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Research Article

Investigation of the Mechanical Properties and Corrosion Resistance of Pure Titanium Sheets Through Climb and Conventional Milling: A Novel Approach for Military and Petrochemical Applications

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ABSTRACT

This study investigates the influence of milling direction—climb milling and conventional milling—on the surface properties of 4 mm-thick pure titanium sheets, machined at a depth of 0.5 mm. The primary objective is to analyze and compare the effects of these milling methods on hardness, wear resistance, and corrosion behavior of titanium. A detailed experimental approach was employed, including hardness testing, wear analysis, and corrosion evaluation.

The results revealed that the milling method plays a crucial role in determining the final properties of titanium. Climb milling produced superior mechanical properties, achieving a maximum hardness of 334 HV, compared to 315 HV in conventional-milled samples, attributed to work hardening and a refined microstructure. Additionally, wear resistance improved with material loss reduced to 10.87 mg in climb-milled samples, compared to 9.99 mg in conventional-milled samples and 18 mg in pure titanium. Meanwhile, corrosion resistance was significantly enhanced in climb-milled samples, with the corrosion rate decreasing to 0.0003 mm/year, compared to 0.02 mm/year in conventional-milled samples. These findings underline the potential of climb milling to enhance the mechanical and corrosion properties of titanium, making it more suitable for critical applications in military, petrochemical, and medical industries. By optimizing milling strategies, the lifespan and performance of titanium components in sensitive engineering and biomedical fields can be substantially improved.

1. Introduction

Titanium alloys are widely used in various industries, including aerospace, medical, and military sectors, due to their unique properties, such as a high strength-to-weight ratio, corrosion resistance, and biocompatibility [1, 2]. Their applications range from nuclear and aircraft

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structural components to machine parts and medical equipment. Understanding the material's deformation behavior and microstructure evolution during hot working is crucial for achieving the desired final mechanical properties [3]. Beyond their excellent mechanical properties, titanium alloys form a robust thin oxide (passivation) layer on their surface, suppressing metal iron release and making them ideal for biomedical implants where biocompatibility is critical [4]. However, machining titanium alloys remains a significant challenge due to their specific properties, which limit machinability [5]. Low thermal conductivity, high chemical reactivity, and a relatively low modulus of elasticity contribute to machining issues such as surface burns, severe tool wear, and deformation recovery [6]. The growing applications of titanium alloys, particularly Ti-6Al-4V, have driven extensive research in recent years on machining both titanium alloys and pure titanium. [7]. Narita et al. [8] studied the machining of inclined surfaces and emphasized the importance of simultaneous contact at lower edges and upper corners for optimal surface roughness. Similarly, Yujian et al. [9] examined high-speed milling of the TC11 titanium alloy and found that increased cutting speed reduces tool wear resistance while significantly increasing cutting forces and surface roughness. Jiang et al. [6] demonstrated that machining path direction significantly affects surface integrity, reducing surface roughness by approximately 40%. Kumar et al. [10] studied the surface roughness in dry micro-milling of Grade 2 and Grade 5 titanium, concluding that cutting depth had minimal impact. Danesh et al. [11] analyzed vibration and tool wear effects on Ti-6Al-4V machining, revealing that increased free-surface vibration leads to surface texture irregularities and reduced component quality. Fastas et al. [12] highlighted the challenge of excessive heat generation in titanium machining, which accelerates tool wear and reduces tool life. Brown et al. [13] observed significant deformation depth during low-speed milling of titanium alloys. Danian et al. [14] found that a machining parameter of Ra = 0.035 µm yields minimal surface roughness during Ti-6Al-4V milling. Zhao et al. [15] compared the surface morphology of Ti-6Al-4V machined with uncoated and TiAlN-coated tools under various lubrication conditions, concluding that tool coatings enhance surface roughness, while uncoated alloys experience greater wear at higher speeds.

