High-Temperature Molten Salt Corrosion and Wear Resistance of a Novel Nb-Alloyed Austenitic Steel for MSR Structural Applications

Authors: Choi, Yongseok, Lee, Dr. Changwoo, Lee, Dr. Hyeon-Geun, Kang, Mr. Seongmin, Park, Mr. Kyeongryeol, Jeong, Prof. Jae-Ho, Lee, Prof. Kyungjun, Lee, Prof. Kyungjun

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Abstract

The next-generation Molten Salt Reactor (MSR) utilizes a liquid-fuel system, in which fissile material is dissolved in high-temperature molten salts. This dual-purpose medium acts as both fuel and primary coolant, offering exceptional thermal stability and inherent safety features. However, MSR poses extreme thermo-chemical challenges to structural materials due to the corrosive and oxidative nature of the high-temperature molten chloride salts. Consequently, structural materials for MSR must exhibit outstanding corrosion and wear resistance to ensure long-term reliability. Therefore, in this study, the corrosion and wear resistance of a newly developed Nb-containing austenitic alloy ("New alloy") against conventional MSR-relevant materials (316SS, 304SS, and Hastelloy C-276) were evaluated and compared. Static corrosion tests were performed at 800 °C in a NaCl-$MgCl_2$-KCl (20-40-40 wt.%) salt mixture. Postcorrosion degradation was assessed via weight loss, surface roughness, cross-sectional SEM, and elemental analysis using EDS and XRD. Scratch and two-body wear tests were also conducted to evaluate mechanical performance. The New alloy exhibited the lowest weight loss (0.057 mg/mm^3), minimal surface roughness increase, and no detectable leaching of Fe, Cr, or Ni into the molten salt. Post-corrosion hardness increased from 250 HV to 310 HV, attributed to the formation of Ni-Nb intermetallics and $M_{23}C_6$ carbide precipitates, which served as protective phases. Compared to 316SS, it showed over 90% lower wear and superior chemical stability. These findings establish the New alloy as a robust, cost-effective structural material for high-temperature MSR environments, capable of resisting both corrosive attack and mechanical degradation.

Full Text

Preamble

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Yong-Seok Choi[1], , Changwoo Lee[2], , Hyeon-Geun Lee[3], Seongmin Kang[1], Kyeongryeol Park[4], Jae-Ho Jeong[5],*, and Kyungjun Lee*[1],

[1] Department of Mechanical Engineering, Gachon University, Gyeonggi-do, 13120, Republic of Korea
[2] Pohang Institute of Materials Industry Advancement, 56, Jigok-ro, Nam-Gu, Pohang, Kyungbuk, 37563, Republic of Korea
[3] Materials Safety Technology Research Division, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989 Beon-gil, Daejeon, 34057, Republic of Korea
[4] Center for Green System and Industry Intelligence, Institute for Advanced Engineering, Yongin, Gyeonggi-do, 17528, Republic of Korea
[5] School of Mechanical Engineering, Chung-Ang University, 84, Heukseok-ro, Dongjak-gu, Seoul, 06974, Republic of Korea

These authors contributed equally to this work: First author (Yong-Seok Choi) / Co-first author (Changwoo Lee)

- Corresponding author E-mail address: leek3@gachon.ac.kr; Phone: +82-10-5234-1269

- Co-corresponding author E-mail address: jaehojeong@cau.ac.kr; Phone: +82-10-7377-

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Abstract

The next-generation Molten Salt Reactor (MSR) utilizes a liquid-fuel system, in which fissile material is dissolved in high-temperature molten salts. This dual-purpose medium acts as both fuel and primary coolant, offering exceptional thermal stability and inherent safety features. However, MSR poses extreme thermo-chemical challenges to structural materials due to the corrosive and oxidative nature of the high-temperature molten chloride salts.

Consequently, structural materials for MSR must exhibit outstanding corrosion and wear resistance to ensure long-term reliability. Therefore, in this study, the corrosion and wear resistance of a newly developed Nb-containing austenitic alloy ("New alloy") were evaluated and compared against conventional MSR-relevant materials (316SS, 304SS, and Hastelloy C-276). Static corrosion tests were performed at 800 °C in a NaCl-$MgCl_2$-KCl (20–40–40 wt.%) salt mixture. Post-corrosion degradation was assessed via weight loss, surface roughness, cross-sectional SEM, and elemental analysis using EDS and XRD. Scratch and two-body wear tests were also conducted to evaluate mechanical performance. The New alloy exhibited the lowest weight loss (0.057 mg/mm^3), minimal surface roughness increase, and no detectable leaching of Fe, Cr, or Ni into the molten salt. Post-corrosion hardness increased from 250 HV to 310 HV, attributed to the formation of Ni–Nb intermetallics and $M_{23}C_6$ carbide precipitates, which served as protective phases. Compared to 316SS, it showed over 90% lower wear and superior chemical stability. These findings establish the New alloy as a robust, cost-effective structural material for high-temperature MSR environments, capable of resisting both corrosive attack and mechanical degradation.

Keywords: Molten salt; Corrosion; Stainless Steel; Wear; Material Life; MSR; 2-body abrasion; 3-body abrasion

1. Introduction

The Molten Salt Reactor (MSR) has emerged as a prominent candidate among Generation IV nuclear systems, primarily due to its distinctive liquid-fuel architecture and intrinsic safety features. Unlike conventional pressurized water reactors (PWRs) that rely on solid nuclear fuel and high-pressure water coolant loops, MSRs employ fissile material dissolved directly in high-temperature molten salt, thereby integrating fuel and coolant within a single phase. This configuration offers several advantages, including elevated thermal efficiency, strong negative temperature coefficient of reactivity, and the elimination of pressurization infrastructure, which collectively contribute to a simplified reactor design and enhanced passive safety performance [**?**]. Moreover, MSR has garnered increasing international attention owing to its potential to achieve superior fuel utilization, significantly mitigate the generation of long-lived transuranic waste, and incorporate thorium-based fuel cycles with low proliferation risks. These attributes collectively position MSR as a strategically advantageous platform for sustainable and secure nuclear energy, prompting widespread research initiatives and development programs globally [**?**].

Despite these thermodynamic and operational advantages, the widespread deployment of MSR is constrained by unresolved technical and material science challenges. Among these, the most pressing issue lies in the identification and long-term qualification of structural materials capable of withstanding the aggressive thermo-chemical environment of molten salts at elevated temperatures. Chloride-based molten salt systems, such as eutectic mixtures of NaCl-$MgCl_2$-KCl, typically operate at temperatures exceeding 800 °C and exhibit high ionic activity and chemical reactivity, which promote accelerated degradation mechanisms in metallic components [**?**]. Such environments facilitate severe corrosion phenomena ranging from uniform dissolution to localized pitting and grain boundary attack, compromising the integrity of reactor internals. If left unmitigated, this degradation may lead to the premature failure of structural elements, ultimately threatening the safety and operability of the system [?, ?]. As such, achieving sustained chemical and mechanical stability of structural materials in high-temperature molten salt environments remains a pivotal prerequisite for the safe, economical, and long-term operation of MSR systems.

Austenitic stainless steels such as 316SS and 304SS, along with nickel-based superalloys like Hastelloy C-276, have long been considered candidate structural materials for MSR applications due to their established high-temperature performance and corrosion resistance in conventional environments [?]. These alloys each offer distinct advantages. The 316SS and 304SS alloys, composed primarily of iron (Fe), chromium (Cr), and nickel (Ni), offer good corrosion resistance but are limited at elevated temperatures [?, ?]. While Hastelloy C-276, a nickel- and molybdenum-rich (Ni, Mo) alloy, provides excellent corrosion resistance, albeit at a significantly higher cost [?, ?].

