Asian Journal of
Computing and Engineering Technology
(AJCET)

Influence of Cryogenic Treatment on Mechanical Response, Tribological Characteristics and Corrosion Resistance of Selected Structural Steel Grades

Adeniyi, E. K and Akanbi, K.O

Asian Journal of Computing and Engineering Technology
ISSN 2959-1775 (online)
Vol.7, Issue 1 No.3, pp 41 - 52, 2026

www.iprjb.org

Influence of Cryogenic Treatment on Mechanical Response, Tribological Characteristics and Corrosion Resistance of Selected Structural Steel Grades

[1]Adeniyi, E. K
Metal Work Technology Unit, Department of Technical Education, Oyo State College of Education, Lanlate, Oyo State, Nigeria

[2]Akanbi, K.O
Metal Work Technology Unit, Department of Technical Education, Oyo State College of Education, Lanlate, Oyo State, Nigeria

Article History

Received 9th July 2026

Received in Revised Form 13th August 2026

Accepted 15th September 2026

How to cite in APA format:

Adeniyi, K., & Akanbi, O. (2026). Influence of Cryogenic Treatment on Mechanical Response, Tribological Characteristics and Corrosion Resistance of Selected Structural Steel Grades. *Asian Journal of Computing and Engineering Technology*, *7*(1), 41–52. https://doi.org/10.47604/ajcet.3971

Abstract

Purpose: This study investigated the influence of deep cryogenic treatment (DCT) on the mechanical response, tribological characteristics and corrosion resistance of selected structural steels, namely AISI 1040, AISI 1045 and AISI 5140. The study specifically examined the effects of DCT on hardness, tensile response, impact toughness, wear resistance, coefficient of friction, microstructure and corrosion behaviour.

Methodology: Three structural steel grades, AISI 1040, AISI 1045 and AISI 5140 were subjected to conventional heat treatment and deep cryogenic treatment. The cryogenic treatment involved cooling the specimens to approximately −185°C, holding them at that temperature for 24 h, followed by controlled return to ambient temperature and subsequent tempering. The treated and untreated specimens were evaluated using hardness, tensile, impact, wear, coefficient-of-friction, microstructural and electrochemical corrosion tests. The experimental results were comparatively analysed to determine the influence of DCT and tempering conditions on the properties of the selected steels.

Findings: The results showed that deep cryogenic treatment improved the hardness of all three steel grades. Mean hardness increased from 317.715 to 336.160 BHN for AISI 1045, from 414.110 to 453.335 BHN for AISI 5140 and from 252.680 to 276.995 BHN for AISI 1040. Impact toughness also increased from 25.84 to 31.17 J for AISI 1045, from 29.24 to 34.35 J for AISI 5140 and from 25.16 to 31.86 J for AISI 1040. Wear resistance increased substantially following cryogenic treatment, with AISI 5140 recording the highest reported value. The coefficient-of-friction measurements showed values of 1.0355 for AISI 1045, 0.6745 for AISI 5140 and 0.6494 for AISI 1040 under the reported experimental conditions. The corrosion results showed that the response to cryogenic treatment varied according to steel grade and treatment condition.

Unique Contribution to Theory, Practice and Policy: The study contributes to the understanding of the relationship between deep cryogenic treatment, microstructural modification and the resulting mechanical and tribological performance of selected structural steels. In practice, the findings demonstrate the potential of DCT as a supplementary treatment for improving hardness, impact toughness and wear resistance of AISI 1040, AISI 1045 and AISI 5140 steels used in engineering components. The findings also provide a basis for selecting appropriate structural steels and treatment conditions for applications involving mechanical loading and wear. From a policy and industrial perspective, the study provides evidence that can support the development of appropriate guidelines for the application and process optimization of cryogenic treatment in structural-steel manufacturing and engineering maintenance.

Keywords: *Deep Cryogenic Treatment, Structural Steels, Wear Resistance, Friction, Corrosion Resistance*

JEL Classification: *C61, 014*

INTRODUCTION

Structural steels like AISI 1040, AISI 1045, and AISI 5140 are industry standards for gears, shafts, axles, and high-strength fasteners due to their excellent balance of strength and toughness. Ultimately, their performance and service life depend entirely on their microstructure and heat treatment. Engineers typically rely on conventional quenching and tempering to strike the right balance between hardness and durability (Mudda et al., 2025). While medium-carbon grades like AISI 1040 and AISI 1045 readily form martensite during rapid quenching, the addition of chromium in AISI 5140 boosts hardenability, ensuring a much more uniform martensitic structure throughout the material.

