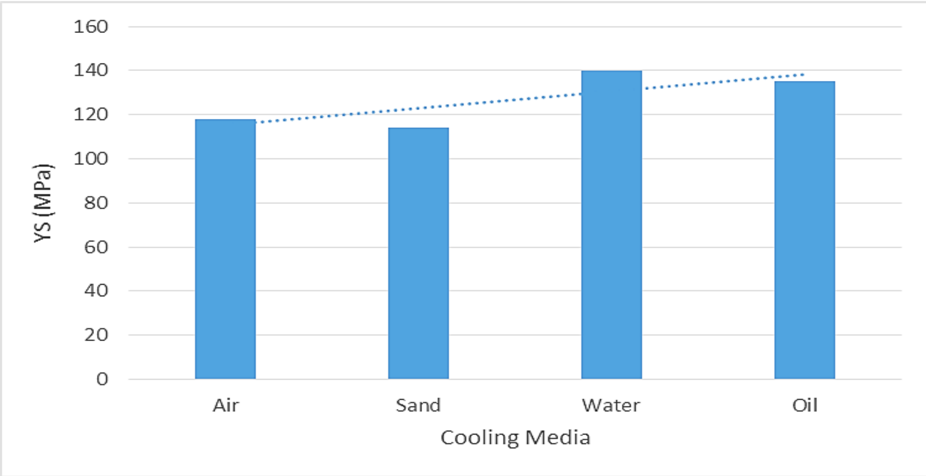


Figure II: Quenching effect on yield strength.

The YS of the oil-quenched welded samples was similar to that of the water-quenched samples due to the higher convectional coefficients facilitating temperature distribution. Additionally, low distortions were observed after oil quenching. The YS of the air and sand-cooled samples were approximately equal since both cases involved slower cooling. Several distortions were observed after water quenching due to its very rapid cooling process. The findings presented in Figure IV illustrate a comparison of the ultimate tensile strength (UTS) among welded joints that were cooled using different quenching media. It was observed that the oil-cooled welded joints displayed higher strength compared to joints cooled in other media. The strength characteristics of the oil-cooled joints were particularly distinctive, showing an improvement of 54MPa compared to the normally air-cooled welded joints. The tensile strength of the oil-cooled joints also exhibited a notable difference of approximately 26MPa when compared to the water-cooled joints. Additionally, Figure III presents the results indicating the ductile behavior of the welded joints cooled in various media. Base metal ductility reduced from 10% elongation to 6% for normal air-cooled welded joints. Oil cooled samples showed 7% elongation, highest amongst other media; thus, oil cooling imparted maximum ductility after welding due to uniform diffusion of precipitates along grains and moderate cooling.

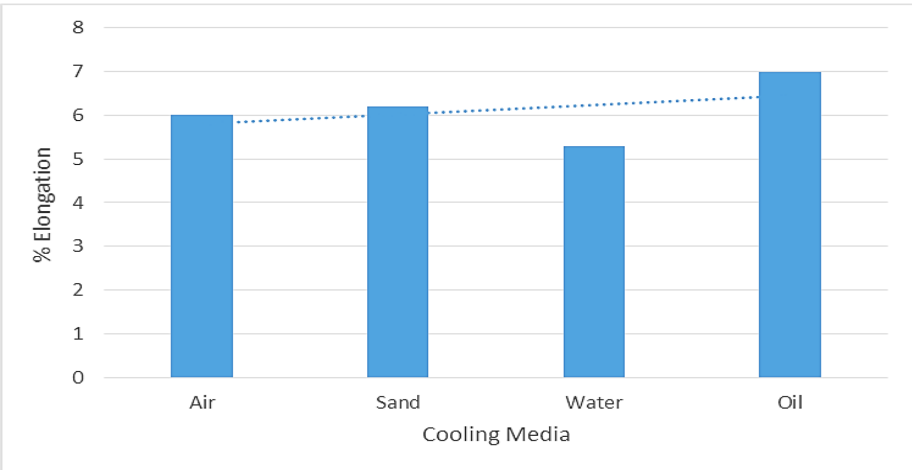


Figure III: Quenching effect on percent elongation.

