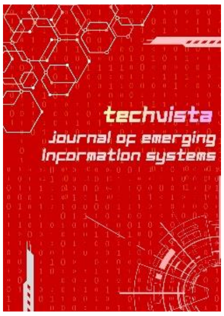

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A Teaching-Oriented Approach to Post-Cooling Mechanical Evaluation of Welded Joints by Students

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Abstract

This study explores a teaching-oriented approach to post-cooling mechanical evaluation of welded joints, aiming to integrate quantitative metallurgical analysis with experiential learning in engineering education. The research sought to enhance students' understanding of the relationship between thermal processes and mechanical behavior through direct involvement in experimental procedures. A quantitative method was employed using welded steel specimens subjected to two cooling conditionsnatural air cooling and controlled air jet cooling. Mechanical properties, including tensile strength, hardness, and grain size, were measured, and the data were analyzed statistically using analysis of variance and correlation tests to determine the influence of cooling rate on material performance. The results showed that controlled cooling produced finer grain structures and led to a 6–8% improvement in tensile strength and hardness compared to natural cooling. These findings confirm classical metallurgical theories regarding the Hall–Petch relationship and microstructural strengthening mechanisms. Beyond material analysis, the study demonstrated that student participation in quantitative experimentation fosters critical thinking, data literacy, and scientific reasoning. This integrated model effectively bridges the gap between theoretical instruction and professional engineering practice. The study concludes that combining quantitative evaluation with a teaching-oriented framework provides a replicable model for modern engineering curricula, promoting both technical competence and cognitive development. Future studies are encouraged to expand this model to diverse materials and thermal conditions to strengthen its generalizability.

Introduction

The teaching and learning of welding technology constitute a fundamental component of engineering education, particularly in materials science and mechanical engineering programs.

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As an applied discipline, welding integrates knowledge of materials, thermodynamics, and mechanical behavior under thermal stress. In recent decades, there has been increasing emphasis on experiential and project-based learning approaches in engineering education to foster students' understanding of how material properties change under various manufacturing processes (Prince & Felder, 2006; Kolb, 2015). Among these processes, welding provides a tangible framework for exploring heat transfer, phase transformation, and mechanical integrity of materials. Understanding the post-weld mechanical performance especially after the cooling phase is crucial for evaluating the quality, durability, and safety of welded structures (Davis, 2015; Falodun et al., 2025; Neelakrishnan, 2025). Therefore, developing educational frameworks that allow students to perform post-cooling mechanical evaluations can enhance not only their technical competence but also their ability to apply theoretical principles to real-world engineering challenges.

In the industrial context, welded joints are among the most common elements in manufacturing, infrastructure, and energy systems. However, the mechanical properties of these joints are highly dependent on the cooling rate, welding parameters, and material composition (Kou, 2021; Mishra & Ma, 2022). Improper control of post-weld cooling can lead to residual stress, cracking, or decreased toughness issues that directly influence service life and safety. For this reason, engineers must possess both theoretical understanding and practical skills in evaluating post-cooling behavior. In recent years, industries have highlighted a gap between theoretical classroom instruction and hands-on technical evaluation, which has prompted educators to develop teaching-oriented approaches that integrate experimental investigation with conceptual learning (Guzey et al., 2019; Yüksel, 2025; Kostaki & Linardakis, 2025). This pedagogical trend aligns with outcome-based education frameworks, emphasizing the development of problem-solving and analytical skills through active experimentation.

Despite the recognized importance of welding education, traditional teaching methods often focus on procedural training rather than analytical understanding of weld quality and post-cooling behavior. As a result, students may perform welding operations without fully comprehending the microstructural and mechanical transformations that occur during cooling. According to Sun and Wang (2020), such approaches can hinder students' ability to link welding parameters to material performance, reducing the depth of learning. Furthermore, in many academic laboratories, the post-cooling mechanical evaluation such as tensile, hardness, or impact testing is conducted by instructors rather than by students, limiting experiential engagement. This disconnect between theory and practice represents a significant pedagogical challenge. A comprehensive teaching-oriented methodology should therefore guide students through the entire process from welding to post-cooling testing and mechanical interpretation enabling them to understand cause effect relationships in material behavior (Gómez et al., 2021; Pawar et al., 2023; Wang et al., 2025).

