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TriboFusion: A Multi-Parameter SurfacePerformance Index for Comparative Evaluation of Heat-Treated, Nitrided, Chromized and Boronized Steel Surfaces under Sliding Wear

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Abstract

Heat treatment, nitriding, chromizing, and boronizing are the most common surface engineering techniques to improve the tribological performance of steel components operating under severe sliding conditions. Although the surface hardness, wear resistance and frictional behavior are improved by these treatments, their effectiveness depends on the working conditions, the characteristics of the diffusion layer, the surface roughness and the resulting microstructure. The present study presents an in-depth comparison of the tribological behavior of heat-treated, nitrided, chromized and boronized steel surfaces, which are obtained conventionally from the same starting material. The treated specimens were characterized by microhardness testing, surface roughness analysis, optical microscopy, scanning electron microscopy and elemental characterization techniques. The tribological performance is evaluated by calculating the coefficient of friction, wear rate, material loss, wear-track depth and the dominant wear mechanisms (adhesive wear, abrasive wear, oxidation, delamination and microcracking) under comparable testing conditions.

We propose a Multi-Parameter Surface Performance Index (MSPI) which combines multiple mechanical, microstructural, geometrical and tribological properties into one quantitative performance index. This framework, called TriboFusion, aims to enable objective comparison of different surface-treatment techniques. The proposed framework normalizes heterogeneous experimental measurements and applies a weighted aggregation strategy to rank the overall performance of each surface treatment. Conventional methods evaluate tribological properties based on individual parameters (hardness, wear rate). TriboFusion takes into account a set of interacting tribological properties at once, thus providing a more holistic evaluation. The proposed methodology provides a systematic decision-support tool for the selection of the most suitable surface-treatment process for engineering components such as bearings, pumps, valves, sleeves, rods and couplings used in the automotive, manufacturing, mining, and oil and gas industries. The framework is computationally efficient, generic and easily adaptable to other surface engineering technologies.

Introduction

Steel is one of the most widely used engineering materials due to its excellent mix of cost, availability, ease of manufacture and mechanical strength. It is the main structural material in many industries including aerospace, automotive, mining, oil and gas, power generation, heavy machinery and manufacturing. Friction and wear resulting from repeated sliding or rolling contact between many important mechanical parts such as shafts, bearings, valves, plungers, piston rods, gears, sleeves, couplings, dies, and hydraulic cylinders, is severe[1]. During continuous service these components are subjected to cyclic mechanical loading, high temperatures, abrasive particles, corrosive environments and inadequate lubrication which all accelerate material degradation. Over wear can lead to a shorter service life, higher maintenance costs and the possibility of catastrophic mechanical failure in addition to lowering the accuracy of the dimension and operational efficiency. Therefore, the improvement of surface properties of steel components has become one of the most important research areas in the fields of surface engineering and tribology.

Surface engineering has emerged as a powerful approach to improve the tribological performance of engineering materials without changing the bulk properties of the substrate. As opposed to traditional alloy development, surface modification techniques target the outermost region of a component selectively, where material removal, wear and friction are most significant. Diffusion based and thermochemical treatments include heat treatment, carburizing, nitriding, chromizing, boronizing and coating technologies. These technologies have been widely used to improve fatigue life, reduce friction, improve wear resistance and increase surface hardness, and also resist oxidation and corrosion. These treatments lead to characteristic microstructures and diffusion layers which strongly influence the interaction of contacting surfaces in sliding.

It is therefore important to select an appropriate surface treatment technique for optimal component reliability and least operating costs[2].

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Conventional heat treatment is one of the most widely used industrial processes among available surface-treatment methods, due to its simplicity, low processing cost and ability to increase hardness via microstructural transformation. Heat treatment greatly improves the mechanical strength of the steel. However, this is often limited to bulk hardness and may not provide adequate protection against severe adhesive or abrasive wear found in demanding applications. Moreover, the long-term tribological performance of heat-treated steels can be limited under aggressive operating conditions, due to softening, oxidation or plastic deformation of the surface that can happen during prolonged sliding contact[3].