However, the long-term viability of these conventional materials in chloride-based molten salt environments, particularly at temperatures above 800 °C, remains questionable. Under such extreme conditions, these alloys are prone to aggressive corrosive attack, resulting in severe surface degradation, grain boundary sensitization, and substantial mass loss. These effects are largely driven by the selective leaching of critical alloying elements such as Fe, Cr, and Ni [?]. The resulting loss of mechanical integrity and dimensional stability raises serious concerns about their suitability for long-term service in MSR systems.

To overcome these limitations, there is a pressing need to develop and evaluate next-generation structural alloys with improved resistance to both corrosion and wear under high-temperature molten salt conditions. This study addresses that need by systematically investigating the corrosion behavior and post-corrosion mechanical integrity of a newly developed Nb-containing austenitic alloy (hereafter referred to as the “New alloy”). Its performance is benchmarked against established MSR-relevant materials, including 316L SS, 304 SS, and Hastelloy C-276. Corrosion tests were conducted at 800 °C in a ternary chloride molten salt mixture composed of NaCl-$MgCl_2$-KCl (20-40-40 wt.%). Quantitative degradation metrics—mass loss, surface roughness evolution, and cross-sectional corrosion penetration—were used to assess the severity of corrosion. These were complemented by microstructural and phase analyses using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD).

The New alloy, engineered with Fe, Cr, Ni, and niobium (Nb), demonstrates superior corrosion and wear resistance along with improved mechanical integrity after exposure to corrosive environments, making it a promising candidate for next-generation MSR systems. The enhanced performance of this Nb-containing alloy stems from the strategic role of Nb as a key alloying element [?]. Nb promotes grain refinement by pinning grain boundaries, thereby improving mechanical strength and creep resistance [?]. It also enhances oxidation resistance by stabilizing protective oxide films, which limit outward diffusion of Fe and reinforce corrosion protection [?, ?]. Furthermore, Nb facilitates the formation of Nb-rich precipitates, particularly Nb(C, N) phases, which contribute to improved wear resistance [?, ?]. Alloys in this class, such as HPNb, exhibit excellent thermal stability and can tolerate service temperatures up to 1100 °C, positioning them as strong candidates for advanced nuclear and energy applications [?].

To assess the structural implications of corrosion-induced degradation, high-temperature tribological tests, including scratch wear and two-body abrasion, were performed on corroded specimens. This integrated approach provides a comprehensive understanding of the interaction between chemical degradation and mechanical performance loss under MSR-representative conditions. Overall, the findings from this study provide valuable mechanistic insights into the degradation behaviors of both conventional and advanced structural materials in molten chloride environments. The superior performance of the New alloy underscores its strong potential as a structural material for MSR systems. These results also establish a comparative performance framework that can inform future alloy development strategies aimed at improving long-term structural reliability and operational safety in next-generation nuclear reactors.

2. Experimental Methods

2.1. Materials and Corrosion Test Procedure

For the molten salt corrosion experiments, four representative structural alloys were selected: 316 stainless steel (316SS), 304 stainless steel (304SS), Hastelloy C-276, and a newly developed niobium-alloyed austenitic steel (hereafter referred to as the "New alloy"). Specimens were machined to dimensions compatible with 100 mL quartz crucibles. Specifically, 316SS and 304SS were prepared as rectangular coupons measuring $25 \times 25 \times 5$ mm^3, while Hastelloy C-276 was fabricated into cylindrical samples with dimensions of Ø25 × 2 mm. Due to limited material availability, the New alloy was machined into smaller cylindrical specimens of Ø10 × 2 mm. All specimen surfaces were mechanically polished to achieve a uniform surface roughness of less than 0.06 nm, as verified using a stylus profilometer (DektakXT, Bruker, Germany). Pre- and post-corrosion mass measurements were carried out using a high-precision electronic balance (Pioneer Excal PX123KR, OHAUS), and microhardness was measured using a Vickers hardness tester (Mitutoyo 810-406K, Japan) under a 300 gf load.

The corrosion environment consisted of a eutectic molten salt mixture composed of 20 wt.% NaCl, 40 wt.% $MgCl_2$, and 40 wt.% KCl. The polished specimens were fully immersed in the molten salt contained in quartz crucibles and exposed to a static environment in an electric furnace (JMF17-4.6UP) maintained at 800 °C for 24 hours. After heat exposure, the specimens were furnace-cooled to ambient temperature, as shown in Fig. 1 [Figure 1: see original paper]. Following cooling, loosely adhered salt residues were gently removed using soft-tipped tweezers to avoid surface damage. Strongly adhered corrosion products were cleaned in accordance with ASTM G1-03 (Sections C.6.1 and C.7.1) (ASTM, 2025). Subsequently, the specimens were dried at 60 °C for 30 minutes in a laboratory oven (OF4-05SW, Lab Companion) and stored in a desiccator until further analysis. Representative images of the specimens before and after corrosion, along with the process of removing the corrosion product, are presented in Fig. 2 [Figure 2: see original paper].

2.2. Tribological Behaviors: Scratch Wear Test & Ball Wear Test

To quantitatively assess the degradation in mechanical performance following high-temperature corrosion, tribological evaluations were conducted using both scratch and two-body wear testing protocols. Scratch tests were performed using a tungsten carbide stylus with a hemispherical tip radius of 20 m, and two-body wear tests were carried out using an alumina oxide (Al_2O_3) ball with an 8 mm diameter (Duksan Pure Chemicals, Republic of Korea). All tests were conducted using a reciprocating wear tester specifically designed and fabricated in-house at Gachon University (Fig. 3 [Figure 3: see original paper]). Specimens were rigidly mounted using four-directional clamping via custom 3D-printed jigs to ensure consistent positioning and contact stability during testing.

For the two-body wear tests, a normal load of 2 kg was applied with reciprocating motion over a 7 mm stroke for a total duration of 10 minutes. Scratch tests were performed under identical load and clamping conditions. However, the reciprocating motion was limited to 10 cycles to avoid excessive scratch penetration and unstable tip behavior (e.g., rattling or bouncing), which could compromise measurement fidelity. To eliminate cross-contamination effects, the wear tip was replaced between each test. All tribological measurements were performed on both pre-corroded and post-corroded specimens under identical test conditions. Wear debris generated during testing was removed using compressed air. Post-test weight loss was determined using a high-resolution analytical balance (Pioneer Excal PX123KR, OHAUS), and surface wear depth was quantified using a stylus profilometer (DektakXT, Bruker, Germany). Surface wear morphologies were further characterized via optical microscopy and high-resolution scanning electron microscopy (SEM) to evaluate damage modes and wear mechanisms.

2.3. Chemical Analysis

To elucidate the underlying mechanisms responsible for the observed variations in hardness and wear behavior before and after corrosion, comprehensive chemical and structural analyses were conducted. These included surface and cross-sectional compositional assessments via energy-dispersive X-ray spectroscopy (EDS) and phase identification through X-ray diffraction (XRD). Elemental mapping and line-scanning analyses were performed using a high-resolution field-emission scanning electron microscope equipped with EDS capabilities (SU-8600, Hitachi High-Tech). These analyses enabled the spatially resolved quantification of elemental redistribution, with a particular focus on the leaching behavior of key alloying constituents (e.g., Fe, Cr, Ni) and the degree of oxygen ingress, indicative of surface oxidation. Both EDS mapping and linear profiling techniques were utilized to evaluate elemental gradients across corrosion interfaces [?, ?].