To push these properties further, Deep Cryogenic Treatment (DCT) subjects the quenched steel to sub-zero temperatures for an extended period. Traditionally, researchers have credited DCT with boosting hardness, wear resistance, and dimensional stability by forcing retained austenite to transform into martensite (Amini et al., 2012; Jurči & Dlouhý, 2024). But there is a catch: well-quenched medium-carbon steels usually hold very little retained austenite to begin with. This suggests that other subtle microstructural shifts such as fine carbide precipitation, altered dislocation densities, and shifting residual stresses might actually be driving the benefits of DCT (Jamali et al., 2019; Jovičević-Klug et al., 2023; Kara et al., 2023).

This study takes a closer look at how DCT impacts AISI 1040, AISI 1045, and AISI 5140 from a broader microstructural perspective. Instead of just looking at phase changes, we evaluate adjustments in carbide morphology, lattice strain, and residual stress, directly linking these features to the steels' mechanical, tribological, and corrosion behavior. By evaluating these three distinct grades side-by-side, we aim to clarify exactly how carbon content and chromium alloying alter a steel's footprint when subjected to deep cryogenic processing.

Statement of the Problem

Deep cryogenic treatment (DCT) is a common method for boosting the hardness and wear resistance of engineering steels. However, these gains often come at a cost, sometimes reducing impact toughness and corrosion resistance. This trade-off poses a significant risk for components operating under concurrent mechanical loads and corrosive environments. Furthermore, a steel's chemical composition heavily dictates its response to DCT. While AISI 1040 and AISI 1045 are plain-carbon steels, AISI 5140 contains chromium an element that alters phase transformation, carbide stability, and corrosion behavior. Consequently, DCT may affect AISI 5140 quite differently than its plain-carbon counterparts.

While prior literature evaluates sub-zero treatments in spring steels (Chen et al., 2023a), low-alloy steels (Chen et al., 2023b; Zhang et al., 2022), and tool steels (Ma et al., 2022; Su et al., 2022), direct comparisons between AISI 1040, 1045, and 5140 under identical cryogenic and tempering conditions remain scarce. Crucially, most studies isolate either mechanical properties or corrosion behavior rather than evaluating them alongside wear performance and microstructural evolution. This fragmentation leaves a gap in our understanding of how DCT influences overall performance.

This study fills that gap by systematically comparing AISI 1040, 1045, and 5140 under controlled DCT and tempering conditions. By evaluating mechanical properties, wear, corrosion, and microstructure together, we provide a comprehensive look at whether the benefits of cryogenic treatment outweigh its drawbacks for components facing friction, impact, and corrosion.

Asian Journal of Computing and Engineering Technology
ISSN 2959-1775 (online)
Vol.7, Issue 1 No.3, pp 41 - 52, 2026

www.iprjb.org

LITERATURE REVIEW

Theoretical Framework

The microstructural evolution of medium-carbon steels during thermal and sub-zero processing is governed by phase transformation, dislocation dynamics, and carbide precipitation. Conventional quenching yields a predominantly martensitic matrix but leaves metastable retained austenite alongside high residual stresses. Deep cryogenic treatment (DCT) exploits ultra-low temperatures to drive the transformation of this retained austenite into martensite, generating microstructural defects that serve as high-energy nucleation sites during subsequent tempering. This accelerated carbon diffusion promotes the precipitation of ultra-fine, homogeneously dispersed secondary carbides that significantly improve hardness and wear resistance by impeding dislocation motion.

However, a critical trade-off exists if excessive precipitation occurs; in chromium-alloyed grades like AISI 5140 steel, severe carbide clustering or matrix depletion can compromise impact toughness and degrade corrosion resistance. Consequently, this theoretical framework establishes a direct causal link between processing inputs specifically cryogenic temperature and soaking duration and the resulting microstructure. By mapping how these parameters dictate austenite transformation, dislocation density, and carbide morphology, the framework provides a predictive basis for balancing and optimizing the steel's competitive mechanical and electrochemical properties.

Theory Or Model :“Cryogenic Treatment–Microstructure–Property Relationship”

Or “Metallurgical Transformation Theory of Cryogenic Treatment.”

Conceptual Framework

This study investigates how heat-treatment conditions and deep cryogenic treatment (DCT) affect the microstructure and mechanical performance of AISI 1040, AISI 1045, and AISI 5140 steels. The austenizing temperature, quenching medium, and cooling rate play important roles in determining the initial microstructure of the steels, including the amount of martensite and retained austenite, carbide distribution, and residual stresses. These microstructural features also influence how the steels respond to DCT at -185°C for 24 hours, followed by tempering.

The changes that occur during each stage of the treatment will be examined to understand their effect on the final properties of the steels. Particular attention will be given to hardness, tensile strength, impact toughness, wear resistance, coefficient of friction, and corrosion resistance. The study therefore aims to establish a clear relationship between the heat-treatment and cryogenic-processing conditions, the resulting microstructural changes, and the overall performance of the three steels.

