Integrated Science Education Journal
Vol. 7, No. 1, January 2026, pp. 127~136
ISSN: 2716-3725, DOI: 10.37251/isej.v7i1.2461

Research Article

Effect of Heat Treatment and Tempering Process on the Hardness of S55c Steel as A Cutting Blade Material for Plastic Shredding Machines

Eko Yudo[1], Ariyanto[1,*], Erwansyah[1], Zaldy Sirwansyah Suzen[1], Sugiyarto[1], Yuli Dharta[1], Zulfitriyanto[1]

[1] Department of Mechanical Engineering and Manufacturing, Politeknik Manufaktur Negeri Bangka Belitung, Kepulauan Bangka Belitung, Indonesia

Article Info

Article history:

Received Oct 15, 2025
Revised Nov 30, 2025
Accepted Dec 31, 2025
OnlineFirst Jan 11, 2026

Keywords:

S55C
Heat Treatment
Quenching
Taguchi Method
Tempering

ABSTRACT

Purpose of the study: This study aims to optimize the heat treatment process of S55C medium-carbon steel by examining the combined effects of austenitizing temperature, quenching media, and tempering temperature on impact toughness.

Methodology: An experimental approach was employed using quenching and tempering treatments. Quenching was performed at three austenitizing temperatures (950°C, 1000°C, and 1050°C) with three different cooling media—salt water, oil, and seawater—followed by tempering at 100°C, 200°C, 300°C, and 400°C. All heating processes were conducted in an electric furnace. Parameter optimization was carried out using the Taguchi method with an L9 orthogonal array. Mechanical performance was evaluated through Charpy impact testing, and confirmation experiments were conducted to validate the optimal parameter combination.

Main Findings: The Taguchi analysis identified the optimal quenching condition at an austenitizing temperature of 1050°C with salt water as the cooling medium, yielding the highest impact toughness. Confirmation tests supported the reliability of this result. Additionally, the tempering process showed that increasing the tempering temperature decreased hardness while significantly improving toughness, indicating effective stress relief and improved ductility in the steel microstructure.

Novelty/Originality of this study: The novelty of this study lies in the integrated optimization of quenching temperature and diverse cooling media, including seawater, using the Taguchi method, with a specific focus on toughness rather than hardness alone. This research provides new insights into tailoring heat treatment parameters for S55C steel to achieve superior impact resistance, offering practical guidance for more efficient and application-oriented heat treatment strategies in manufacturing industries.

Corresponding Author:
Ariyanto,
Department of Mechanical Engineering and Manufacturing, Politeknik Manufaktur Negeri Bangka Belitung, Kawasan industri air kantung, Kabupaten Bangka, Kepulauan Bangka Belitung, 33215, Indonesia
Email: ariyanto2176@gmail.com

1. INTRODUCTION

Steel is an alloy primarily composed of iron (Fe) and carbon (C), with additional alloying elements such as manganese (Mn), silicon (Si), phosphorus (P), sulfur (S), and trace residual elements including aluminum, nitrogen, and oxygen. Among these elements, carbon plays the most critical role in determining the mechanical properties of steel, particularly hardness and tensile strength. Generally, the carbon content in steel ranges from 0.2% to 2.1% by weight, and variations within this range significantly influence microstructure formation and performance characteristics [1]-[6].

This study focuses on S55C medium-carbon steel, which contains approximately 0.48% carbon and is widely used in mechanical components requiring a balance between strength, hardness, and toughness. The chemical composition of S55C steel consists of 0.48% C, 0.24% Si, 0.7% Mn, 0.011% P, 0.007% S, 0.01% Ni, and 0.02% Cu. Due to its favorable mechanical properties and good machinability, S55C steel is commonly applied in the manufacturing of components such as sprocket gears, shafts, and other power transmission elements. However, to meet specific performance requirements, S55C steel often requires appropriate heat treatment processes. One of the most critical aspects of heat treatment is the selection of quenching media such as salt water, oil, or seawater which must be carefully matched to the steel's hardenability, component geometry, section thickness, and the desired cooling rate to obtain optimal microstructures [7]-[12]. In this research, the hardening process was performed at temperatures of 950°C, 1000°C, and 1050°C, followed by quenching using salt water, oil, and seawater as cooling media.

Heat treatment is a controlled sequence of heating and cooling processes applied to metals to modify their mechanical and metallurgical properties according to specific design requirements [13]-[17]. Several heat treatment processes are relevant to this study. Annealing is primarily intended to soften the metal, improve ductility, relieve internal stresses, and refine grain structure. The effectiveness of annealing depends on parameters such as material composition, heating temperature, holding time, and cooling rate [18]-[22]. In contrast, hardening is conducted to significantly increase hardness, wear resistance, and strength. Steel exhibits hardenability, which enables the formation of martensite during rapid cooling or quenching. Martensite is a supersaturated solid solution formed through atomic displacement and lattice distortion during rapid cooling, and it is the primary phase responsible for enhanced hardness and strength in hardened steel [23]-[26]. However, the formation of martensite is also accompanied by high residual stresses and increased brittleness, which may negatively affect impact resistance.