To complement the compositional analysis, XRD measurements were conducted using the XRDynamic 500 diffractometer (Anton Paar, Austria) to determine phase evolution and oxide formation resulting from molten salt exposure. The analysis aimed to identify corrosion products, such as Fe_2O_3 and Cr_2O_3, as well as intermetallic and carbide precipitates (e.g., Nb–Ni phases and $M_{23}C_6$-type carbides), using a scan range of 2 = 30° to 120° under standard high-resolution conditions [?, ?]. The resulting EDS and XRD datasets were systematically tabulated and visualized for each alloy, enabling direct comparative interpretation. Correlating these findings with mechanical performance degradation allowed for the identification of elemental depletion and oxide formation as primary contributors to the deterioration (or enhancement) of material durability post-corrosion. These results provide mechanistic insights into the chemical stability of structural alloys under high-temperature molten salt conditions.

3. Results and Discussion

3.1. Physical Changes

To quantify the physical degradation resulting from molten salt corrosion, weight loss per unit volume and changes in surface roughness were systematically evaluated before and after exposure. These parameters were selected as primary indicators due to their high sensitivity to corrosion-induced surface damage and their capacity to distinguish degradation behaviors among the tested alloys. Weight loss per unit volume served as a quantitative metric for material dissolution, while changes in surface roughness reflected the extent and morphology of surface deterioration [?]. Additionally, SEM was used to qualitatively assess surface wear patterns and microstructural alterations.

The pre-corrosion masses of 316SS, 304SS, Hastelloy C-276, and the New alloy were 27.27 g, 26.73 g, 23.03 g, and 2.63 g, respectively. After 24-hour exposure to molten salt at 800 °C, the corresponding post-corrosion masses were reduced to 23.98 g, 24.59 g, 22.55 g, and 2.62 g, respectively, yielding total mass losses of 12.06%, 8.00%, 2.08%, and 0.38%. When normalized to sample volume, the weight loss per unit volume was calculated as follows: $0.97\,\mathrm{mg/mm^3}$ for 316SS, $0.63\,\mathrm{mg/mm^3}$ for 304SS, $0.089\,\mathrm{mg/mm^3}$ for C-276, and $0.057\,\mathrm{mg/mm^3}$ for the New alloy (Fig. 4 [Figure 4: see original paper]). These values indicate a substantial difference in corrosion susceptibility, with the New alloy exhibiting the lowest material loss.

Surface profilometry results further corroborated these trends. The average surface roughness (Ra) of the samples before corrosion was 0.041 m (316SS), 0.033 m (304SS), 0.033 m (C-276), and 0.061 m (New alloy). After corrosion, these values increased to 111.90 m, 36.07 m, 13.66 m, and 0.74 m, respectively. The corresponding roughness amplification factors were approximately 2,729 times for 316SS, 1,093 times for 304SS, 414 times for C-276, and 12 times for the New alloy. The pronounced increase in roughness observed in 316SS and 304SS is consistent with their higher weight loss, indicating extensive pitting and surface destabilization. Conversely, the minor roughness changes observed in C-276, especially in the New alloy, reinforce their superior resistance to chloride-induced high-temperature corrosion (Fig. 5 [Figure 5: see original paper]).

The surface morphology of the specimens before and after corrosion exposure was examined using SEM (SU8600, Hitachi High-Tech, Japan). Before corrosion, all four alloys exhibited uniformly polished surfaces with no visible signs of surface degradation, aside from minor machining marks. In contrast, post-corrosion SEM imaging revealed distinct corrosion morphologies depending on alloy type. Both 316SS and 304SS exhibited widespread pitting corrosion, characterized by numerous hemispherical cavities distributed across the surface, indicating a high susceptibility to localized attack in molten chloride environments [**?**, **?**]. Hastelloy C-276 displayed isolated pitting confined to discrete regions, with the majority of the surface remaining structurally intact. In the case of the New alloy, only mild discoloration or oxide-related surface staining was observed, without any discernible pitting or localized structural deterioration. These observations suggest that the New alloy exhibited minimal surface damage under the same test conditions (Fig. 6 [Figure 6: see original paper]).

Cross-sectional SEM analysis corroborated the surface findings by providing quantitative insight into pit penetration depth and area. Using ImageJ software for image-based analysis, the average corrosion-affected cross-sectional area per unit length was measured as 166 mm^2/mm for 316SS, 132 mm^2/mm for 304SS, 18.5 mm^2/mm for C-276, and only 0.05 mm^2/mm for the New alloy. These values translate to approximately 3,320×, 2,640×, and 370× greater penetration compared to the New alloy for 316SS, 304SS, and C-276, respectively (Fig. 7 [Figure 7: see original paper]). The extremely low pit depth and minimal propagation observed in the New alloy highlight its superior resistance to localized corrosion phenomena. Collectively, these results affirm the alloy's robustness against chloride-induced attack and its capability to effectively suppress pitting initiation and growth under aggressive high-temperature molten salt exposure [**?**].

3.2. Mechanical Properties

To evaluate the effect of high-temperature molten salt corrosion on the mechanical integrity of the tested materials, Vickers microhardness measurements were conducted before and after corrosion exposure using a standardized 300 gf load (Mitutoyo 810-406K, Japan). The comparative analysis of surface hardness provided a direct indication of corrosion-induced strengthening or degradation mechanisms.

Before corrosion, the measured hardness values were 190 HV for 316SS, 269 HV for 304SS, 231 HV for C-276, and 250 HV for the New alloy. Following 24-hour exposure to molten NaCl-$MgCl_2$-KCl at 800 °C, the hardness of 316SS, 304SS, and C-276 decreased to 123 HV, 197 HV, and 227 HV, respectively, corresponding to reductions of 35.3%, 26.8%, and 1.8%. These decreases suggest that microstructural softening is likely due to the selective leaching of alloying elements (e.g., Cr, Fe), localized pitting, or the breakdown of passive layers that otherwise contribute to hardness retention.

In contrast, the New alloy exhibited a substantial increase in hardness from 250 HV to 310 HV (+24.0%) after corrosion. This enhancement is attributed to the in-situ formation of Nb-containing strengthening phases, such as Ni–Nb intermetallics or $M_{23}C_6$ carbides, and the stabilization of protective oxide films under high-temperature conditions [**?**, **?**, **?**]. These microstructural modifications likely act synergistically to impede dislocation motion and reinforce surface hardness [**?**, **?**]. The distinct behavior of the New alloy highlights its superior thermo-mechanical stability in corrosive molten salt environments (Fig. 8 [Figure 8: see original paper]).

3.3. Tribological Behaviors

To evaluate the degradation in mechanical properties and wear resistance resulting from high-temperature corrosion, both scratch and two-body reciprocating wear tests were conducted on all specimens before and after exposure to molten salt. Wear performance was assessed based on two quantitative metrics: maximum wear depth and total mass loss, enabling a direct comparison of tribological degradation among the tested alloys.

In the scratch tests, all testing parameters were held constant across the specimens, with the exception of test duration. The scratch tests were limited to 10 reciprocating cycles, while the two-body wear tests were conducted for 10 minutes. Before corrosion, maximum scratch depths were 55.8 m for 316SS, 49.3 m for 304SS, 40.7 m for Hastelloy C-276, and 38.5 m for the New alloy (Fig. 9a [Figure 9: see original paper]). After corrosion, the wear depths increased significantly to 526.6 m (316SS), 127.1 m (304SS), 66.2 m (C-276), and 41.1 m (New alloy), as shown in Fig. 9b. These results correspond to relative increases of approximately 9.4×, 2.6×, and 1.6× for 316SS, 304SS, and C-276, respectively. In contrast, the New alloy exhibited only a minor increase of 1.07×, indicating excellent retention of surface mechanical strength under aggressive, high-temperature corrosive conditions.