Fine grain boundaries generally enhance the endurance limit, leading to improved fatigue strength. Rapid cooling methods such as water and oil cooling can further increase fatigue resistance by maximizing dislocation hindrance. In contrast, coarse grain boundaries formed through slower cooling methods like air and sand cooling may reduce fatigue strength due to lower resistance to dislocation movement. Additionally, slow cooling can result in gas porosity, which creates stress concentrations and further diminishes endurance properties.

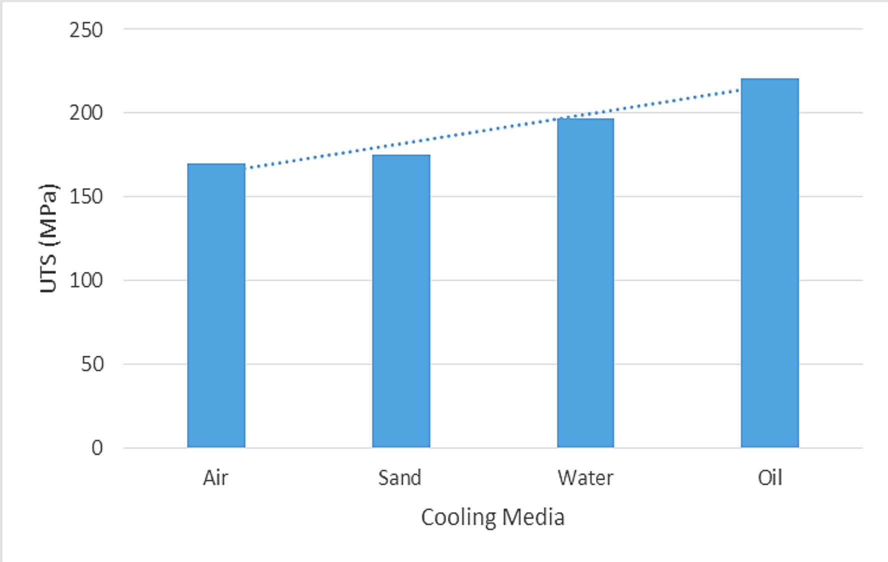


Figure IV: Quenching effect on ultimate tensile strength.

3.3 Welding Efficiency. - The results presented in Figure V demonstrate an enhancement in welding efficiency when utilizing different quenching media for the welded joints compared to normal air-cooled joints. Among the quenching methods, oil-quenched joints exhibited the highest weld efficiency of 72.5%.

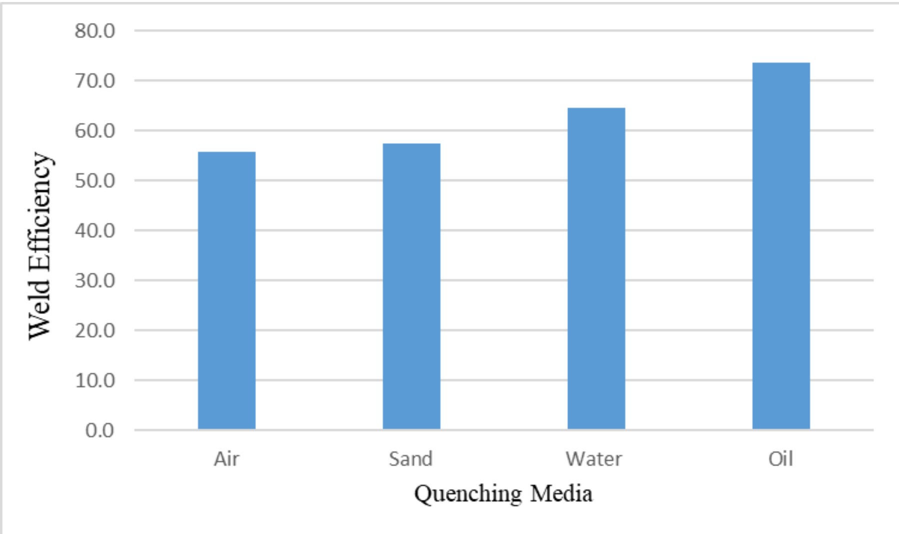


Figure V: Welding Efficiency.

