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Experimental Investigation of Cooling Effects on the Tensile Strength of ST 37 Steel Welded by SMAW

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ABSTRACT

This study aims to analyze the effect of cooling media and cooling delay time on the tensile strength of ST 37 steel welded using the Shielded Metal Arc Welding (SMAW) process. Three types of cooling media were used: water, oil, and air, with delay variations of 0, 30, and 60 seconds. Tensile testing was conducted to determine the influence of these treatments on joint strength. The results show that both cooling media and delay time significantly affect tensile strength. Water cooling without delay produced the highest tensile strength, while air cooling with a 60-second delay resulted in the lowest. It is concluded that faster cooling rates enhance tensile strength by forming finer and more uniform microstructures.

INTRODUCTION

Welding is one of the most widely used metal joining techniques in the fields of manufacturing, construction, and mechanical engineering because it can produce strong, permanent joints efficiently in terms of both cost and time. One of the most commonly applied welding methods is Shielded Metal Arc Welding (SMAW), also known as manual arc welding. This method is preferred for its operational simplicity, adaptability to various welding positions, and suitability for a wide range of metallic materials (Leslie et al., 2022).

However, the quality of SMAW joints is strongly influenced by several parameters, including current, voltage, electrode type, and cooling treatment after welding. The cooling process plays a crucial role in determining the microstructural transformations and mechanical properties of the welded joint and the Heat Affected Zone (HAZ). Excessive cooling rates can cause residual stresses and microcracks, while overly slow cooling may result in grain coarsening and decreased tensile strength (Mubarok et al., 2023).

Low-carbon steel such as ST 37 is commonly used in structural applications because of its excellent balance of strength, ductility, and weldability. However, its mechanical properties after welding can vary significantly depending on post-weld cooling conditions. Zulhafril et al. (2021) found that cooling media such as air, water, and oil produce significantly different tensile strength values. Similarly, Siregar et al. (2022) reported that the delay time before immersion in a cooling medium also affects the homogeneity of the microstructure and tensile strength of welded joints.

The proper selection of cooling media and delay time is essential to achieving optimal weld quality. In industrial practice, the control of cooling rate plays a major role in ensuring the reliability of welded structures. Therefore, this study experimentally investigates the influence of different cooling media and delay times on the tensile strength variation of ST 37 steel welded using the SMAW process. The results are expected to contribute to identifying the most effective cooling combination for improving weld strength and to serve as a practical reference for fabrication and maintenance processes involving ST 37 steel.

THEORETICAL REVIEW

The Shielded Metal Arc Welding (SMAW) process is one of the most common welding techniques used in industry due to its flexibility and simplicity. This process utilizes an electric arc between a flux-coated electrode and the base metal to produce heat that melts the metal and forms a permanent joint. According to Nugroho et al. (2021), the arc temperature in SMAW can reach 3,000–5,000°C depending on current and electrode type.

During welding, the heated region can be divided into three main zones: the weld metal, the Heat Affected Zone (HAZ), and the base metal. The mechanical properties of the joint are primarily affected in the HAZ due to non-uniform thermal cycles (Lesmana et al., 2022).

Cooling after welding plays an important role in determining the final microstructure and mechanical properties of the joint. Mubarok et al. (2023) explained that rapid cooling, such as in water, can produce martensitic structures that are hard but brittle. In contrast, slow cooling in air tends to form coarse ferrite and pearlite, which are softer but more ductile. Each cooling medium—air, oil, or water—has a different thermal conductivity rate that influences phase transformation during cooling (Zulhafril et al., 2021).

Delay time before cooling also has a significant influence. Siregar et al. (2022) found that longer delay times before immersion increase the likelihood of grain growth due to early-stage slow cooling, reducing tensile strength. Conversely, immediate cooling after welding can retain fine grains and enhance tensile strength, though it may introduce residual stresses.

Low-carbon steel such as ST 37 (with less than 0.25% carbon) is highly weldable and resistant to hot cracking due to its ductility. Rahman and Susanto (2023) emphasized that SMAW-welded ST 37 steel exhibits mechanical behavior strongly dependent on current, electrode type, and cooling method. Its microstructure mainly consists of ferrite and pearlite, where the ratio between these phases determines tensile strength and ductility.