In the two-body ball-on-flat wear tests, the 8 mm curvature of the contact ball reduced localized contact pressure, resulting in shallower wear tracks across all samples. Pre-corrosion wear depths were measured as 15.4 m (316SS), 11.6 m (304SS), 10.4 m (C-276), and 5.2 m (New alloy) as shown in Fig. 9a. Following corrosion, these values increased to 269.1 m, 69.3 m, 32.4 m, and 13.6 m, respectively (Fig. 9b). The wear depth increase ratios were approximately 17.5×

for 316SS, 6.0× for 304SS, 3.1× for C-276, and 2.6× for the New alloy. The New alloy demonstrated exceptional wear resistance under both test conditions, maintaining structural stability and minimizing degradation after exposure to molten salt corrosion. This confirms its suitability for durable MSR structural components that are resistant to corrosion and wear.

To further quantify wear-induced material loss, specimen masses were recorded before and after each wear test. Under pre-corrosion conditions, all alloys exhibited negligible mass loss, with changes too small to register beyond the fourth decimal place, indicating minimal surface abrasion and no significant material detachment. However, following exposure to high-temperature molten salt, significant mass losses were recorded across all specimens, reflecting the weakening of surface layers due to corrosion-induced degradation. In the post-corrosion scratch wear tests, mass losses were measured as 2.371 mg for 316SS, 0.900 mg for 304SS, 0.267 mg for C-276, and 0.133 mg for the New alloy (Fig. 10a [Figure 10: see original paper]). These values highlight the degree of surface instability caused by phenomena such as oxide spallation, localized pitting, and selective leaching, which promote increased material removal during mechanical contact. A similar trend was observed in the two-body wear tests, with post-corrosion mass losses of 1.800 mg (316SS), 0.400 mg (304SS), 0.350 mg (C-276), and 0.150 mg (New alloy), respectively (Fig. 10b). Notably, the New alloy demonstrated over 90% lower mass loss compared to 316SS in both wear configurations, underscoring its excellent resistance to wear even after high-temperature corrosion.

These tribological findings, when considered alongside previously reported hardness enhancements, confirm the severe degradation of 316SS in molten salt environments and highlight its unsuitability for long-term structural use in MSR systems. In contrast, the New alloy maintained its surface integrity and dimensional stability, reinforcing its suitability as a durable structural material for advanced MSR, where both corrosion and wear resistance are critical.

To investigate the wear mechanisms responsible for the observed performance trends, surface morphologies of all specimens were examined via scanning electron microscopy (SEM). In the pre-corrosion condition, all alloys exhibited typical plowing-type wear, characterized by furrowed grooves along the direction of reciprocating motion and material pile-up along the ridges, indicative of ductile abrasive wear (Fig. 11a [Figure 11: see original paper]). No subsurface damage such as brinelling, cracking, or delamination was observed under these conditions.

In contrast, post-corrosion SEM observations revealed markedly different wear responses among the alloys. For 316SS and 304SS, extensive surface degradation was evident, with the emergence of deep pitting, intergranular attack, and widespread delamination. These features contributed to increased surface roughness and irregular topography, with wear track widths exceeding 300 m. Severe spalling phenomena, analogous to concrete flaking, were also observed, indicating brittle failure of the corroded surface layers (Fig. 11b, c). This is in good agreement with the rapid increase in scratch depth from 55.8 m to 526.6 m for 316SS and from 49.3 m to 127.1 m for 304SS, as well as the corresponding decrease in hardness (from 190 HV to 123 HV and from 269 HV to 197 HV, respectively), indicating that mechanical softening and loss of surface elements were confirmed.

In the case of C-276, only localized grain boundary corrosion was observed, and the surface remained comparatively stable. Although minor spallation and delamination were occasionally detected along the wear path, the overall wear morphology remained closer to the pre-corrosion condition. The scratch depth increased only moderately from 40.7 m to 66.2 m, while the hardness remained nearly constant (231 HV → 227 HV), suggesting minimal mechanical degradation and good retention of surface toughness.

However, the New alloy demonstrated exceptional surface and mechanical stability throughout the corrosion and wear process (Fig. 11b, c). Even after exposure to high-temperature molten salt, only plowing-type wear was evident, without any signs of pitting, cracking, or oxide delamination. The wear track width remained limited to approximately 229 m, and the wear depth increased only slightly (38.5 m → 41.1 m). Furthermore, hardness increased from 250 HV to 310 HV post-corrosion, indicating thermally induced phase strengthening. These observations collectively underscore the alloy's superior resistance to both corrosive degradation and wear damage, confirming its potential as a structural material for advanced reactor environments characterized by concurrent thermal, chemical, and mechanical stresses.

In the two-body wear experiments, wear morphologies similar to those observed in scratch tests were identified; however, distinct differences in wear mechanisms emerged due to the altered contact conditions. The tests were conducted using 8 mm-diameter alumina balls under reciprocating sliding for 10 minutes. Under these conditions, abrasive cutting became the dominant wear mode, as opposed to the localized ridging and material accumulation observed in scratch tests. Consequently, wear depths were generally shallower; however, in samples affected by pitting corrosion, both wear depth and width increased significantly due to subsurface weakening and delamination along the wear tracks (Fig. 12 [Figure 12: see original paper]).

For 316SS, the pre-corrosion maximum wear depth was 15.4 m, with a wear track width of approximately 1.0 mm. Post-corrosion measurements revealed dramatic increases in depth to 269.1 m and in width to approximately 1.4 mm, representing increases of 17.5 times and 40%, respectively. These results are attributed to surface discontinuities such as pitting corrosion, which act as stress concentrators and significantly accelerate wear progression under mechanical loading. Similarly, 304SS exhibited an increase in wear depth from 11.6 m to 69.3 m and in width from ~0.9 mm to ~1.3 mm, corresponding to a 6.0-fold depth increase and a 31% width expansion, reaffirming its susceptibility to surface degradation under high-temperature molten salt exposure.

In contrast, C-276 showed a modest increase in wear from 10.4 m to 32.4 m in depth and from 0.8 mm to 1.1 mm in width, corresponding to increases of 3.1 times and 28%, respectively. The limited extent of grain boundary corrosion observed in C-276 contributed to the preservation of its mechanical properties and relatively stable tribological behavior under post-corrosion conditions.

The New alloy demonstrated the most stable performance. The pre-corrosion wear depth and width were 5.2 m and 0.7 mm, respectively. After corrosion, these values increased to 13.6 m and 0.9 mm. Despite the thermal and chemical exposure, the alloy's post-corrosion wear depth remained comparable to or better than the pre-corrosion values of conventional alloys, and the width increase rate was the lowest among all samples at ~22%. These results indicate that the New alloy possesses excellent resistance to wear degradation under coupled corrosive and mechanical stress conditions, further establishing its promise as a structural material for next-generation high-temperature nuclear systems (Fig. 12).

To comprehensively evaluate the influence of corrosion-induced surface changes on tribological characteristics, wear analysis of the counterpart ball was conducted following two-body wear testing. Measurement of ball wear scar area changes before and after corrosion revealed increases of 8.24% for 316SS, 11.35% for 304SS, and 20.62% for Hastelloy C-276, while the New alloy exhibited a contrasting result with a 20.10% decrease (Fig. 13 [Figure 13: see original paper]). The increased ball wear observed in conventional alloys is attributed to an increase in surface roughness and the formation of surface undulations caused by corrosion. These surface modifications increase instantaneous contact stress compared to the New alloy, resulting in enhanced ball wear. Additionally, relatively minimal corrosion damage, corrosion-weakened surfaces detach during wear testing, forming additional debris that induces secondary wear.