This improvement can be attributed to the development of fine grain boundaries, which occurred due to the higher cooling rate provided by oil quenching compared to air and sand. Additionally, the width of the HAZ was reduced, resulting in improved mechanical properties, as a narrower HAZ is associated with better performance. In both the HAZ and WZ, the coarsening of precipitation size was not significant due to the rapid cooling process, leading to smaller and finer precipitates. Consequently, the oil-quenched joints exhibited higher strength compared to the other methods. On the other hand, water-quenched joints showed strength improvements of up to 64.6%. However, their strength was lower than that of oil-cooled joints due to the extremely rapid cooling in water. Although the water-quenched joints displayed lower tensile strength due to the generation of internal stresses, their yield strength was higher than that of the oil-quenched joints. This can be attributed to the presence of fine grain boundaries and the hindrance of dislocations caused by the rapid water cooling.

3.4 Hardness Testing. - The hardness testing results presented in Figure VI illustrate a comparison among the WZ of welded joints that were subjected to quenching in various media. Among the different quenching methods employed, the welded joints quenched in water displayed the highest hardness in the WZ. This can be attributed to the segregation of fine grain boundaries and the formation of narrow precipitates, which were more pronounced in comparison to the other quenched joints. The utilization of oil cooling resulted in an enhancement of hardness, increasing it from 56HV (for joints cooled in normal air) to 68HV.

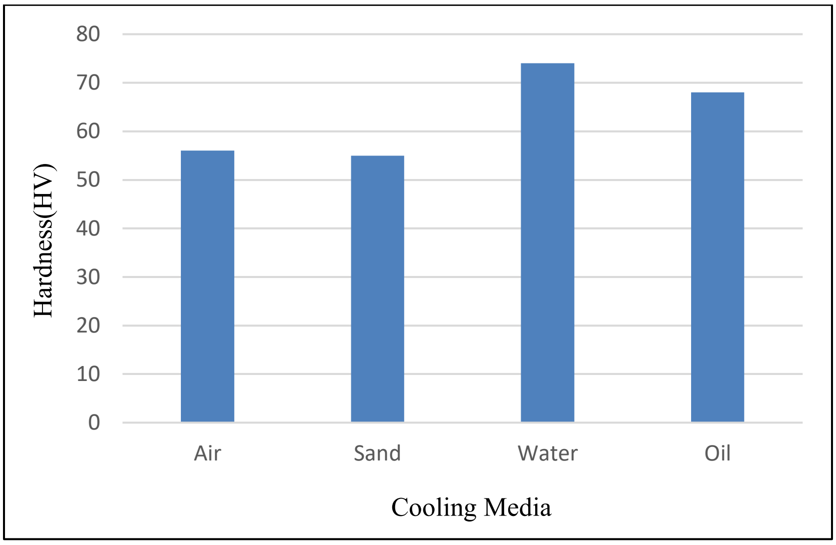


Figure VI: Quenching effect on WZ hardness.

Notably, sand cooling did not yield any significant changes in the welded joints, as the results were similar to those of the air-cooled joints. The input heat effected the width of both the WZ and the HAZ, leading to a decrease in hardness for joints that were slowly cooled (via air and sand) from 90HV to approximately 55HV. The results presented in Figure VII demonstrate a comparison of the hardness in the HAZ of different welding joints after quenching. The HAZ hardness of joints quenched in water was found to be the highest among the various joints, primarily due to the rapid cooling process. The oil-cooled joints exhibited a similar level of hardness in the HAZ, closely following the water-cooled joints. The increased hardness observed in the water and oil-cooled joints can be attributed to the extremely narrow width of the HAZ and the presence of fine precipitates. The rapid cooling employed in these methods restricts the movement of dislocations, leading to the generation of stresses across the crystallographic planes. However, it should be noted that the fast cooling of welded joints in water can result in brittleness, which further increases the hardness and can have a detrimental effect on the tensile strength of the joints.

