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Effect of Titanium Microalloying on the Microstructure, Wear, and Corrosion Behavior of ASTM A216 Cast Steel for Fishing Vessel Stern Tube Applications.

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Abstract

This study investigates the effect of titanium modification on the microstructure, hardness, wear resistance, and electrochemical corrosion behavior of ASTM A216 cast steel for potential application in fishing-vessel stern tubes. Two cast-steel conditions were comparatively evaluated: a reference steel (Sample B) and a Ti-modified steel (Sample A). The materials were produced by conventional sand casting, followed by chemical analysis, optical and SEM–EDS characterization, Vickers hardness testing, pin-on-disk wear testing, electrochemical corrosion measurements in 5 wt.% NaCl solution, and numerical solidification analysis using SOLIDCast. The microstructural examination revealed that Ti modification promoted a finer and more homogeneous ferrite–pearlite structure, with characteristic grain dimensions decreasing from approximately 55 and 40 μm in the reference condition to 40.5 and 35.2 μm in the modified steel. Localized Ti-rich second-phase constituents were also observed. This microstructural refinement was accompanied by an increase in Vickers hardness from approximately 173 to 188 HV. The tribological results showed a substantial improvement in wear resistance, with total mass loss decreasing from 5.32 to 2.72 g, corresponding to an approximately 49% reduction. At 1400 rpm, the wear-rate value decreased from 3.496 for Sample B to 0.366 for Sample A, representing an approximately 9.5-fold improvement. Electrochemical measurements further demonstrated a markedly enhanced corrosion response for the Ti-modified steel. The polarization/charge-transfer resistance increased from approximately 96.41 Ω to 1899.2 Ω . In addition, the corrosion current and calculated corrosion rate of the reference steel were approximately 13 times higher than those of the Ti-modified condition. Numerical solidification analysis revealed non-uniform thermal behavior associated with variations in section thickness, including localized differences in cooling rate, liquidus time, temperature distribution, and hot-spot formation. Overall, the results establish a clear microstructure–property relationship in which Ti-related microstructural refinement and localized second-phase constituents contribute to improved hardness, wear resistance, and electrochemical stability. The Ti-modified ASTM A216 cast steel therefore demonstrates promising potential for stern-tube applications requiring enhanced resistance to simultaneous mechanical and chloride-induced degradation.

Keywords: ASTM A216 cast steel; Titanium microalloying; Stern tube; Fishing vessels; Microstructure; Wear resistance; Corrosion behavior; Marine applications.

1. Introduction

Marine propulsion systems operate under a combination of mechanical loading, hydrodynamic excitation, thermal variation, and aggressive environmental exposure. Within these systems, the stern tube forms the structural transition through which the propeller shaft passes from the vessel hull to the external marine environment. It houses the shaft-supporting bearings, maintains shaft alignment, limits seawater ingress, prevents lubricant leakage, and transfers the static and dynamic loads generated by the propeller–shaft assembly. Consequently, the reliability of the stern tube directly affects propulsion efficiency, navigational safety, environmental compliance, and vessel availability. Recent investigations have demonstrated that journal deflection, shaft misalignment, bearing deformation, and non-uniform lubricant-film thickness can significantly alter the dynamic characteristics and load distribution of aft stern tube bearings [1–4]. These effects are particularly critical in fishing vessels, which commonly operate for long periods under fluctuating rotational speeds, repeated manoeuvring, variable propeller immersion, and limited maintenance opportunities.

The stern tube is a critical component of the marine propulsion system, providing support and alignment for the propeller shaft while accommodating bearings and sealing elements that prevent lubricant leakage and seawater ingress [1, 2]. A schematic longitudinal arrangement of the stern tube system and shaft-line layout in a fishing vessel is shown in **Fig. 1**.

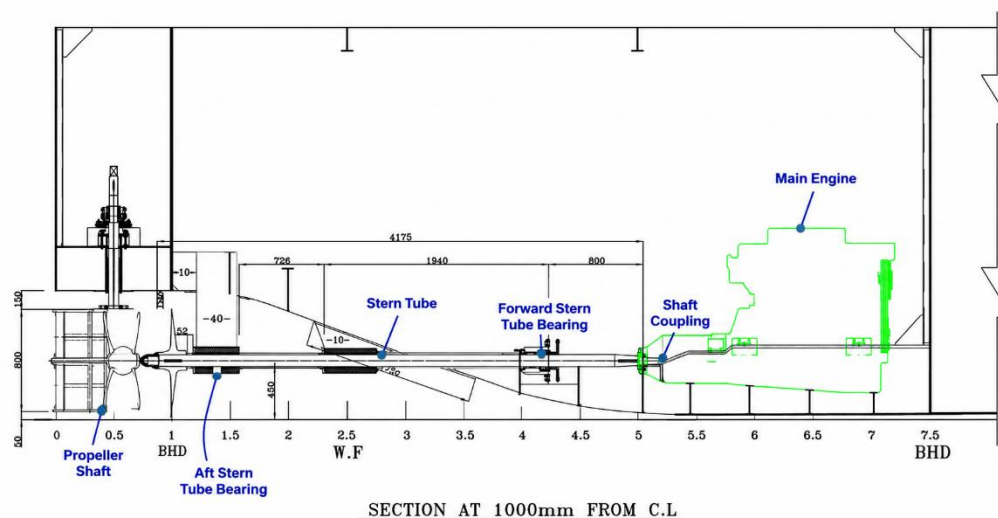


Fig. 1. Schematic longitudinal section showing the stern tube, shaft line, and associated propulsion components in a fishing vessel.

The performance and reliability of the stern tube assembly are strongly influenced by shaft alignment, bearing condition, lubrication efficiency, and exposure to the marine environment.

Unlike large commercial ships operating under comparatively controlled propulsion regimes, fishing vessels experience frequent changes in shaft speed and propeller loading associated with sailing, trawling, hauling, and low-speed manoeuvring. These conditions may produce shaft eccentricity, edge loading, insufficient lubricant-film formation, local temperature rise, seal deterioration, and accelerated bearing wear. Experimental and numerical studies published since 2020 have shown that improper lubrication, inadequate cooling, groove geometry, journal misalignment, and bearing surface deformation strongly influence the frictional response and failure behaviour of marine stern bearings [5–9]. Under boundary or mixed-lubrication regimes, direct asperity interaction may occur, generating abrasive and adhesive wear, local plastic deformation, surface fatigue, and friction-induced heating. If these effects are not controlled, progressive material loss can increase shaft clearance, intensify vibration, disturb alignment, and ultimately cause leakage or propulsion-system failure.

The marine environment introduces an additional electrochemical degradation mechanism. Stern tube materials and adjacent components may be exposed to seawater, chloride-containing moisture, oxygen-concentration differences, lubricant contamination, and galvanic coupling with dissimilar metallic parts. Chloride ions can destabilize surface oxide films and promote localized corrosion, while mechanically damaged or worn regions continuously expose fresh metal to the corrosive environment. The resulting interaction between surface damage and electrochemical attack can accelerate deterioration beyond that caused by wear or corrosion acting independently. Although oil-lubricated stern tube systems generally provide better hydrodynamic lubrication than water-lubricated arrangements, seal failure may allow seawater ingress and oil discharge. Environmentally acceptable lubricants have therefore received increasing attention, but their viscosity, shear stability, frictional behaviour, and temperature response can differ from those of conventional mineral oils [10–13]. This situation increases the importance of developing stern tube materials that retain adequate hardness, dimensional stability, wear resistance, and corrosion resistance under imperfect lubrication and marine exposure.

Cast carbon steels offer important engineering advantages for manufacturing geometrically complex marine components, including high load-carrying capacity, good castability, weldability, machinability, repairability, and relatively low production cost. ASTM A216 cast steel is conventionally specified for pressure-containing steel castings and provides a practical balance between strength, ductility, manufacturability, and economic feasibility. However, conventional carbon-steel microstructures may contain relatively coarse ferrite–pearlite regions, segregated constituents, casting-related heterogeneity, and non-metallic inclusions. Such features can create preferential sites for crack initiation, abrasive material removal, localized corrosion, and unstable passive-film formation. Therefore, applying ASTM A216 cast steel in a seawater-exposed stern tube requires more than satisfying its nominal chemical and mechanical requirements; its microstructure must be engineered to resist simultaneous mechanical and environmental degradation. Recent research on carbon and low-alloy steels confirms that grain morphology, secondary-phase distribution, inclusion population, surface condition, and residual stresses govern their hardness, wear response, and electrochemical stability [14–16].

Microalloying is an effective metallurgical route for improving steel performance without the high alloying cost associated with stainless steels or heavily alloyed wear-resistant grades. Titanium is particularly attractive because of its strong chemical affinity for carbon, nitrogen, oxygen, and sulfur. Depending on composition, melting conditions, solidification rate, and titanium recovery, it may form TiC, TiN, Ti (C, N), and titanium-containing complex inclusions. Properly controlled titanium-bearing precipitates can restrict austenite-grain growth through grain-boundary pinning, promote heterogeneous nucleation during solidification, refine the final microstructure, and contribute to precipitation strengthening [17–20]. A refined microstructure increases the density of grain boundaries that obstruct dislocation motion and can improve hardness and load-bearing capacity. Titanium can also modify the size, chemistry, and morphology of inclusions, although excessive addition or poor dispersion may generate coarse TiN particles, agglomerates, or brittle inclusions that reduce toughness and act as crack-initiation sites. Thus, titanium content and processing conditions must be carefully controlled to achieve beneficial microalloying rather than detrimental particle accumulation.

Recent studies have shown that titanium microalloying can improve the hardness, strength, fracture behaviour, and wear resistance of different steel families. Kostryzhev et al. reported that

titanium alloying enhanced the abrasion and impact-wear resistance of martensitic wear-resistant steels through precipitation and microstructural modification [21]. Kim et al. demonstrated that small titanium additions altered the microstructure and mechanical properties of cast brake-disc steel [22]. Investigations of high-titanium wear-resistant steels have similarly associated the formation of titanium carbides with increased hardness and improved resistance to material removal [23]. More recent work on low-carbon cast steels has explored in situ TiC reinforcement as a route to producing locally wear-resistant steel castings [24]. Nevertheless, the beneficial effect is not determined solely by hardness. Particle distribution, matrix–particle bonding, carbide size, porosity, casting quality, and the ability of the matrix to support hard precipitates collectively determine the wear mechanism. An excessively hard but heterogeneous microstructure may experience particle pull-out, microcracking, or localized delamination rather than stable wear resistance.

The influence of titanium on aqueous corrosion is more complex and remains less systematically understood in cast carbon steels. Grain refinement can promote a more uniform electrochemical response and reduce the dimensions of localized galvanic cells, while fine, stable titanium compounds may support the formation of a more compact corrosion-product or oxide layer. Conversely, coarse particles, inclusions, segregation, and particle–matrix interfaces may act as preferential initiation sites for microgalvanic corrosion. Electrochemical techniques including open-circuit potential, linear polarization resistance, and electrochemical impedance spectroscopy are therefore required to determine whether a titanium-modified structure genuinely improves interfacial stability in chloride media [25,26]. Parameters such as corrosion current density, polarization resistance, charge-transfer resistance, impedance magnitude, and phase angle provide complementary information regarding corrosion kinetics and protective-film behaviour. Accordingly, corrosion performance should be interpreted together with microstructural observations rather than inferred from hardness or chemical composition alone.

Despite the growing body of research on titanium-microalloyed steels, stern bearing tribology, environmentally acceptable lubricants, and marine shaft alignment, a clear research gap remains at their intersection. Most titanium microalloying studies focus on rolled, forged, martensitic, weathering, railway, or mining steels, whereas comparatively limited attention has been given to titanium-modified ASTM A216 cast steel for stern tube applications. Similarly, recent stern tube

studies largely address lubricant selection, polymeric bearing materials, alignment, surface geometry, thermal behaviour, or monitoring, without experimentally investigating whether the cast steel surrounding the bearing and sealing assembly can be metallurgically modified to resist both wear and chloride-induced corrosion. Furthermore, the separate evaluation of microstructure, hardness, sliding wear, and electrochemical corrosion is essential for determining whether titanium produces a balanced improvement rather than enhancing one property at the expense of another.

Research hypothesis and objective

The central hypothesis of this study is that introducing a controlled titanium content into ASTM A216 cast steel will promote microstructural refinement and the formation of dispersed titanium-rich carbide and nitride phases, thereby increasing hardness and resistance to sliding wear while improving electrochemical stability in a chloride-containing environment. It is further hypothesized that the performance improvement will arise from the combined effects of grain-boundary pinning, precipitation strengthening, reduced microstructural heterogeneity, improved load support, and the development of a more stable surface film.