To mitigate the adverse effects of hardening, tempering is applied as a subsequent heat treatment process. Tempering aims to reduce residual stresses and brittleness while improving ductility and toughness. Although tempering generally results in a slight reduction in hardness and tensile strength, it significantly enhances the material's ability to absorb energy and resist fracture under dynamic loading conditions [27]-[33]. Therefore, the combination of hardening and tempering is essential to achieve a balanced set of mechanical properties suitable for engineering applications. Evaluation of mechanical property changes resulting from heat treatment is commonly conducted through hardness and impact testing [34]-[36]. Hardness testing provides an indication of a material's resistance to permanent deformation or indentation and is widely used to assess the effectiveness of heat treatment processes. The most commonly employed hardness testing methods include Rockwell, which is based on indentation depth, as well as Brinell and Vickers methods. In addition to hardness, impact testing is essential to evaluate material toughness, defined as the ability to absorb energy under sudden or impact loading conditions. Impact tests provide critical insight into the material's resistance to brittle fracture, particularly after hardening and tempering treatments [37]-[39].

Although numerous studies have investigated the effects of heat treatment on medium-carbon steels, existing research predominantly focuses on single quenching media or limited hardening temperature ranges. Comparative investigations that systematically examine the combined influence of multiple austenitizing temperatures and different quenching media (salt water, oil, and seawater) on both hardness and impact toughness of S55C steel remain limited. Furthermore, the use of seawater as a quenching medium despite its availability and potential industrial relevance has received relatively little attention in controlled experimental studies. Additionally, many previous studies emphasize hardness improvement as the primary performance indicator, while the corresponding changes in impact toughness are often insufficiently explored. This creates a knowledge gap regarding the trade-off between hardness enhancement and toughness degradation, which is critical for components such as sprocket gears that are subjected to both static and dynamic loads.

To address these gaps, the present study systematically investigates the effects of varying hardening temperatures (950°C, 1000°C, and 1050°C) and different quenching media (salt water, oil, and seawater) on the hardness and impact properties of S55C carbon steel. The findings of this study are expected to provide a more comprehensive understanding of the heat treatment–property relationship and offer practical guidance for selecting appropriate heat treatment parameters for industrial applications requiring an optimal balance between hardness and toughness.

2. RESEARCH METHOD

This study employed an experimental research method aimed at investigating the effects of quenching temperature and cooling media on the hardness of S55C steel, which is a crucial property for cutting tool applications. To ensure experimental efficiency and robustness, the Taguchi method was adopted using an L9 orthogonal array. This approach allows systematic evaluation of multiple process parameters with a reduced number of experimental runs while maintaining reliable statistical analysis.

This study employs two main factors (independent variables), each consisting of three levels, which are efficiently represented by the Taguchi L9 orthogonal array.

Table 1. Factors and Levels

Factor (Independent Variable)	Symbol	Level 1	Level 2	Level 3
Quenching Temperature (T)	A	950°C	1000°C	1050°C
Cooling Media (M)	B	Salt Water	Oil	Seawater

Fot L9 Orthogonal array matrix can see in Table 2.

Table 2. L9 Orthogonal Array Matrix

Experiment No.	Factor A (Temperature)	Factor B (Cooling Media)
1	950°C	Salt Water
2	950°C	Oil
3	950°C	Seawater
4	1000°C	Salt Water
5	1000°C	Oil
6	1000°C	Seawater
7	1050°C	Salt Water
8	1050°C	Oil
9	1050°C	Seawater

The material used in this study was S55C medium-carbon steel, prepared in standard specimen dimensions suitable for hardness and impact testing. The main equipment included a heat treatment furnace capable of accurately maintaining the specified quenching temperatures, as well as a hardness testing machine (Vickers or Rockwell) to measure the resulting hardness values after heat treatment. Additional equipment was used to support impact testing using the Charpy method.

In This experimental procedure consists of specimen preparation, heat treatment (austenitizing, quenching, and tempering), followed by hardness and impact testing to evaluate the resulting mechanical properties. S55C steel was cut into nine identical test specimens, corresponding to the number of runs in the L9 orthogonal array,The surface of each specimen was ground and polished to ensure accurate hardness measurement results. Proper Each specimen underwent heat treatment according to the parameter combinations listed in the L9 matrix.

Heating (Austenitizing), The specimens were heated in the furnace to the designated quenching temperatures of 950°C, 1000°C, or 1050°C and held for an appropriate soaking time to ensure uniform austenite formation. Rapid Cooling (Quenching), The specimens were removed from the furnace and immediately immersed in the assigned cooling media (salt water, oil, or seawater). Quenching was performed until the material reached room temperature. Tempering Process, Although S55C is classified as medium-carbon steel and hardness can be measured directly after quenching, in actual cutting tool applications tempering is commonly performed to reduce brittleness. For this study, tempering was carried out at temperatures of 100°C, 200°C, 300°C, and 400°C to obtain sufficient toughness prior to mechanical testing. Impact Testing (Charpy Method), The impact test was conducted to evaluate the toughness of the steel under dynamic loading conditions. The Charpy method was used, in which the specimen is positioned horizontally on the support during testing. A higher absorbed energy value indicates better toughness of the material [9].

The hardness data (response) will be analyzed using Analysis of Variance (ANOVA) to determine which variable quenching temperature or cooling media has the most significant influence on the hardness of S55C steel. The Taguchi method employs the S/N ratio to evaluate data quality. Since the objective of this research is to maximize hardness (as required for cutting tool applications), the "Larger-is-Better" criterion is used.

$$Rasio\frac{S}{N} = -10\ Log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_1^2}\right) \dots (1)$$

Where *yi* represents the hardness result for the *i-th* test, and *n* is the number of repeated measurements (replications). The average S/N values for each factor level (quenching temperatures of 950°C, 1000°C, 1050°C and cooling media of salt water, oil, and seawater) will be calculated. The factor level with the highest S/N value indicates the optimum condition for achieving maximum and stable (robust) hardness. Based on the S/N ratio and ANOVA analysis, the following conclusions will be drawn. The optimal combination of quenching temperature (X °C) and cooling media (Y) required to achieve maximum hardness. The relative contribution of each factor toward the improvement of hardness.