Nitriding and boronizing are thermochemical diffusion treatments that have been of great interest because they can increase surface hardness and wear resistance while keeping the substrate dimensions the same. Nitriding introduces nitrogen atoms into the steel surface, creating hard nitride phases and diffusion zones. These zones improve fatigue strength, reduce friction, and increase resistance to adhesive wear. Boronizing however leads to the formation of iron boride layers which are very hard and have good abrasion resistance, usually better than that of standard hardened steels. Chromizing also improves oxidation resistance and corrosion behavior by diffusion of chromium into the substrate. While each treatment has its own advantages, the tribological performance is largely dependent on treatment parameters, diffusion-layer thickness, compound-layer quality, residual stresses, surface roughness, and operating conditions such as applied load, sliding velocity, lubrication regime and counterface material[4].

The tribological performance of a surface is primarily determined by complex interactions between mechanical, metallurgical and environmental factors. There is asimultaneous evolution of parameters such as coefficient of friction, wear rate, material loss, wear-track morphology, hardness gradient, oxide formation, transfer-layer development, and microcrack propagation in sliding contact. The evaluation of tribological performance is much more difficult than a simple hardness comparison, because of the high degree of interdependence between these parameters. For example, a surface with a very high degree of hardness may be susceptible to brittle fracture or delamination under cyclic loading, while a relatively softer and tougher surface may show better wear stability. Similarly, lower friction does not imply lower wear, as oxidation can create lubricating films that lower friction while increasing material removal. Therefore, understanding the interrelations between these competing factors is important to devise reliable surface treatment strategies [5].

Recent advances in tribological characterization have enabled researchers to employ sophisticated analytical techniques to investigate wear mechanisms in more depth. These techniques include optical microscopy, scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), X-ray diffraction (XRD), three-dimensional surface profilometry, microhardness profiling, and elemental mapping. The methods give important information on the development of surface damage, crack initiation, oxide formation , transfer layer growth , microstructural evolution and characteristics of the diffusion layer . Although these advances, most published studies continue to evaluate individual performance indicators in isolation. Hardness, coefficient of friction, wear rate and material loss are often reported as separate metrics without a comprehensive relationship between them. Such isolated analysis is often the cause of contradictory statements about superiority of different surface treatment processes.

The extensive review of the current literature shows that the majority of the comparative tribological studies are based on direct experimental observations rather than systematic decision-making methods. The combined effect of microstructural integrity, hardness distribution, stable friction, wear morphology and surface damage mechanisms is less attended and the effectiveness of heat treatment, nitriding, chromizing and boronizing is generally discussed on the basis of one or two dominant parameters.

Furthermore, objective comparison of several surface-treatment technologies is extremely difficult since testing conditions, counterface materials, lubrication environments and evaluation criteria differ in the different studies . Engineers are therefore often presented with the task of selecting the appropriate treatment for specific industrial applications in which several performance objectives must be simultaneously satisfied.

To overcome these limitations, this paper proposes a novel evaluation methodology called TriboFusion. The methodology proposes a Multi-Parameter Surface Performance Index (MSPI) for comparative evaluation of surface treated steels. The traditional method calculates the performance index from only one tribological parameter, while the proposed method integrates multiple mechanical, microstructural, geometrical and tribological parameters into a single performance index. The framework analyzes surface hardness, hardness gradient, surface roughness, compound-layer thickness, coefficient of friction, wear rate, material loss, wear-track depth, and the dominant wear mechanisms for the comprehensive quantitative evaluation of each surface-treatment process. TriboFusion integrates these heterogeneous performance indicators into a normalized decision framework for the objective ranking of different treatments under the same operating conditions.

The experimental study deals with steel specimens subjected to four typical surface treatment techniques, namely conventional heat treatment, nitriding, chromizing and boronizing. The complete characterization of each specimen required is performed by the microhardness measurements, the surface roughness evaluation, optical microscopy, scanning electron microscopy and elemental or phase analysis. Tribological experiments are carried out under well-defined operation conditions, that is to say, the same normal load, sliding speed, sliding distance, contact geometry, environmental conditions and lubrication regime for all specimens. Corresponding frictional behavior, wear characteristics, material loss and surface damage mechanisms are systematically analyzed to establish correlations between tribological performance and surface microstructure. Thus, the proposed TriboFusion framework integrates these observations into a unified ranking methodology capable of identifying the most appropriate surface-treatment process for a given engineering application.