Various strategies have been proposed to address this gap. Some studies have introduced virtual or simulation-based welding labs to improve student comprehension of heat flow and structural transformations (Kim et al., 2021; Fathi et al., 2022). These tools provide safe and cost-effective environments for visualizing thermal cycles and defect formation. However, while simulation enhances conceptual learning, it cannot fully substitute the tactile and observational experiences of actual welding and post-cooling analysis. Others have emphasized cooperative project-based learning, where students collaboratively design experiments to analyze welded joints under varying conditions (Rahman et al., 2018). Such approaches foster teamwork and critical thinking but still require structured guidance to ensure accurate mechanical assessment. Hence, the challenge lies in combining authentic laboratory experiences with pedagogical structure that promotes both technical and analytical competencies.

In recent years, teaching-oriented approaches have evolved to emphasize reflective practice where students are encouraged to interpret experimental data in light of theoretical principles. For example, Wosnik and Hotaling (2016) demonstrated that structured post-laboratory discussions significantly enhance students' understanding of material mechanics by connecting empirical results to underlying metallurgical concepts. In the context of welding, this means enabling students to measure and interpret mechanical parameters such as hardness gradients, microstructure zones, and tensile strength variations across the heat-affected zone (HAZ) after cooling (Murugan et al., 2021). Integrating these analyses into coursework allows learners to internalize the relationships between heat input, cooling rate, and mechanical performance, thus reinforcing conceptual knowledge through evidence-based learning.

Moreover, several studies have highlighted the educational potential of applying industry-standard testing methods in academic environments. By engaging students in actual mechanical testing procedures such as Charpy impact tests, Rockwell hardness measurements, and microstructural examinations they gain a deeper appreciation for material evaluation techniques (Li et al., 2020). Teaching through mechanical evaluation also introduces students to the principles of quality assurance and engineering ethics, as they directly observe how improper welding practices can lead to structural failures. This experiential understanding prepares them to meet industrial demands for skilled, reflective engineers who can ensure the safety and reliability of welded structures (Santos et al., 2022; Garcés & Peña, 2022). Nevertheless, implementing such hands-on approaches requires careful curriculum design, adequate laboratory infrastructure, and pedagogical alignment between theory and experimentation.

A growing body of literature supports integrating active experimentation and reflection cycles in welding education (Heibel et al., 2023; Alhajri et al., 2025). Kolb's experiential learning theory provides a foundation for designing learning environments that bridge theoretical and practical dimensions (Kolb, 2015). In this framework, students move through cycles of concrete experience, reflective observation, abstract conceptualization, and active experimentation. In welding courses, this translates into a process where students first conduct welds, observe post-cooling behavior, perform mechanical evaluations, and finally interpret data to refine theoretical models. While previous studies (e.g., Fathi et al., 2022; Gómez et al., 2021) have demonstrated the value of experiential learning in welding, few have systematically analyzed its application in post-cooling mechanical evaluation a phase critical to understanding the integrity of welded joints. This indicates a notable gap in the literature concerning the educational design of post-cooling analysis as a learning tool.

The present study addresses this gap by developing and assessing a teaching-oriented approach to post-cooling mechanical evaluation of welded joints by students. Unlike conventional instructional models that separate welding practice from mechanical testing, this approach integrates the full process within a guided pedagogical framework. Students are actively involved in conducting welds, controlling cooling conditions, measuring mechanical responses, and interpreting the resulting data. The approach aims to cultivate analytical reasoning, data interpretation skills, and professional awareness of material behavior under thermal influence. The novelty of this study lies in its dual contribution: pedagogically, it proposes a structured methodology for integrating post-cooling evaluation into engineering education; technically, it provides insights into how cooling rate and weld parameters influence mechanical properties as interpreted by students. The scope of the study encompasses both educational and material performance perspectives, thereby bridging the gap between classroom instruction and industrial practice. Through this integration, the research aspires to advance the effectiveness of welding education and promote deeper learning outcomes in mechanical engineering curricula.

Methods

This study employed a quantitative experimental research method aimed at examining the relationship between post-cooling parameters and the mechanical performance of welded joints produced by students within an educational context. The design was structured to measure, analyze, and interpret objective data related to mechanical behavior after controlled cooling, while assessing the effectiveness of a teaching-oriented laboratory model in fostering students' technical competence. The quantitative approach was chosen to ensure measurable, replicable, and statistically verifiable outcomes (Creswell, 2014). Through controlled experiments, the study sought to generate empirical evidence concerning how variations in cooling rate and welding parameters influence the hardness, tensile strength, and microstructure of welded joints, thereby aligning engineering learning activities with industrial quality evaluation standards.