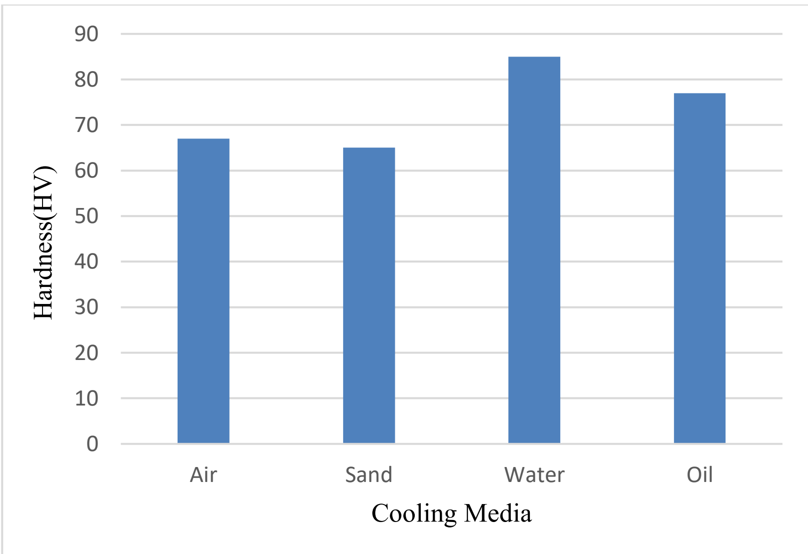


Figure VII: Quenching effect on HAZ Hardness.

3.5 Impact Testing. - The impact absorbed energy (measured in Joules) of the WZ in different media after quenching

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is presented in Figure VIII. The amount of impact energy absorbed during testing directly reflects the toughness of the welded joints, as toughness is directly proportional to impact energy. It was observed that the water-cooled welded joints exhibited brittleness. On the other hand, slow cooling in air and sand resulted in generally good toughness due to their favorable ductile nature. The slow cooling process minimizes the generation of internal stresses. However, it should be noted that the microstructure of the sand and air-cooled samples showed signs of porosity. In comparison, the air and sand-cooled welded joints displayed higher impact energy in the WZ compared to the water-cooled joints. In contrast, the WZ of oil-cooled joints exhibited enhanced toughness compared to the other joints. This improvement can be attributed to the fact that the viscosity of the oil allowed for the uniform distribution of input heat throughout the entire area around the WZ, effectively reducing porosity. The moderate cooling provided by the oil, which has higher viscosity than other media, contributed to an overall improvement in impact resistance. Abrupt temperature changes due to fast cooling in water resulted in severe internal stresses and restricted dislocation movement eventually causing the welded joints to become brittle.

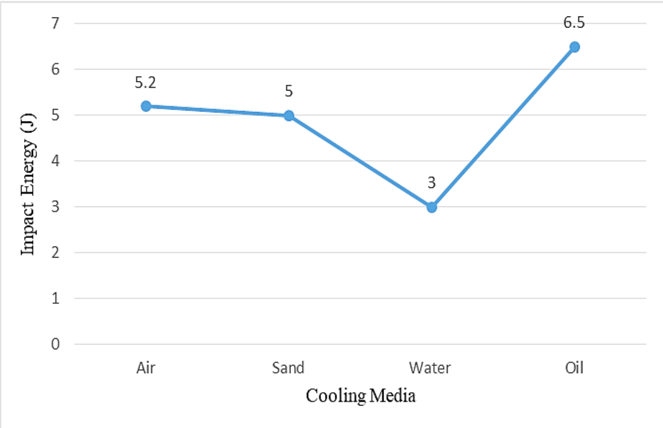

Figure VIII: Quenching effect on WZ Impact Energy

The impact energy of the HAZ in welded joints, quenched using different media, is depicted in Figure IX. Among the various quenching methods, the oil-cooled joints displayed the highest impact energy, measuring 25.5 Joules. This superior performance can be attributed to the uniform distribution of input heat achieved through the moderate viscosity of the oil. Although oil cooling is a faster process compared to air and sand cooling, water cooling is even faster than oil cooling. As a result, the water-cooled joints exhibited a lower impact energy due to the rapid cooling process, which restricts dislocation motion owing to the extremely narrow HAZ. On the other hand, air and sand-cooled joints experienced uneven heat distribution, which facilitated dislocation motion and led to a wider HAZ. Consequently, these joints demonstrated lower impact energy. However, when the welded joints were oil-cooled, they exhibited mild effects and demonstrated enhanced impact energy. This suggests that the oil cooling method had positive effects on the joints. It is important to note that the quenching media used in the experiments were assumed to be at standard temperature. All the experiments were conducted within a carefully controlled laboratory environment, without any heating or cooling of the quenching media being performed.