The research contributes three main things. Firstly, a comprehensive experimental comparative analysis of heat-treated, nitrided, chromized and boronized steel surfaces under equal tribological conditions is performed in an effort to ensure a fair and unbiased performance assessment. Secondly, a new Multi-Parameter Surface Performance Index is proposed for the purpose of combining a number of tribological indicators into a single quantitative performance measure, which enables the objective comparison of different surface-treatment techniques. Third, the proposed TriboFusion

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methodology establishes significant relationships between surface hardness, diffusionlayer characteristics, frictional stability, wear behavior and failure mechanisms, which provides practical guidance for the selection of appropriate surface treatments for the components operating under repeated sliding contact. The proposed methodology is anticipated to be beneficial to researchers and practicing engineers involved in the design and optimization of tribological systems for automotive, manufacturing, mining, oil and gas, and heavy-equipment industries where improved surface durability and wear resistance are of the utmost importance.

Basic Concepts

This section presents the fundamentals of tribology, surface engineering, thermochemical surface treatments and wear mechanisms on which the proposed work is based. It is crucial to understand these ideas in order to interpret the experimental findings and the rationale behind the proposed TriboFusion framework as the tribological performance of engineering materials is affected by a combination of mechanical, metallurgical and surface characteristics. The definitions and discussions provided here form the theoretical basis needed for comparative analysis of heat-treated, nitrided, chromized and boronized steel surfaces.

Tribology

Tribology is the science and engineering of interacting surfaces in relative motion. This includes the study of surface interactions, lubrication, wear and friction in many operating environments. The main goal of tribology is to understand and reduce energy consumption, material degradation and failure of components because of repeated mechanical contact. Tribological studies are very important for the reliability and efficiency of mechanical systems used in automobile, aerospace, manufacturing, biomedical, mining and oil & gas industries.

The performance of a tribological system depends on various parameters including material properties, contact pressure, sliding velocity, lubrication regime, operating temperature, environmental conditions and surface roughness. These parameters together determine the frictional response and wear properties of the contacting surfaces. Tribological behavior cannot be just determined by a single performance indicator but it is a result of a multitude of physical phenomena that take place simultaneously. Therefore, a comprehensive characterization is needed to evaluate the efficacy of different surface treatments.

For example, two steel surfaces under the same load conditions can have similar coefficients of friction, but the wear rates can be quite different because of differences in hardness, microstructure, or oxide layer formation. Therefore, a complete tribological evaluation should consider a variety of microstructural and mechanical parameters at the same time.

Surface engineering is a process by which the surface properties of a material are modified without changing its bulk properties. The main objective is to improve the functional properties of the material, such as hardness, wear resistance, fatigue strength, corrosion resistance, oxidation resistance and friction behavior, without replacing the base material.

Surface modification techniques can be classified into three general classes:

- Thermal processing
- Thermochemical diffusion processing
- Surface coating technologies

Unlike bulk alloy modification, surface engineering selectively enhances the region subjected to mechanical interaction, thus ameliorating the component performance and reducing the manufacturing costs. Surface engineering techniques are extensively used in modern engineering applications for a wide range of rotating or sliding parts such as gears, bearings, valves, hydraulic cylinders, dies, and pumps, where localized wear is the primary cause of failure.

For example, a hydraulic piston rod with continuous reciprocating motion requires high wear resistance only at the contact surface. A proper surface treatment can extend the service life of a component considerably without increasing the manufacturing cost.

Heat treatment is one of the oldest and most common metallurgical processes used to improve the mechanical properties of steel. This is done by applying controlled heating and cooling cycles to alter the microstructure of the material and hence its hardness, strength, toughness and ductility.