3. RESULTS AND DISCUSSION

The chemical composition of the material was obtained from the material certificate, including the percentage content of each element Table 3.

Table 3. Chemical Composition of S55C

Composition (%)	C	Si	Mn	P	S	Ni	Cu
	0.48	0.24	0.70	0.011	0.007	0.01	0.02

The prepared specimens were subjected to a heating process according to the predetermined experimental parameters. The chemical composition of the S55C steel, as presented in Table 3, confirms that the material belongs to the medium-carbon steel category, with a carbon content of 0.48%. This carbon level is sufficient to promote martensitic transformation during rapid quenching, making S55C suitable for applications requiring high hardness such as cutting tools and mechanical components subjected to wear [40], [41]. The presence of manganese (0.70%) further enhances hardenability by delaying pearlite formation, while the low levels of phosphorus and sulfur indicate good metallurgical quality, minimizing brittleness and hot shortness during heat treatment [42]. After the heat treatment process was completed, hardness testing was carried out to obtain the hardness values. The detailed results of the testing can be seen in Table 4.

Table 4. Hardening Process Results

Temperature (°C)	Quenching Medium	R1	R2	R3	Average
950	Salt Water	35.6	40.0	31.5	35.7
950	Sea Water	35.4	35.7	36.2	35.8
950	Oil	32.6	41.7	35.9	36.7
1000	Salt Water	41.5	47.4	38.2	42.4
1000	Sea Water	40.4	42.6	34.9	39.3
1000	Oil	38.3	40.8	39.7	39.6
1050	Salt Water	39.6	41.8	40.6	40.7
1050	Sea Water	37.6	48.8	43.8	43.4
1050	Oil	35.0	37.5	37.4	36.6

The hardening results presented in Table 4 show a clear influence of quenching temperature on the resulting hardness values. At 950°C, the average hardness values remain relatively moderate across all quenching media, suggesting that austenitization at this temperature may not have fully dissolved carbides or produced a sufficiently homogeneous austenitic structure. As the quenching temperature increases to 1000°C, a significant increase in hardness is observed, particularly when salt water is used as the quenching medium, yielding the highest average hardness of 42.4 HRC. This behavior can be attributed to more complete austenite formation and increased carbon solubility at higher temperatures, which subsequently promotes the formation of harder martensite upon quenching [43]. At 1050°C, although the temperature is higher, the hardness does not continue to increase consistently and even decreases for certain quenching media, such as oil. This phenomenon can be explained by grain coarsening at excessive austenitizing temperatures, which reduces the effectiveness of martensitic strengthening and may increase retained austenite content [44]-[46]. Coarser austenite grains reduce the number of martensite nucleation sites, leading to less uniform hardness despite rapid cooling.

The effect of quenching media is evident in the experimental data but is less dominant compared to temperature. Salt water generally produces higher hardness values due to its higher cooling rate, which suppresses diffusion-controlled transformations such as pearlite and bainite, favoring martensite formation [47]-[49]. Oil, which provides a slower cooling rate, results in lower hardness values, particularly at higher temperatures, as it allows partial transformation into softer microstructures. Seawater exhibits intermediate behavior, likely due to its salt content, which increases cooling severity compared to freshwater but remains less aggressive than salt water solutions.

Table 5. ANOVA Experimental Results Processing

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Temperature	2	109.38	25.85%	109.38	54.69	4.12	0.030
Cooler	2	21.46	5.07%	21.46	10.73	0.81	0.459
Error	22	292.27	69.08%	292.27	13.28		
Lack-of-Fit	4	67.01	15.84%	67.01	16.75	1.34	0.294
Pure Error	18	225.26	53.24%	225.26	12.51		
Total	26	423.10	100.00%				

```
Response Table for Signal to Noise Ratios
Larger is better

Level  TEMPERATUR  PENDINGIN
1           31,06      31,85
2           32,06      31,82
3           32,02      31,46
Delta        1,00       0,39
Rank            1          2
```

Figure 2. S/N Ratio Values

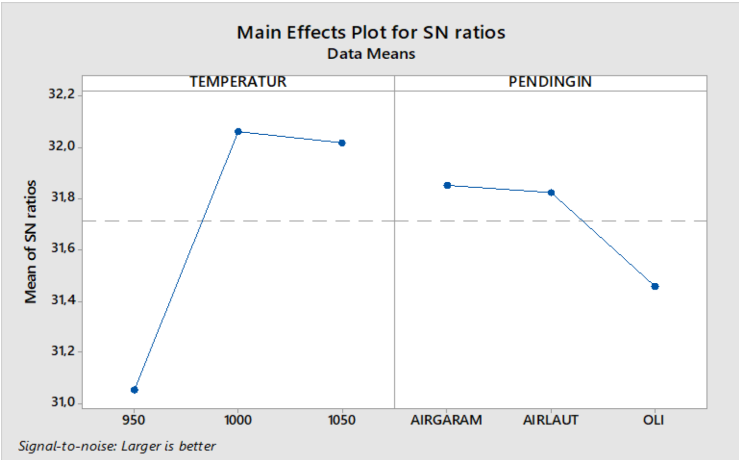

Figure 3. Experimental Values Influencing the Hardness of the Specimens

These observations are statistically supported by the ANOVA results shown in Table 5. The temperature factor exhibits a P-value of 0.030, indicating a statistically significant effect on hardness at a 95% confidence level. In contrast, the cooling medium shows a P-value of 0.459, suggesting that its effect is not statistically significant within the tested parameter range. This finding reinforces the conclusion that austenitizing temperature plays a more critical role than quenching medium in determining the hardness of S55C steel, particularly when the carbon content is sufficiently high to ensure martensitic transformation [50], [51]. The relatively large contribution of experimental error (69.08%) may be attributed to inherent variability in heat treatment processes, such as temperature fluctuations, immersion time differences, and microstructural heterogeneity.