In contrast, the New alloy demonstrated a distinctive result with a 20.10% reduction in ball wear after corrosion exposure. This phenomenon is attributed to the beneficial effects of strengthening phases (Ni-Nb intermetallic compounds and $M_{23}C_6$ carbides) formed on the surface, leading to surface hardening (250 HV → 310 HV). This surface hardening not only protects the alloy itself but also maintains the surface in its pre-corrosion state, thereby reducing wear on the counterpart through enhanced tribological compatibility.

The correlation between ball wear and surface roughness has a significant impact on fluid flow efficiency in MSR applications. Materials that induce excessive wear in counterparts inevitably cause increased surface roughness throughout the system, which is particularly pronounced at sliding contact interfaces such as pump components, valve seats, and heat exchanger tube supports. According to the Darcy-Weisbach equation and Colebrook-White relationship, the friction factor in turbulent flow is directly dependent on relative roughness (/D). Increased surface roughness causes elevated friction factors, consequently resulting in increased pressure losses and head losses. The increase in friction factor due to surface roughness elevation leads to increased pumping power requirements, thereby reducing overall system efficiency [**?**, **?**]. Excessive ball wear observed in conventional alloys can cause problems, including increased pumping costs, shortened component lifespan, and reduced system reliability. Conversely, the New alloy's ability to reduce wear on its counterpart suggests self-improving characteristics that can enhance long-term system efficiency.

3.4. Chemical Changes

To investigate compositional changes induced by high-temperature molten salt corrosion, Energy Dispersive X-ray Spectroscopy (EDS) mapping was performed on all samples, with a specific focus on Fe, Cr, Ni, and O as representative indicators of corrosion progression and passive film behavior. Fe was tracked as the principal matrix element in austenitic alloys, where its depletion indicates dissolution under corrosive stress. Cr, a key component for passivation, was monitored to evaluate the stability of the oxide film and its protective capability. Ni, essential for corrosion resistance in nickel-based alloys, was used to assess selective leaching, while O content served as an indicator for surface oxidation and oxide film development.

In 316SS, severe elemental depletion was observed post-corrosion. Fe content decreased from 63.30 wt.% to 35.10 wt.% and Cr from 17.40 wt.% to 6.93 wt.%, representing losses exceeding 50% in both cases. Meanwhile, Ni content remained relatively stable (11.60 wt.% → 11.40 wt.%), suggesting selective leaching of Fe and Cr. The oxygen content increased markedly from 0.00 wt.% to 17.70 wt.%, indicating the formation of an extensive surface oxide layer. A similar trend was observed in 304SS, where Fe and Cr decreased from 68.30 wt.% to 48.60 wt.% and 18.30 wt.% to 12.80 wt.%, respectively, while O content rose to 11.30 wt.%. These elemental losses correspond directly to mechanical degradation, as evidenced by significant reductions in hardness from 190 → 123 HV (316SS) and 269 → 197 HV (304SS). This confirmed a strong correlation between chemical instability and reduced mechanical integrity (Fig. 14 [Figure 14: see original paper], Fig. 15 [Figure 15: see original paper]).

Conversely, C-276 exhibited exceptional chemical stability. Elemental variations were minimal, with Fe (5.71 → 5.11 wt.%), Cr (15.50 → 13.90 wt.%), and Ni (55.00 → 53.50 wt.%) showing only slight changes. The oxygen content rose modestly to 4.44 wt.%, consistent with limited surface oxidation. These minimal hardness changes (231 → 227 HV) reaffirm the alloy's robustness under corrosive and mechanical stress.

The New alloy demonstrated outstanding compositional preservation. Fe remained essentially unchanged (62.30 → 62.80 wt.%), and Cr decreased only marginally (19.00 → 16.87 wt.%). The oxygen content was measured at 6.97 wt.%, indicating a uniformly distributed oxide film without significant surface transformation due to corrosion. Despite a slight Cr reduction, the alloy retained high Fe stability, which, combined with an increase in hardness from 250 to 310 HV and a negligible change in wear depth, confirms the superior corrosion and wear resistance of this alloy under molten salt conditions (Fig. 14, Fig. 15). These findings highlight the critical role of Fe and Cr retention in determining alloy performance in aggressive molten salt environments. Alloys that minimize the selective leaching of these key elements are better able to preserve both chemical stability and mechanical functionality. The New alloy, in particular, demonstrated the most favorable combination of elemental retention, hardness improvement, and minimal wear damage, making it a compelling candidate for structural applications in extreme service environments such as next-generation molten salt reactors.

To assess elemental dissolution behavior and confirm the presence of corrosion-derived oxides following high-temperature molten salt corrosion, compositional analysis was performed on the solidified molten salt. This analysis enabled direct evaluation of metallic element detachment and dissolution from alloy surfaces during exposure to the molten salt environment. The experiment utilized a ternary salt mixture composed of 20 wt.% NaCl, 40 wt.% $MgCl_2$, and 40 wt.% KCl. After cooling and solidification, the molten salt formed ochre- or yellow-hued crystalline solids (Fig. 16 [Figure 16: see original paper]), reflecting the chemical changes and the incorporation of corrosion products.

For 316SS, the solidified salt contained significant concentrations of Fe (13.55 wt.%) and Cr (10.02 wt.%), strongly indicating severe elemental leaching into the salt medium. The high oxygen content (24.82 wt.%) further suggests the formation of metal oxides, such as Fe_2O_3 and Cr_2O_3, at the alloy–salt interface. These findings corroborate previous SEM observations of extensive pitting corrosion and surface degradation, confirming active dissolution pathways for 316SS in chloride-based molten salts. Similarly, 304SS exhibited pronounced Fe dissolution (12.47 wt.%) and moderately elevated O content (18.45 wt.%). Although Cr was detected at lower-than-expected levels, it is likely that chromium dissolution occurred but was either heterogeneously distributed or fell outside the localized detection zone of the EDS analysis. The compositional trends remain consistent with previous observations of mechanical weakening and oxide formation on the alloy surface.

In contrast, the salt used with Hastelloy C-276 exhibited minimal Fe (0.30 wt.%) and Cr (0.16 wt.%) content, indicating substantially enhanced resistance to elemental leaching. However, traces of Ni were detected, suggesting that while surface passivation was largely effective, minor corrosion activity could not be entirely suppressed. These findings align with the modest degradation observed in hardness and wear depth for C-276 (Fig. 16).

Remarkably, in the case of the New alloy, no detectable levels of Fe, Cr, or Ni were present in the solidified salt. This suggests that elemental detachment and diffusion into the molten salt were effectively suppressed, highlighting the exceptional corrosion resistance and interfacial stability of this alloy under extremely high-temperature chloride conditions. The complete absence of leached metals in the salt phase is consistent with the alloy's post-corrosion hardness enhancement, minimal wear depth change, and the absence of surface pitting observed through SEM and EDS analyses. A comparative visualization of elemental dissolution into the salt (Fig. 17 [Figure 17: see original paper]) clearly illustrates the superior performance of the New alloy, showing negligible metal loss relative to the significant dissolution observed for conventional stainless steels. These findings further validate the alloy's potential as a next-generation structural material capable of enduring aggressive molten salt environments with minimal degradation in chemical and mechanical performance.