Accordingly, the objective of the present work is to experimentally determine the effect of approximately 0.32 wt.% Ti on the microstructure, hardness, wear resistance, and corrosion behaviour of ASTM A216 cast steel intended for fishing-vessel stern tube applications. The titanium-modified alloy is compared with unmodified ASTM A216 steel using optical and scanning electron microscopy, elemental analysis, Vickers hardness testing, pin-on-disk wear testing at different rotational conditions, and electrochemical testing in 5 wt.% NaCl, including open-circuit potential, impedance, phase-angle, and polarization measurements. This integrated methodology is intended to establish scientifically supported microstructure–property relationships and assess the technical feasibility of titanium microalloying as a cost-effective route for extending stern tube service life, reducing maintenance demand, and enhancing the reliability of fishing-vessel propulsion systems.

2. Materials and Methods

ASTM A216 cast carbon steel was selected as the base material according to ASTM A216/A216M [29], and two experimental conditions were prepared: a reference steel containing less than 0.005 wt.% Ti (Sample B) and a titanium-modified steel containing approximately 0.32 wt.% Ti (Sample

A), with titanium representing the principal metallurgical variable. The steel was melted in an electric furnace, Ti was manually introduced into the molten metal at approximately 1450 °C, and the melt temperature was subsequently increased to approximately 1600 °C. The sand mold was prepared using a dimensionally defined stern-tube pattern and core-print arrangement to reproduce the required hollow geometry and maintain proper positioning of the internal core during casting, as illustrated in **Fig. 2**. The resulting sand mold cavity and associated gating features prepared prior to pouring are shown in **Fig. 3**. The molten steel was subsequently transferred using a ladle and manually poured into the prepared sand mold, followed by natural solidification and cooling under ambient conditions. The corresponding temperature–time cooling profile is presented in **Fig. 4.a**. After complete solidification and mold removal, the resulting as-cast specimens were visually inspected prior to subsequent machining and characterization, as shown in **Fig. 4.b**. The cast specimens were then sectioned, machined, ground, and polished following the general metallographic preparation procedures of ASTM E3 [32]. The chemical compositions of both materials were determined by optical emission spectroscopy (OES) according to ASTM E415 [33] to verify the titanium concentration and the comparability of the remaining alloying elements. Microstructural characterization was performed using optical microscopy and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDS), with metallographic etching conducted according to ASTM E407 [34] and grain-size assessment referenced to ASTM E112 [35]. The microstructural analysis focused on ferrite–pearlite morphology, grain refinement, structural homogeneity, and the occurrence of Ti-rich precipitates chemically consistent with titanium carbide/nitride phases. Vickers hardness measurements were conducted according to ASTM E92 [36] using polished specimens and a dwell time of 15 s. Tribological performance was evaluated using a pin-on-disk configuration following ASTM G99 [37], where nine tests were performed for each material using normal loads corresponding to 1.05, 2.20, and 3.55 kg at rotational speeds of 761, 1127, and 1400 rpm for 5 min per test. Wear resistance was quantified primarily from specimen mass loss while accounting for the different nominal contact areas of 56.4 and 80 mm² for Samples A and B, respectively. Electrochemical corrosion behavior was evaluated in a 5 wt.% NaCl solution using a conventional three-electrode cell after 1800 s of open-circuit-potential stabilization, followed by electrochemical impedance spectroscopy (EIS) and linear polarization measurements. EIS verification, polarization-resistance measurements, and electrochemical corrosion-rate calculations were referenced to ASTM G106 [38], ASTM G59 [39],

and ASTM G102 [40], respectively. The resulting chemical, microstructural, hardness, wear, and electrochemical data were finally correlated to establish the influence of 0.32 wt.% Ti addition on the performance of ASTM A216 cast steel for fishing-vessel stern-tube applications.

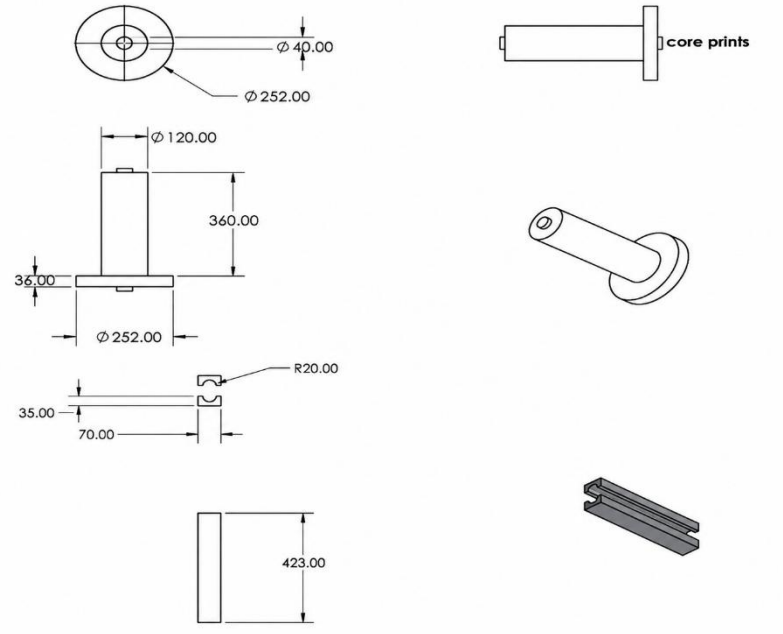


Fig. 2. Engineering drawings and three-dimensional models of the stern tube pattern and core-print components used for sand-mold preparation.



Fig. 3. As-cast ASTM A216 steel specimens prepared for the comparative evaluation of the reference and Ti-modified conditions.



Fig. 4.a. As-cast ASTM A216 steel specimens prepared for the comparative evaluation of the reference and Ti-modified conditions.

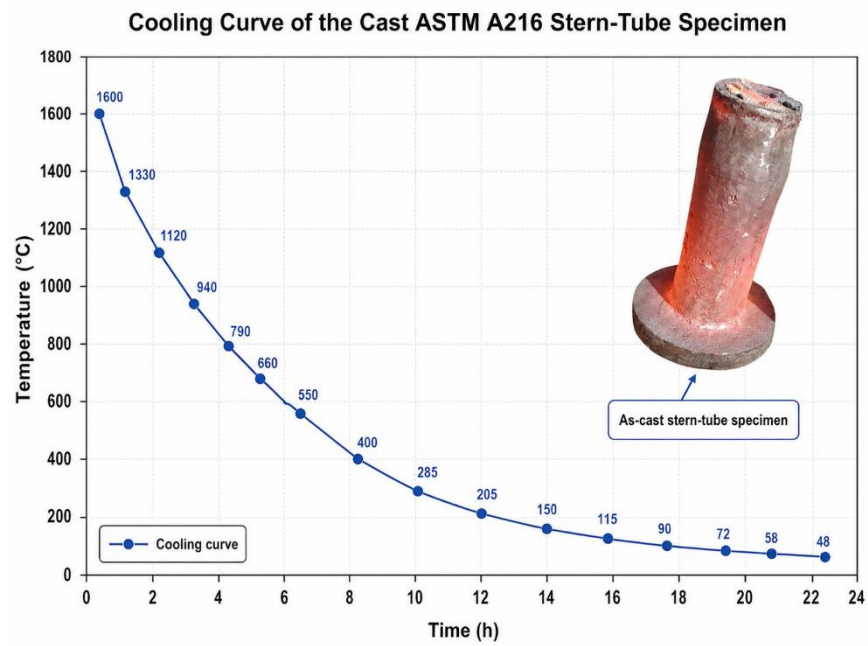


Fig. 4.b. Cooling curve of the cast ASTM A216 steel specimen during natural solidification under ambient conditions.

2.1. Numerical Simulation of Casting and Solidification

A three-dimensional numerical model of the cast component was developed using SOLIDCast to examine the thermal behavior during cooling and solidification. The casting geometry was discretized using the software-generated mesh, and silica sand was assigned as the mold material. The thermal properties of the casting and mold, initial casting temperature, mold temperature, and interfacial heat-transfer conditions were defined within the numerical model based on the adopted casting conditions. The simulation was continued until complete solidification of the casting.

The numerical analysis was primarily used to evaluate the temperature distribution, cooling-rate variation, liquidus-time distribution, and thermal hot-spot locations within the casting. These outputs were employed to identify regions of relatively slow solidification and possible thermal accumulation arising from differences in section thickness. The numerical results were used as a complementary interpretation of the experimental casting process rather than as an independent prediction of mechanical or corrosion properties.

3. Results and Discussion

3.1. Chemical Composition and Assessment of Titanium Recovery

The chemical composition determined by OES, as presented in **Table 1**, showed that both samples were Fe-based steels with comparable carbon contents of 0.316 and 0.304 wt.% for Samples A and B, respectively. Most alloying elements remained within relatively close ranges, while Sample A exhibited a higher measured Ti content of 0.0023 wt.% compared with <0.0005 wt.% in Sample B. Although the nominal Ti addition during melting was approximately 0.32 wt.%, the substantially lower bulk OES value indicates limited titanium recovery in the analyzed matrix. This difference may result from oxidation, segregation, or reaction of Ti with C and N to form localized Ti-containing precipitates; however, the present chemical analysis alone cannot distinguish among these mechanisms.

The measured nitrogen contents, 0.0066 wt.% for Sample A and 0.0071 wt.% for Sample B, are metallurgically relevant because Ti–N interactions strongly influence TiN precipitation and grain-growth control. Fine Ti-containing precipitates can promote grain refinement and precipitation strengthening, whereas coarse or clustered particles may reduce the beneficial effect of titanium [41–43]. In addition, Sample A contained somewhat higher Mn, Nb, and V, while Sample B showed higher Al and Si; therefore, the subsequent property changes should be interpreted as the response of the Ti-modified casting condition rather than being attributed exclusively to titanium.

This interpretation agrees with previous studies showing that Ti microalloying affects steel performance through a combined mechanism of grain refinement, precipitation behavior, and dislocation–particle interaction, and that the response depends strongly on Ti content and precipitate morphology rather than on nominal addition alone [41,44,45]. The chemical results therefore provide the compositional basis for the subsequent microstructural analysis, where the finer and more homogeneous structure observed in Sample A can be assessed in relation to the presence of Ti-rich precipitates.

Table 1. Average chemical composition of the investigated ASTM A216 cast-steel samples determined by OES (wt.%).

Element	Sample A	Sample B
Fe	97.700	97.700
C	0.316	0.304
Si	0.339	0.415
Mn	0.508	0.451
P	0.0752	0.0231
S	0.0261	0.0223
Cr	0.545	0.556
Mo	0.0210	0.0213
Ni	0.128	0.121
Al	0.0087	0.109
Co	0.0052	0.0056
Cu	0.0891	0.0937
Nb	0.0385	0.0165
Ti	0.0023	<0.0005
V	0.0695	0.0522
W	<0.0050	<0.0050
Pb	<0.0050	<0.0050
Sn	0.0085	0.0089
B	0.0018	0.0019
Ca	0.0008	0.0007
Zr	0.0049	0.0032
Zn	0.0118	0.0134
Bi	<0.0010	<0.0010
As	0.0079	0.0072
N	0.0066	0.0071
Se	<0.0010	<0.0010
Sb	0.0106	0.0090
Ta	0.0338	0.0337

3.2. Microstructural Evolution of Ti-Modified ASTM A216 Cast Steel

3.2.1. Optical Microstructure and Grain Refinement

Optical microscopy revealed a clear difference between the reference ASTM A216 steel (Sample B) and the Ti-modified condition (Sample A), as shown in **Fig. 5**. Sample B exhibited a relatively coarse and heterogeneous ferrite–pearlite microstructure characterized by large pearlite colonies, pronounced grain boundaries, and localized porosity, whereas Sample A showed a noticeably finer and more homogeneous structure with a more uniform distribution of ferrite and pearlite. Quantitative grain-size measurements, presented in **Fig. 6**, further confirmed this refinement; the characteristic grain dimensions decreased from approximately 55 and 40 μm in Sample B to 40.5 and 35.2 μm in Sample A, respectively. This reduction indicates that the Ti-modified casting condition restricted grain coarsening during solidification and promoted a higher density of grain boundaries.

The observed refinement is consistent with the established behavior of Ti-microalloyed steels, in which Ti-containing particles can provide heterogeneous nucleation sites and exert a pinning effect on migrating grain boundaries. Wang et al. [46] reported that the metallurgical effectiveness of Ti microalloying is strongly governed by the precipitation state, size, and distribution of Ti-containing second-phase particles, particularly TiC and TiN, which can suppress grain growth and alter phase-transformation behavior. Similarly, Huo et al. [47] demonstrated that nanoscale TiC precipitation inhibits recrystallization and contributes significantly to austenite grain refinement and precipitation strengthening. These mechanisms provide a reasonable explanation for the finer and more homogeneous microstructure observed in Sample A.