The Taguchi Signal-to-Noise (S/N) ratio analysis further confirms that the optimal condition for achieving maximum and stable hardness is a quenching temperature of 1000°C with salt water as the cooling medium. This condition represents a balance between sufficient austenitization and avoidance of excessive grain growth, while the high cooling severity ensures the formation of predominantly martensitic microstructures. Similar optimal temperature ranges have been reported in previous studies on medium-carbon steels subjected to hardening treatments [52]-[54].

After the hardening process was carried out on the S55C steel and the optimal hardness value was obtained, the next stage was tempering. The tempering treatment resulted in changes in mechanical properties, particularly in hardness and toughness of the S55C steel. The initial toughness value before the hardening and tempering processes, based on the impact test, was recorded at 34 Joules.

Table 6. Hardness Test and Impact Test Results After Tempering Process

Tempering Temperature (°C)	Hardness (HRC)	Impact Test (Joule)
100	42.1	15.3
200	40.7	16.3
300	36.7	21.3
400	33.8	29.3

From Table 6, it can be observed that an increase in tempering temperature results in a decrease in the hardness of S55C steel. Higher tempering temperatures promote the transformation of quenched martensite into tempered martensite, during which the carbide (cementite) precipitates become more spherical, refined, and uniformly distributed. This microstructural modification leads to a reduction in hardness while simultaneously increasing the ductility and toughness of the material. Following hardening, the tempering results presented in Table 6 illustrate the classical trade-off between hardness and toughness. As the tempering temperature increases from 100°C to 400°C, hardness decreases progressively from 42.1 HRC to 33.8 HRC, while impact energy increases from 15.3 J to 29.3 J. This behavior is characteristic of tempered martensite, where increased tempering temperature promotes carbide precipitation, recovery of the martensitic structure, and reduction of internal stresses [55], [56]. At lower tempering temperatures, the structure remains relatively brittle due to the presence of supersaturated carbon and high dislocation density, resulting in low impact toughness.

At higher tempering temperatures, particularly at 300°C and 400°C, cementite particles become more refined and spheroidized, leading to improved ductility and energy absorption capacity during impact loading. This microstructural evolution explains the substantial increase in toughness, which approaches the initial toughness value of 34 J observed before hardening and tempering. These findings are consistent with established tempering behavior of medium-carbon steels, where controlled tempering is essential to achieve an optimal balance between hardness and toughness for practical engineering applications [57]. Overall, the results demonstrate that quenching temperature is the primary factor governing hardness in S55C steel, while the quenching medium plays a secondary role within the tested conditions. Furthermore, the tempering process is shown to be crucial in tailoring mechanical properties to meet application-specific requirements. This comprehensive understanding of heat treatment effects provides a strong scientific basis for optimizing S55C steel for cutting tool and wear-resistant applications.

The novelty of this study lies in the integrated experimental and statistical demonstration that, for S55C medium-carbon steel, austenitizing temperature plays a more dominant role than quenching media in controlling hardness, even though different cooling severities are applied. Unlike many previous studies that emphasize the quenching medium as the primary determinant of hardness, this research quantitatively confirms through ANOVA and Taguchi S/N ratio analysis that temperature contributes significantly (P-value = 0.030), whereas the cooling medium does not show a statistically significant effect within the investigated range. Furthermore, this study uniquely combines hardening optimization using the Taguchi method with a systematic tempering toughness evaluation, thereby providing a more complete heat-treatment framework relevant to cutting tool applications rather than focusing solely on hardness improvement. From a metallurgical perspective, the findings reinforce the fundamental theory that austenite formation and carbon solubility at elevated temperatures govern martensitic hardness more strongly than cooling severity, provided the quenching rate is sufficient to suppress diffusion-controlled transformations. The statistically dominant influence of temperature supports existing phase transformation theory and highlights the importance of controlling austenitizing conditions to achieve consistent martensitic microstructures in medium-carbon steels. Practically, the results provide clear guidance for industrial heat-treatment processes of S55C steel. The identification of 1000°C with salt water quenching as the optimal condition offers a reliable parameter set to achieve high hardness without excessive grain growth. Moreover, the tempering results demonstrate that hardness–toughness balance can be effectively tailored by selecting appropriate tempering temperatures, enabling manufacturers to adjust mechanical properties according to specific cutting tool or wear-resistant component requirements. This can reduce trial-and-error practices, improve production efficiency, and enhance component reliability.

Despite its contributions, this study has several limitations. First, the investigation was limited to two process variables quenching temperature and cooling media while other influential parameters such as soaking time, agitation rate during quenching, and specimen geometry were not considered. Second, microstructural characterization (e.g., optical microscopy or SEM) was not performed, which limits direct correlation between hardness changes and specific microstructural features such as martensite morphology or carbide distribution. Third, the relatively high experimental error contribution observed in the ANOVA suggests the presence of uncontrolled variability inherent to the heat-treatment process, which may affect result reproducibility. Future research should incorporate microstructural analysis to directly correlate hardness and toughness results with martensitic structure, grain size, and carbide precipitation behavior. Additional studies should also examine the effects of soaking time, quenching agitation, and alternative cooling strategies, such as polymer quenchants or environmentally friendly media. Furthermore, extending the Taguchi approach to multi-response optimization, including wear resistance and tool life, would enhance the applicability of the findings to real cutting tool performance. Finally, long-term performance testing under actual service conditions is recommended to validate the industrial relevance of the optimized heat-treatment parameters.