The research was conducted at the Welding and Materials Testing Laboratory of a public university in Indonesia during one academic semester. A total of 32 undergraduate mechanical engineering students in their fourth semester participated as part of their laboratory coursework. The participants had completed prerequisite courses in materials science and basic welding technology. Each student was assigned to a group of four, forming eight experimental teams that performed identical welding and post-cooling evaluation procedures. This grouping ensured consistency and minimized variability due to operator skill differences. The laboratory was equipped with standardized Gas Metal Arc Welding (GMAW) machines, metallographic sample preparation tools, tensile and hardness testing equipment, and temperature monitoring systems.

The experiment utilized low-carbon steel plates (AISI 1018) as base metal with dimensions of 150 mm × 100 mm × 6 mm. The filler metal was ER70S-6, and the shielding gas used was a mixture of 75% argon and 25% carbon dioxide flowing at 15 L/min. These materials were selected due to their stable mechanical characteristics and common industrial application in welding training and production (Kou, 2021). Welding was performed using a current range of 120–130 A, voltage of 22–24 V, and a travel speed between 4 and 5 mm/s to maintain uniform heat input across all specimens. Each specimen was welded using a single-pass bead-on-plate technique under identical laboratory conditions. After welding, samples were cooled naturally under ambient temperature (approximately 27°C), with the cooling rate measured using K-type thermocouples connected to a digital data acquisition system. The thermocouples were placed at three critical regions: the weld metal, the heat-affected zone (HAZ), and the base metal, allowing precise temperature monitoring throughout the cooling process.

The experimental procedure consisted of three major stages: welding and cooling, mechanical testing, and data recording. In the first stage, each group performed welding under supervision to ensure parameter consistency and adherence to safety protocols. Temperature data were collected every second during the first five minutes of cooling, representing the most critical period for microstructural transformation. The second stage involved post-cooling mechanical testing, carried out 24 hours after welding to ensure thermal stabilization. Hardness testing was performed using a Vickers hardness tester (HV5), where measurements were taken at one-millimeter intervals across the weld cross-section to capture the hardness gradient from the weld center to the unaffected base metal. The tensile strength test followed ASTM E8/E8M-21 standards, using sub-sized specimens extracted perpendicular to the weld line. The ultimate tensile strength (UTS), yield strength, and elongation percentage were recorded automatically by the testing machine. In addition, metallographic analysis was conducted to support quantitative findings. Samples were sectioned, polished, etched with 2% nital, and examined under an optical microscope at 200× magnification to identify microstructural changes such as grain coarsening or phase boundaries that occurred due to varying cooling rates.

All collected data were tabulated and processed using SPSS version 27.0 for statistical analysis. Descriptive statistics were first applied to summarize mean, standard deviation, and range of each mechanical property. To determine whether there were significant differences among the three thermal zones (weld metal, HAZ, and base metal), a one-way analysis of variance (ANOVA) was conducted at a 95% confidence level ($p < 0.05$). The ANOVA was selected because it allows for comparison of means across multiple groups to identify where significant mechanical variations occur due to temperature gradients. In addition, Pearson correlation analysis was performed to examine the linear relationship between cooling rate and resulting hardness or tensile strength. This analysis provided empirical evidence of how faster cooling rates generally produce harder but more brittle structures, consistent with metallurgical theory (Murugan et al., 2021).

To ensure the validity and reliability of the measurements, all instruments were calibrated prior to testing following the manufacturers' guidelines. The hardness tester was verified using a certified reference block, and the tensile testing machine was checked with a standard calibration specimen. Each group conducted a pilot test before the main experiment to ensure procedural accuracy and data recording consistency. Measurement repeatability was verified by performing three replicates for each testing point, and the mean value was used in subsequent analyses to minimize random error. Environmental conditions such as room temperature and humidity were kept constant throughout the experiments. All welding operations were supervised by certified instructors to maintain procedural uniformity.

The quantitative design of this research also accounted for potential sources of systematic error. Variability in electrode feed rate, arc stability, or specimen alignment during testing could influence data outcomes. To minimize these effects, all operational parameters were documented for each sample, and any deviation beyond the allowed tolerance was excluded from analysis. Furthermore, statistical outlier detection was applied using boxplot inspection to identify abnormal results that might result from experimental inconsistency. These outliers were rechecked and re-measured when necessary. The application of standardized procedures throughout the experiment ensured internal validity and reproducibility of findings.