The microstructural response is also consistent with the findings of Fojt-Dymara et al. [48], who showed that Ti micro-addition modifies precipitation behavior and microstructural evolution in low-carbon steels through stable TiN-type particles. Their results emphasize that Ti-bearing precipitates can influence grain-boundary stability and thereby improve the structural homogeneity of the steel matrix. Therefore, the measured grain refinement in the present study provides the first microstructural indication that the Ti-modified condition should exhibit improved resistance to localized deformation and subsequent wear, which is examined in the following sections.

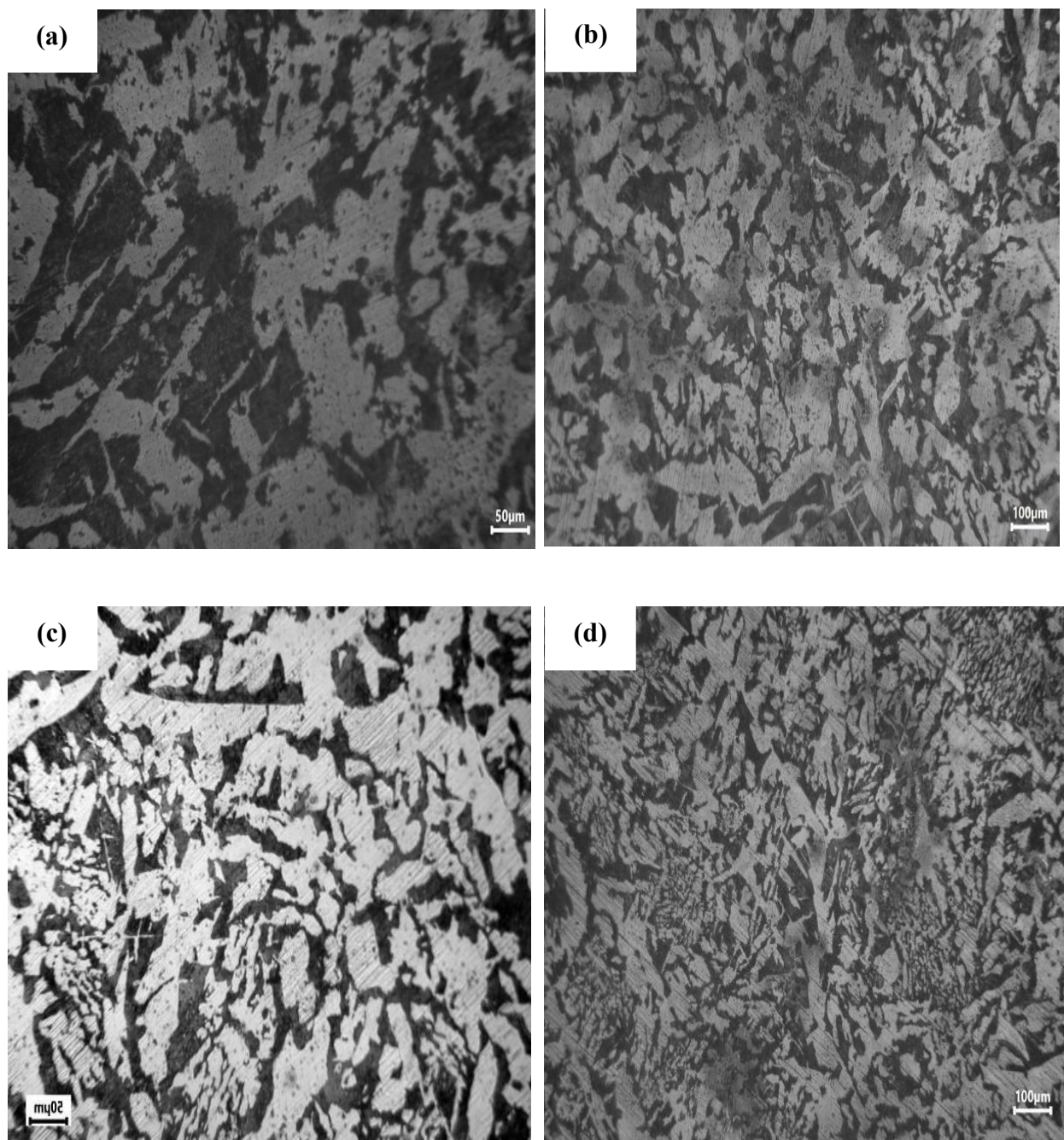


Fig. 5. Optical microstructures of (a, b) reference ASTM A216 steel (Sample B) and (c, d) Ti-modified ASTM A216 steel (Sample A) at 10× and 20× magnifications.

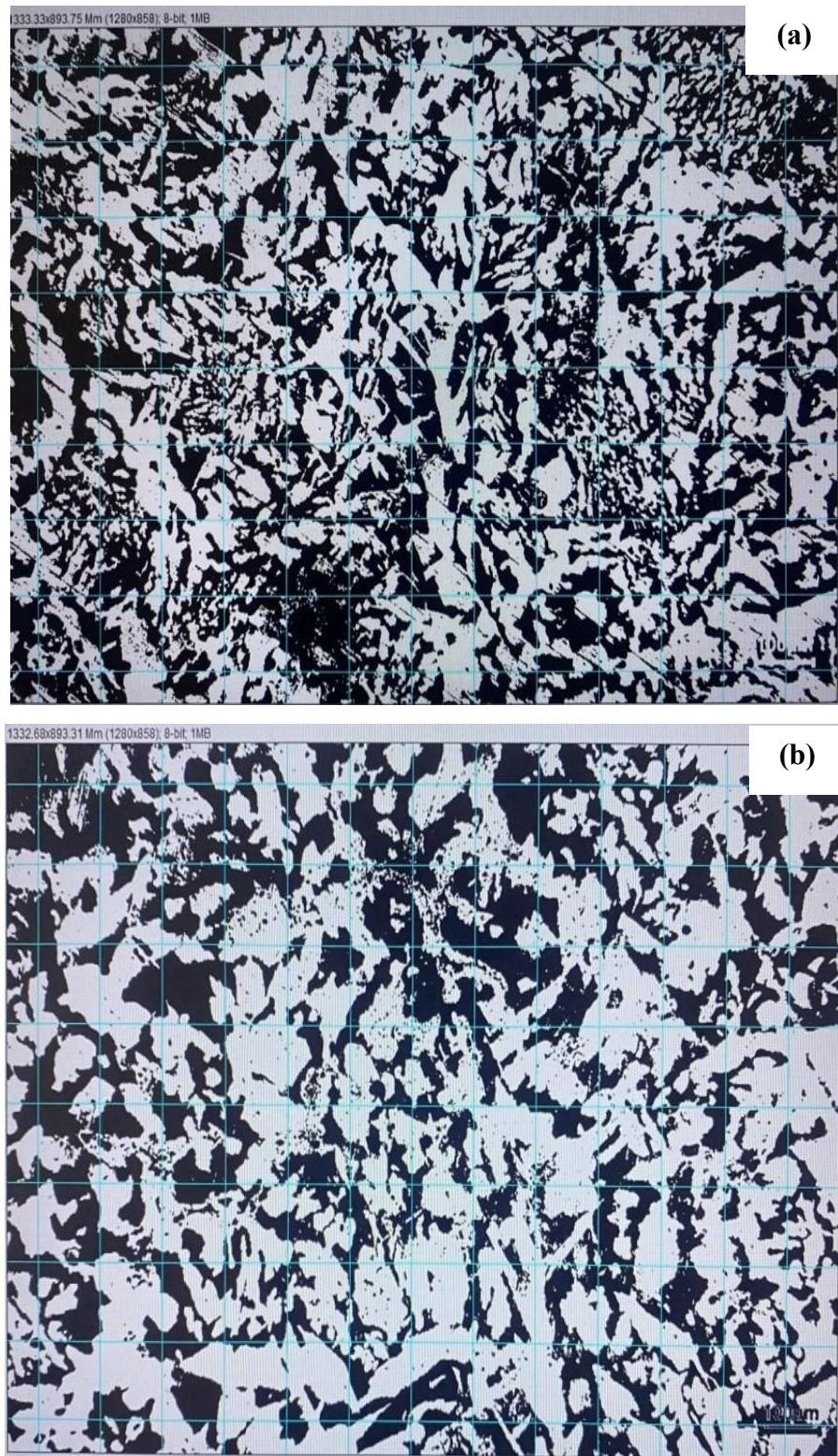


Fig. 6. Representative grain-size measurements of (a) reference and (b) Ti-modified ASTM A216 cast steels.

3.2.2. Ti-Rich Precipitates and Microstructural Strengthening Mechanism

The microstructural features presented in Fig. 7 show that Sample A exhibited a finer and more homogeneous ferrite–pearlite structure than the reference Sample B, together with a more uniform distribution of second-phase constituents and only limited local clustering. These observations are consistent with the grain-size measurements, which showed a reduction in the characteristic grain dimensions after Ti modification.

The SEM–EDS characterization presented in Fig. 8(a–c) further supports the presence of localized Ti-rich constituents within the steel matrix. The SEM observations reveal discrete second-phase particles distributed within the refined ferrite–pearlite structure, while the corresponding EDS analysis indicates Ti enrichment at the selected regions relative to the surrounding Fe-rich matrix. The project likewise reports that Ti-containing regions were associated with grain-growth restriction and strengthening of the modified steel. This behavior agrees with Wang et al. [46], who demonstrated that the strengthening response of Ti-microalloyed steels is strongly controlled by the size, distribution, and precipitation state of Ti-containing particles. Fine and well-dispersed precipitates can restrict grain-boundary migration and impede dislocation motion, whereas particle clustering reduces the effectiveness of these strengthening mechanisms. Huo et al. [47] similarly reported that Ti-containing precipitates contribute to grain refinement and precipitation strengthening, while Moreira et al. [49] demonstrated that Ti-containing carbide-rich regions can enhance the local refinement and wear resistance of low-carbon cast steels.

Accordingly, the microstructural evolution of Sample A can be interpreted as the combined result of grain refinement, grain-boundary pinning, and precipitation-related strengthening. The refined ferrite–pearlite matrix observed in Fig. 7, together with the Ti-rich constituents detected by SEM–EDS in Fig. 8, provides a consistent explanation for the subsequent increase in hardness and improvement in wear resistance observed for the Ti-modified ASTM A216 cast steel.

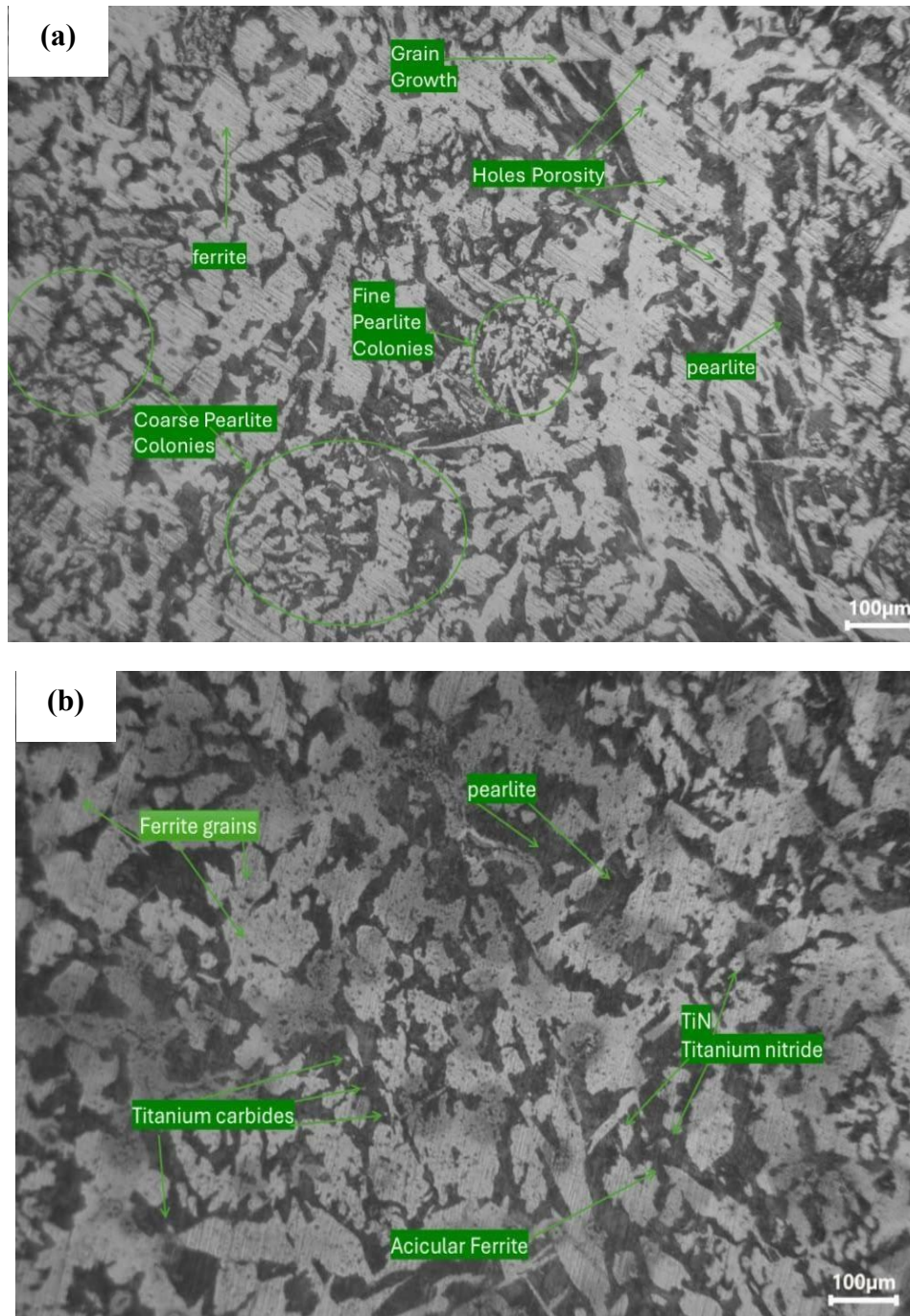


Fig. 7. Comparison of the characteristic microstructural phases in (a) reference and (b) Ti-modified ASTM A216 cast steels.