Machining processes are essential for shaping nearly all engineering materials and play a vital role in defining the properties of critical components in advanced equipment [16–18]. During machining, the tool edges interact with the workpiece surface, leading to a combination of compression, scratching, plowing, and cutting actions that facilitate material removal or plastic deformation of the machined surface [19–21]. The tool path direction is closely linked to surface modifications, making an understanding of surface integrity crucial for enhancing the properties and performance of complex titanium components. However, limited research exists on the impact of tool movement direction on the mechanical and surface behavior of titanium during milling. This study addresses this gap by systematically comparing the effects of conventional milling and climb milling on the mechanical properties and corrosion behavior of pure titanium sheets. The results offer valuable insights for improving the design and performance of titanium components in advanced industries, particularly the petrochemical and military sectors. This research examines surface roughness, which directly influences adhesion capability and wear resistance in harsh industrial environments; hardness variations, which reflect mechanical resistance and surface damage stability; and corrosion rate analysis, which is critical for applications in chemically aggressive and military environments. These findings are especially relevant for military applications that demand durability, stability, and long-term performance, as well as for the petrochemical industry, where titanium components are exposed to extreme corrosive conditions.

2. Materials and Methods

2.1. Materials and manufacturing process

The milling experiments were conducted on an FP4MD three-axis machine in both climb and conventional milling modes, without the use of coolant, on the workpiece surface. The chemical composition of the pure titanium sheet used in this study is presented in Table 1, while the machining conditions and corresponding images are provided in Table 2 and Fig. 1, respectively.

For clarity, the sample produced using the climb milling method is referred to as Sample-a, while the sample obtained through the conventional milling is designated as Sample-b.

Table 1. Chemical composition of the pure titanium sheet

Impurity content (mass%)	Ti	O	Fe	H	C	N
	99.95	0.18	0.20	0.015	0.08	0.03

Table 2. Experimental milling conditions

Tool diameter	Tool material	Milling depth	Type of coolant	Rotational speed	Table speed
25 mm	TiAlN	0.4 mm	–	1250 rpm	35 m/h

2.2. Experiments

To further investigate the phases present in the samples, X-ray diffraction (XRD) analysis was performed using an Explorer diffractometer (GNR, Italy) under operating conditions of 40 kV and 30 mA. Morphological changes were analyzed using field emission scanning electron microscopy (FESEM) with a MIRA microscope (TESCAN, Czech Republic), capable of a 1.5 nm resolution at 15 kV. The hardness of the samples was measured using the Vickers method with an INNOVATEST NEXUS XL8000 hardness tester, applying a 612.9 N load with a 2.5 mm tungsten indenter and a dwell time of 15 seconds, in accordance with ASTM A370 (2020). Each sample was tested at least three times to ensure statistical accuracy. Wear performance was conducted using the pin-on-disk method in a controlled laboratory environment, following ASTM G99 standards. The test was conducted under dry conditions at room temperature with a 5 N load, a duration of 3600 seconds, and a rotational speed of 60 rpm, using a steel pin as the abrasive material.

Surface roughness of the machined samples was measured following ISO 21920-3:2021 standards at 25 °C and 19% relative humidity. Electrochemical corrosion tests were conducted within a voltage range of -250 to +250 mV, with a scan rate of 1 mV and a total duration of 1200 seconds at open circuit potential (OCP).