4. CONCLUSION

This study concludes that the optimization of the heat treatment process for S55C steel using the Taguchi method with an L9 orthogonal array is effective in identifying parameter combinations that maximize hardness while clarifying the trade-off between hardness and toughness. The experimental results demonstrate that increasing tempering temperature leads to a systematic decrease in hardness accompanied by improved toughness, which is primarily associated with the transformation of martensite into tempered martensite and the refinement, rounding, and coarsening of carbide precipitates. The highest hardness after tempering was achieved at a low tempering temperature of 100 °C, whereas the lowest hardness occurred at 400 °C, confirming that elevated tempering temperatures promote softening through carbide spheroidization and microstructural stabilization. Furthermore, Taguchi S/N ratio and ANOVA analyses identified the optimal heat treatment parameters for maximizing hardness as a quenching temperature of 1000 °C combined with a brine cooling medium, which consistently produced a dominant martensitic structure and significantly enhanced hardness. The implications of these findings are substantial for industrial applications, particularly in the manufacturing of cutting tools and machine components where high hardness and wear resistance are critical. The results provide a systematic and efficient guideline for selecting heat treatment parameters to achieve desired mechanical properties while minimizing experimental cost and variability. Practically, industries can adopt these optimized conditions to improve product performance and process consistency, while strategically adjusting tempering temperatures to balance hardness and toughness according to service requirements. Academically, this study reinforces the effectiveness of the Taguchi approach in metallurgical process optimization and offers a foundation for future research to extend the analysis toward fatigue behavior, wear resistance, and microstructural stability under long-term service conditions.

ACKNOWLEDGEMENTS

The authors would like to express sincere gratitude to all parties who contributed to and supported the completion of this research, including the instructors, and colleagues who provided guidance, assistance, and valuable feedback throughout the study.

AUTHOR CONTRIBUTIONS

FF designed the study, conducted the analysis, collected the data, and wrote the manuscript. EY and ZK, supported the availability of research data, and reviewed the research results.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

REFERENCES

[1] H. Wang, C. Wang, J. Liang, A. Godfrey, Y. Wang, V. Weng, and W. Cao, "Effect of alloying content on microstructure and mechanical properties of Fe–Mn–Al–C low-density steels," *Materials Science and Engineering: A*, vol. 886, pp. 145675, 2023, doi: 10.1016/j.msea.2023.145675.

[2] R. Liu, N. Ivanovich, C. Zhu, Y. P. Yeo, X. Wang, M. Seita, and F. M. Lauro, "Influence of grain size and crystallographic orientation on microbially influenced corrosion of low-carbon steel in artificial seawater," *Materials & Design*, vol. 234, pp. 112353, 2023, doi: 10.1016/j.matdes.2023.112353.

[3] T. T. Win, L. Prasittisopin, P. Jongvivatsakul, and S. Likitlersuang, "Investigating the role of steel and polypropylene fibers for enhancing mechanical properties and microstructural performance in mitigating conversion effects in calcium aluminate cement," *Construction and Building Materials*, vol. 430, pp. 136515, 2024, doi: 10.1016/j.conbuildmat.2024.136515.

[4] Y. J. Tian, M. Pang, and F. Q. Ji, "Study on the impact of laser power variation on the performance of Ti-6Al-4 V coating by laser cladding on HT250," *Optics & Laser Technology*, vol. 175, pp. 110809, 2024, doi: 10.1016/j.optlastec.2024.110809.

[5] T. Alomayri, A. Raza, K. M. Elhadi, and F. Shaikh, "Mechanical, microstructural, and thermal characterization of geopolymer composites with nano-alumina particles and micro steel fibers," *Structural Concrete*, vol. 26, no. 2, pp. 1540-1559, 2025, doi: 10.1002/suco.202400477

[6] Y. Shang, M. Fan, S. Jiang, and Z. Zhang, "Effects of carbon content on the microstructure and tensile properties of a low-density steel," *International Journal of Minerals, Metallurgy and Materials*, vol. 32, no. 2, pp. 391-401, 2025, doi: 10.1007/s12613-024-2937-1.

[7] A. O. Araoyinbo, A. Samuel, A. M. M. Abdullah, and M. Biodun, "The effect of quenching on high-temperature heat treated mild steel and its corrosion resistance," *Pertanika Journal of Science & Technology*, vol. 30, no. 1, 2022, doi: 10.47836/pjst.30.1.16.

[8] L. Lebea, and M. Pita, "The effect of cooling media on the corrosion behavior of mild steel after heat treatment," *Int. J. Emerg. Technol. Adv. Eng*, vol. 12, no. 9, pp. 158-164, 2022, doi: 10.46338/ijetae0922_16.

[9] T. S. Amosun, S. O. Hammed, A. M. G. de Lima, and I. Habibi, "Effect of quenching media on mechanical properties of welded mild steel plate," *Mechanical Engineering for Society and Industry*, vol. 3, no. 1, pp. 4-11, 2023, doi: 10.31603/mesi.7121.

[10] Q. Guo, Y. Deng, and W. Ma, "An experimental study on quenching of metallic spheres in seawater," *Experimental Thermal and Fluid Science*, vol. 148, pp. 110990, 2023, doi: 10.1016/j.expthermflusci.2023.110990.