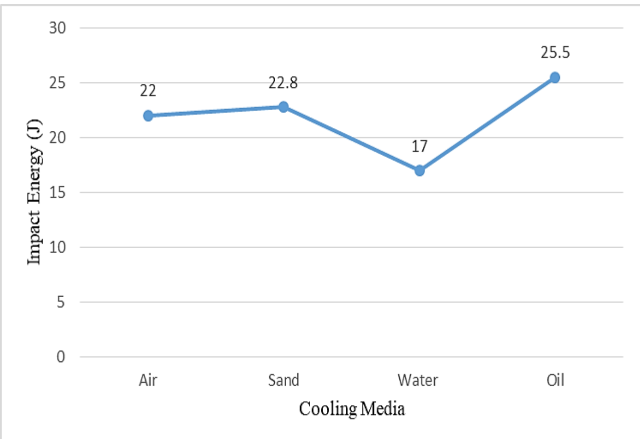

Figure IX: Quenching effect on HAZ Impact Energy.

Table III presents the statistical analysis of the data, highlighting that the ultimate tensile strength exhibited the highest standard deviation. This variability can be attributed to rapid cooling, as UTS increased significantly due to post-weld quenching. Furthermore, the UTS data demonstrated the largest range of 48, reinforcing the correlation between enhanced UTS and swift cooling in comparison to air and sand cooling methods. Similarly, the hardness of the HAZ showed a notable improvement, likely due to refined grain boundaries and precipitate formation. A range of 20 was observed in hardness values, indicating a substantial variation in response to different cooling conditions.

		Mean	Median	Standard Deviation	Range
UTS		189.2	184.5	19.7	48
YS		126.75	126	10.52	25
% Elongation		6.13	6	0.61	1.7
Hardness	**WZ**	63.25	62	8.04	19
	HAZ	73.5	71	9.13	20
Impact Energy	**WZ**	4.9	5.1	1.4	3.5
	HAZ	21.8	22.4	3.53	8.5

Table III: Statistical Analysis of data.

4. Conclusion. - The utilization of different media for quenching weld joints leads to improved mechanical properties due to rapid heat dissipation from the joint area, key improvements are listed below:

- The strength of welded joints is compromised by normal air cooling, resulting in a decrease of up to 50%. Among the various quenching media, water-cooled joints exhibited the highest YS of 140 MPa.
- Oil cooling enhanced the UTS of joints cooled in air from 170 MPa to 221 MPa. Likewise, oil-cooled joints demonstrated the highest percentage of elongation, indicating superior ductility.
- Oil quenching resulted in the maximum weld efficiency of 72.5%, surpassing the 55.7% efficiency of normally air-cooled joints. The notable weld efficiency achieved in oil-cooled joints can be attributed to the moderate viscosity of hydraulic oil.
- The water-cooled joints exhibited higher hardness in the WZ and HAZ compared to other joints. The increased hardness is attributed to residual internal stresses at crystallographic planes.
- The impact energy of water-cooled welded joints decreased to 3 Joules in the WZ, while the impact energy of oil-cooled joints surpassed other joints. In the HAZ, the impact energy of oil-cooled joints was distinct and the highest among all joints due to the narrow width of the HAZ, fine grain boundaries, and fine precipitates.
- Overall, oil-quenched welded joints demonstrated superior performance compared to other welded joints.

5. Future Recommendation. - This study conducted microstructural analysis and mechanical characterization, including tensile, hardness, and impact testing, on quenched welded joints. The scope of mechanical evaluation can be further expanded by incorporating fatigue and creep analysis. Additionally, post-weld heat treatment can be employed to assess the performance of the welded joints. Processes such as solution heat treatment and artificial aging have the potential to induce significant microstructural modifications and alter the mechanical properties of the material.

References

[1] Baskutis, S., Bendikiene, R., & Ciuplys, A. (2019). Effect of weld parameters on mechanical properties and tensile behavior of tungsten inert gas welded AW6082-T6 aluminum alloy. Journal of Mechanical Science and Technology, 33(2), 765–772.

[2] Kaba, L., Djeghlal, M. E., Ouallam, S., & Kahla, S. (2021). Dissimilar welding of aluminum alloys 2024 T3 and 7075 T6 by TIG process with double tungsten electrodes. International Journal of Advanced Manufacturing Technology, 118, 937–948.

[3] Kumar, A., & Sundarrajan, S. (2009). Effect of welding parameters on mechanical properties and optimization of pulsed TIG welding of Al-Mg-Si alloy. International Journal of Advanced Manufacturing Technology, 42(1-2), 118–125.