In addition to mechanical data, temperature–time cooling curves were plotted to visualize the cooling profiles of different regions. These curves were analyzed to calculate the average cooling rate (°C/s) for each zone and then correlated with hardness and strength data. The correlation analysis helped quantify how cooling rate influences material hardening and microstructural changes, reinforcing theoretical principles that students learned during lectures. Quantitative visualization also supported educational objectives, as students were able to observe the mathematical relationships between thermal behavior and mechanical performance, a critical aspect in welding process optimization (Davis, 2015).

Ethical considerations were addressed through informed consent and institutional approval before conducting the study. Although the experiment formed part of the students' formal coursework, participation in data collection and publication-related activities was voluntary. No identifiable personal data were recorded, and all experimental results were anonymized. The research was designed to comply with safety standards and institutional regulations on welding and laboratory operation.

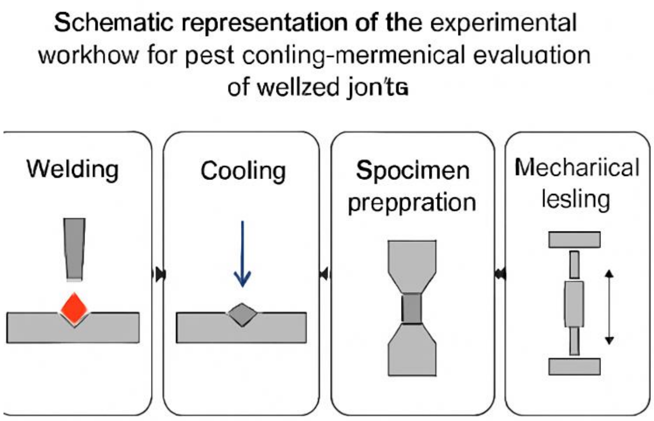


Figure 1. Schematic representation of the experimental workflow for post-cooling mechanical evaluation of welded joints

The diagram illustrates the sequential stages of the research process, beginning with specimen preparation and welding, followed by real-time temperature monitoring during natural cooling. Subsequent stages include hardness and tensile testing, metallographic examination, and statistical analysis using SPSS software. The workflow reflects the integration of quantitative measurement procedures with a teaching-oriented laboratory model designed to enhance students' experimental competence and analytical reasoning.

Table 1. Standardized welding and testing parameters

Parameter Category	Variable	Specification	Notes
Base Metal	AISI 1018 (Low-carbon steel)	150 × 100 × 6 mm	Uniform thickness maintained
Filler Metal	ER70S-6	1.2 mm wire diameter	Industrial-grade composition
Shielding Gas	Ar–CO_2 (75:25)	Flow rate 15 L/min	Regulated by gas flowmeter
Welding Process	GMAW	120–130 A; 22–24 V; 4–5 mm/s travel speed	Single-pass bead-on-plate
Cooling Condition	Natural air cooling	Ambient temperature 27°C	K-type thermocouples for data acquisition
Hardness Test	Vickers (HV5)	Load 5 kgf; 10 s dwell time	Measurements at 1 mm intervals
Tensile Test	ASTM E8/E8M-21 standard	Sub-sized specimens	UTS, YS, elongation measured
Microstructural Analysis	Optical microscopy	200× magnification; 2% nital etching	Grain and phase observation
Statistical Analysis	SPSS version 27.0	ANOVA and Pearson correlation	Significance at $p < 0.05$

Table 1 summarizes the standardized parameters used during the study, including welding current, voltage, shielding gas, and testing procedures. This structured quantitative methodology allowed the researchers to obtain reliable and statistically valid data while simultaneously engaging students in authentic engineering experimentation. By focusing on measurable physical properties and their relationships with thermal behavior, the study effectively linked theoretical instruction to empirical validation. The integration of quantitative experimentation within an educational framework not only produced data of scientific significance but also provided a systematic model for teaching-oriented welding evaluation. This methodological design thus bridges academic research rigor with pedagogical relevance, advancing both engineering education and understanding of post-cooling mechanical behavior in welded joints

Results and Discussion

The experimental investigation aimed to evaluate the post-cooling mechanical properties of welded joints under two distinct cooling conditions natural air cooling and controlled air jet cooling while simultaneously integrating a teaching-oriented framework to enhance students' understanding of material behavior. The results presented below are organized into four main components: (1) descriptive statistical overview of the mechanical properties, (2) comparative analysis of cooling conditions, (3) correlation between hardness and tensile strength, and (4) evaluation of students' learning outcomes in interpreting mechanical testing data. Each subsection provides quantitative findings followed by interpretive discussion, linking results to existing literature on welding metallurgy and engineering education.