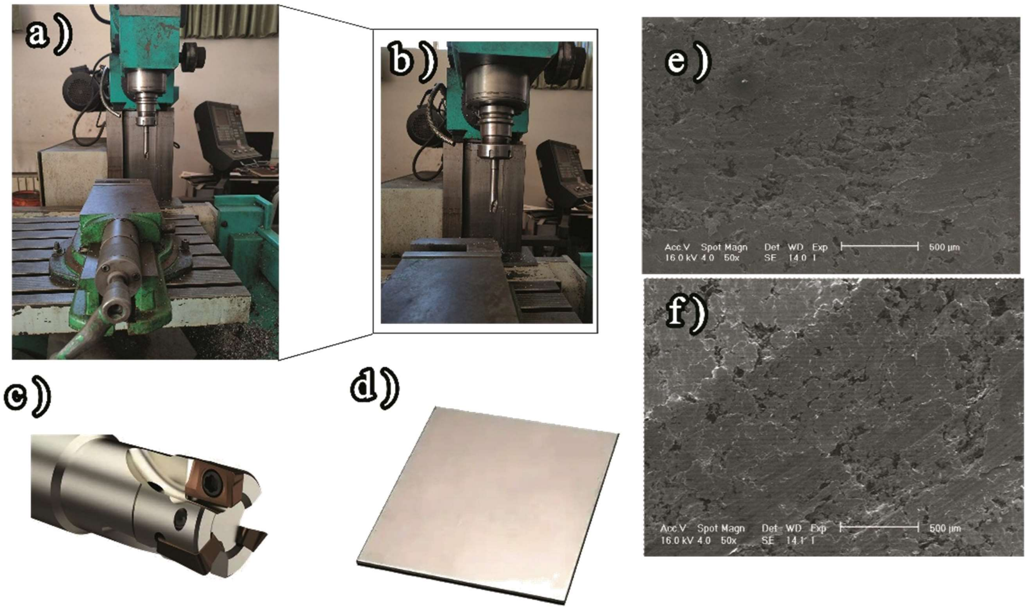

Fig. 1. (a, b) The milling machine used, (c) the machining tool, (d) the pure titanium sheet, (e) the SEM image of the machined surface of Sample-a (climb milling), and (f) the SEM image of the machined surface of Sample-b (conventional milling).

3. Results and Discussion

3.1. XRD analysis

The XRD results, as illustrated in Fig. 2, indicate a significant reduction in peak intensity at approximately 35° in titanium samples machined using both climb and conventional milling methods. This decrease in peak intensity is primarily attributed to structural changes in the titanium lattice [22, 23]. The milling process, particularly at a depth of 0.5 mm, alters grain distribution and increases crystalline defects such as dislocations and grain boundaries, directly influencing the XRD peak intensities. These variations reflect modifications in the crystal structure and internal stresses within the material. The mechanical stresses and work hardening induced by both milling climbs contribute to titanium crystal disformation and an increase in dislocation density. The higher density of grain boundaries, particularly at the machined depth, leads to alterations in the crystal structure, which are evident in the X-ray diffraction patterns. These structural changes result in reduced XRD peak intensities, highlighting the impact of the milling process on the material's crystallographic characteristics. The observed modifications in the crystal structure play a crucial role in enhancing the mechanical properties and corrosion resistance of the machined samples. Increased dislocation density and grain boundaries contribute to improved hardness and improved wear resistance. These structural transformations, driven by mechanical stresses and work hardening during milling, enhance the mechanical performance of titanium.

Consequently, these features significantly improve the durability and performance of titanium components, particularly in military and petrochemical applications. In military applications, enhanced wear and corrosion resistance are critical. Components with optimized crystal structures and superior corrosion resistance demonstrate greater effectiveness in harsh environments, including exposure to corrosive agents in marine and atmospheric conditions. The improved service life and reduced maintenance requirements under such conditions contribute to increased efficiency and lower operational costs. In the petrochemical industry, minimizing the corrosion and wear of titanium components enhances both safety and equipment reliability. Reduced maintenance and repair costs, increased productivity, and minimized process downtime provide additional advantages. Overall, the milling process, by inducing favorable changes in the crystal structure of titanium, significantly improves the performance and longevity of components in these industries, ultimately enhancing safety and reducing operational costs.

3.2. Surface roughness

An analysis of the surface roughness of the machined samples, as shown in Fig. 3, indicates that the sample produced using climb milling (Ra = 2.709) exhibits a significantly smoother surface compared to the sample produced using conventional milling (Ra = 7.129). This difference is primarily attributed to the direction of tool movement in each milling method. In climb milling, the tool moves in the same direction as the material removal process, leading to a more uniform surface with reduced roughness. This method minimizes the impact of cutting forces and enhances surface quality.