To quantitatively assess the depth-dependent distribution of key alloying elements following molten salt corrosion, EDS line scanning was conducted across the cross-sections of the samples. Measurements were performed in the regions exhibiting the most pronounced corrosion damage, as identified by SEM (Fig. 18 [Figure 18: see original paper]), to evaluate the elemental diffusion profile of Fe and Cr and to determine the extent of surface element depletion. For 316SS, the concentrations of Fe and Cr at the surface were significantly reduced, with suppressed levels persisting to a depth of approximately 300 m. Beyond this region, the elemental concentrations gradually returned to their bulk values, indicating a clear penetration front of corrosion-driven dissolution. Although Fe and Cr exhibited slightly different depth profiles, both elements experienced substantial depletion near the surface, quantitatively corroborating the extensive leaching of active species in the molten salt environment. Similarly, 304SS exhibited a surface-depleted zone, but the affected depth was limited to approximately 150 m, representing a relatively shallower corrosion penetration compared to that of 316SS. This observation aligns with previous results on weight loss, hardness degradation, and wear depth, indicating a moderately improved corrosion resistance in 304SS under the same testing conditions.

In contrast, C-276 and the New alloy maintained stable Fe and Cr concentrations across the entire scanned depth, from the surface to the interior. No significant compositional gradients or element depletion zones were detected, confirming minimal surface-element dissolution even after prolonged exposure to high-temperature chloride-based molten salt. These findings are entirely consistent with earlier EDS surface analysis and the absence of Fe, Cr, and Ni elements in the post-corrosion molten salt. Overall, these cross-sectional compositional profiles provide direct quantitative evidence of corrosion-induced diffusion behavior and degradation of surface integrity. Notably, the New alloy and C-276 demonstrate exceptional stability against elemental leaching and internal diffusion, reinforcing their applicability as structural materials for advanced molten salt reactors requiring long-term corrosion resistance and surface-interior chemical integrity.

To elucidate the origin of the New alloy's superior corrosion resistance in high-temperature molten salt environments, X-ray diffraction (XRD) analysis was conducted using an Anton Paar XRDynamic 500 diffractometer. The objective was to identify intermetallic compounds and precipitated phases formed during corrosion exposure and to assess their potential contributions to surface passivation and mechanical reinforcement. Post-corrosion XRD patterns for 316SS, 304SS, and C-276 revealed only weak reflections corresponding to complex carbides. No discernible peaks associated with the formation of stable surface-protective metal oxides or intermetallic phases were observed. These findings suggest that the traditional alloys lacked sufficient surface reconstruction mechanisms under aggressive chloride conditions, consistent with their observed post-corrosion hardness reduction and degradation in wear resistance.

On the other hand, distinct intermetallic compounds and complex carbide precipitated phases were observed in the New alloy. Specifically, Ni-Nb intermetallic compound peaks were detected at 2 = 83.2°, indicating that Nb may have reacted with Ni to induce the formation of a protective film preferentially [?]. Additionally, $M_{23}C_6$ complex carbide peaks of $(Cr, Fe, W, Mo)_{23}Fe_{21}$ and $(W, Mo)_2C_{12}$ series were distinctly observed around 2 = 111.2° (Fig. 19 [Figure 19: see original paper]). These precipitated phases are known to suppress diffusion of surface metal elements in high-temperature environments and perform protective functions against wear and oxidation [?, ?]. The formation of Ni–Nb intermetallics is particularly noteworthy, as this phase likely acts as a sacrificial and stabilizing barrier layer, limiting the outward diffusion of active metallic elements and suppressing surface degradation. Simultaneously, the stabilization of $M_{23}C_6$ carbides near the surface is believed to contribute significantly to the observed hardness enhancement and structural integrity. These multiphase protective architectures provide synergistic defense mechanisms against corrosion and wear, aligning with the minimal element dissolution, low weight loss, and enhanced post-corrosion hardness (from 250 HV to 310 HV) of the New alloy. Taken together, these XRD findings provide compelling evidence that the exceptional performance of the New alloy arises from its ability to form stable, high-hardness protective surface phases that resist dissolution and mechanical failure in extreme molten salt conditions.

4. Conclusions

This study conducted a comprehensive evaluation of corrosion, wear, and mechanical degradation behavior in a newly developed Nb-containing austenitic alloy ("New alloy") compared to conventional structural materials (316SS, 304SS, and Hastelloy C-276) under high-temperature molten salt conditions representative of MSR operating environments. All samples were exposed to a eutectic $NaCl-MgCl_2-KCl$ salt mixture at 800 °C for 24 hours, and degradation was systematically assessed through physical, mechanical, chemical, and microstructural analyses.

- The New alloy demonstrated the lowest corrosion-induced weight loss per unit volume (0.057 mg/mm^3), significantly outperforming 316SS (0.97 mg/mm^3), 304SS (0.63 mg/mm^3), and C-276 (0.089 mg/mm^3). Surface roughness increased by only 12 times in the New alloy, compared to 2,729× in 316SS, 1,093× in 304SS, and 414× in C-276, confirming superior surface stability. Cross-sectional SEM revealed that corrosion-affected areas in the New alloy were more than 3,000 times smaller than in 316SS. Pitting corrosion was absent in the New alloy but severe in 316SS and 304SS, and moderate in C-276.

- Post-corrosion Vickers microhardness measurements showed a 24% increase in the New alloy (from 250 HV to 310 HV), in contrast to decreases in 316SS (–35.3%), 304SS (–26.8%), and C-276 (–1.8%). This improvement in the New alloy was attributed to thermally induced strengthening via Ni–Nb intermetallic and $M_{23}C_6$ carbide formation.
- In scratch wear tests, post-corrosion wear depths increased from 38.5 m to 41.1 m in the New alloy (1.07×), while 316SS showed an increase from 55.8 m to 526.6 m (9.4×). Two-body ball wear tests showed similar trends: wear depth increased modestly in the New alloy (5.2 m to 13.6 m, 2.6×), whereas 316SS increased from 15.4 m to 269.1 m (17.5×). Wear mass loss after corrosion was also lowest in the New alloy (0.133 mg in scratch and 0.150 mg in ball wear), over 90% lower than 316SS. SEM analysis confirmed that the New alloy exhibited only mild plowing-type wear, with no spalling or delamination, while severe cracking and oxide layer failure were evident in 316SS and 304SS.
- EDS surface analysis revealed that Fe and Cr leaching was minimal in the New alloy, unlike 316SS and 304SS, which showed more than 50% depletion. Oxygen content increased moderately in the New alloy (to 6.97 wt.%), suggesting uniform oxide formation without destabilizing surface layers. Importantly, post-test molten salt analysis showed no detectable Fe, Cr, or Ni from the New alloy, indicating complete suppression of elemental dissolution, unlike the high levels found in salts exposed to 316SS and 304SS. Cross-sectional EDS line scans further confirmed negligible elemental depletion and no measurable corrosion front in the New alloy.
- XRD analysis revealed the formation of protective Ni–Nb intermetallics (2 = 83.2°) and $M_{23}C_6$ carbides (2 = 111.2°) in the New alloy after corrosion. These phases contributed to both the improved surface hardness and resistance to oxide layer spallation. In contrast, no protective oxide or carbide phases were observed in 316SS, 304SS, or C-276 under the same conditions.

The results comprehensively demonstrate that the Nb-containing New alloy offers the best overall resistance to corrosion, wear, and mechanical degradation in high-temperature molten salt environments, while maintaining chemical integrity and forming beneficial surface phases. Compared to commercial alternatives, it not only outperformed 316SS and 304SS in all metrics but also exceeded the corrosion and wear performance of C-276, while potentially offering greater economic viability due to lower alloying cost. These findings position the New alloy as a strong candidate for MSR structural applications, particularly for high-temperature pressure vessels and components exposed to aggressive chloride-based molten salt environments.