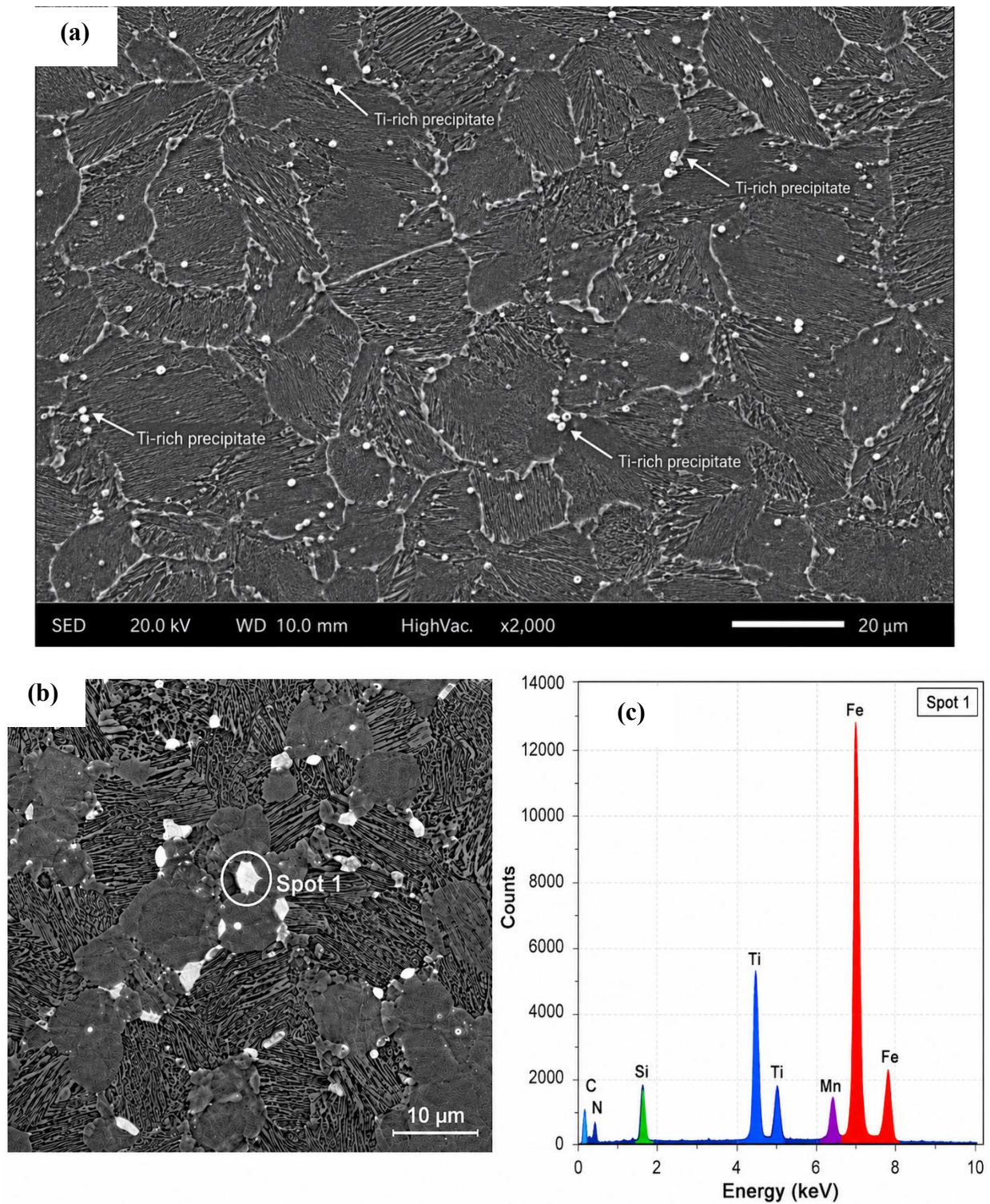


Fig. 8. SEM–EDS characterization of Ti-modified ASTM A216 cast steel: (a) SEM micrograph showing the distribution of second-phase particles within the ferrite–pearlite matrix, (b) higher-magnification SEM image of a selected Ti-rich region, and (c) corresponding EDS spectrum of the analyzed region.

3.3. Vickers Hardness and Strengthening Response

The Vickers hardness results revealed a clear improvement in the mechanical response of the Ti-modified ASTM A216 cast steel. As shown in Fig. 9, the average hardness increased from approximately 173 HV for the reference Sample B to 188 HV for Sample A, corresponding to an improvement of about 8.7%. The repeat measurements showed comparable values of approximately 173.6 HV and 186.2 HV for Samples B and A, respectively, confirming the consistency of the observed increase.

The higher hardness of Sample A is consistent with the microstructural refinement discussed in Section 3.2. The reduction in characteristic grain dimensions from approximately 55 and 40 μm in Sample B to 40.5 and 35.2 μm in Sample A increases the density of grain boundaries, which provide additional barriers to dislocation motion. In addition, the Ti-rich second-phase constituents observed within the refined ferrite–pearlite matrix can contribute to precipitation-related strengthening and further restrict localized plastic deformation. Therefore, the measured hardness increase is most reasonably attributed to the combined effects of grain refinement and second-phase strengthening, rather than to a single strengthening mechanism.

This interpretation is strongly supported by previous investigations on Ti-microalloyed steels. Wang et al. [46] showed that small Ti additions can significantly modify the mechanical properties of low-alloy steels through the interaction of grain refinement and Ti-containing second-phase particles. Their review emphasized that fine Ti-containing precipitates can simultaneously restrict grain growth and hinder dislocation motion, thereby increasing resistance to plastic deformation. Huo et al. [47] similarly demonstrated that Ti-containing nanoscale precipitates contribute to both microstructural refinement and precipitation strengthening in Ti-microalloyed steels, confirming the close relationship between precipitate evolution, refined microstructure, and enhanced mechanical response.

The present increase of approximately 8.7% in hardness is therefore consistent with the relatively moderate but clearly measurable microstructural modification produced in Sample A. Importantly, the improvement was obtained without a major change in the bulk carbon content, which remained close between the two investigated materials. This observation further supports the interpretation that the improved hardness is associated primarily with the modified microstructural state,

including the finer ferrite–pearlite morphology and Ti-rich constituents, rather than with a substantial change in the carbon level.

From an engineering perspective, the increase in hardness is particularly relevant to stern-tube applications because greater resistance to localized plastic deformation generally improves the ability of the material to withstand repeated surface contact and sliding interaction. The higher hardness of Sample A therefore provides a direct mechanical link between the refined microstructure presented in **Fig. 9.** and the superior tribological response observed subsequently. This relationship becomes especially important in the wear analysis, where Sample A exhibited considerably lower material loss despite being subjected to comparable testing conditions.

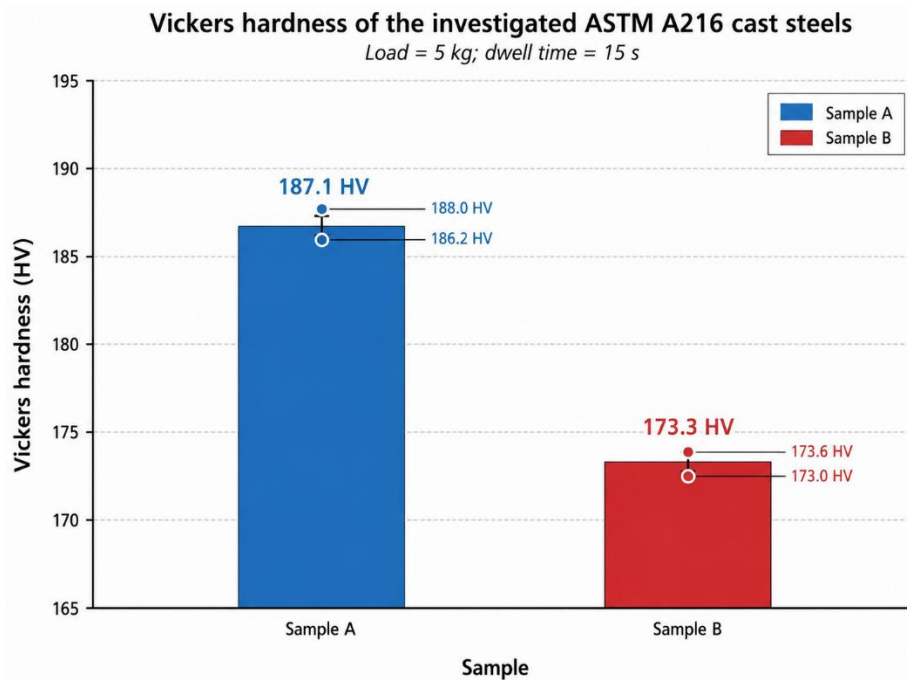


Fig. 9. Vickers hardness measurements of the reference ASTM A216 steel (Sample B) and Ti-modified steel (Sample A) under a 5 kg load and 15 s dwell time.

3.4. Tribological Behavior and Wear Resistance

3.4.1. Wear-Rate Behavior at Different Rotational Speeds

The wear behavior of the reference and Ti-modified ASTM A216 cast steels showed a pronounced dependence on both material condition and rotational speed. As presented in **Fig. 10(a)**, Sample A exhibited lower wear-rate values than Sample B over the entire investigated speed range. At 761 rpm, the wear-rate value decreased from 0.465 for Sample B to 0.018 for Sample A, corresponding

to an approximately 25-fold difference between the two materials. At 1127 rpm, the corresponding values were 0.412 and 0.257, respectively, whereas at 1400 rpm the difference became particularly pronounced, with wear-rate values of 3.496 for Sample B and 0.366 for Sample A. Thus, at the highest rotational speed, the reference steel exhibited a wear rate approximately 9.5 times higher than that of the Ti-modified condition.

A particularly important feature of these results is that Sample A maintained its superior wear resistance despite its smaller nominal cross-sectional area of 56.4 mm², compared with 80 mm² for Sample B. Consequently, Sample A was exposed to a higher nominal surface pressure under the same applied load, yet it consistently exhibited lower wear-rate values. This observation indicates that the improvement is primarily associated with the modified material response rather than with a more favorable contact condition.

The enhanced wear resistance of Sample A is consistent with the higher hardness and refined microstructure discussed in Sections 3.2 and 3.3. The increase in hardness from approximately 173 to 188 HV improves resistance to localized plastic deformation, while the finer ferrite–pearlite structure and Ti-rich second-phase constituents provide additional barriers to subsurface deformation and material removal during sliding. Similar behavior has been reported by Kostryzhev et al. [50], who demonstrated that Ti alloying improved the wear resistance of martensitic steels through microstructural refinement and Ti-containing precipitates. Liu et al. [51] also showed that TiC-containing steels exhibited improved abrasive-wear resistance and related this response to the distribution and interaction of hard TiC particles with the wear surface.

The effect becomes particularly significant at 1400 rpm, where the wear rate of Sample B increased sharply, whereas Sample A maintained a substantially lower value. The result suggests that the refined and harder microstructure of Sample A was more effective in resisting the intensified surface deformation and material removal associated with the more severe sliding condition. Lan et al. [52] similarly reported a close relationship between Ti-containing precipitates, hardness, microstructural condition, and improved wear resistance in Ti-containing low-alloy wear-resistant steel.

3.4.2. Total Mass Loss and Microstructure–Wear Relationship

The cumulative mass-loss measurements further confirm the improvement in wear resistance produced by the Ti-modified condition. As shown in Fig. 10(b), Sample A exhibited a total mass loss of only 2.72 g, compared with 5.32 g for Sample B. These values correspond to approximately 12.0% and 26.7% of the respective initial specimen masses and represent an overall reduction in material loss of approximately 49% for Sample A. The visual appearance of the worn specimens presented in **Fig. 11** provides additional qualitative support for the difference in material removal between the two conditions.