[11] Ejiko, S. O., Fatona, A. S., & Ibikunle, R. A. (2024). Investigation of quenching on microstructure and mechanical properties of mild steel. *IOSR Journal of Engineering (IOSRJEN)*, *14*(4), 29-38, 2024, doi: .

[12] S. H. Khazaal, and H. F. Makki, "Characterization of corrosion behavior of ST37-2 low-carbon steel in a cooling tower using seawater as the working media," *Journal of Bio-and Tribo-Corrosion*, vol. 11, no. 4, pp. 97, 2025, doi: 10.1007/s40735-025-01018-4.

[13] I. J. Khamas, and H. D. Lafta, "Effect of heat treatments and carbon content on the damping properties of structural steel," *Journal of Engineering*, vol. 29, no. 7, pp. 106-119, 2023, doi: 10.31026/j.eng.2023.07.07.

[14] Y. Wang, R. Wang, W. Yu, and Y. Gao, "Effect of heat treatment parameters on the modification of nano residual austenite of low-carbon medium-chromium steel," *Nanomaterials*, vol. 13, no. 11, pp. 2829, 2023, doi: 10.3390/nano13212829.

[15] N. Çömez, M. Yurddaskal, and H. Durmuş, "Effect of solutionizing and quenching treatment on Ti6Al4V alloy: a study on wear, cavitation erosion and corrosion resistance," *Journal of Materials Science*, vol. 58, no. 24, pp. 10201-10216, 2023, doi: 10.1007/s10853-023-08688-w.

[16] J. Xu, T. Zhang, and X. Li, "Research on the process, energy consumption and carbon emissions of different magnesium refining processes," *Materials*, vol. 16, no. 9, pp. 3340, 2023, doi: 10.3390/ma16093340.

[17] K. Gao, Y. Zhang, J. Yi, F. Dong, and P. Chen, "Overview of surface modification techniques for titanium alloys in modern material science: A comprehensive analysis," *Coatings*, vol. 14, no. 1, pp. 148, 2024, doi: 10.3390/coatings14010148.

[18] Z. Huang, H. Xiao, J. Yu, H. Zhang, H. Huang, K. Yu, and R. Zhou, "Effects of different annealing cooling methods on the microstructure and properties of TA10 titanium alloys," *Journal of Materials Research and Technology*, vol. 18, pp. 4859-4870, 2022, doi: 10.1016/j.jmrt.2022.04.149.

[19] M. Gaggiotti, L. Albini, P. E. Di Nunzio, A. Di Schino, G. Stornelli, and G. Tiracorrendo, "Ultrafast heating heat treatment effect on the microstructure and properties of steels," *Metals*, vol. 12, no. 8, pp. 1313, 2022, doi: 10.3390/met12081313.

[20] M. Tayyebi, and M. DerakhshaniMolayousefi, "A review on the effect of various rolling regimes (cryo, cold, warm, hot) and post-annealing on high-entropy alloys: microstructure evolution, deformation mechanisms, and mechanical properties," *Archives of Civil and Mechanical Engineering*, vol. 24, no. 1, pp. 16, 2023, doi: 10.1007/s43452-023-00826-0.

[21] X. Lu, C. Chen, G. Zhang, M. Chiumenti, M. Cervera, H. Yin, L. Ma, and X. Lin, "Thermo-mechanical simulation of annealing heat treatment of Ni-based GH4099 superalloy made by laser powder bed fusion," *Additive Manufacturing*, vol. 73, pp. 103703, 2023, doi: 10.1016/j.addma.2023.103703.

[22] H. Z. Jiang, Z. Y. Li, T. Feng, P. Y. Wu, Q. S. Chen, S. K. Yao, and J. Y. Hou, "Effect of annealing temperature and strain rate on mechanical property of a selective laser melted 316L stainless steel," *Acta Metallurgica Sinica (English Letters)*, vol. 35, no. 5, pp. 773-789, 2022, doi: 10.1007/s40195-021-01342-x.

[23] P. J. Yu, C. Y. Huang, Y. T. Lin, Y. S. Su, H. W. Yen, C. A. Hsu, S. H. Wang, J. W. Yeh, W. S. Hou, T. R. Lin, and T. W. Hsu, "Crystalline characteristics of a dual-phase precipitation hardening stainless steel in quenched solid solution and aging treatments," *Materials Chemistry and Physics*, vol. 280, pp. 125804, 2022, doi: 10.1016/j.matchemphys.2022.125804.

[24] L. Liu, J. Yang, X. Li, M. Sun, Y. Ren, M. Li, H. Yang, and H. Wang, "A heat-resistant steel with excellent high-temperature strength-ductility based on a combination of solid-solution strengthening and precipitation hardening," *Materials Science and Engineering: A*, vol. 915, pp. 147218, 2024, doi: 10.1016/j.msea.2024.147218.

[25] T. Z. Xu, T. Wang, M. S. Wang, S. Zhang, C. H. Zhang, C. L. Wu, X. Y. Sun, H. T. Chen, and J. Chen, "Influence of solid solution time on microstructure and precipitation strengthening of novel maraging steels," *Materials Science and Engineering: A*, vol. 920, pp. 147535, 2025, doi: 10.1016/j.msea.2024.147535.

[26] C. Rodenkirchen, A. K. Ackerman, P. M. Mignanelli, A. Cliff, G. J. Wise, P. Breul, J. O. Douglas, P. A. J. Bagot, M. P. Moody, M. Appleton, M. P. Ryan, M. C. Hardy, S. Pedrazzini, and H. J. Stone, "Effect of alloying on the microstructure, phase stability, hardness, and partitioning behavior of a new dual-superlattice nickel-based superalloy," *Metallurgical and Materials Transactions A*, vol. 54, no. 5, pp. 1902-1923, 2023, doi: 10.1007/s11661-023-06972-7.