In military engineering, this distinction in surface roughness is particularly relevant for the design and fabrication of components requiring stealth and minimal light reflection. Smoother surfaces reduce light scattering, thereby lowering the detectability of military parts and equipment.

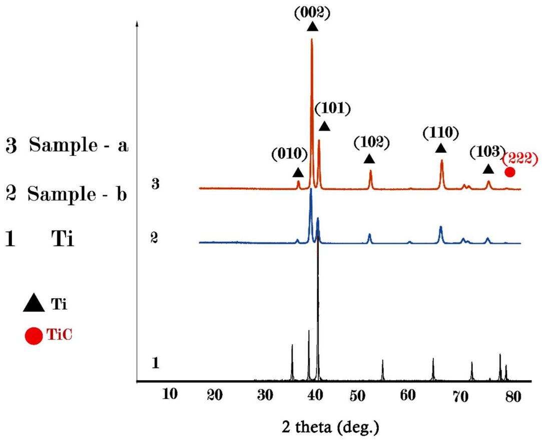

Fig. 2. XRD results at different stages of the process.

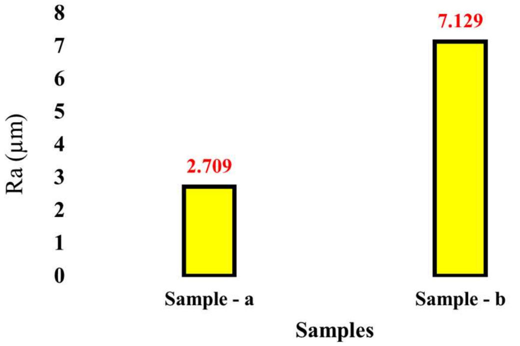

Fig. 3. Surface roughness test results.

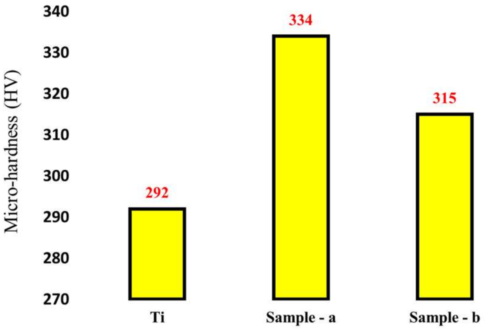

Fig. 4. Vickers microhardness test results.

Additionally, reduced roughness enhances the performance of components under critical conditions by minimizing structural weak points. In the petrochemical industry, surface roughness plays an equally significant role. Smoother surfaces are less prone to deposit formation and contaminant accumulation, which can reduce maintenance costs and extend equipment service life. This is especially crucial in fluid transfer systems exposed to corrosive chemicals, where reduced roughness mitigates erosion and surface corrosion, ultimately improving system efficiency and safety.

3.3. Hardness analysis

The Vickers hardness test results, which indicate a material's resistance to deformation under pressure, reveal significant changes in titanium hardness under different machining conditions. The pure cast titanium sheet used in this study had an initial hardness of 292 HV, serving as the baseline for comparison. As shown in Fig. 4, machining with the climb milling method resulted in a substantial increase in hardness to 334 HV, while the sample machined using conventional milling exhibited a lower hardness of 315 HV. This variation highlights the distinct effects of shear forces and heat generated during the machining processes.

In climb milling, the alignment of tool movement with the material flow promotes a more uniform distribution of the stresses on the surface. This leads to the formation of compressive residual stresses, which enhance structural densification and increase hardness. The more effective distribution of shear forces across the material results in greater resistance to deformation.

In contrast, conventional milling, where the tool moves against the material flow, generates a less uniform stress distribution, leading to tensile residual stresses on the surface. These tensile stresses increase the likelihood of surface defects and contribute to lower hardness levels [24].

The observed differences in hardness have significant implications for the performance of titanium components in industrial applications. In the petrochemical industry, titanium equipment is exposed to harsh chemical environments and high temperatures, where wear and corrosion resistance are critical. Components with higher hardness, such as those machined using the climb milling method, exhibit superior resistance to chemical attack and wear caused by fluid and gas flows. The enhanced surface hardness improves the durability of critical equipment, including heat exchangers and pumps.