The lower mass loss of Sample A agrees well with the microstructural and hardness results obtained in the present work. The refined ferrite–pearlite matrix increases resistance to localized deformation, while the Ti-rich second-phase constituents identified in the modified steel contribute to restricting deformation and material removal at the sliding surface. Consequently, the higher hardness measured for Sample A is accompanied by a substantially lower cumulative material loss, establishing a clear microstructure–hardness–wear relationship.

This interpretation is in agreement with Liu et al. [51], who reported that hard TiC precipitates can improve the abrasive-wear response of low-alloy steel by resisting penetration and material removal during contact. Kostryzhev et al. [50] likewise demonstrated that titanium addition can enhance steel wear resistance through the combined effects of precipitation and microstructural modification. More recently, Moreira et al. [53] reported that TiC-reinforced regions in low-carbon cast steel exhibited increased hardness and a 24% reduction in abrasive wear rate, accompanied by reduced plastic deformation and shallower wear grooves. These findings independently support the relationship observed in the present ASTM A216 cast steel between Ti-related microstructural modification, increased hardness, and reduced wear damage.

Overall, the tribological results demonstrate that the Ti-modified Sample A provides substantially greater resistance to sliding-induced material loss than the reference Sample B. The persistence of this improvement over the investigated rotational-speed range, together with the approximately 49% reduction in cumulative mass loss, supports the effectiveness of the modified microstructure under increasingly severe wear conditions. For stern-tube applications, where repeated sliding contact and progressive surface degradation can directly affect dimensional stability and

component reliability, this improved wear response represents an important functional advantage of the Ti-modified ASTM A216 cast steel.

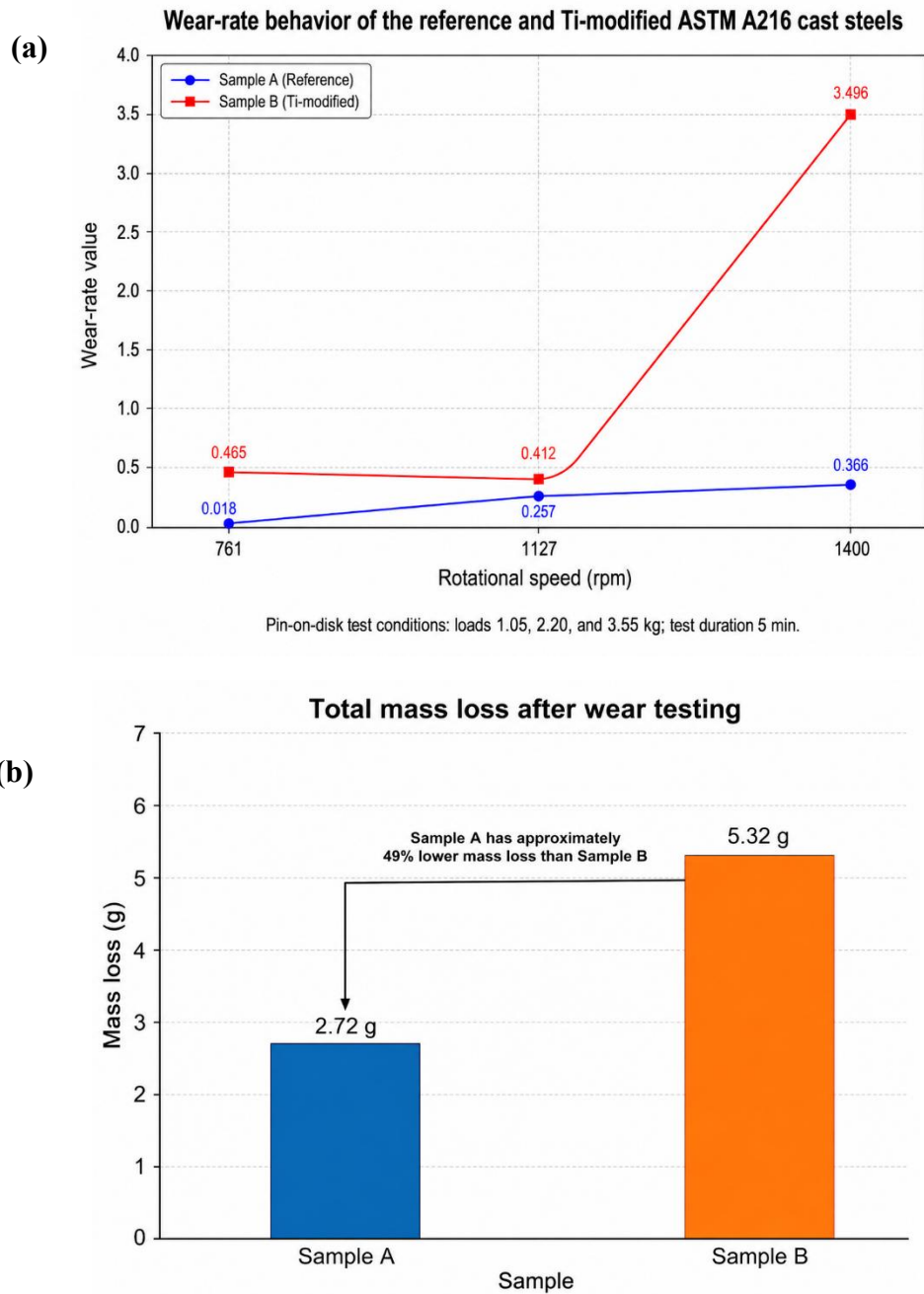


Fig. 10. Wear behavior of the reference and Ti-modified ASTM A216 cast steels: (a) variation of wear-rate value with rotational speed and (b) total mass loss after the complete wear-testing sequence.



Fig. 11. Macroscopic appearance of the worn surfaces of the reference and Ti-modified ASTM A216 cast-steel specimens after pin-on-disk testing.

3.5. Electrochemical Corrosion Behavior

The electrochemical corrosion behavior of the reference and Ti-modified ASTM A216 cast steels was evaluated in 5 wt.% NaCl solution using open-circuit potential (OCP), electrochemical impedance spectroscopy (EIS), and linear polarization measurements. The combined electrochemical response consistently showed superior corrosion resistance for Sample A compared with the reference Sample B. This improvement is consistent with the refined microstructure and Ti-rich constituents discussed previously, which modify the electrochemical heterogeneity of the steel surface and favor the development of a more stable interfacial response in the chloride-containing environment.

3.5.1. Open-Circuit Potential Behavior

The evolution of the open-circuit potential during the initial 1800 s exposure is presented in **Fig. 12**. Both materials exhibited a progressive potential shift before approaching a relatively stable condition, indicating continued adjustment of the steel/electrolyte interface during immersion. Sample A maintained a comparatively more noble potential response than Sample B over most of the stabilization period, suggesting a lower tendency toward active electrochemical dissolution.

The more stable OCP response of Sample A is consistent with its finer and more homogeneous microstructure. A reduction in microstructural heterogeneity can decrease the intensity of localized electrochemical differences between neighboring constituents and thereby reduce preferential anodic activity. Zong and Liu [54] similarly demonstrated that modification of the microstructure of microalloyed low-carbon bainitic steel influenced its seawater-corrosion response, with more favorable microstructural conditions producing improved corrosion resistance.

The OCP results should not be considered independently as a quantitative measure of corrosion rate; rather, they establish the stabilized electrochemical state from which the subsequent impedance and polarization measurements can be interpreted. In the present work, the relatively favorable potential response of Sample A is therefore consistent with the substantially improved EIS and polarization behavior discussed below.

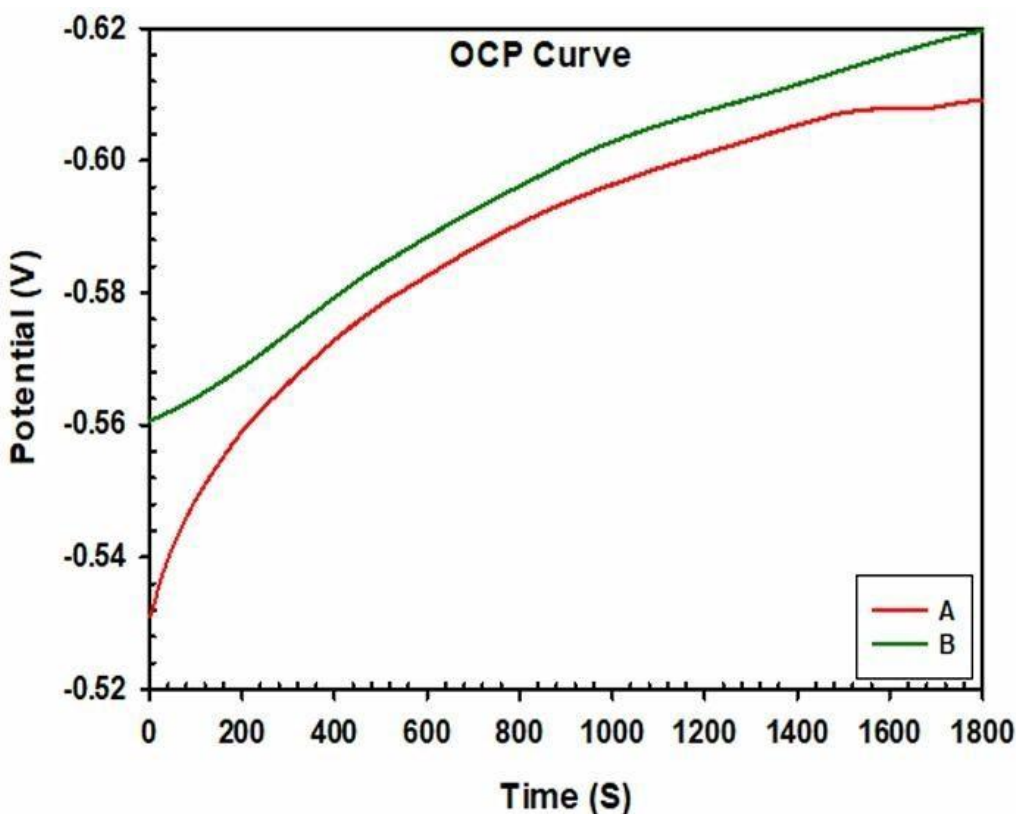


Fig. 12. Open-circuit potential evolution of the reference and Ti-modified ASTM A216 cast steels during 1800 s immersion in 5 wt.% NaCl solution.

3.5.2. Electrochemical Impedance Spectroscopy

A much clearer distinction between the two investigated materials was obtained from the EIS measurements. The Nyquist response shown in **Fig. 13(a)** exhibited a considerably larger impedance response for Sample A than for Sample B. The experimental Nyquist plots reached approximately 300 Ω for Sample A compared with about 70–75 Ω for Sample B, indicating a pronounced increase in resistance to electrochemical charge transfer in the Ti-modified material.

The same trend is evident in the Bode impedance plot in **Fig. 13(b)**, where Sample A maintained a higher impedance response over the measured frequency range. In electrochemical corrosion analysis, an increased low-frequency impedance is commonly associated with greater resistance to interfacial electrochemical reactions. The superior response observed for Sample A therefore indicates that the modified microstructure provided a more resistive metal/electrolyte interface than that formed on Sample B.

The phase-angle response in **Fig. 13(c)** provides additional support for this interpretation. Sample A exhibited a maximum phase angle of approximately 55°, compared with only about 25° for Sample B. The higher phase-angle response indicates a more pronounced capacitive behavior of the interface and is consistent with the development of a more stable surface layer. The simultaneous increase in impedance magnitude and phase angle therefore confirms that the electrochemical response of Sample A was substantially more protective than that of the reference steel.

This behavior agrees with recent findings on microalloyed steels. Feng et al. [55] reported that microalloying of low-carbon bainitic steel increased corrosion resistance in chloride-containing environments, with EIS demonstrating improved interfacial resistance resulting from changes in microstructure and corrosion-product characteristics. Zong and Liu [54] also linked improved corrosion performance of microalloyed low-carbon steel to microstructural refinement and changes in the distribution of electrochemically active constituents. These studies support the present observation that the refined microstructure of Sample A is associated with an enhanced electrochemical impedance response.