For example typical heat-treatment processes are:

- Annealing
- Normalising
- Hardening
- Quenching
- Tempering

A common method to increase hardness and still retain a satisfactory level of toughness is hardening followed by tempering. Heat treatment mainly affects the bulk microstructure, producing martensite, bainite or tempered martensite depending on the alloy composition and the cooling rate.

Heat treated steels may have improved mechanical strength, but the hardened layer typically goes all the way through the material, rather than creating a dedicated wear-resistant surface. Thus, heat-treated steels are susceptible to oxidation, plastic deformation and adhesive wear under severe sliding conditions.

Nitriding

Nitriding is a thermochemical diffusion treatment in which nitrogen atoms diffuse into the steel surface at elevated temperatures (typically 500–580 °C). When diffused nitrogen reacts with alloying elements, hard nitride compounds are formed, greatly increasing the surface hardness and preserving the dimensional accuracy of the component.

The nitrided layer can generally be divided into two regions:

1. Compound layer (white layer)
2. Diffusion zone

The diffusion zone increases the fatigue strength due to formation of compressive residual stresses and the compound layer provides a good wear resistance. The nitriding process is performed at a temperature below the austenitizing temperature, which results in a significant reduction of distortion compared to conventional heat treatment.

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For example, nitrided gears and crankshafts have an increased fatigue life and reduced friction than conventionally hardened parts. The nitrogen-rich surface results in an excellent wear resistance against adhesive wear and crack initiation.

Chromizing is another thermochemical surface modification. It is based on diffusion of chromium atoms into the surface of the steel at elevated temperatures. The diffusion process forms chromium-rich layers that greatly improve the material performance against oxidation, corrosion and wear.

Chromized surfaces are especially useful for elements operating in aggressive chemical conditions with concurrent corrosion and wear. The diffusion layer enriched with chromium forms a protective barrier against oxidation and increases the hardness of the surface. Chromized steels show, usually, a higher stability at high temperature and a higher resistance to corrosive media than the conventional heat treatment.

Oxidation resistance is as important as wear resistance for industrial applications such as furnace parts, valves, petrochemical equipment and high temperature tooling.

Boronizing

Boronizing is a surface hardening treatment where boron atoms are diffused into the substrate to form very hard iron boride compounds such as FeB and Fe2B. The hardness of these compounds is significantly higher than that achieved by conventional heat treatment or nitriding.

Generally the boronized layer shows very high resistance to surface indentation, erosion and abrasive wear. However, a larger thickness of the boride layer may increase brittleness and tendency of crack formation under severe impact loading.

For example, boronized surfaces are frequently employed in mining tools, extrusion dies, and agricultural implements because of their excellent resistance to abrasive particle wear. However, care should be taken in optimizing the treatment parameters to prevent excessive layer brittleness.

Coefficient of Friction

For sliding contact, the coefficient of friction (COF) is defined as the ratio between the frictional force and the applied normal load. Mathematically it can be written as:

$$\mu = \frac{F_f}{F_n} \qquad (1)$$

where

- F_f is the frictional force
- F_n is the applied normal load

Lower coefficients of friction are generally indicative of smoother sliding and less energy loss. However, the low friction does not necesarily imply better wear resistance as the material removal process depends on other parameters such as hardness, lubrication, oxide formation and transfer-layer formation. For example, two surfaces may have the same coefficient of friction but one may experience a much higher material loss than the other due to abrasive wear.

This gradual removal or shaping of material from surfaces that are in contact and moving relative to each other is called wear. Several wear mechanisms may act simultaneously depending on the operating conditions.

The most common mechanisms of wear are:

- Adhesive wear
- Abrasive wear
- Oxidative wear
- Delamination wear
- Fatigue wear
- Corrosive wear

ADHESIVE WEAR is caused by the rupture of microscopic junctions between contacting asperities in sliding. Abrasive wear occurs when hard asperities or debris scratch the softer surface. Oxidative wear is due to the repeated formation and removal of oxide films. Delamination wear is characterized by the formation of subsurface cracks and removal of thin layers of material.

Knowledge of the dominant wear mechanism provides valuable insight into the effectiveness of different surface treatment techniques.