Data Availability

The raw and processed data supporting the findings of this study are not publicly available at this time, as they are part of an ongoing research project. Data may be made available upon reasonable request after the completion of the broader study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

All authors contributed to the conception, design, and execution of the study and approved the final version of the paper.

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References

[1] E.C. Herrera-Hernández, A.D. Pérez-Valseca, C.G. Aguilar-Madera, A. Vázquez-Rodríguez, Heat transfer coefficients for bubbly molten salt nuclear reactors, Nuclear Engineering and Design, 414 (2023) 112549
[2] Robin Roper, Megan Harkema, Piyush Sabharwall, Catherine Riddle, Brandon Chisholm, Brandon Day, Paul Marotta, Molten salt for advanced energy applications: A review, Annals of Nuclear Energy, 169 (2022) 108924
[3] David E. Holcomb, Christopher P. Chwasz, James A. King, Liquid Fuel Qualification for Molten Salt Reactors: Identification of Gaps and Challenges, Advanced Reactor Technology Program, INL/RPT-24-80651

[4] Uğur Köse, Ufuk Koç, Latife Berrin Erbay, Erdem Öğüt, and Hüseyin Ayhan, Heat exchanger design studies for molten salt fast reactor, Nuclear Sciences & Technologies, 5, 12 (2019)
[5] V. Ignatiev, O. Feynberg, I. Gnidoi, A. Merzlyakov, A. Surenkov, V. Uglov, A. Zagnitko, V. Subbotin, I. Sannikov, A. Toropov, V. Afonichkin, A. Bovet, V. Khokhlov, V. Shishkin, M. Kormilitsyn, A. Lizin, A. Osipenko, Molten salt actinide recycler and transforming system without and with Th–U support: Fuel cycle flexibility and key material properties, Annals of Nuclear Energy, 64 (2014) 408–420
[6] International Atomic Energy Agency, Status of molten salt reactor technology, International Atomic Energy Agency, ISSN 0074–1914 ; no. 489
[7] D. Heuer, E. Merle-Lucotte, M. Allibert, M. Brovchenko, V. Ghetta, P. Rubiolo, Towards the thorium fuel cycle with molten salt fast reactors, Annals of Nuclear Energy, 64 (2014) 421–429
[8] G.C. Lia, P. Congd, C.G. Yua, Y. Zoua, J.Y. Suna, J.G. Chena, H.J. Xua, Optimization of Th-U fuel breeding based on a single-fluid double-zone thorium molten salt reactor, Progress in Nuclear Energy, 108 (2018) 144–151
[9] Marvin BakerSchaffer, Abundant thorium as an alternative nuclear fuel Important waste disposal and weapon proliferation advantages, Energy Policy, 60(2013)4–12
[10] Niketan S. Patel, Viliam Pavlík & Miroslav Boča, High-Temperature Corrosion Behavior of Superalloys in Molten Salts – A Review, Critical Reviews in Solid State and Materials Sciences, 2017, VOL. 42, NO. 1, 83–97
[11] Qing Gong, Andrea Hanke, Fiona Kessel, Alexander Bonk, Thomas Bauer, Wenjin Ding, Molten chloride salt technology for next-generation CSP plants: Selection of cold tank structural material utilizing corrosion control at 500℃, Solar Energy Materials and Solar Cells, 253 (2023) 112233
[12] Qing Gong, Hao Shi, Yan Chai, Rui Yu, Alfons Weisenburger, Dihua Wang, Alexander Bonk, Thomas Bauer, Wenjin Ding, Molten chloride salt technology for next-generation CSP plants: Compatibility of Fe-based alloys with purified molten $MgCl_2$-KCl-NaCl salt at 700℃, Applied Energy, 324 (2022) 119708
[13] Badawy M. Elsheikh, Safety assessment of molten salt reactors in comparison with light water reactors, Journal of Radiation Research and Applied Sciences, 6 (2013) 63-70
[14] Brandon M. Chisholm, Steven L. Krahn, Andrew G. Sowder. A unique molten salt reactor feature – The freeze valve system: Design, operating experience, and reliability, Nuclear Engineering and Design, 368 (2020) 110803cc
[15] Mingjing Wang, Song Zeng, Huihui Zhang, Ming Zhu, Chengxin Lei and Boshuai Li, Molten Salt Corrosion of Stainless Steels and Low-Cr Steel in CSP Plants, Oxid Met, (2012) 78:329–348
[16] Wei Zhai, Bo Yang, Maodong Li, Shiping Li, Mingliang Xin, Shuanghong Zhang and Guojia Huang, Study on corrosion of metal materials in nitrate molten salts, AIP Conf. Proc., 1794, 020016 (2017)
[17] Tianle Liu, Xinhai Xu, Wenrui Liu, Xiaoru Zhuang, Corrosion of alloys in high temperature molten-salt heat transfer fluids with air as the cover gas, Solar Energy, 191 (2019)

[18] Mingjing Wang, Song Zeng, Huihui Zhang, Ming Zhu, Chengxin Lei, and Boshuai Li, Corrosion behaviors of 316 stainless steel and Inconel 625 alloy in chloride molten salts for solar energy storage, High Temperature Materials and Processes, 2020; 39: 340–350

[19] Pengfei Lu, Lili Guo, Qi Liu, Linlin Liu, T.J. Pan, Zhongfeng Tang, Excellent high temperature corrosion resistance of 304 stainless steel immersed in purified NaCl–$MgCl_2$ eutectic salts, Materials Chemistry and Physics, 296 (2023) 127216

[20] Jun Woo Park, Hyunjin Boo, Suhyeon Lee, Seungmo Yeon, Byung Gi Park, Jong-Il Yun, Corrosion behaviors of stainless steel 316 in NaCl-$MgCl_2$ molten salt thermal convection loop, Journal of Nuclear Materials, 2025 615, 155991

[21] Mani Pandi A S., V.S. Senthil Kumar, A review: Fabrication techniques of the Hastelloy (super alloy) composites and it impacts on the properties, Mater Today Proc, 2024.05.1

[22] Seather, Inconel Alloy 625 vs. Hastelloy Alloy C-276: A Comprehensive Comparison, Seather Technology, 2025.07

[23] Ketan Kumar Sandhi and Jerzy Szpunar, Analysis of Corrosion of Hastelloy-N, Alloy X750, SS316 and SS304 in Molten Salt High-Temperature Environment, Energies, 2021, 14,

[24] Sen Ren, Yanjun Chen, Xiang-Xi Ye, Li Jiang, Shuai Yan, Jianping Liang, Xinmei Yang, Bin Leng, Zhijun Li, Zezhong Chen, Zhimin Dai, Corrosion behavior of carburized 316 stainless steel in molten chloride salts, Solar Energy, 223 (2021) 1–10

[25] Guiqiu Zheng, Lingfeng He, David Carpenter, Kumar Sridharan, Corrosion-induced microstructural developments in 316 stainless steel during exposure to molten Li_2BeF_4(FLiBe) salt, Journal of Nuclear Materials, 482 (2016) 147e155

[26] Ming Zhu, Song Zeng, Huihui Zhang, Junyi Li, Boyuan Cao, Electrochemical study on the corrosion behaviors of 316 SS in HITEC molten salt at different temperatures, Solar Energy Materials and Solar Cells, 186 (2018) 200–207

[27] Dandan Men, Jian Xiong, Wenyi Peng, Lingyun Bai, Study on Molten Salt Corrosion Behavior of Several Stainless Steel Alloys, IOP Publishing Ltd, 1885 (2021) 032005