In military applications, titanium components must withstand extreme operational conditions, including high-impact stresses and prolonged wear. The enhanced hardness achieved through climb milling improves resistance to impact, wear, and fatigue, critical properties for components such as armor plating, engine parts, and aerospace structures exposed to severe conditions. Selecting an appropriate machining method can significantly extend component lifespan, reducing the need for frequent replacements or repairs, which is crucial for the safety and efficiency of military systems.

In conclusion, optimizing machining strategies, particularly through climb milling, not only improves the hardness and resistance to wear and corrosion of titanium components but also enhances their overall performance in demanding industrial and military environments. The ability to effectively enhance surface hardness contributes to longer-lasting components, better operational efficiency, and greater safety in critical applications.

3.4. Weight loss after wear test

The results of the wear test indicate that titanium samples machined using the climb milling method (where the tool moves in the same direction as the material removal process) exhibit greater wear resistance compared to those machined using the conventional milling method (where the tool moves against the material flow). The sample machined with the conventional method experienced a weight loss of 10.87 mg, while the sample machined using the climb milling method showed a lower weight loss of 9.99 mg, demonstrating superior wear resistance.

This difference in performance can be attributed to variations in the surface structures produced by the two machining methods. Titanium surfaces machined via climb milling tend to exhibit enhanced wear resistance due to the formation of a hardened surface layer, a finer microstructure, improved surface chemistry, and reduced residual stresses. In contrast, conventional milling generates greater plastic deformation, increasing residual strain, surface heterogeneity, and thermal stress, which can lead to brittleness and microcrack formation. The difference in material removal mechanisms further impacts wear behavior, with climb milling producing a more uniform and compressively stressed surface, thereby reducing wear rates.

From a metallurgical perspective, conventional milling imposes higher tensile residual stresses, accelerating microcrack initiation and surface failure. Conversely, climb milling induces compressive residual stresses, which enhance surface toughness and mitigate wear. SEM images corroborate these findings, showing that the wear track in conventional milling samples exhibits deeper wear and wider grooves, indicative of adhesive and abrasive wear mechanisms. In contrast, climb-milled samples display shallower wear tracks and narrower grooves, signifying micro-cutting and oxidative wear mechanisms that result in lower material loss and improved wear resistance [25, 26].

The implications of these findings extend to various industries. In military engineering, components with enhanced wear resistance exhibit longer service life and reduced maintenance requirements, an essential factor in combat and operational scenarios where access to maintenance is limited. Wear-resistant components also perform better under harsh environmental conditions, reducing repair costs and enhancing operational efficiency. In the petrochemical industry, wear-resistant surfaces are crucial for chemical transfer and storage equipment, as they help prevent leaks, sudden failures, and excessive costs while improving overall industrial safety. A comparison with pure titanium further highlights the advantages of climb milling. While pure titanium possesses high ductility and toughness, its lower hardness makes it more susceptible to wear. Intense plastic deformation on its surface results in higher wear rates. However, machined titanium samples, especially those processed using climb milling, benefit from strain hardening, leading to higher surface hardness and reduced wear. The wear test results and SEM analyses confirm that climb milling enhances wear resistance by minimizing tensile residual stresses, ensuring uniform surface hardness, and optimizing wear mechanisms. As shown in Fig. 5, these findings underscore the importance of selecting an appropriate machining strategy to extend the lifespan of titanium components, ultimately improving performance and reducing operational costs. Additionally, Fig. 6 presents SEM images of the wear path, providing deeper insight into the analysis and confirming the numerical results. These images reveal that the depth and width of wear grooves are significantly greater in Sample-b (machined using conventional milling) compared to Sample-a (machined using climb milling). Furthermore, the scattered particles in the wear path of the conventional milling sample exhibit a larger average size and higher quantity, further validating the enhanced wear resistance of climb milling.