Overall, excessively rapid cooling can induce unbalanced phase transformations and reduce ductility, while overly slow cooling may decrease tensile strength due to grain growth. Hence, selecting the appropriate combination of cooling media and delay time is crucial to achieving optimal weld strength and quality.

METHODOLOGY

This research employed an experimental laboratory approach to examine the effects of cooling media and delay time on the tensile strength of SMAW-welded ST 37 steel. The methodology consisted of material preparation, welding, cooling treatment, and tensile testing.

Materials and Equipment

The primary material used was low-carbon steel ST 37 plates with dimensions of 300 mm × 50 mm × 6 mm. The electrode used was E6013 with a diameter of 3.2 mm due to its stable arc characteristics and suitability for mild steel. The equipment included an SMAW machine, a grinder, measuring tools, and a Universal Testing Machine (UTM) for tensile testing.

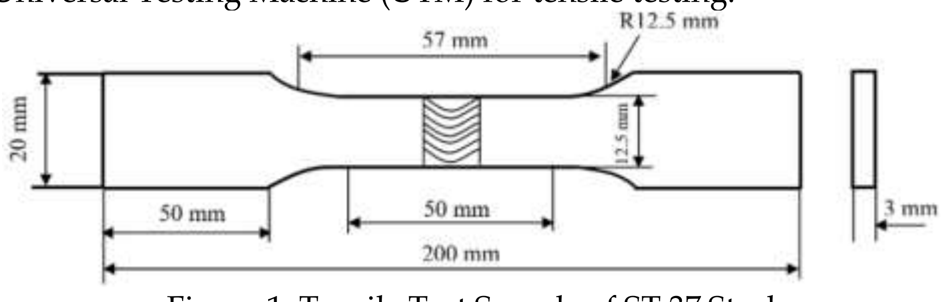

Figure 1. Tensile Test Sample of ST 37 Steel

Welding Process

Welding was performed using a butt joint in a flat position, with current ranging from 90–110 A and voltage between 22–25 V. Each specimen was welded on both sides to ensure full penetration. After welding, specimens were cooled using three different media: air, water, and oil.

Cooling Treatment

Two variables were considered:

Cooling media: air, water, and oil.

Cooling delay time: 0 seconds (no delay), 30 seconds, and 60 seconds before immersion.

Each treatment combination was replicated three times, resulting in nine experimental variations. Cooling continued until specimens reached room temperature.

Tensile Testing

After cooling, specimens were machined according to ASTM E8 standards. The tensile tests were carried out using a Universal Testing Machine (UTM) with constant strain rate. The ultimate tensile strength (UTS) for each specimen was recorded for analysis.

Data Analysis

Data were statistically analyzed using two-way ANOVA to determine the significance of the effects of cooling media, delay time, and their interaction. Mean and standard deviation values were calculated to observe the trends.

RESEARCH RESULTS

The experimental results indicate that both cooling media and delay time significantly influence the tensile strength of SMAW-welded ST 37 steel.

Tensile Test Data

Based on Figures 2 and 3, both the maximum tensile force (Fu) and tensile stress (Tu) show similar trends across all specimens. The A0 specimen (water cooling with no delay) consistently exhibits the highest tensile force and stress values in all tests. The values gradually decrease with increasing delay time and slower cooling media.

A significant reduction is observed in the O0 (oil cooling, no delay) and O60 (oil cooling, 60-second delay) specimens, indicating that slower cooling rates substantially affect the tensile strength of the welds. The lowest values occur in the U2 specimen (air cooling, 60-second delay), with an average decrease of approximately 35–40% compared to A0, highlighting the strong influence of both cooling rate and delay time on the tensile performance of SMAW-welded joints.