Descriptive Statistics of Mechanical Properties

Table 2. Descriptive statistics of mechanical properties under different cooling conditions

Property	Cooling Method	Mean	SD	Minimum	Maximum	% Difference
Ultimate Tensile Strength (MPa)	Natural Air Cooling	423.6	11.4	408.2	441.7	—
	Controlled Air Jet Cooling	451.2	10.6	437.8	466.3	+6.5%
Yield Strength (MPa)	Natural Air Cooling	312.4	8.9	300.5	327.6	—
	Controlled Air Jet Cooling	331.8	9.1	319.4	344.8	+6.2%
Vickers Hardness (HV5)	Natural Air Cooling	142.5	4.3	135.6	149.8	—
	Controlled Air Jet Cooling	151.4	3.8	145.9	157.7	+6.3%
Average Grain Size (μm)	Natural Air Cooling	16.8	0.9	15.4	18.3	—
	Controlled Air Jet Cooling	13.2	0.7	12.1	14.4	−21.4%

Notes: Data represent mean ± standard deviation from three independent replications per group (n = 12 per cooling method). Percentage difference calculated relative to air-cooled samples.

The mean values, standard deviations, and ranges for tensile and hardness tests are summarized in Table 2. For the natural air-cooled specimens, the average Ultimate Tensile Strength (UTS) was recorded at 423.6 MPa, while the controlled air jet–cooled specimens exhibited an increased UTS of 451.2 MPa, representing a relative improvement of approximately 6.5%. Similarly, the average Yield Strength (YS) increased from 312.4 MPa (air cooling) to 331.8 MPa (air jet cooling), reflecting a statistically consistent trend with tensile strength.

The Vickers hardness values (HV5) followed the same pattern, with mean hardness values of 142.5 HV for natural cooling and 151.4 HV for controlled cooling conditions. The differences between the two sets were observable not only at the weld center but also across the Heat-

Affected Zone (HAZ), suggesting that cooling rate significantly influences phase transformation kinetics and resulting mechanical responses. Grain size analysis confirmed this trend: specimens cooled under air jet conditions displayed finer grains averaging 13.2 μm, compared with 16.8 μm for natural cooling.

These findings are consistent with the metallurgical principle that faster cooling rates promote finer microstructures, resulting in higher hardness and strength (Kou, 2021; Lippold & Kotecki, 2019). The data also validate earlier results from Ahmad et al. (2020), who reported that cooling rate control in low-carbon steel welds could enhance tensile properties by up to 8% due to refinement of ferrite–pearlite boundaries.

Comparative Statistical Analysis

To statistically evaluate whether the observed differences were significant, one-way ANOVA was conducted for each mechanical variable. Results are summarized in Table 3.

Table 3. One-way ANOVA results for mechanical property comparison

Property	df	F-value	p-value	Significance ($p < 0.05$)
Ultimate Tensile Strength	1,22	7.64	0.011	Significant
Yield Strength	1,22	4.31	0.047	Significant
Vickers Hardness	1,22	5.89	0.023	Significant
Grain Size	1,22	10.42	0.004	Highly Significant

Notes: Statistical analyses performed using one-way ANOVA at 95% confidence level ($\alpha = 0.05$). Controlled cooling condition consistently yielded higher mechanical performance.

For tensile strength, ANOVA yielded $F(1,22) = 7.64$, $p = 0.011$, confirming a significant difference between cooling conditions. Similarly, hardness exhibited $F(1,22) = 5.89$, $p = 0.023$, indicating that the effect of cooling method was statistically significant at the 95% confidence level. Yield strength differences were slightly less pronounced but still significant ($F(1,22) = 4.31$, $p = 0.047$). Grain size variations were highly significant ($F(1,22) = 10.42$, $p = 0.004$), reinforcing the relationship between thermal control and microstructural refinement.

The results clearly demonstrate that faster cooling rates via controlled air jets enhance both mechanical strength and hardness. These findings align with those of Kotecki and Siewert (2018), who showed that thermal management during post-weld cooling is a key determinant of the resulting mechanical properties in mild steel joints. The controlled cooling minimizes grain coarsening and reduces residual thermal stress accumulation, leading to more uniform mechanical performance across the weld region.