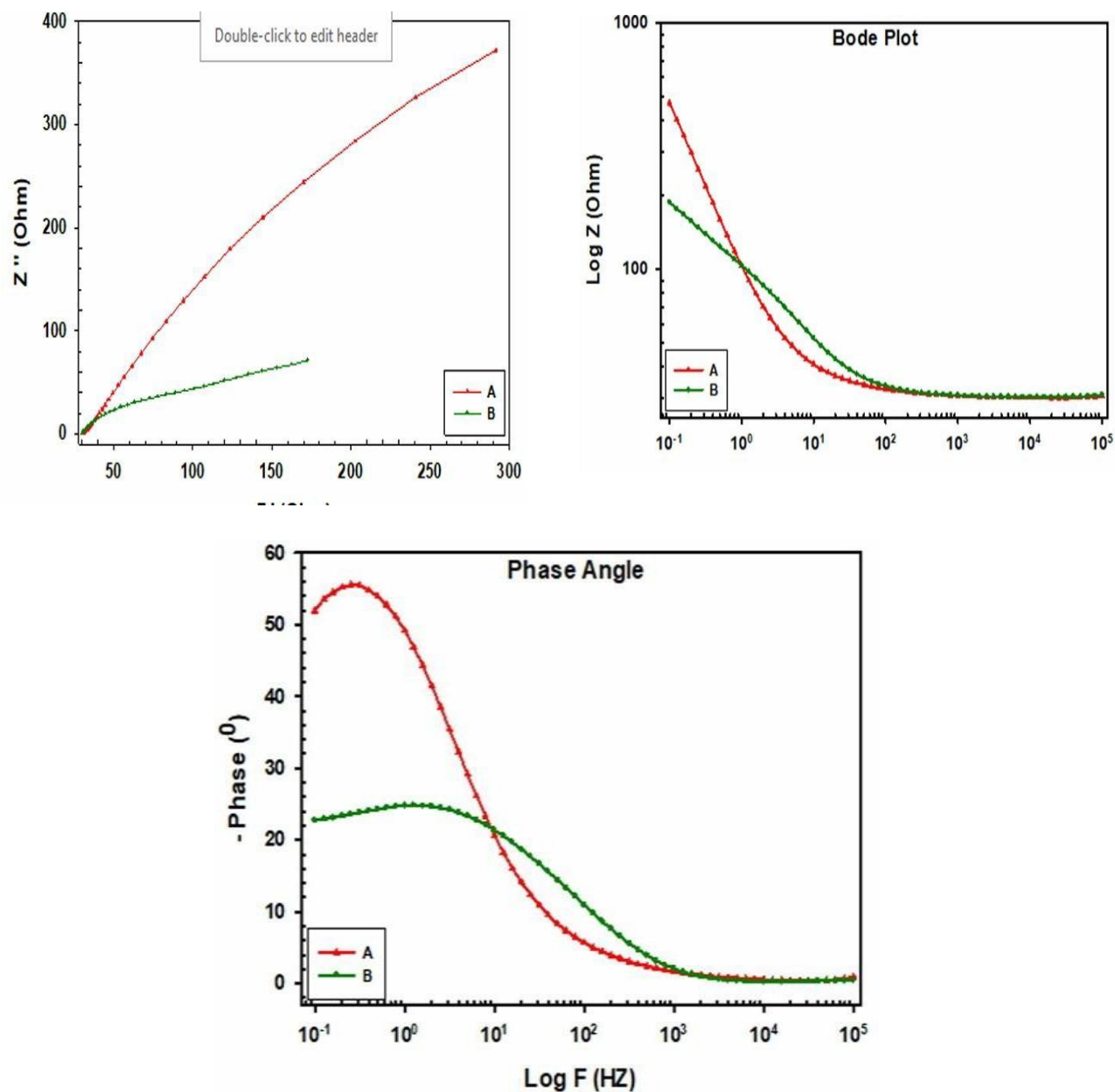


Fig. 13. EIS response of the reference and Ti-modified ASTM A216 cast steels in 5 wt.% NaCl solution: (a) Nyquist plots, (b) Bode impedance plots, and (c) phase-angle plots.

3.5.3. Equivalent-Circuit Parameters

The equivalent-circuit parameters provide a quantitative assessment of the differences observed in the impedance spectra. As summarized in **Fig. 14**, the solution resistances, (R_s), were very similar

for the two specimens, with values of approximately 33.35 Ω for Sample A and 30.28 Ω for Sample B. The small difference in (R_s) confirms that the substantial variation in electrochemical response was not caused by a meaningful change in electrolyte resistance.

In contrast, the polarization/charge-transfer resistance, (R_p), exhibited a pronounced difference. Sample A showed an (R_p) value of 1899.2 Ω , whereas Sample B exhibited only 96.41 Ω . Thus, the resistance of Sample A was approximately 19.7 times greater than that of Sample B. This is one of the strongest quantitative findings of the corrosion investigation and directly demonstrates that charge transfer across the steel/electrolyte interface was markedly suppressed in the Ti-modified specimen.

The constant-phase-element response also remained compatible with the more capacitive behavior observed for Sample A. The corresponding exponent (n) increased from approximately 0.729 for Sample B to 0.765 for Sample A, indicating a somewhat less heterogeneous interfacial response in the modified material. This trend agrees with the more homogeneous ferrite–pearlite structure observed in Sample A and supports the relationship between microstructural refinement and electrochemical uniformity.

A similar relationship between microalloying, microstructure, and corrosion resistance has been reported by Feng et al. [55], who found that microalloying improved the EIS response of low-carbon bainitic steel in NaCl solution. In a related Fe-based alloy system, Jesus et al. [56] showed that Ti-containing alloy modification can significantly alter corrosion behavior in 3.5 wt.% NaCl through changes in microstructure and passive/interfacial stability. Although the alloy systems and Ti levels differ from the present ASTM A216 steel, these findings support the broader interpretation that Ti-related microstructural modification can improve the stability of the electrochemical interface in chloride-containing environments.

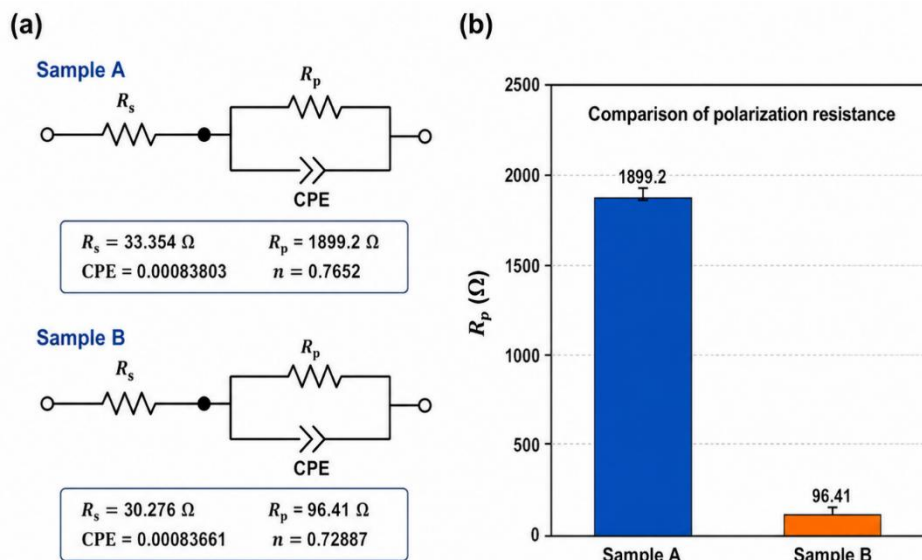


Fig. 14. Equivalent-circuit parameters derived from electrochemical impedance spectroscopy (EIS): (a) equivalent electrical circuit models and fitted parameters for Samples A and B, and (b) comparison of polarization resistance (R_p) between the two samples.

3.5.4. Linear Polarization and Corrosion Resistance

The linear polarization curves shown in **Fig. 15** further confirm the superior corrosion performance of Sample A. The Ti-modified material exhibited a more positive corrosion potential than Sample B, indicating a reduced thermodynamic tendency toward active corrosion. More importantly, the corrosion current of Sample B was approximately 13 times higher than that measured for Sample A. The calculated corrosion rate consequently followed the same trend, with Sample B exhibiting a corrosion rate approximately 13 times greater than Sample A.

These polarization results are fully consistent with the EIS measurements. The lower corrosion current of Sample A agrees with its substantially higher (R_p), larger impedance response, and higher phase angle. Collectively, these results indicate that the electrochemical reactions responsible for metal dissolution were substantially restricted in the Ti-modified ASTM A216 cast steel.

The present behavior is also consistent with the findings of Feng et al. [55], who observed that microalloying decreased electrochemical activity and improved both polarization and impedance responses in low-carbon bainitic steel. Jesus et al. [56] likewise reported a beneficial influence of

Ti-containing modification on the corrosion response of Fe–Cr-based alloys exposed to 3.5 wt.% NaCl. These previous findings strengthen the interpretation that the improved corrosion behavior measured for Sample A is associated with the combined effects of its refined microstructure and modified interfacial electrochemical characteristics.

Overall, the agreement between OCP, Nyquist impedance, bode response, phase angle, equivalent-circuit parameters, and linear polarization provides strong evidence that Sample A possesses substantially greater resistance to chloride-induced electrochemical degradation than Sample B. The approximately 19.7-fold increase in (R_p), together with the approximately 13-fold decrease in corrosion current and corrosion rate, represents a significant improvement for the intended stern-tube application, where prolonged exposure to chloride-containing environments is an important contributor to material degradation.

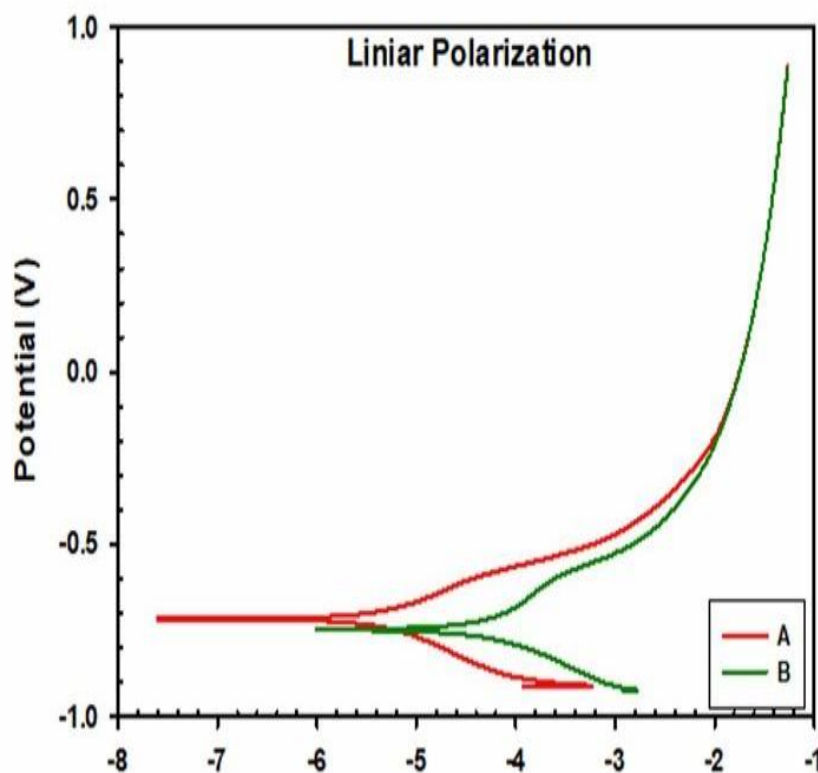


Fig. 15. Linear polarization curves of the reference and Ti-modified ASTM A216 cast steels in 5 wt.% NaCl solution.

3.6. Microstructure–Property Correlation

The integrated microstructure–property relationship is summarized in **Fig. 16**. The experimental results demonstrate a consistent relationship between the microstructural modification of ASTM A216 cast steel and the resulting mechanical, tribological, and electrochemical performance. Compared with the reference Sample B, the Ti-modified Sample A exhibited a finer and more homogeneous ferrite–pearlite microstructure, together with localized Ti-rich second-phase constituents. The characteristic grain dimensions decreased from approximately 55 and 40 μm in Sample B to 40.5 and 35.2 μm in Sample A. This microstructural refinement was accompanied by an increase in Vickers hardness from approximately 173 HV to 188 HV, indicating a greater resistance to localized plastic deformation.

The improvement in hardness is consistent with the combined contribution of grain refinement and Ti-related second-phase strengthening. The higher grain-boundary density associated with the refined microstructure increases the resistance to dislocation movement, while the Ti-rich constituents can further restrict local deformation and grain-boundary migration. Wang et al. [46] reported that the mechanical response of Ti-microalloyed steels is governed by the combined effects of grain refinement and Ti-containing precipitates, with particle size and distribution playing an important role in strengthening. As summarized in **Fig. 16**, a similar relationship is observed in the present study, where the refined microstructure and Ti-rich constituents are associated with the improved hardness, wear resistance, and electrochemical performance of Sample A. Kim et al. [57] similarly demonstrated that Ti addition can modify the microstructure and precipitation behavior of cast steel, resulting in improved mechanical properties.

The same microstructural features provide a consistent explanation for the improved wear behavior of Sample A. The increase in hardness reduced the susceptibility of the surface to plastic deformation and material removal during sliding, while the refined matrix provided a more uniform load-bearing response. Consequently, Sample A maintained lower wear-rate values over the entire investigated rotational-speed range. At 1400 rpm, the wear-rate value was only 0.366 for Sample A compared with 3.496 for Sample B, whereas the total mass loss decreased from 5.32 g to 2.72 g, corresponding to an approximately 49% reduction. These results establish a direct relationship between the refined microstructure, increased hardness, and enhanced resistance to sliding-induced material loss.