Empirical Review

We already know from previous research that deep cryogenic treatment (DCT) can shake up the microstructure and properties of steel. However, how much it actually changes things depends heavily on how the steel was initially heat-treated and its specific chemical makeup. Past studies on grades like 16MnCr5, HY-TUF, AISI 4140, and bearing steels like AISI 52100 generally point to better hardness and wear resistance after DCT. Researchers usually credit these improvements to the transformation of retained austenite and shifts in how carbides form and spread out (Amini et al., 2012; Jamali et al., 2019; Jovičević-Klug et al., 2023; Kara et al., 2023). That said, it's not all positives, some data warns that leaving the steel in cryogenic conditions for too long can actually hurt its impact toughness.

Interestingly, plain-carbon and low-alloy structural steels haven't gotten nearly as much attention. For instance, Chen et al. (2023b) looked at how DCT alters the corrosion behavior of 42CrMo by shifting its carbide distribution. But when it comes to AISI 1040, the literature is pretty thin, especially for raw, baseline conditions. Most existing work focuses on surface-treated variations, like borided steel, which makes it tough to isolate exactly what DCT does to the base metal itself. On top of that, a lot of the corrosion work involving cryo-treatments focuses heavily on non-ferrous metals, particularly aluminum alloys (Ma et al., 2022; Su et al., 2022). Right now, we simply don't have a direct, side-by-side comparison of how medium-carbon steels (AISI 1040 and 1045) stack up against a low-alloy steel (AISI 5140) when they all go through the exact same austenizing, quenching, and cryogenic cycle. This study steps in to fill that exact gap, tracking and comparing their microstructural and performance shifts head-to-head.

Research Gaps

Even though deep cryogenic treatment (DCT) is a staple research topic for tool, bearing, and spring steels, we rarely see studies that put plain medium-carbon steels like AISI 1040 and 1045 head-to-head with a low-alloy chromium steel like AISI 5140 under identical conditions. These steels aren't going to react the same way to sub-zero temperatures. Because they have different carbon levels and chromium additions, their austenite transformation, residual stresses, and post-quench microstructures are bound to differ. On top of that, past research has been a bit narrow often zooming in on just one property, like hardness or dry sliding wear, while overlooking how these microstructural shifts might hit mechanical, tribological, and electrochemical performance all at the same time.

To bridge this gap, this study runs AISI 1040, AISI 1045, and AISI 5140 through the exact same heat-treatment loop, followed by a 24-hour deep cryogenic soak at −185°C and final tempering. Taking this baseline approach will help clarify exactly how much a steel's chemical makeup dictates its microstructural changes and overall performance after it goes through deep cryo.

METHODOLOGY

Three structural steel grades, AISI 1040, AISI 1045 and AISI 5140 were selected. The supplied materials were machined from bars of approximately 30 mm diameter and 250 mm length, with individual specimens prepared to suit the relevant tests. Chemical composition was determined using inductively coupled plasma optical emission spectrometry (ICP-OES), as reported in the experimental work Table 1.

Table 1: Spectroscopic Chemical Analysis of AISI 1040, AISI 1045 and 5140 Steels

Element	AISI 1040	AISI 1045	AISI 5140
C	0.331	0.335	0.206
Mn	0.834	0.935	1.46
Si	0.527	0.599	0.627
Cr	0.387	0.0817	0.476
Al	0.0403	0.0567	0.0526
Ni	0.0305	0.0262	0.0188
Mo	0.0086	0.0065	0.0066
P	0.0210	0.0217	0.0243
S	0.0181	0.0201	0.0254
V	0.0068	0.0045	0.0060
Fe	97.7957	97.9136	97.0973

The heat-treatment programme comprised conventional austenitisation and oil quenching, followed by either conventional tempering or deep cryogenic treatment inserted between quenching and tempering. For DCT, the oil-quenched samples were cooled gradually to approximately −185°C, held for 24 h and returned gradually to room temperature to reduce thermal shock. The cooling/heating rate reported in the experimental work s was approximately 1.8°C/min. Tempering was subsequently performed at 200°C and 300°C.

Microstructural preparation included grinding through progressively finer silicon-carbide papers, polishing and etching with 2% Nital before microscopic examination. Optical microscopy and scanning electron microscopy were used for microstructural characterization, while X-ray diffraction was referenced in the experimental work s for phase-related assessment.

Mechanical response was assessed through hardness, tensile strength and impact toughness testing. Tribological behaviour was assessed through wear testing and coefficient-of-friction measurements. Corrosion behaviour was evaluated electrochemically in sulphuric-acid medium, with corrosion potential, corrosion current and corrosion rate used as principal indicators. The comparative design considered conventionally heat-treated and cryogenically treated specimens across the three steel grades.