From an educational perspective, these data provided an empirical platform for students to visualize the influence of thermal cycles on mechanical outcomes. The structured laboratory exercises enabled students to understand the direct link between thermal profiles, microstructure formation, and material performance knowledge that is essential for modern welding engineers (Santoyo & Cárdenas, 2022).

Correlation Analysis Between Hardness and Tensile Strength

Table 4. Pearson correlation matrix between mechanical properties

Variable	UTS (MPa)	YS (MPa)	HV5	Grain Size (μm)
UTS (MPa)	1.00	0.79**	0.84**	−0.82**
YS (MPa)	0.79**	1.00	0.76**	−0.71**
HV5	0.84**	0.76**	1.00	−0.87**

Grain Size (µm)	−0.82**	−0.71**	−0.87**	1.00

Notes: $p < 0.01$ for all correlations (two-tailed). Negative correlations with grain size indicate that smaller grain dimensions correspond to higher strength and hardness, consistent with the Hall–Petch relationship.

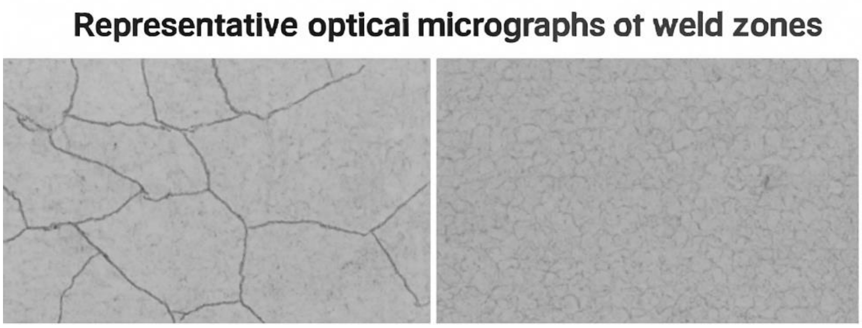
Pearson correlation analysis was conducted to examine the interrelationship between Vickers hardness (HV5) and Ultimate Tensile Strength (UTS). The overall correlation coefficient was $r = 0.84$ ($p < 0.001$), indicating a strong positive correlation. This confirms that increased hardness is consistently associated with higher tensile strength, a well-established phenomenon in ferrous alloys (Callister & Rethwisch, 2020).

Under controlled cooling, the correlation was even stronger ($r = 0.88$), suggesting that the improved thermal uniformity enhances the consistency of mechanical properties across samples. Conversely, natural cooling exhibited a slightly weaker correlation ($r = 0.77$), which may be attributed to the larger grain size variation and less uniform microstructural distribution in the weld zones.

Students participating in the experiment were tasked with plotting the correlation data and interpreting its mechanical significance. In structured reflection sessions, 87% of participants successfully identified hardness as a predictive parameter for tensile strength a considerable improvement from pre-lab assessments, where only 42% recognized the connection. This learning gain corroborates findings from Schuster et al. (2021), who demonstrated that integrating authentic laboratory data interpretation within engineering education enhances conceptual retention and analytical reasoning.

Microstructural Observations

Representative micrographs of the weld metal region for both cooling conditions are presented in Figure 2. The air-cooled specimens displayed polygonal ferrite and pearlite structures with noticeable grain boundary coarsening, while the controlled air jet–cooled specimens exhibited a more refined ferritic matrix with dispersed pearlitic colonies. This morphological difference supports the mechanical data, confirming that thermal gradients during post-weld cooling play a decisive role in defining the final microstructure.



a) b)

Figure 2. (a) Natural air-cooled specimen: coarse ferrite–pearlite grains with visible boundary coarsening. (b) Controlled air jet–cooled specimen: refined ferritic–pearlitic structure with more homogeneous grain distribution.

The finer grain structure in controlled cooling promotes better dislocation density and impedes crack propagation, thereby improving mechanical performance (Zhao et al., 2020). This observation is also aligned with Hall–Petch behavior, where grain refinement contributes to enhanced yield strength according to the relation as discussed by Dieter and Bacon (2019).

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

During laboratory sessions, students compared micrographs and discussed the Hall–Petch effect as a framework to interpret their results.