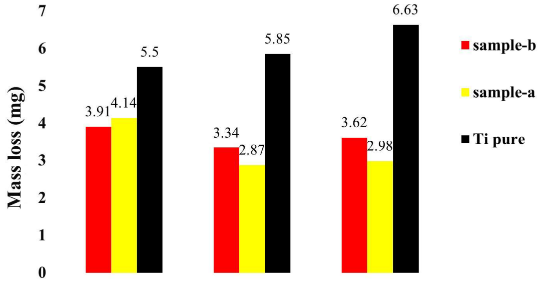

Fig. 5. Weight loss results from wear test.

3.5. Corrosion rate

The results of the corrosion tests, as shown in Fig. 7 and Table 3, demonstrate that the climb milling method significantly reduces the corrosion rate of titanium. Specifically, the corrosion rate decreases from 0.02 mm per year (in conventional milling) to 0.0003 mm per year (in climb milling), highlighting the influence of machining-induced surface modifications. This notable difference can be attributed to microstructural, mechanical, and electrochemical factors. Conventional milling generates tensile residual stresses, which promote the formation of microscopic cracks and surface defects, providing pathways for corrosive solutions to penetrate the material. In contrast, climb milling creates a more uniform and denser surface with lower roughness, reducing vulnerable points and slowing the electrochemical degradation process.

From a mechanical perspective, conventional milling induces higher residual tensile stresses, which facilitate crack initiation and accelerate stress corrosion cracking (SCC). Conversely, climb milling generates compressive residual stresses, which delay crack formation and enhance the material's resistance to degradation.

From an electrochemical standpoint, the rougher surface produced by conventional milling increases the effective contact area, thereby accelerating corrosion reactions. Under these conditions, rougher areas can act as localized anodes, intensifying corrosion [27]. In contrast, the smoother, more uniform surface obtained through climb milling facilitates the formation of a stable protective oxide layer, which serves as a barrier against corrosive ion penetration.

These findings hold significant practical importance. In the defense industry, reducing the corrosion rate directly extends the service life of equipment operating in marine and humid environments, thereby lowering costs and improving reliability.

Table 3. Corrosion test results

Parameter	Ti	Sample-a	Sample-b
E_{corr}(V)	-0.34872	-0.28852	-0.43748
I_{corr} (μA/cm^2)	1.9404 E-08	2.9697 E-08	2.2287 E-06
b_a (V/dec)	0.47624	0.20876	0.11333
b_c (V/dec)	0.41601	0.11638	0.17254
R_p (ohm)	4528.7	2.8763 E+05	3508.1
Corrosion rate (μm/year)	0.0718451	0.00034448	0.025853

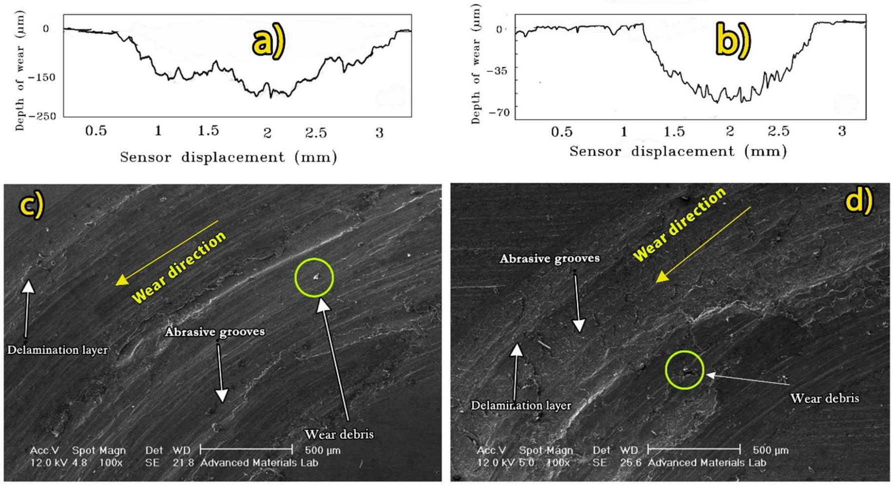

Fig. 6. Wear depth analysis of titanium samples: (a) climb milling, (b) conventional milling. SEM images of the wear path: (c) climb milling, (d) conventional milling.