Table 2: Mean Hardness Values before and after Cryogenic Treatment

Steel grade	Non-cryogenic hardness (BHN)	Cryogenic hardness (BHN)	Change (%)
AISI 1045	317.715	336.160	5.81
AISI 5140	414.110	453.335	9.47
AISI 1040	252.680	276.995	9.62

RESULTS AND DISCUSSION

Hardness Response

The hardness results show a consistent increase following cryogenic treatment. AISI 5140 remained the hardest of the three grades under both conditions, while AISI 1040 recorded the lowest mean hardness. The cryogenic treatment raised the mean hardness of AISI 1045 from 317.715 to 336.160 BHN, AISI 5140 from 414.110 to 453.335 BHN and AISI 1040 from 252.680 to 276.995 BHN. The thesis attributes the improvement to microstructural changes

Asian Journal of Computing and Engineering Technology
ISSN 2959-1775 (online)
Vol.7, Issue 1 No.3, pp 41 - 52, 2026

associated with retained-austenite transformation and carbide-related strengthening. The results are consistent with the broader observation that cryogenic processing can increase hardness through phase transformation and carbide refinement.

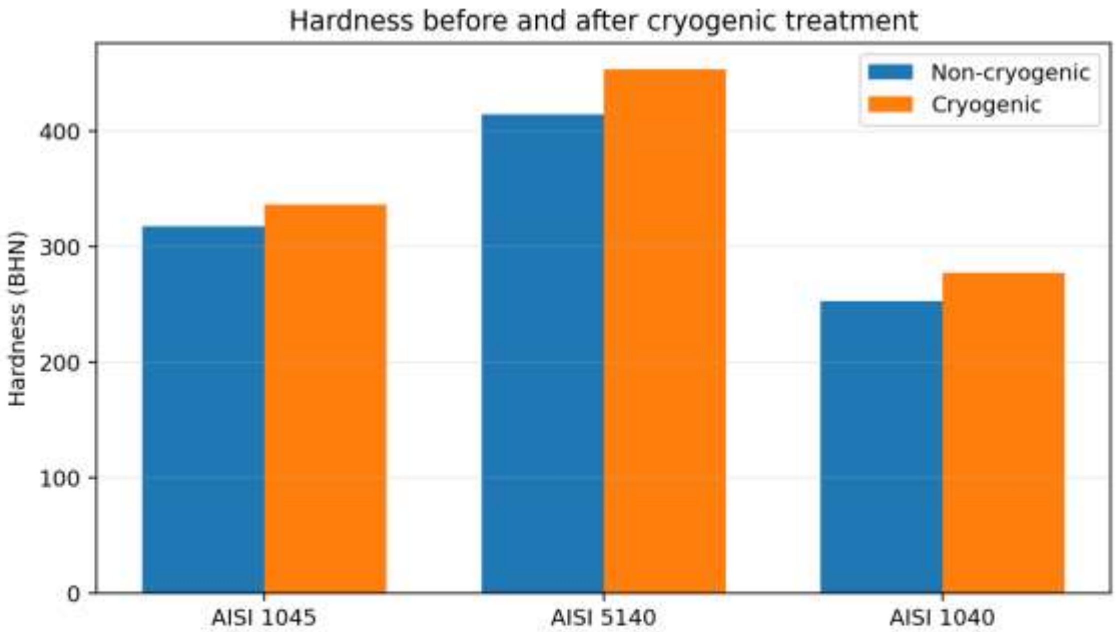

Figure 1: Mean Hardness of the Selected Steel Grades before and after Cryogenic Treatment

Impact Toughness

Cryogenic treatment also increased the measured impact toughness of all three steel grades in the direct comparison. AISI 1045 increased from 25.84 to 31.17 J, AISI 5140 from 29.24 to 34.35 J and AISI 1040 from 25.16 to 31.86 J. The experimental work s further reports that impact toughness increased with tempering temperature from 200°C to 300°C under both treatment conditions. The increase is interpreted in relation to the tempered martensitic structure and the changes produced by cryogenic processing. AISI 5140 maintained the highest direct-comparison impact toughness, while AISI 1045 and AISI 1040 showed comparable lower values.