[27] Y. Zhang, J. Yang, D. Xiao, D. Luo, C. Tuo, and H. Wu, "Effect of quenching and tempering on mechanical properties and impact fracture behavior of low-carbon low-alloy steel," *Metals*, vol. 12, no. 7, pp. 1087, 2022, doi: 10.3390/met12071087.

[28] E. Tkachev, S. Borisov, A. Belyakov, T. Kniaziuk, O. Vagina, S. Gaidar, and R. Kaibyshev, "Effect of quenching and tempering on structure and mechanical properties of a low-alloy 0.25 C steel," *Materials Science and Engineering: A*, vol. 868, pp. 144757, 2023, doi: 10.1016/j.msea.2023.144757.

[29] E. Tang, Q. Yuan, R. Zhang, J. Ren, Z. Li, and G. Xu, "Rapid heat treatment yields excellent strength and ductility balance in a wear-resistant steel," *Journal of Materials Research and Technology*, vol. 30, pp. 2596-2608, 2024, doi: 10.1016/j.jmrt.2024.04.003.

[30] M. Yang, Z. Jiang, C. Jia, and X. Chen, "Exploring the variable ranges of tensile strength of a high-toughness low-alloy CrNiMo steel," *Materials Today Communications*, vol. 44, pp. 112057, 2025, doi: 10.1016/j.mtcomm.2025.112057.

[31] D. Grima, N. Layeb, R. Li, B. Zammit, B. Attard, A. Zammit, and G. Cassar, "Enhancing fatigue resistance in WAAM AZ80 magnesium and wrought Al6082 through shot peening: A comparative study," *Progress in Additive Manufacturing*, vol. 10, no. 12, pp. 11627-11645, 2025, doi: 10.1007/s40964-025-01306-y.

[32] X. Pan, S. Xin, J. Sun, S. Zhang, W. Zhou, and J. Cai, "Achieving improved dynamic mechanical properties in twinning-dominated titanium alloys," *Materials Science and Engineering: A*, *920*, 147570, 2025, doi: 10.1016/j.msea.2024.147570.

[33] Y. Yu, X. Wang, Y. Wu, M. Ma, and G. Gao, "The impact of backplate support conditions on ceramic fracture and energy absorption in the penetration resistance process of ceramic/metal composite armor," *Ceramics International*, vol. 50, no. 7, pp. 10325-10339, 2024, doi: 10.1016/j.ceramint.2023.12.344.

[34] A. Diniță, A. Neacșa, A. I. Portoacă, M. Tănase, C. N. Ilinca, and I. N. Ramadan, "Additive manufacturing post-processing treatments, a review with emphasis on mechanical characteristics," *Materials*, vol. 16, no. 13, pp. 4610, 2023, doi: 10.3390/ma16134610.

[35] Elshaer, R. N., El-Hadad, S., & Nofal, A. (2023). Influence of heat treatment processes on microstructure evolution, tensile and tribological properties of Ti6Al4V alloy. *Scientific Reports*, *13*(1), 11292, 2023, doi: .

[36] G. H. Lee, M. Park, B. Kim, J. B. Jeon, S. Noh, and B. J. Kim, "Evaluation of precipitation phase and mechanical properties according to aging heat treatment temperature of Inconel 718," *Journal of Materials Research and Technology*, vol. 27, pp. 4157-4168, 2023, doi: 10.1016/j.jmrt.2023.10.196.

[37] G. Toktaş, and A. Biçer, "Fracture surface morphology of the impact-loaded tempered spring steels," *Sakarya University Journal of Science*, vol. 28, no. 6, pp. 1315-1325, 2024, doi: 10.16984/saufenbilder.1527971.

[38] C. H. Lee, J. M. Baek, H. Y. Ju, S. J. Park, U. S. Ko, J. S. Kwack, and H. U. Hong, "Microstructure-driven post-seam annealing design for enhanced toughness in X70 electric-resistance welded pipes," *Journal of Materials Research and Technology*, vol. 36, pp. 3726-3740, 2025, doi: 10.1016/j.jmrt.2025.04.035.

[39] N. Thammachot, N. Taweejun, T. Praditja, P. Juijerm, and W. Homjabok, "Correlation of microstructure, mechanical properties, and strain hardening response via kocks-mecking analysis in heat-treated JIS SK85 high-carbon steel," *The International Journal of Advanced Manufacturing Technology*, vol. 139, no. 9, pp. 4613-4630, 2025, doi: 10.1007/s00170-025-16213-3.

[40] Y. Liu, J. Tang, H. Liu, and W. Jiang, "The influence of carbon content gradient and carbide precipitation on the microstructure evolution during carburizing-quenching-tempering of 20MnCr5 bevel gear," *Surface and Coatings Technology*, vol. 494, pp. 131387, 2024, doi: 10.1016/j.surfcoat.2024.131387.

[41] J. M. Valentino, A. S. Pramono, A. Syaifudin, H. K. Agustin, L. Shalahuddin, A. Windharto, and K. Sasaki, "Enhancing S45C steel for the primary component of an automatic coupler using quench-tempering techniques," *Journal of Applied Engineering Science*, vol. 22, no. 1, pp. 215-222, 2024, doi: 10.5937/jaes0-43988.