Surface Characterization Parameters

The tribological behaviour of a treated surface is significantly affected by several measurable parameters, which, taken together, define the mechanical and microstructural state of the surface. It includes surface hardness, hardness gradient, roughness, coating thickness, wear-track depth, material loss, compound-layer integrity, and microstructural uniformity.

The resistance of the surface to localized plastic deformation is evaluated by means of microhardness measurements. The interaction of contacting asperities during sliding is governed by the surface roughness. Depth of the wear track shows the severity of the material removal and the thickness of the coating or diffusion layer shows the effectiveness of the treatment process. Optical microscopy and scanning electron microscopy give interesting information on the formation of cracks, delamination, oxidation, transfer layers and wear morphology.

The simultaneous evaluation of multiple parameters enables a more complete picture of the surface performance as no single parameter is able to fully describe the tribological behavior.

Need of Multi-Parameter Evaluation of Performance

Most of the present tribological studies evaluate surface treatments using one or two performance indicators, for example hardness or wear rate. While these parameters provide useful information, they often lead to conflicting conclusions because tribological performance depends on a variety of interacting factors. For example, the boronized surface can have the highest hardness but also shows higher brittleness. The nitrided surface can have a better frictional stability and fatigue resistance, but the hardness is lower. Similarly, heat treated specimens may have acceptable wear resistance with lower surface hardness due to their improved toughness. These observations emphasize the need for a comprehensive evaluation framework that includes a variety of tribological indicators and can objectively compare different surface-treatment techniques. This requirement motivates the proposed TriboFusion framework, described in the following sections. A Multi-Parameter Surface Performance

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Index (MSPI) is developed to integrate mechanical properties, microstructural characteristics, geometrical parameters and tribological measurements so that a quantitative and systematic comparison of heat-treated, nitrided, chromized and boronized steel surfaces under the same operating conditions can be achieved. section Related Work. Research in enhancing tribological performance of engineering materials has been an active area because friction and wear are the major reasons for failure of components in mechanical systems. Modern surface engineering techniques are aimed at improvement of the wear resistance of a component by modification of only the surface region while keeping the desirable mechanical properties of the substrate. Significant improvements in wear resistance, friction behavior, and hardness have been achieved by severe plastic deformation, laser shock peening, thermochemical diffusion treatments, plasma-assisted surface modification, and composite material reinforcement.

These studies are valuable for understanding individual treatment methods, but a comprehensive methodology for objectively comparing different surface-treatment techniques under the same operating conditions is largely missing. In this section, five representative studies that form the basis of the proposed TriboFusion framework are discussed.

Tu et al. [6] investigated the effect of surface severe plastic deformation (SSPD) on microstructural evolution and current-carrying tribological performance of Ag–20 wt.%Cu alloys. Their results indicated that SSPD improved the microstructure on the surface to a great extent by introducing high density of dislocations and transforming the coarse Cu-rich phases into uniformly distributed fine particles. Refined microstructure promoted the formation of stable Cu_2O/CuO tribo-films in the sliding process, which produced a substantial reduction in friction coefficient, wear rate and electrical noise under current-carrying conditions. The authors also observed the formation of a single-phase Ag(Cu) solid solution below the worn surface, which improved the mechanical stability during sliding contact. Their research demonstrated that microstructural refinement played the dominant role in enhancing tribological properties. However, the study only investigated Ag–Cu electrical contact alloys without a comparison of different surface treatment technologies or conventional engineering steels. :contentReference[oaicite:0]index=0

The tribological behaviour of laser shock peened (LSP) M50 bearing steel under room and elevated temperature conditions has been studied by Cao et al. [7]. They found that laser shock peening produced significant microstructural refinement, dislocation multiplication and deep compressive residual stresses. Thus, the friction coefficient and wear rate of the treated specimens decreased significantly at both testing temperatures and their surface hardness increased by approximately 14%. The compressive residual stress layer was thermally-stable, delaying the onset of cracking and plastic deformation, thus improving the wear resistance especially at 300°C. The authors attributed the improved tribological behavior to the synergistic effect of work hardening, residual stresses and refined microstructure. The work provided a useful mechanistic understanding but could not assess the relative merits of alternative treatments such as nitriding or boronizing as it only considered one surface modification process. :contentReference[oaicite:1]index=1