Asian Journal of Computing and Engineering Technology
ISSN 2959-1775 (online)
Vol.7, Issue 1 No.3, pp 41 - 52, 2026

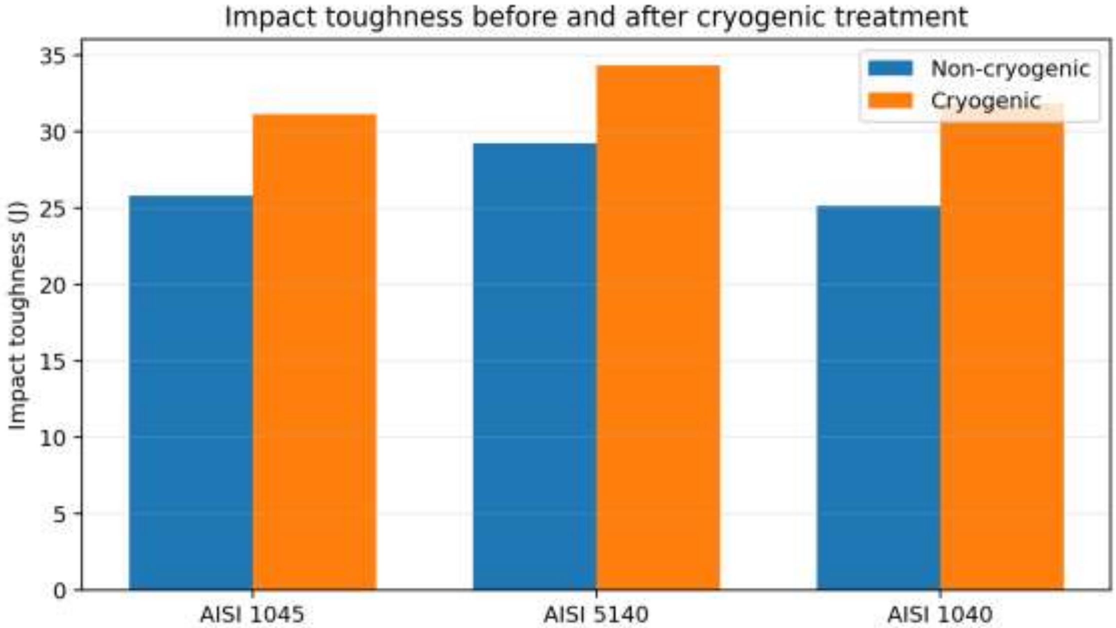

Figure 2: Mean Impact Toughness of the Selected Steel Grades before and after Cryogenic Treatment

Tensile Response

The tensile results in the experimental work s indicate that the response to cryogenic treatment was not equally uniform across all specimens. For example, the AISI 1045 cryogenic condition tempered at 200°C exhibited substantial variation between the two reported trials, with maximum tensile stresses of 491.82 MPa and 268.04 MPa. The corresponding mean was reported as 379.93 MPa. This variability indicates that specimen-to-specimen differences or microstructural heterogeneity may influence the tensile response even when specimen geometry is controlled. The experimental work s conclusion nevertheless reports an overall tensile-strength improvement of approximately 4–11% after DCT compared with conventional heat treatment.

Tribological Characteristics

A marked improvement in wear resistance was reported after cryogenic treatment. The mean wear-resistance values increased from 3.09 to 100.30 mm/mm³ for AISI 1045, from 6.81 to 182.79 mm/mm³ for AISI 5140, and from 2.12 to 69.52 mm/mm³ for AISI 1040. AISI 5140 therefore recorded the highest wear-resistance value under both treatment conditions. The experimental work also reports that wear resistance increased with tempering temperature from 200°C to 300°C and remained higher for cryogenically treated samples.

The improvement in wear resistance was associated with the increased hardness of the cryogenically treated steels, transformation of retained austenite and the contribution of refined carbide distributions to load bearing. The experimental results further demonstrate that the wear resistance of each steel grade increased as the tempering temperature increased from 200°C to 300°C, with the cryogenically treated specimens maintaining higher wear-resistance values than their non-cryogenic counterparts.

Asian Journal of Computing and Engineering Technology
ISSN 2959-1775 (online)
Vol.7, Issue 1 No.3, pp 41 - 52, 2026
www.iprjb.org

Coefficient of Friction

The coefficient of friction (μ) was also evaluated as part of the tribological characterization of the selected structural steels. In the experimental work, the coefficient of friction was determined with respect to an aluminium surface using the angle-of-inclination method, where the coefficient of friction was calculated from $\mu = \tan \theta$.

The results showed that AISI 1045 recorded the highest coefficient of friction of 1.0355 at an inclination angle of 46°, followed by AISI 5140 with a coefficient of friction of 0.6745 at 34°, while AISI 1040 recorded the lowest coefficient of friction of 0.6494 at 33°.

The results therefore indicate that, under the experimental aluminium-surface contact condition, AISI 1040 exhibited the lowest resistance to sliding among the three measured values, while AISI 1045 exhibited the highest. The experimental work further notes that the coefficient of friction increased with increasing angle of inclination.