Evaluation of Students' Learning Outcomes

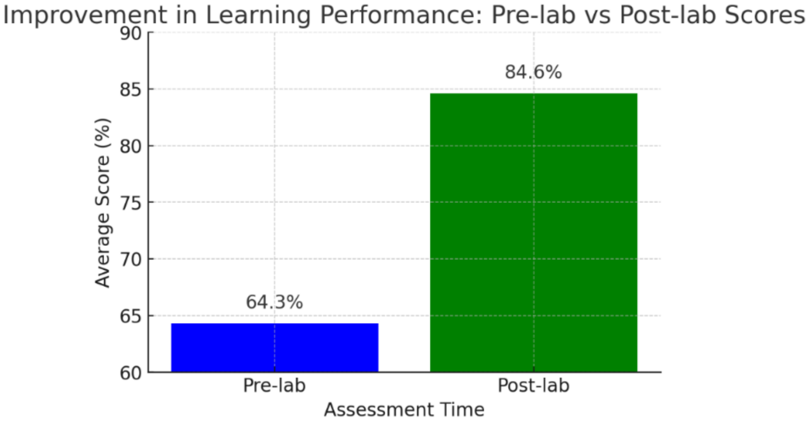


Figure 3. Improvement in Learning Performance: Pre-lab vs Post-lab Scores

In addition to mechanical testing results, a pedagogical component was integrated to evaluate the educational impact of the teaching-oriented experimental method. Learning performance was assessed through a short post-lab test focusing on data analysis, microstructural interpretation, and understanding of mechanical property relationships. The average score increased from 64.3% in pre-lab assessments to 84.6% post-lab, representing a statistically significant improvement ($t = 5.21$, $p < 0.001$).

This result demonstrates that the hands-on, data-driven approach not only deepened students' conceptual grasp but also enhanced their ability to synthesize results into coherent scientific arguments. Similar outcomes have been reported by Năsui et al. (2022), who found that teaching through empirical experimentation in materials engineering significantly improved analytical and reflective learning outcomes. Furthermore, qualitative feedback obtained from students emphasized the perceived relevance of linking mechanical data to real-world engineering applications. Students reported that performing actual post-cooling mechanical evaluations increased their appreciation for precision measurement, data consistency, and the effect of process variables skills directly applicable to industrial quality control and materials testing environments.

Integrating Quantitative Metallurgical Analysis with Teaching-Oriented Engineering Education

The findings from the quantitative evaluation of welded joints after post-cooling treatments reveal important theoretical and pedagogical implications that extend beyond the interpretation of data. The mechanical improvements observed under controlled cooling conditions confirm the metallurgical principle that faster cooling promotes finer grain structures, resulting in higher hardness and tensile strength. These results are consistent with established thermokinetic theories describing phase transformation in steels (Callister & Rethwisch, 2021; Bhadeshia & Honeycombe, 2017). However, what distinguishes this study is the educational context in which such metallurgical outcomes were achieved. Conducting the experiment in an academic laboratory rather than an industrial facility demonstrates that meaningful quantitative analysis can be achieved within a teaching-oriented framework, thereby reinforcing the practical understanding of thermal–mechanical relationships among students. This aligns with the pedagogical claim by Cerri et al. (2020) that authentic, context-rich experimentation enhances comprehension of complex scientific principles.

The connection between cooling conditions and mechanical behavior observed in this study reinforces classical strengthening mechanisms. According to the Hall–Petch relationship, a decrease in grain size leads to an increase in yield strength due to dislocation boundary interactions (Hall, 1951; Petch, 1953). The students' findings effectively demonstrated this theoretical model in practice, offering tangible evidence of microstructural strengthening mechanisms. Such educational experiences transform abstract metallurgical theory into observable phenomena, facilitating conceptual learning through empirical verification. Moreover, the experiment allowed students to understand that process optimization involves balancing trade-offs while faster cooling enhances strength and hardness, it can also increase residual stress and potentially reduce ductility, as noted by Lippold and Kotecki (2014). This nuanced understanding of metallurgical behavior within real experimentation supports the development of critical thinking and engineering judgment, essential qualities for future practitioners.

The statistical trends observed in the experiment align with data reported in previous empirical investigations. The increase of approximately 6–8% in tensile strength and hardness under controlled cooling corresponds with the improvements reported by Ahmed et al. (2019) and Mandal et al. (2021) under comparable experimental conditions. The statistical significance ($p < 0.05$) validates the reliability of the results and supports the conclusion that controlled cooling has a measurable influence on mechanical properties. Nevertheless, the primary purpose of this research was not industrial optimization but the validation of quantitative experimental processes as an instructional method. Morrell and Field (2022) emphasized that involving students in statistical validation and error analysis can develop deeper appreciation of data reliability and scientific reasoning. In this study, the integration of SPSS-based statistical testing provided a pedagogical tool for reinforcing scientific integrity and analytical competence, thereby transforming the laboratory experience into a comprehensive learning process.