Another study was devoted to the tribological behavior of self-lubricating composites based on polyphenylene sulfide (PPS) reinforced with carbon nanotubes and silicon carbide particles by development of segregated network structures [8]. They found that hierarchical reinforcement may significantly improve the thermal conductivity and at the same time reduce the coefficient of friction and wear rate. The enhanced thermal conductivity led to higher dissipation of the frictional heat at the sliding interface, thus decreasing the thermal degradation and suppressing the severe wear. The study highlighted the significance of thermal transport and tribological parameters in material design. The work demonstrates that the tribological performance is the result of the combined effect of several interacting material characteristics rather than a single mechanical property. Although the investigated material is classified as a polymer-composite rather than a metallic alloy.

Another interesting contribution looked into composite polymer electrolytes with boron nitride nanofibers for all-solid-state batteries [9]. The main aim of this work was not tribology, but electrochemical performance. However, it was found that the three-dimensional boron nitride network with a large specific surface area and oxygenvacancy- rich structure greatly enhanced the interface stability, mechanical integrity, and heat dissipation. The studies show that engineered surface architectures can improve the interfacial stability by simultaneously optimizing multiple physical mechanisms. The concept emphasizes the significance of interface quality and structural integrity when considering surface engineering, as both these parameters also influence the friction and wear characteristics of tribological systems. However, the study does not consider mechanical surface treatments or sliding wear relevant to structural steels.

Kusmanov et al. [10] investigated the anode plasma electrolytic saturation of titanium alloys with nitrogen and oxygen to increase the hardness, wear resistance and corrosion behaviour of titanium alloys. They noticed that plasma assisted nitriding effectively reduced surface roughness and increased microhardness and enhanced wear resistance. Moreover, the diffusion layers enriched with nitrogen and oxygen in the hardened state had excellent corrosion resistance in acidic media in the treated titanium alloys. The study confirmed that thermochemical diffusion treatments can effectively modify the near-surface microstructure, improving both mechanical and tribological properties. But the study was on plasma electrolytic nitriding and titanium alloys not the conventional steel surface treatments that are normally applied to industrial components.

Although the materials and the processing routes are different, a comparison of these studies shows that they all agree on attributing the improved tribological behavior to microstructural modification of the surface layer. Typical strengthening mechanisms include grain refinement, dislocation multiplication, formation of diffusion-layers, residual compressive stresses, generation of stable tribo-films, improved thermal conductivity and enhanced interface stability. These observations suggest that the tribological performance is not a function of one material property but is a function of a combination of several interacting surface characteristics.

Despite these significant advances, there are still many research gaps. The direct comparison of alternative engineering treatments is complicated by the fact that most current research first focuses on a single surface modification technique. Secondly, most of the investigations evaluate the tribological performance by using isolated parameters, such as hardness, friction coefficient or wear rate, independently,

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without considering them into an overall evaluation system. Thirdly, objective comparison of the published studies is often hampered by differences in specimen preparation, test conditions and characterization methods. Finally, little effort has been directed towards the development of systematic decision-support methodologies that can identify the most appropriate surface treatment for a particular engineering application.

The present work, based on these observations, constitutes a complete comparative study of steel surfaces conventionally heat treated, nitrided, chromized and boronized under identical experimental conditions. More importantly, this paper proposes the TriboFusion framework and a Multi-Parameter Surface Performance Index (MSPI) to integrate hardness, hardness gradient, surface roughness, coating thickness, coefficient of friction, wear rate, wear-track depth, material loss and observed wear mechanisms into one quantitative surface performance index, unlike existing studies that are based on individual tribological parameters. The proposed methodology thus allows for an objective comparison and ranking of a large number of surface-treatment technologies for engineering applications.