[4] Kumar, K., Kumar, C. S., Masanta, M., & Pradhan, S. (2022). A review on TIG welding technology variants and its effect on weld geometry. Materials Today: Proceedings, 50, 999-1004.

[5] Li, J.-f., Zheng, Z.-q., Na, J., & Tan, C.-y. (2005). Localized corrosion mechanism of 2XXX series Al alloy containing S(Al2CuMg) and (Al2Cu) precipitates in 4.0% NaCl solution at pH 6.1. Journal of Materials Chemistry and Physics, 91, 325−329.

[6] Miao, W. F., & Laughlin, D. E. (1999). Precipitation hardening in aluminum alloy 6022. Elsevier Science, 40(7), 873–878.

[7] Murali, N., & Li, X. (2021). TIG welding of dissimilar high-strength aluminum alloys 6061 and 7075 with nano-treated filler wires. In L. Perander (Ed.), The Minerals, Metals & Materials Series. Springer.

[8] Muzamil, M., Wu, J., Samiuddin, M., Majeed, A., Siddiqui, S. U., & Mudassir, M. (2020). Macro-mechanical behavior of unique surface welded joints (AA5083) utilizing tungsten inert gas welding against single-stage homogenization annealing. Revista de Metalurgia, 56(3), e173.

[9] Prabhukhot, A. R., & Prasad, K. (2015). Effect of heat treatment on hardness of 6082-T6 aluminum alloy. International Journal of Scientific & Engineering Research, 6.

[10] Rajkumar, T., Prabakara, M. P., Arunkumar, G., & Antony, A. G. (2020). Study on the feasibility in welding of low carbon steel and austenitic stainless steel joint using CO2 laser welding process and analysis of its metallurgical and mechanical properties. Wu Tan Hua Tan Ji Suan Ji Shu, 106(5), 471–476.

[11] Rajkumar, T., Raja, K., Lingadurai, K., Vetrivel, S. D., & Antony, A. G. (2020). Interfacial microstructure analysis of AA2024 welded joints by friction stir welding. Journal of New Materials for Electrochemical Systems, 23(2), 123–132.

[12] Reboul, M. C., & Baroux, B. (2011). Metallurgical aspects of corrosion resistance of aluminum alloys. Journal of Materials and Corrosion, 62, 215−233.

[13] Shazad, A., Astif, M., Uzair, M., & Zaidi, A. A. (2024). Evaluation of preheating impact on weld residual stresses in AH-36 steel using Finite Element Analysis. Memoria Investigaciones en Ingeniería, (26), 225-243.

[14] Shazad, A., Jadoon, J., Uzair, M., & Akhtar, M. (2022). Effect of composition and microstructure on the rusting of MS Rebars and ultimately their impact on mechanical behavior. Transactions of the Canadian Society for Mechanical Engineering.

[15] Shazad, A., Uzair, M., Jamil, T., & Muhammad, N. (2024, December). A Comparative Study on the Joint Hardness and tensile properties of Dissimilar Aluminum Alloy using Tungsten Inert Gas (TIG) Welding. In 4th International Conference on Key Enabling Technologies (KEYTECH 2024) (pp. 173-178). Atlantis Press.

[16] Shazad, A., Uzair, M., & Tufail, M. (2024). Influence of multiple post-weld repairs on mechanical and microstructural properties of butt weld joint utilized in structural members. International Journal of Precision Engineering and Manufacturing, 1, 1–8.

[17] Sathish, T., Armalingam, S., Mohanavel, V., et al. (2021). Weldability investigation and optimization of process variables for TIG-welded aluminum alloy. Advances in Materials Science and Engineering.

[18] Tan, C. F., & Said, M. R. (2009). Effect of hardness test on precipitation hardening aluminum alloy 6061-T6. Science Journal, 36(3), 276–286.

[19] Zhu, J., Jiang, W., Li, G., Guan, F., Yu, Y., & Fan, Z. (2020). Microstructure and mechanical properties of SiCnp/Al6082 aluminum matrix composites prepared by squeeze casting combined with stir casting. Journal of Materials Processing Technology, 283, 116699.

Author contribution:

1. Conception and design of the study
2. Data acquisition
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4. Discussion of the results
5. Writing of the manuscript
6. Approval of the last version of the manuscript

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