[42] A. Leal Matilla, D. Ferrández, M. I. Prieto Barrio, and H. Varum, "Systematic review on the behaviour of carbon and stainless steel reinforcing bars in buildings under high temperatures," *Buildings*, vol. 15, no. 9, pp. 1539, 2025, doi: 10.3390/buildings15091539.

[43] G. G. Ribamar, J. D. Escobar, A. K. Da Silva, N. Schell, J. A. Ávila, A. S. Nishikawa, J. P. Oliveira, and H. Goldenstein, "Austenite carbon enrichment and decomposition during quenching and tempering of high silicon high carbon bearing steel," *Acta Materialia*, vol. 247, pp. 118742, 2023, doi: 10.1016/j.actamat.2023.118742.

[44] F. Badkoobeh, H. Mostaan, M. Rafiei, H. R. Bakhsheshi-Rad, and F. Berto, "Microstructural characteristics and strengthening mechanisms of ferritic–martensitic dual-phase steels: a review," *Metals*, vol. 12, no. 1, pp. 101, 2022, doi: .

[45] He, C., Xiao, G., Hui, P., Li, M., Tong, L., Zhang, Z., & Zou, D. (2024). The new design to improve the stability of retained austenite and mechanical properties in super martensitic stainless steel. *Materials Characterization*, *217*, 114342, 2024, doi: .

[46] Wang, Y. L., Shen, Y. F., Jia, N., Wang, J. J., & Zhao, S. X. (2022). Acicular martensite induced superior strength-ductility combination in a 20Cr2Ni2MoV steel. *Materials Science and Engineering: A*, *848*, 143400, 2022, doI: .

[47] C. Li, C. Liu, Z. Cao, M. Shan, and Y. Bing, "Effect and mechanism of induced crystallization softening treatment on water quality in drinking water distribution system with high hardness water source," *Journal of Environmental Chemical Engineering*, vol. 11, no. 5, pp. 110474, 2023, doi: 10.1016/j.jece.2023.110474.

[48] S. I. Müller, G. Chapanova, T. Diekow, C. Kaiser, L. Hamelink, I. P. Hitsov, L. Wyseure, D. H. Moed, L. Palmowski, and T. Wintgens, "Comparison of cooling tower blowdown and enhanced make up water treatment to minimize cooling water footprint," *Journal of Environmental Management*, vol. 367, pp. 121949, 2024, doi: 10.1016/j.jenvman.2024.121949.

[49] W. Luo, X. Yuan, Z. Zhang, C. Cheng, H. Liu, H. Qiu, and X. Cheng, "Effect of volumetric energy density on the mechanical properties and corrosion resistance of laser-additive-manufactured AlCoCrFeNi2. 1 high-entropy alloys," *Journal of Alloys and Compounds*, vol. 1010, pp. 178032, 2025, doi: 10.1016/j.jallcom.2024.178032.

[50] G. V. Golwa, D. Romahadi, and I. G. A. Arwati, “Analysis of characteristics of S45C steel changes due to the quenching and tempering process,” *World Chemical Engineering Journal*, vol. 6, no. 2, pp. 39-43, 2022, doi: 10.62870/wcej.v6i2.17611.

[51] R. Saha, and P. Biswas, “Current status and development of external energy-assisted friction stir welding processes: A review,” *Welding in the World*, vol. 66, no. 3, pp. 577-609, 2022, doi: 10.1007/s40194-021-01228-7.

[52] T. Chen, C. Ji, J. Yang, Y. Chi, and M. Zhu, “Grain growth kinetics model of high-temperature ferrite and austenite in Ti microalloyed steel during continuous casting,” *International Journal of Minerals, Metallurgy and Materials*, vol. 32, no. 6, pp. 1390-1403, 2025, doi: 10.1007/s12613-024-2991-8.

[53] C. Ye, M. Wang, Y. Cheng, T. Fu, D. Qin, T. Huang, X. Yang, Z. Li, S. Ma, L. Fu, G. Zhu, and A. Shan, “Efficient grain refinement and remarkable strengthening in low-carbon low-alloy steels by coordinating carbide dissolution and Austenitization,” *Materials Characterization*, vol. 231, pp. 115838, 2025, doi: 10.1016/j.matchar.2025.115838.

[54] C. H. Magalhães, P. H. Silva, P. C. Azzi, and G. L. Faria, “Effect of austenite grain size on phase transformation and Q&P design for a commercial CMnSi steel,” *Journal of Materials Engineering and Performance*, vol. 33, no. 13, pp. 6586-6600, 2024, doi: 10.1007/s11665-023-08432-0.

[55] W. Jiang, D. Wu, Q. Zhang, M. Li, and W. Liu, “Effect of tempering time on the microstructure and properties of martensitic stainless steel,” *Metals*, vol. 14, no. 3, pp. 322, 2024, doi: 10.3390/met14030322.

[56] Y. Zhu, Q. Zhang, Q. Yuan, J. Guan, Y. Yang, and G. Xu, “Effects of tempering temperature on the microstructure, strength, and toughness of medium-carbon Ti–Mo-bearing martensitic steel,” *Arabian Journal for Science and Engineering*, vol. 47, no. 7, pp. 9061-9073, 2022, doi: 10.1007/s13369-021-06537-z.

[57] Y. Chen, W. Ding, L. Liang, X. Liu, H. Wang, S. Xiao, Q. Chao, Y. Yang, and W. Yang, “Intervention mechanism of carbide precipitation during tempering and its impact on residual stress and mechanical properties of wear-resistant steels,” *Ironmaking & Steelmaking*, vol. 51, no. 5, pp. 502-512, 2024, doi: 10.1177/03019233241250136.