This relationship agrees with Kostyrychev et al. [50], who demonstrated that Ti alloying increased the wear resistance of steel through a combination of precipitation strengthening and microstructural modification. Moreira et al. [53] also reported that TiC-containing reinforced regions in low-carbon cast steel exhibited substantially increased hardness and reduced abrasive wear, with the improved response attributed to the interaction between hard Ti-containing phases and the surrounding refined matrix. Although the Ti concentration and processing route in that study differ from those used in the present work, the reported structure–property relationship is consistent with the behavior observed in Sample A.

The microstructural modification also coincided with a pronounced improvement in electrochemical behavior. Sample A exhibited a substantially larger impedance response, a higher phase angle, and markedly higher polarization/charge-transfer resistance than Sample B. The measured (R_p) increased from approximately 96.41 Ω in Sample B to 1899.2 Ω in Sample A, while the corrosion current and calculated corrosion rate of Sample B were approximately 13 times greater than those of Sample A. These results indicate that the refined and more homogeneous microstructure of Sample A provided a more stable electrochemical response in the chloride-containing environment.

The improved corrosion response may be associated with a reduction in local microstructural heterogeneity and the development of a more uniform metal/electrolyte interface. In a coarse and heterogeneous ferrite–pearlite structure, differences between adjacent microstructural constituents can promote localized electrochemical activity. By contrast, refinement of the matrix and a more homogeneous distribution of second-phase constituents can reduce the dimensions and intensity of such electrochemically active regions. Previous investigations on microalloyed steels have similarly shown that changes in grain size, phase distribution, and precipitate characteristics can significantly influence corrosion behavior by modifying the electrochemical uniformity of the steel surface.

Therefore, the overall performance improvement observed in Sample A should not be interpreted as the consequence of a single mechanism. Instead, the experimental results indicate a synergistic relationship in which microstructural refinement and Ti-rich second-phase constituents increase hardness, the higher hardness and more homogeneous matrix reduce sliding-induced material loss, and the refined microstructure simultaneously contributes to improved electrochemical stability.

This combined structure–property relationship explains why Sample A exhibited superior mechanical, tribological, and corrosion performance compared with the reference ASTM A216 cast steel.

The resulting correlation is particularly relevant to stern-tube applications, where the material is simultaneously required to resist mechanical surface damage and chloride-induced degradation. The simultaneous increase in hardness, reduction in wear loss, and improvement in electrochemical resistance therefore indicates that the Ti-modified microstructure provides a more favorable balance of properties for this application than the reference condition.

The overall relationship between the microstructural modification and the resulting mechanical, tribological, and electrochemical responses is summarized in **Fig. 16**.

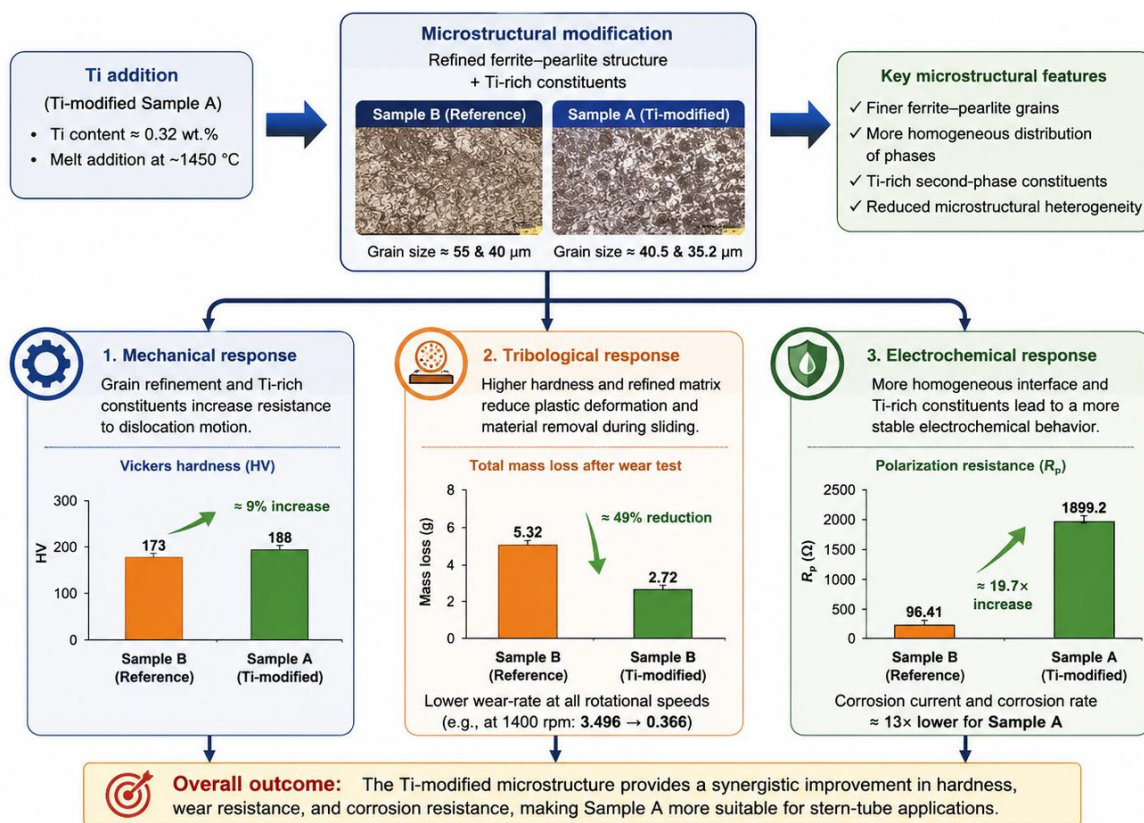


Fig. 16. Schematic correlation between the Ti-induced microstructural modification and the resulting mechanical, tribological, and electrochemical performance of ASTM A216 cast steel, highlighting grain refinement, increased hardness, reduced wear loss, and enhanced corrosion resistance of the Ti-modified Sample A.

As illustrated in **Fig. 16**, the refined ferrite–pearlite structure and Ti-rich constituents in Sample A are consistently associated with the increase in hardness, the reduction in wear loss, and the substantial improvement in polarization resistance.

3.7. Engineering Implications for Fishing-Vessel Stern-Tube Applications

The combined mechanical, tribological, and electrochemical results indicate that the Ti-modified ASTM A216 cast steel offers a more favorable performance profile for stern-tube applications than the reference condition. Stern-tube components are exposed during operation to repeated mechanical loading, sliding contact, lubricant-related disturbances, and chloride-containing environments, making wear and corrosion two important contributors to progressive material degradation. The present results are therefore particularly relevant because Sample A exhibited simultaneous improvements in hardness, wear resistance, and electrochemical stability rather than an enhancement in only one isolated property.

From a tribological perspective, the approximately 49% reduction in total mass loss, together with the markedly lower wear-rate values over the investigated rotational-speed range, suggests a greater ability of Sample A to resist progressive material removal during sliding contact. This is especially significant because Sample A maintained its superior wear response despite being subjected to higher nominal surface pressure owing to its smaller contact area. The project itself identifies wear resistance as a critical factor governing stern-tube service performance and relates reduced material loss to improved operational reliability and lower susceptibility to premature degradation.

The importance of this result is consistent with recent investigations of marine stern-tube bearings. Chang et al. [58] demonstrated experimentally that unfavorable shaft/bearing contact conditions can increase local bearing pressure and accelerate wear in stern-bearing systems. Similarly, Gilges et al. [59] showed that severe loading of aft stern-tube bearings can produce mixed-friction conditions associated with significant wear risk, emphasizing that resistance to material removal is a key requirement for reliable propulsion-system operation. These findings support the practical relevance of the substantially lower wear rate measured for the Ti-modified steel in the present work.

The corrosion results provide an additional advantage for stern-tube service. Sample A exhibited a substantially higher polarization resistance, increasing from 96.41 Ω in Sample B to 1899.2 Ω , together with higher impedance and phase-angle responses and lower corrosion current. Such behavior indicates a more stable electrochemical interface in chloride-containing solution. In the project application analysis, the improvement in corrosion resistance was specifically linked to enhanced suitability under salt-rich marine conditions, where prolonged exposure can accelerate degradation of stern-tube-related metallic components. The simultaneous enhancement of wear and corrosion resistance is particularly important because mechanical surface damage can expose fresh metallic areas and promote subsequent electrochemical attack.

This interaction between corrosion and wear has also been demonstrated in recent bearing-steel research. Zhao et al. [60] reported that corrosion exposure can significantly modify subsequent wear behavior of bearing steel, confirming that mechanical and electrochemical degradation mechanisms should not always be considered independently. Therefore, the combined improvement observed in Sample A is potentially more valuable for stern-tube applications than an improvement in hardness or corrosion resistance considered separately.

The refined ferrite–pearlite microstructure and Ti-rich constituents identified in Sample A provide a consistent explanation for this combined response. Grain refinement increased hardness and reduced susceptibility to localized deformation, while the more homogeneous microstructure contributed to improved electrochemical behavior. As summarized in **Fig. 17**, these changes result in three practical benefits relevant to stern-tube operation: reduced surface material removal, greater resistance to chloride-induced degradation, and improved dimensional stability of the component during service.

Importantly, the present laboratory results should be interpreted as evidence of improved material-level suitability rather than as a direct prediction of a specific increase in stern-tube service life. Actual service durability also depends on shaft alignment, lubrication regime, contact pressure, rotational speed, temperature, operating environment, and maintenance condition. Recent stern-tube studies likewise show that bearing wear is strongly affected by loading and lubrication conditions, indicating that material improvement represents one component of overall system reliability rather than an independent solution.

Accordingly, the Ti-modified ASTM A216 cast steel can be considered a promising material condition for fishing-vessel stern-tube applications. Its refined microstructure, increased hardness, approximately 49% lower mass loss, markedly reduced wear rate, and substantially improved electrochemical resistance indicate an enhanced ability to withstand the combined mechanical and corrosive demands associated with stern-tube service. Further full-scale or long-term marine exposure studies would be required to quantify the resulting service-life extension under actual vessel operating conditions.

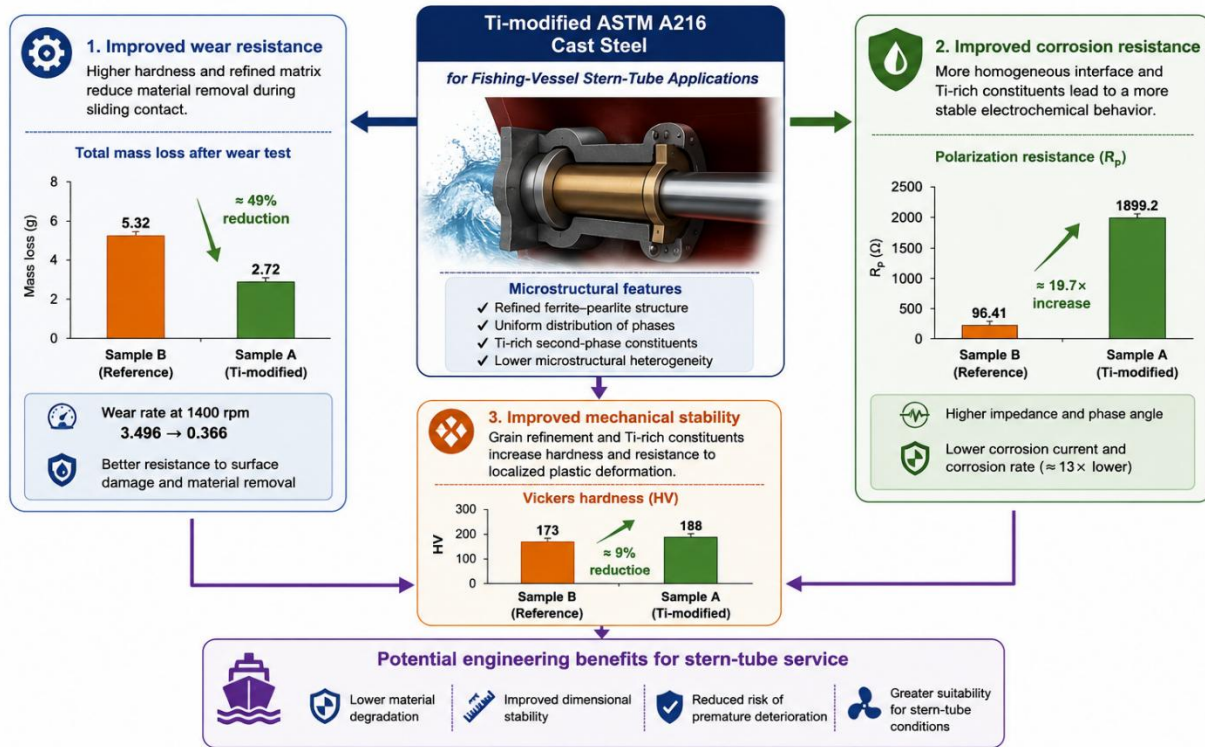


Fig. 17. Engineering implications of the Ti-modified ASTM A216 cast steel for fishing-vessel stern-tube applications based on the measured mechanical, wear, and electrochemical performance.