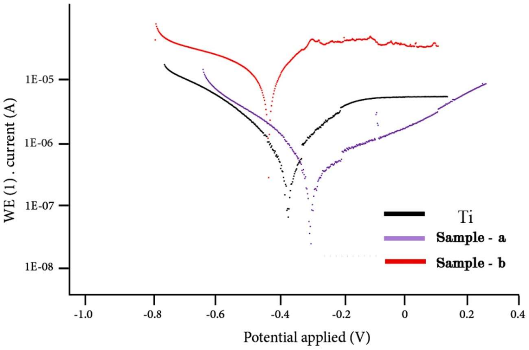

Fig. 7. Potentiodynamic polarization test curves.

In the petrochemical industry, corrosion-resistant equipment minimizes the risk of chemical leaks and failures, enhancing both safety and operational efficiency.

The striking difference in the corrosion rates of titanium samples machined by the two different methods underscores the critical role of the selected machining strategy in improving surface properties and increasing component lifespan. By reducing destructive stresses, refining microstructure, and lowering surface roughness, climb milling significantly enhances the corrosion resistance of titanium, making it an optimal choice for advanced applications.

Corrosion of titanium components in military and petrochemical applications presents a critical challenge that can severely impact equipment performance and safety. In military environments, aerospace and naval equipment exposed to harsh atmospheric conditions, high humidity, and corrosive environments are prone to mechanical degradation. Corrosion not only increases maintenance costs but also jeopardizes the reliability of mission-critical operations. In the petrochemical industry, titanium equipment is subjected to aggressive chemicals and high temperatures, which can lead to hazardous leaks and costly failures. A reduction in corrosion resistance increases the likelihood of industrial accidents and environmental contamination.

Therefore, optimizing machining methods such as climb milling that enhances surface durability and corrosion resistance plays a pivotal role in cost reduction, safety improvement, and overall equipment performance enhancement in these industries.

4. Conclusions

This study highlights the significant effects of climb and conventional milling methods on the mechanical and corrosion properties of pure titanium sheets.

1. Hardness increase: The hardness of the machined samples, particularly in the climb milling method, reached 334 HV, demonstrating a notable improvement in mechanical strength and durability. This increase in hardness is attributed to structural modifications and work hardening at the surface. Consequently, titanium components processed via climb milling exhibit superior resistance to pressure and wear, making them highly suitable for military and petrochemical applications.
2. Wear reduction: The wear analysis revealed a lower material loss (9.99 mg) in climb-milled samples compared to 10.87 mg in conventional-milled samples, indicating enhanced wear resistance. This property is particularly beneficial in harsh industrial environments, such as the petrochemical sector, where components are constantly exposed to abrasive materials.
3. Corrosion rate decrease: The significant reduction in corrosion rate to 0.0003 mm/year in climb-milled samples, compared to 0.02 mm/year in conventional-milled samples, suggests an extended service life for titanium components, which is critical in both military and petrochemical environments.
4. XRD peak intensity reduction: The observed decrease in XRD peak intensities at 35° and 40° reflects structural modifications at the crystallographic level, correlating with the increased hardness and improved corrosion and wear resistance. These changes are likely due to the formation of crystallographic defects and internal stresses induced by milling, further enhancing the material's mechanical properties.

Overall, findings suggest that conventional milling is an effective strategy for improving the durability, wear resistance, and corrosion performance of titanium components, making it a preferred choice for industrial and military applications.

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Conflict of interest

The authors declare no financial interests or personal relationships that could have influenced the findings presented in this study.

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Data availability

All relevant data and findings have been presented in this manuscript. Additional details or supplementary information can be obtained by contacting the corresponding author via email.

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