It is important to note that the coefficient-of-friction experiment reported in the thesis does not provide separate cryogenic and non-cryogenic coefficient-of-friction values. Consequently, the present journal article reports the measured values directly rather than attributing a specific reduction in coefficient of friction to DCT. This distinction is important for accurately representing the experimental evidence.

Table 3: Coefficient of Friction of the Selected Structural Steels against Aluminium Surface

Steel grade	Angle of inclination, θ	Coefficient of friction, μ = tan θ
AISI 1045	46°	1.0355
AISI 5140	34°	0.6745
AISI 1040	33°	0.6494

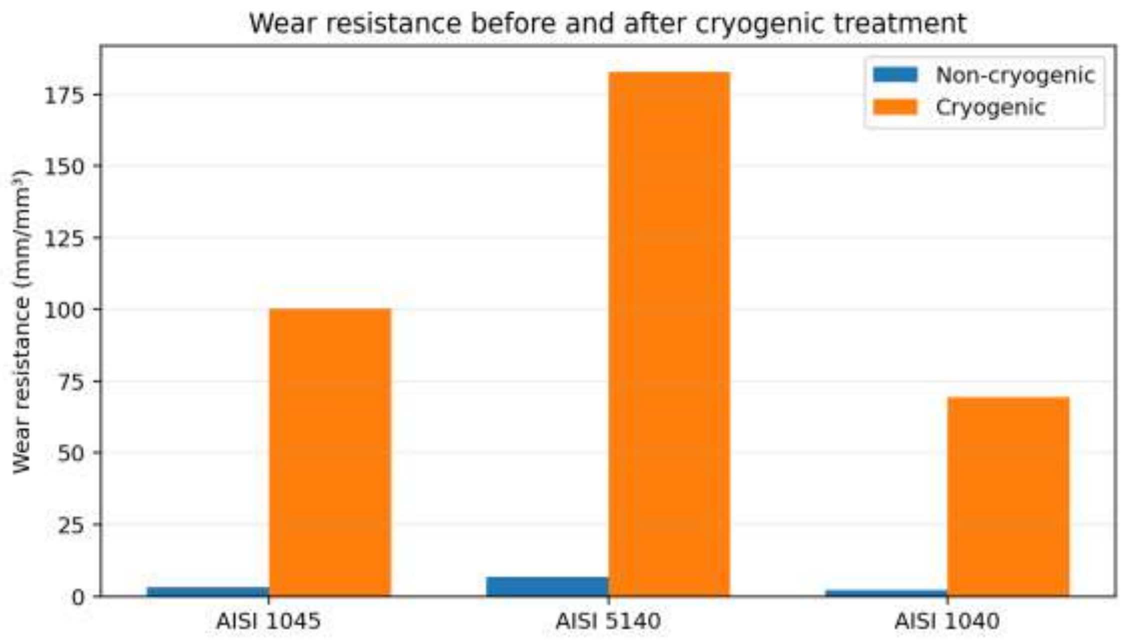

Figure 3: Mean Wear Resistance before and after Cryogenic Treatment

Asian Journal of Computing and Engineering Technology
ISSN 2959-1775 (online)
Vol.7, Issue 1 No.3, pp 41 - 52, 2026

www.iprjb.org

Corrosion Behaviour

Corrosion behaviour was grade-dependent. The reported corrosion-rate values in Table 4.37 were 465.0 mm/y for cryogenic AISI 1040 compared with 778.1 mm/y for its DHT counterpart, 305.6 mm/y for cryogenic AISI 1045 compared with 767.0 mm/y for DHT AISI 1045, and 235.9 mm/y for cryogenic AISI 5140 compared with 654.7 mm/y for DHT AISI 5140. Thus, within the reported dataset, the cryogenic condition had a lower numerical corrosion rate for each grade. The studys discussion nevertheless identifies AISI 1045 as showing some localized-pitting susceptibility and emphasizes that alloy composition and carbide distribution can influence corrosion behaviour.