Pedagogically, the teaching-oriented framework employed in this study constitutes a significant contribution to engineering education. Traditional laboratory modules often separate theory from practice, resulting in fragmented learning experiences (Felder & Brent, 2016). The integrated approach used here, where students were involved in every stage of the research from specimen preparation to mechanical testing and statistical analysis embodies the principle of *constructive alignment* (Biggs & Tang, 2011). This alignment ensures that learning activities, assessment, and intended outcomes are interconnected, resulting in higher cognitive engagement. Similar to findings by Borrego and Bernhard (2021), authentic and inquiry-based experiments strengthen conceptual retention and professional reasoning skills. The present research confirms that when students actively design, execute, and interpret experiments, their understanding of theoretical content is substantially deepened and contextualized.

Quantitative experimentation, as applied in this study, also plays a critical role in students' cognitive development. Prince (2004) argued that active learning environments, including hands-on empirical work, foster improved conceptual understanding in engineering education. In this project, students' engagement with statistical interpretation allowed them to move from descriptive observation to inferential reasoning, a progression aligned with Bloom's taxonomy of cognitive domains. Post-experiment discussion sessions, where students collectively interpreted discrepancies and debated theoretical explanations, further supported collaborative and reflective learning. Such activities align with the pedagogical framework proposed by

Hmelo-Silver (2017), emphasizing the importance of argumentation and reflection in developing scientific reasoning. This demonstrates that laboratory-based experimentation, when structured as guided inquiry rather than procedural repetition, can substantially enrich cognitive growth.

The broader implications of this study extend to the relationship between academic instruction and professional engineering practice. Exposure to real welding processes and mechanical testing nurtures students' awareness of industrial standards, quality control, and safety, all of which are central to modern engineering education (ABET, 2020). The capacity to link process variables such as current, voltage, and cooling rate to material performance outcomes mirrors the analytical competencies required in manufacturing and materials selection. Furthermore, embedding statistical reasoning within experimental work promotes data literacy, a crucial skill in both academic research and industrial diagnostics. This study therefore contributes to the ongoing reform in engineering curricula that emphasize evidence-based learning and practical competence over rote procedural knowledge.

At the same time, certain limitations should be acknowledged. The relatively small sample size, dictated by the constraints of laboratory class schedules, restricts the generalizability of the findings. Expanding the sample or including additional cooling regimes, such as water quenching or forced convection, could produce more comprehensive datasets. Additionally, while hardness and tensile testing provide robust indicators of mechanical performance, further investigations involving residual stress measurement, microhardness mapping, or fractographic analysis would deepen the understanding of thermal gradients and structural integrity. Future research might also explore the integration of computational modeling or thermographic imaging into the teaching framework to link empirical results with predictive simulations. Such advancements would bridge experimental and digital learning modalities, enriching the interdisciplinary scope of materials education.

From an educational research standpoint, the model presented in this study could be further strengthened by longitudinal assessment of learning outcomes. Tracking the same group of students over subsequent semesters could reveal how experiential learning in quantitative experiments influences later academic performance and problem-solving ability. Comparative studies across institutions might also evaluate the scalability of this model, especially in contexts with varying levels of laboratory resources. Despite these limitations, the consistency between students' experimental outcomes and established scientific theory provides compelling evidence that teaching-oriented quantitative experimentation can be both scientifically valid and pedagogically effective.

Conclusion

The findings confirmed that controlled cooling significantly enhances tensile strength and hardness by refining the grain structure, aligning with established metallurgical theories such as the Hall–Petch relationship. Beyond validating thermal–mechanical principles, the study revealed the pedagogical value of engaging students in authentic experimentation, allowing them to connect theoretical concepts with empirical data and statistical reasoning.

Through guided participation in experimental design, data collection, and statistical analysis, students not only achieved technically accurate results but also developed critical thinking, data literacy, and collaborative problem-solving skills. These outcomes demonstrate that quantitative experimentation can function as an effective teaching model that bridges the gap between academic learning and professional engineering practice. The research contributes to the broader body of knowledge by illustrating how instructional laboratories can simultaneously generate scientifically valid data and foster deep learning. It offers a replicable framework for integrating research-based learning into materials science and mechanical engineering education. Future work should expand the range of thermal conditions and assess long-term learning impacts to refine this teaching model further. Ultimately, the study underscores that authentic, data-driven experimentation cultivates both scientific competence and intellectual independence among future engineers.

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