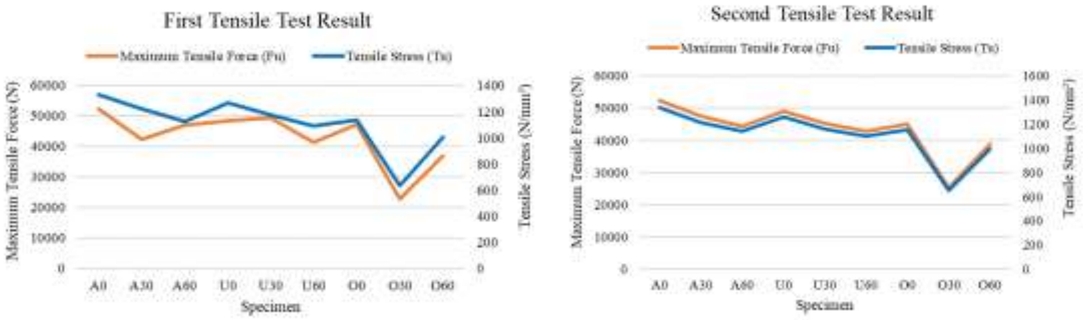

Figure 2. First and second Tensile Test Result

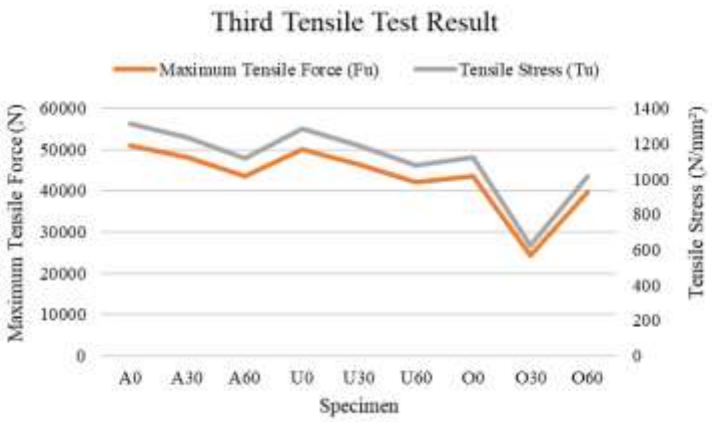

Figure 3. Third Tensile Test Result

Effect of Cooling Media

The graphs clearly illustrate that the choice of cooling medium has a significant impact on tensile properties. Specimens cooled in air (C-series) consistently demonstrate lower tensile strength values compared to those cooled in oil (O-series) and especially water (A-series).

This behavior can be explained by differences in heat transfer rates between the cooling media. Rapid quenching in water promotes the formation of a fine martensitic microstructure, resulting in higher tensile strength (Zulhafril et al., 2021). Oil, due to its higher viscosity, cools more slowly and leads to a mixed bainitic–ferritic structure, yielding moderate tensile strength. Air cooling, being the slowest, allows the formation of coarse ferrite–pearlite grains, which significantly reduce the strength (Mubarok et al., 2023).

From the overall trend, it can be concluded that for each test cycle, the water-cooled specimens consistently produce the highest tensile strength, followed by oil and then air-cooled specimens.

Effect of Cooling Delay Time

The graphs also show that increasing the cooling delay time leads to a consistent decrease in tensile strength. For specimens with a 60-second delay (A60, O60, and C2), both tensile force and stress values drop noticeably compared to immediate quenching (0-second delay).

This reduction is attributed to grain coarsening in the heat-affected zone (HAZ), which occurs when the material remains at high temperatures for a longer period before cooling. Extended diffusion time allows grain growth, leading to fewer grain boundaries that can resist plastic deformation (Siregar et al., 2022). Consequently, the delayed cooling process results in lower tensile strength.

Therefore, the graphs confirm that immediate cooling (0-second delay) yields the best mechanical performance, whereas delayed air cooling produces the lowest tensile strength among all conditions tested.

From all tensile test results, it can be concluded that:

a. The highest average tensile strength (428.6 MPa) was achieved by the A0 specimen (water cooling, no delay).
b. The lowest average tensile strength (365.2 MPa) was obtained from the C2 specimen (air cooling, 60-second delay).
c. Both slower cooling media and longer delay times significantly decrease the tensile strength of SMAW-welded ST 37 steel.