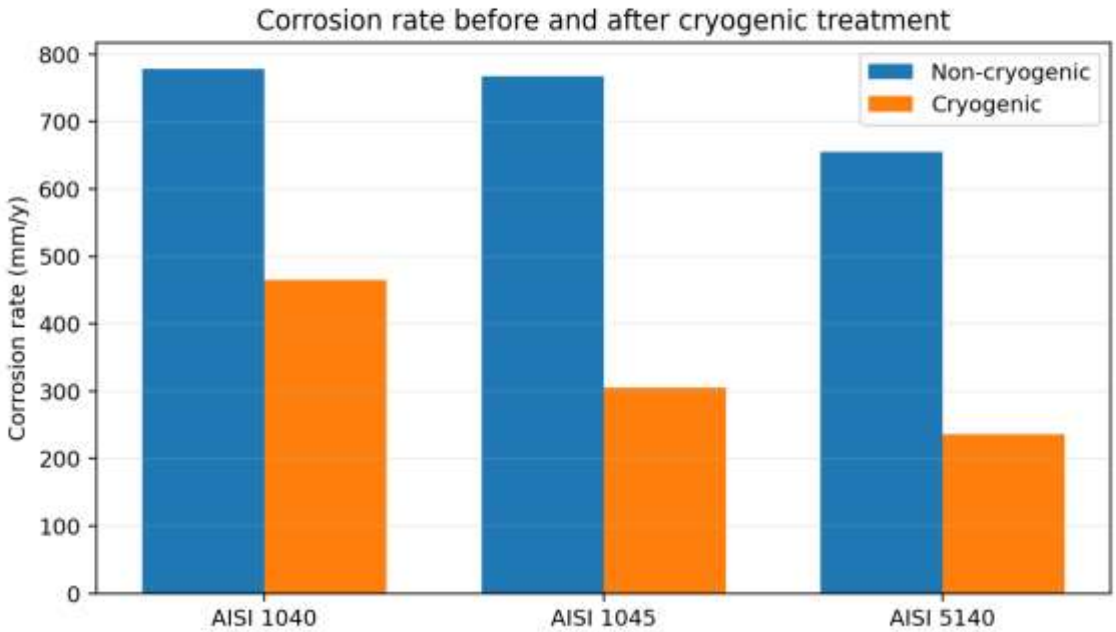

Figure 4: Reported Corrosion Rates for Conventional and Cryogenic Conditions

Table 2: Selected Electrochemical Corrosion Parameters Reported in the Studies

Steel grade	Treatment	Ecorr (mV)	Icorr	CR (mm/y)
AISI 1040	Cryogenic	−585.0	1.020 mA	465.0
AISI 1040	DHT	−595.0	1.700 mA	778.1
AISI 1045	Cryogenic	−571.0	669.0 µA	305.6
AISI 1045	DHT	−631.0	1.680 mA	767.0
AISI 5140	Cryogenic	−612.0	516.0 µA	235.9
AISI 5140	DHT	−611.0	1.430 mA	654.7

Integrated Interpretation

Taken together, the results indicate that DCT can improve several performance indicators simultaneously. The strongest and most consistent benefits were observed in hardness, impact toughness and wear resistance. AISI 5140 generally recorded the highest hardness, impact toughness and wear resistance, which is consistent with the role of alloy chemistry and chromium-containing hardenability effects. AISI 1040 generally recorded the lowest hardness and wear-resistance values but still benefited from DCT. The corrosion results demonstrate that improvements in mechanical and tribological properties should not automatically be assumed to translate into identical corrosion behaviour for every grade. Consequently, DCT parameters and post-treatment tempering should be selected with the intended service environment in mind.

Conclusion

Deep cryogenic treatment at approximately −185°C for 24 h, followed by tempering, produced measurable changes in the mechanical, tribological and corrosion-related behaviour of AISI 1040, AISI 1045 and AISI 5140 structural steels. Mean hardness increased for all three grades, with the largest absolute value occurring in AISI 5140. Impact toughness also increased in the direct cryogenic/non-cryogenic comparison. Wear resistance showed the most pronounced improvement, with AISI 5140 recording the highest reported cryogenic value. The corrosion results were grade-dependent but showed lower reported corrosion rates under the cryogenic condition for all three grades in the dataset presented.

The findings support the use of DCT as a complementary processing route where increased hardness, strength and wear performance are required. For corrosion-critical applications, however, the treatment should be optimized for the particular alloy because carbide chemistry and distribution can influence localized corrosion behaviour.

Implications of the Study

The findings of this study have important implications for the application of structural steels in engineering components subjected to mechanical loading, sliding contact and corrosive environments. The observed improvement in hardness and wear resistance following deep cryogenic treatment suggests that DCT can potentially extend the service performance of components manufactured from AISI 1040, AISI 1045 and AISI 5140 steels.

The superior wear-resistance response observed for AISI 5140 indicates its potential suitability for components where resistance to material loss and surface degradation is particularly important. The improvement in hardness following DCT may also contribute to improved resistance to deformation under service loading.

The study further demonstrates that **cryogenic treatment should not be considered independently of tempering temperature**. The observed changes across the 200°C and 300°C tempering conditions indicate that the final properties of the treated steels are influenced by the combined effect of cryogenic processing and subsequent tempering.

The coefficient-of-friction results also have implications for tribological applications. Since the selected steels exhibited different coefficients of friction under the experimental conditions, material selection for sliding-contact applications should consider both wear resistance and frictional behaviour rather than hardness alone.