3.8. Numerical Solidification Characteristics

The numerical solidification analysis provided additional insight into the thermal behavior of the stern-tube casting during cooling. As illustrated in **Fig. 18**, the temperature field was non-uniform across the component, primarily because of the substantial difference in section thickness between the flange and the cylindrical body. The thicker flange region retained thermal energy for a longer

period, whereas heat extraction occurred more rapidly from the thinner cylindrical sections. This behavior produced spatial variations in cooling rate and solidification time within the casting.

The predicted cooling-rate distribution, shown in **Fig. 18(a)**, varied across the casting geometry, indicating that different regions experienced different local solidification conditions. Such variations are important because cooling rate directly influences the evolution of the solidification structure, including nucleation, grain growth, and the resulting scale of the cast microstructure. Numerical casting studies have similarly demonstrated that local cooling conditions and temperature gradients strongly affect solidification behavior and the final microstructural condition of cast components [61–63].

The thermal hot-spot analysis in **Fig. 18(b)** identified the flange-to-body transition as one of the regions exhibiting delayed heat dissipation. Thermal hot spots represent zones that remain at elevated temperature for comparatively longer periods and therefore tend to solidify later than surrounding material. Similar numerical approaches have been widely employed to identify last-to-solidify regions and areas potentially susceptible to solidification-related defects in complex castings [62,64]. In the present geometry, this behavior can be attributed primarily to the larger local thermal mass at the flange and the change in section thickness between the flange and cylindrical region.

The liquidus-time distribution presented in **Fig. 18(c)** further confirms this non-uniform solidification sequence. Regions adjacent to the flange exhibited relatively longer liquid-state persistence, whereas the cylindrical body experienced earlier progression toward complete solidification. The temperature-distribution results in **Fig. 18(d)** show the corresponding spatial thermal gradients generated during cooling. The combined results indicate directional heat removal from the casting toward the surrounding silica-sand mold, with the highest thermal retention occurring in the thicker portions of the component.

The predicted thermal behavior provides a useful physical basis for interpreting the experimentally observed cast microstructure. Local differences in cooling rate can influence ferrite–pearlite morphology and grain size, while relatively slow-cooling regions are more susceptible to coarser solidification structures. Previous numerical and experimental studies have likewise demonstrated a close relationship between simulated cooling conditions and the resulting microstructural features of cast alloys [61,63]. Nevertheless, because the present simulation was used primarily to

characterize the thermal solidification pattern, the experimentally measured microstructure remains the principal basis for assessing the effect of Ti modification on the ASTM A216 steel.

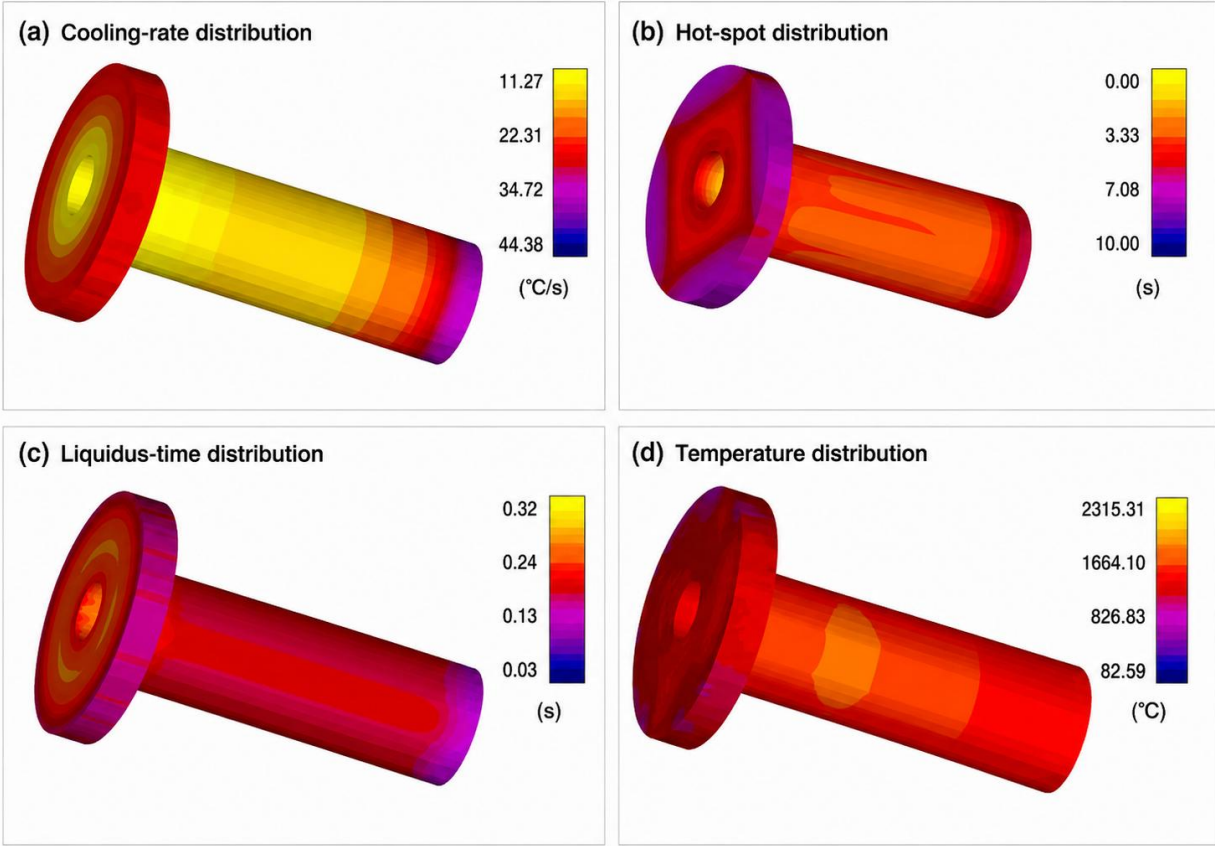


Fig. 18. Numerical simulation of the solidification behavior of the stern-tube casting: (a) cooling-rate distribution, (b) predicted thermal hot-spot distribution, (c) liquidus-time distribution, and (d) temperature field during solidification.

The present study demonstrates the potential of Ti modification to improve the microstructural, mechanical, tribological, and electrochemical performance of ASTM A216 cast steel for fishing-vessel stern-tube applications. However, the results should be interpreted within the scope of the experimental conditions adopted in this work. The investigation was limited to two material conditions, namely the reference steel and a single Ti-modified condition; therefore, the optimum Ti addition level was not established. In addition, the actual bulk Ti content measured by OES in Sample A was substantially lower than the nominal amount introduced during melting, indicating that Ti recovery and distribution during casting require further investigation. The wear tests were performed under controlled laboratory conditions using selected loads, rotational speeds, and test

durations, which do not fully reproduce the complex combination of lubrication, misalignment, vibration, temperature variation, and long-term loading encountered in an operating stern-tube system. Similarly, the electrochemical corrosion evaluation was conducted in 5 wt.% NaCl solution and therefore represents a controlled chloride-containing environment rather than complete long-term marine exposure. The numerical solidification analysis was used mainly to support interpretation of the thermal and solidification behavior of the casting and was not experimentally validated using direct temperature–time measurements during casting. Furthermore, the present work did not include full-scale stern-tube testing or long-term service evaluation; consequently, the measured improvements in hardness, wear resistance, and corrosion behavior should not be directly converted into a specific increase in component service life. Despite these limitations, the consistent improvement observed across the microstructural, hardness, wear, and electrochemical results provides a strong basis for further investigation of Ti-modified ASTM A216 cast steel under more representative marine operating conditions.

4. Conclusions

Based on the experimental and numerical results obtained in the present study, the following conclusions can be drawn:

1. The Ti-modified ASTM A216 cast steel exhibited a clear microstructural refinement compared with the reference condition. The characteristic grain dimensions decreased from approximately 55 and 40 μm in Sample B to 40.5 and 35.2 μm in Sample A, producing a finer and more homogeneous ferrite–pearlite structure.
2. OES analysis confirmed a higher Ti level in Sample A (0.0023 wt.%) than in Sample B (<0.0005 wt.%). Together with the SEM–EDS observations, this result supports the presence of localized Ti-rich second-phase constituents within the modified steel matrix.
3. The microstructural refinement was accompanied by a noticeable improvement in hardness. The Vickers hardness increased from approximately 173 HV for Sample B to 188 HV for Sample A, corresponding to an improvement of about 8.7%. This increase is attributed to the combined contribution of grain refinement and Ti-related second-phase strengthening.
4. The Ti-modified steel showed substantially improved tribological performance under all investigated rotational speeds. At 1400 rpm, the wear-rate value decreased from 3.496 for

Sample B to 0.366 for Sample A, with the reference material exhibiting a wear rate approximately 9.5 times higher.

5. The total mass loss decreased from 5.32 g in Sample B to 2.72 g in Sample A, representing an overall reduction of approximately 49%. This result confirms the improved resistance of the refined Ti-modified microstructure to sliding-induced material removal.
6. Electrochemical testing in 5 wt.% NaCl demonstrated a pronounced enhancement in corrosion resistance. Sample A exhibited a higher impedance response and a phase angle of approximately 55° , compared with approximately 25° for Sample B, indicating a more stable electrochemical interface.
7. The polarization/charge-transfer resistance increased markedly from approximately 96.41 Ω for Sample B to 1899.2 Ω for Sample A, corresponding to an increase of about 19.7 times. In addition, the corrosion current and calculated corrosion rate of Sample B were approximately 13 times greater than those of Sample A.
8. The numerical solidification analysis revealed non-uniform thermal behavior within the cast geometry, with variations in cooling rate, temperature distribution, liquidus time, and thermal hot-spot location. The flange and flange-to-body transition showed greater thermal retention due to their larger local thermal mass, providing a useful numerical explanation for spatial variations in solidification behavior.
9. A consistent microstructure–property relationship was established. The refined ferrite–pearlite structure and Ti-rich constituents increased hardness, reduced wear-related material loss, and contributed to improved electrochemical stability.
10. Overall, the Ti-modified ASTM A216 cast steel demonstrated a more favorable combination of microstructural, mechanical, tribological, and corrosion properties than the reference material. These improvements indicate that the modified material is a promising candidate for fishing-vessel stern-tube applications where simultaneous resistance to wear and chloride-induced degradation is required.

5. Recommendations

Based on the findings of the present study, the following recommendations are proposed:

1. Further investigations should evaluate different Ti addition levels to determine the optimum Ti content that provides the best balance between grain refinement, hardness, wear resistance, and corrosion resistance.
2. Long-term wear and corrosion experiments under more representative operating conditions are recommended to assess the durability of the modified material under prolonged service.
3. Future work should investigate the combined effect of sliding wear and corrosive exposure to reproduce more closely the coupled tribological and electrochemical conditions encountered in marine stern-tube systems.
4. Full-scale or pilot-scale stern-tube components should be produced and evaluated under realistic shaft loading, rotational speed, lubrication, alignment, and environmental conditions before industrial implementation.
5. Additional characterization of Ti-rich constituents may be considered in future work to determine their composition, morphology, distribution, and contribution to the observed strengthening mechanisms more precisely.
6. Numerical solidification modeling should be extended to investigate the influence of casting parameters, mold conditions, and local section thickness on cooling rate, hot-spot formation, and solidification-related defects, with the aim of optimizing the casting process.
7. Future research should correlate laboratory performance with actual marine-service data to quantify potential improvements in component durability, maintenance intervals, and operational reliability.
8. The combined use of material modification, optimized casting conditions, and condition-monitoring approaches is recommended as a promising route for improving the reliability of stern-tube systems in fishing vessels.

Declarations

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

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Authors contributions

S.M.A.A., M.A.M. E.M.M. contributed to the experimental and theoretical work of this study. M.A.M., S.M.A.A. E.M.M. contributed to drafting this manuscript. S.M.A.A. contributed to drawing its figures and its tables. Both authors contributed to revising this manuscript and its figures and tables. The authors read and approved the final manuscript.

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Declarations

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

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Authors contributions

S.M.A.A., M.A.M. E.M.M. contributed to the experimental and theoretical work of this study. M.A.M., S.M.A.A. E.M.M. contributed to drafting this manuscript. S.M.A.A. contributed to drawing its figures and its tables. Both authors contributed to revising this manuscript and its figures and tables. The authors read and approved the final manuscript.

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