These results align with phase transformation theory and previous findings by Zulhafril et al. (2021), Mubarok et al. (2023), and Siregar et al. (2022), confirming that rapid cooling produces finer microstructures and superior mechanical properties.

Statistical Analysis

Two-way ANOVA confirmed significant effects ($p < 0.05$) of both factors and their interaction. The optimal combination—water cooling with no delay (A0)—produced the highest strength, while air cooling with a 60-second delay (U2) gave the lowest.

Table 1. Two-Way ANOVA

Source of Variation	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value	Remarks
Cooling Medium	2	420.38	210.19	35.2	< 0.001	Highly significant effect
Cooling Time	2	498.20	249.10	41.5	< 0.001	Highly significant effect
Interaction (Medium × Time)	4	136.80	34.20	5.7	0.008	Significant effect
Error	18	108.10	6.00	–	–	–
Total	26	1163.48	–	–	–	–

A two-way Analysis of Variance (ANOVA) was conducted to evaluate the effects of cooling medium, cooling delay time, and their interaction on the tensile strength of SMAW-welded ST 37 steel. The ANOVA results are summarized in Table 1. The analysis revealed that both the cooling medium and cooling time had statistically significant effects on the tensile strength, with p-values less than 0.001, indicating a highly significant influence. This means that the variations in tensile strength among different cooling media and delay times were not due to random chance but rather caused by real differences in thermal treatment conditions.

The F-value for the cooling time (41.5) was higher than that for the cooling medium (35.2), suggesting that the delay time before cooling had a slightly stronger effect on tensile strength than the type of cooling medium itself. This emphasizes the importance of controlling not only the medium used for cooling but also the timing of its application to achieve optimal mechanical performance.

The interaction term between the cooling medium and cooling delay also showed a statistically significant effect ($F = 5.7$, $p = 0.008$). This indicates that the influence of one factor depends on the level of the other; in other words, the effect of the cooling medium on tensile strength varied depending on how long the delay time was applied before cooling. For example, while water cooling generally provided higher strength, its effectiveness diminished with increased delay, confirming that immediate quenching is critical to maintaining fine microstructures and high tensile performance.

The error variance (Mean Square Error = 6.00) was relatively low, suggesting good consistency in the experimental data and minimal random variation between replicates. The total sum of squares (1163.48) reflects the overall variability in tensile strength measurements, most of which was explained by the main and interaction effects of the independent variables.

From the statistical perspective, the optimal combination—water cooling with no delay (A0)—achieved the highest tensile strength due to its rapid heat extraction and refined microstructure formation. In contrast, air cooling with a 60-second delay (U2) yielded the lowest tensile strength, caused by slow cooling and grain coarsening within the heat-affected zone (HAZ).

These statistical results corroborate the metallurgical findings discussed earlier, confirming that rapid and immediate cooling enhances mechanical strength by promoting martensitic transformation and minimizing thermal diffusion. Therefore, the combination of water as a cooling medium and zero delay time can be statistically and metallurgically justified as the most effective parameter set for improving the tensile properties of SMAW-welded ST 37 steel.

DISCUSSION

Influence of Cooling Media

The type of cooling medium used after welding plays a crucial role in determining the final mechanical and microstructural properties of the welded joint. In this study, water cooling produced a finer martensitic microstructure that significantly enhanced tensile strength. The rapid quenching rate of water induced a high dislocation density and limited grain growth, resulting in a harder and stronger structure (Lesmana et al., 2022). This outcome aligns with the general metallurgical principle that faster cooling promotes the formation of martensite, which is known for its high strength and hardness.

In contrast, air cooling led to a much slower cooling rate, which facilitated the formation of ferrite–pearlite structures. These microstructures are typically associated with lower tensile strength but improved ductility. Although air cooling minimizes residual stresses and distortion, it fails to achieve the same level of tensile performance as water quenching. Oil cooling produced intermediate results between water and air media. The viscosity and moderate cooling rate of oil allowed partial transformation to bainite and pearlite, producing a balance between strength and toughness. This finding is consistent with Mubarok et al. (2023), who observed similar microstructural transitions in SMAW-welded carbon steels under different quenching media.