[28] Marina Yu. Panchenko, Galina G. Maier, Valentina A. Moskvina, Sergey V. Astafurov, Evgenii V. Melnikov, Kseniya A. Reunova, Evgenii A. Kolubaev, Elena G. Astafurova, Microstructure and mechanical properties of Nb-alloyed austenitic CrNi steel fabricated by wire-feed electron beam additive manufacturing, Materials Characterization, 190 (2022) 112063

[29] Wanjian Xu, Guodong Jia, Jie Pan, Zixie Wang, Jun Li and Xueshan Xiao, Effects of Nb on Creep Properties and Hot Corrosion Resistance of New Alumina-Forming Austenitic Steels at 700 °C, Metals, 2024, Vol. 14, Page 870 14

[30] Zhaodandan Ma, Shuo Cong, Huan Chen, Zhu Liu, Yuanyuan Dong, Rui Tang, Tian Qiu, Yong Chen and Xianglong Guo, Corrosion Behavior of Alumina-Forming Austenitic Steel in Supercritical Carbon Dioxide Conditions:

Effects of Nb Content and Temperature, Materials, 2023, Vol. 16, Page 4081 16, 4081
[31] Lu-yan Sun, Xiang Liu, Xi Xu, Shu-wei Lei, Hui-gai Li & Qi-jie Zhai, Review on niobium application in microalloyed steel, Journal of Iron and Steel Research International, (2022) 29:1513–1525
[32] Shigenari Hayashi, Haruki Utsumi, Shota Omori, Suzue Yoneda, Role of Nb in promoting protective scale formation on Al_2O_3-forming austenitic alloys, Corrosion Science, 209 (2022) 110751
[33] Fan Wang, Gui-zhi Xiao, De-ning Zou, Kai-xin Zhang, Xiao-ming Zhang, Yang Li, Li-bo Tong, Yi-cheng Jiang & Bo Song, Effect of Nb on high-temperature oxidation of austenitic stainless steel at 850 °C, Journal of Iron and Steel Research International, (2025) 32:
[34] Frances Wang and Derek O. Northwood, The effect of carbon content on the microstructure of an experimental heat-resistant steel, MATERIALS CHARACTERIZATION, 31:3-10 (1993)
[35] A. S. Dorcheh, R. N. Durham, M. C. Galetz, High temperature corrosion in molten solar salt: The role of chloride impurities, Solar Energy, 201 (2020) 437–452
[36] Ming Liu, Stuart Bell, Steven Ta, Geoffrey Will, Wasim Saman, Frank Bruno, Stability and Corrosion Testing of a High Temperature Phase Change Material for CSP Applications, AIP Conference Proceedings, 1734, 050029 (2016)
[37] Stéphanie Guillot, Abdessamad Faik, Aydar Rakhmatullin, Julien Lambert, Emmanuel Veron, Patrick Echegut, Catherine Bessada, Nicolas Calvet, Xavier Py, Corrosion effects between molten salts and thermal storage material for concentrated solar power plants, Applied Energy, 94 (2012) 174–181
[38] Anabel Palacios, Maria Elena Navarro, Zhu Jiang, Aina Avila, Geng Qiao, Ernesto Mura, Yulong Ding, High-temperature corrosion behaviour of metal alloys in commercial molten salts, Solar Energy, 201 (2020) 437–452
[39] C. Cuevas-Arteaga, J. Uruchurtu-Chavarin, J. Porcayo-Calderon, G. Izquierdo-Montalvo, J. Gonzalez, Study of molten salt corrosion of HK-40m alloy applying linear polarization resistance and conventional weight loss techniques, Corrosion Science, 46 (2004) 2663–26
[40] N. Sunitha, K.G. Manjunatha, Evaluation of Corrosion Studies of as Casted and Heat Treated Aluminum 6065 Metal Matrix Composite by Weight Loss Method, Materials Today: Proceedings, 5 (2018) 22727–22733
[41] S.H. Goods and R.W. Bradshaw, Corrosion of Stainless Steels and Carbon Steel by Molten Mixtures of Commercial Nitrate Salts, Journal of Materials Engineering and Performance, (2004) 13:78-87
[42] A. Sobolev, D. Bograchev, M. Zinigrad, Borodianskiy, Evolution of corrosion on microstructure of ceramic coating produced by plasma electrolytic oxidation in molten salt, Ceramics International, 48 (2022) 10990–10998
[43] Carolina Villada, Alejandra Toro, Francisco Bolívar, Corrosion performance of austenitic stainless steel SS304 in molten nitrate salts and Raman microscopy for stability analysis in thermal energy storage applications, Journal of Energy Storage, 44 (2021) 103465

[44] Sumit Mahajan, Rahul Chhibber, Hot corrosion studies of boiler steels exposed to different molten salt mixtures at 950 °C, Engineering Failure Analysis, 99 (2019) 210–224

[45] Weilong Wanga, Bang Guan, Xiaolong Li, Jianfeng Lu, Jing Ding, Corrosion behavior and mechanism of austenitic stainless steels in a new quaternary molten salt for concentrating solar power, Solar Energy Materials and Solar Cells, 194 (2019) 36–46

[46] Alan Kruizenga, David Gill, Corrosion of iron stainless steels in molten nitrate salt, Energy Procedia, 49 (2014) 878–887

[47] Yu Gao, Kai Chong, Chang Liu, Yingwen Cao, Dongting Wu, Yong Zou, Electrochemical corrosion and high temperature hot corrosion behavior of NbTaTiV and CrNbTaTiV high entropy alloy, Journal of Materials Research and Technology, 28 (2024) 216–234

[48] Fei Weng, Huijun Yu, Kai Wan and Chuanzhong Chen, The influence of Nb on hot corrosion behavior of Ni-based superalloy at 800 °C in a mixture of Na_2SO_4–NaCl, J. Mater. Res, Vol. 29, No. 21, Nov 14, 2014

[49] Tyler D. Doležal, Adib J. Samin, A first-principles study on the early-stage corrosion of a NiWNb alloy in a chloride salt environment, Journal of Nuclear Materials, 582 (2023)

[50] Conrado R.M. Afonso, Katherine Martinez-Orozco, Vicente Amigo, Carlos A. Della Rovere, Jose E. Spinelli, Claudio S. Kiminami, Characterization, corrosion resistance and hardness of rapidly solidified Ni–Nb alloys, Journal of Alloys and Compounds, 829 (2020) 15

[51] Ying Wu, Lishi Ma, Xiaolong Zhou, Yonghua Duan, Li Shen, Mingjun Peng, Insights to electronic structures, elastic properties, fracture toughness, and thermal properties of $M_{23}C_6$ carbides, International Journal of Refractory Metals and Hard Materials, 109 (2022) 10

[52] Dagmara Berztiss, Armin Zahs, André Schneider, Michael Spiegel, Helmut Viefhaus and Hans Jürgen Grabke, Role of Carbides in the High Temperature Corrosion of Steels in HCl-containing Atmospheres, Z. Metallkd, 90 (1999) 1

[53] Renata T. de A. Minhoni, Francisca F. S. Pereira, Tatiane B. G. da Silva, Evanize R. Castro, João C. C. Saad, THE PERFORMANCE OF EXPLICIT FORMULAS FOR DETERMINING THE DARCY-WEISBACH FRICTION FACTOR, Engenharia Agrícola, 1809-443

[54] Farnoush Aghaee Daneshvar · Nasser Talebbeydokhti · Seyed Mehdi Dehghan · Seyed Mohammad Mehdi Elhamian, Evaluation of Darcy–Weisbach Friction Factors of Fiberglass Pipes Based on Internal Surface Roughness Measurement, Iranian Journal of Science and Technology, (2023) 47:1749–1762

Note: Figure translations are in progress. See original paper for figures.