Finally, the corrosion findings imply that improvement in mechanical and wear properties should not automatically be interpreted as equivalent improvement in corrosion resistance. Consequently, DCT parameters should be selected according to the specific operating environment and performance requirements of the steel component.

Recommendations

- Optimize DCT soaking time and cooling/heating rates specifically for medium-carbon and low-alloy structural steels rather than directly transferring parameters developed for tool steels.

Asian Journal of Computing and Engineering Technology
ISSN 2959-1775 (online)
Vol.7, Issue 1 No.3, pp 41 - 52, 2026

- Use advanced microstructural techniques such as transmission electron microscopy to characterize nano-scale carbide nucleation, growth and distribution.
- Extend corrosion and fatigue investigations to field-service environments and cyclic loading conditions.
- Develop composition–retained-austenite–DCT parameter relationships that can guide material and process selection for engineering applications.
- Undertake life-cycle and techno-economic studies comparing DCT-treated structural steels with conventionally treated alternatives.

REFERENCES

Amini, K., Akhbarizadeh, A., & Javadpour, S. (2012). Effect of deep cryogenic treatment on the formation of nano-sized carbides and the wear behavior of D2 tool steel. International Journal of Minerals, Metallurgy and Materials, 19, 795–799. https://doi.org/10.1007/s12613-012-0630-2

Chen, Z., Jing, L., Gao, Y., Huang, Y., Guo, J., & Yan, X. (2023a). Impact of cryogenic treatment process on the performance of 51CrV4 steel. Materials, 16(12), 4399. https://doi.org/10.3390/ma16124399

Chen, Z., Li, C., Su, H., Huang, Y., & Yan, X. (2023b). Influence of cryogenic treatment on the corrosion properties of 42CrMo low alloy steel. Materials, 16(3), 899. https://doi.org/10.3390/ma16030899

Danish, M., Gupta, M. K., Rubaiee, S., Ahmed, A., Sarıkaya, M., & Krolczyk, G. M. (2022). Environmental, technological and economic aspects of cryogenic-assisted hard machining operation of Inconel 718. Journal of Cleaner Production, 337, 130483.

Jamali, A. R., Khan, W., Chandio, A. D., Anwer, Z., & Jokhio, M. H. (2019). Effect of cryogenic treatment on mechanical properties of AISI 4340 and AISI 4140 steel. Mehran University Research Journal of Engineering & Technology, 38(3), 755–766. https://doi.org/10.22581/muet1982.1903.18

Jovičević-Klug, P., Jovičević-Klug, M., Sever, T., Feizpour, D., & Podgornik, B. (2021). Impact of steel type, composition and heat treatment parameters on the effectiveness of deep cryogenic treatment. Journal of Materials Research and Technology, 14, 1007–1020. https://doi.org/10.1016/j.jmrt.2021.07.022

Jurči, P., & Dlouhý, I. (2024). Cryogenic treatment of martensitic steels: Microstructural fundamentals and implications for mechanical properties and wear and corrosion performance. Materials, 17(3), 548. https://doi.org/10.3390/ma17030548

Kara, F., Çiçek, A., & Demir, H. (2023). Effect of deep cryogenic treatment on microstructure, mechanical properties, and residual stress of AISI 52100 bearing steel. Engineered Science, 24. https://doi.org/10.33019/es960

Ma, S. Y., Su, R. M., Li, G. L., Qu, Y. D., & Li, R. D. (2022). Effect of deep cryogenic treatment on corrosion resistance of AA7075-RRA. Journal of Physics and Chemistry of Solids, 167, 110747. https://doi.org/10.1016/j.jpcs.2022.110747

Mudda, S ., Hedge, A ., Sharma, S ., Gurumurthy, B. M., Shettar, M., & Gowrishankar, M . C . (2025). Effect of various heat treatment methods and optimization of their parameters on mechanical properties of AISI 4140 steel. Scientific Reports, 15(1), 31854. DOI 10:1038/s41598-025-17299-1

Su, R. M., Ma, S. Y., Wang, K. N., Li, G. L., Qu, Y. D., & Li, R. D. (2022). Effect of cyclic deep cryogenic treatment on corrosion resistance of 7075 alloy. Metallurgical and Materials Transactions/Materials and Metallurgical Engineering literature as cited in the thesis, 28, 862–870. https://doi.org/10.1007/s12540-021-00975-y

Zhang, H., et al. (2022). Effect of cryogenic treatment on the microstructure and wear resistance of 17Cr2Ni2MoVNb carburizing gear steel. Coatings, 12(2), 281. https://doi.org/10.3390/coatings12020281