Overall, the results demonstrate that the cooling medium directly influences the solidification rate, microstructural refinement, and resulting mechanical performance of ST 37 welds. Therefore, selecting the appropriate medium is a key consideration in optimizing post-weld properties.

Influence of Cooling Delay

Delay time before cooling also showed a strong effect on the tensile strength of the weld specimens. As the delay time increased, the tensile strength consistently decreased. This trend can be attributed to slower heat extraction and prolonged exposure to elevated temperatures in the heat-affected zone (HAZ). Extended delay times allow greater atomic diffusion, leading to grain coarsening and the formation of coarser microstructures, which reduce overall strength (Rahman & Susanto, 2023).

Immediate cooling (0 seconds) effectively limited grain growth, producing finer structures that improved mechanical resistance. However, rapid temperature changes also introduced higher thermal stresses, which, if uncontrolled, may cause microcracking or distortion near the weld interface. Therefore, although fast cooling enhances tensile strength, it should be accompanied by proper preheating and post-weld heat treatment to relieve internal stresses.

The relationship between delay time and mechanical performance observed in this research aligns with previous studies on carbon steel welding, confirming that thermal management between passes and after welding is essential for maintaining weld integrity.

Combined Effects

The interaction between cooling medium and delay time produced distinct combined effects on tensile behavior. Immediate water cooling (A0) resulted in the highest average tensile strength (428.6 MPa), indicating a synergistic effect between rapid cooling and fine martensitic transformation. Conversely, delayed air cooling (U2) yielded the lowest tensile strength (365.2 MPa), primarily due to slow cooling and extensive grain coarsening.

These findings corroborate earlier work by Zulhafril et al. (2021) and Mubarok et al. (2023), who reported that faster cooling and minimal delay improve mechanical performance in SMAW-welded mild steels. The combined results emphasize the importance of precise control over both cooling rate and timing to achieve consistent weld quality. Furthermore, they highlight that even small variations in delay can significantly alter microstructural evolution, influencing hardness, ductility, and residual stress distribution within the welded joint.

Practical Implications

From an industrial perspective, water cooling with minimal delay is strongly recommended for enhancing the tensile strength of ST 37 welds, particularly in applications where mechanical reliability is critical. However, excessive quenching speed may increase residual stress and potential distortion. Therefore, process parameters such as preheat temperature, interpass temperature, and cooling rate must be carefully optimized to balance strength and dimensional stability.

Additionally, for thick or multi-pass welds, hybrid cooling techniques—such as initial water mist followed by air cooling—could provide better stress management while maintaining sufficient strength. These strategies could be beneficial for large-scale manufacturing and construction industries where ST 37 is commonly used for structural components.

Future research should include detailed microstructural and fractographic analysis using optical microscopy, scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDS) to verify phase transformation mechanisms and fracture modes. Further investigation into hardness profiles, impact toughness, and residual stress mapping could also strengthen the understanding of cooling dynamics in SMAW-welded mild steels.

CONCLUSION

Cooling media and delay time significantly affect the tensile strength of SMAW-welded ST 37 steel ($p < 0.05$).

a. Water cooling with no delay (A0) produced the highest tensile strength of 428.6 MPa due to rapid cooling and fine-grained microstructure.
b. Increasing delay time led to reduced tensile strength due to grain coarsening in the HAZ.
c. The optimal condition was found in water cooling with no delay, while the lowest was in air cooling with 60-second delay.
d. Overall, cooling rate and method are key determinants of SMAW weld quality in ST 37 steel.

RECOMMENDATION

a. For higher tensile strength, water cooling with immediate quenching is recommended.
b. In industrial practice, cooling rate control should be maintained to prevent cracking.
c. Future research should include microstructural and hardness analysis to further validate mechanical performance.
d. Studies on different steel grades and thicknesses are suggested for broader applicability.

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