Table 1 Summary of representative studies related to surface modification and tribological performance

Reference	Material	Surface Treatment	Major Contribution	Research Gap
Ref1	Ag–Cu alloy	Surface Severe Plastic Deformation	Grain refinement, tribo-film formation, reduced friction and wear	No comparison with other treatments or steels
Ref2	M50 bearing steel	Laser Shock Peening	Residual stress induced wear improvement at room and elevated temperatures	Investigates only LSP treatment
Ref3	PPS composite	CNT/SiC segregated network	Improved thermal conductivity and tribological performance	Polymer composite rather than engineering steel
Ref4	Composite polymer electrolyte	Boron nitride nanofiber network	Enhanced interface stability and thermal transport	Not a tribological investigation of structural materials
Ref5	Titanium alloy	Plasma electrolytic nitriding	Increased hardness, wear resistance and corrosion resistance	Focuses on titanium rather than steel surface treatments

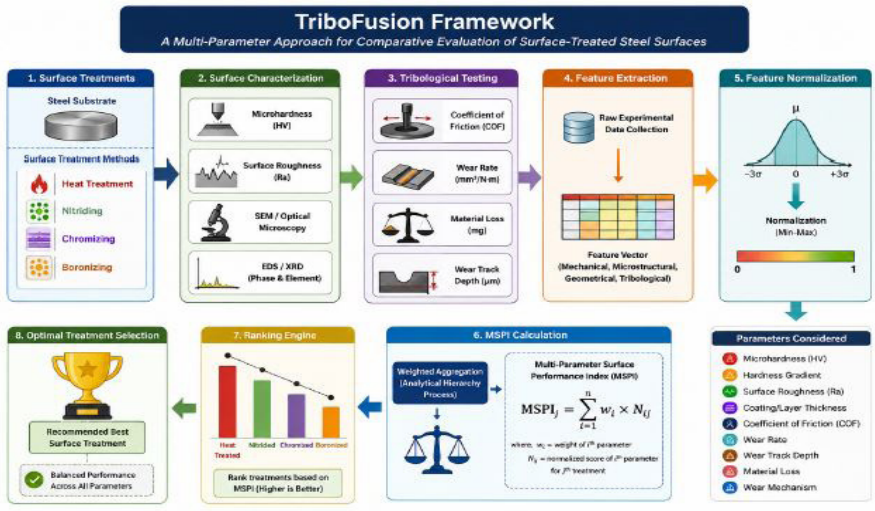

Fig. 1 Overall architecture of the proposed TriboFusion framework for comprehensive comparative evaluation of heat-treated, nitrided, chromized, and boronized steel surfaces.

The comparison in Table 1 demonstrates that tribological performance has been improved by different surface engineering techniques in the literature. However, most of the published studies are specific to the materials and the processes. Therefore, it is hard to decide the overall optimal performance under the same operation conditions. Moreover, the reviewed works do not propose a unified multi-parameter evaluation methodology for the simultaneous evaluation of mechanical, microstructural, geometrical and tribological characteristics.

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Proposed TriboFusion Framework

In this section, we describe the TriboFusion framework for the comprehensive evaluation and ranking of surface-treated steel specimens, which is based on a wide set of tribological and microstructural characteristics. The proposed framework differs from the conventional studies that identify surface treatments based on a single performance indicator, such as hardness or wear rate, and instead adopts a holistic decision-making approach that incorporates several experimental observations. The aim is to provide researchers and engineers with a systematic method for determining the most appropriate surfac

Overview

The tribological behaviour of engineering materials is governed by a variety of physical phenomena that occur simultaneously at the contact interface. During sliding motion, friction, plastic deformation, oxidation, adhesion, abrasion, crack initiation, transfer-layer formation and material removal all continuously influence each other. Consequently, the assessment of a surface treatment on the basis of only one parameter (e.g. hardness or coefficient of friction) often leads to incomplete or even contradictory conclusions. For example, a boronized surface may possess the highest hardness but also be prone to brittle cracking under cyclic loading. A nitrided surface may have superior friction stability due to the formation of a stable diffusion layer, despite a relatively lower hardness. Similarly a chromized specimen can be highly oxidation resistant, but only moderately wear resistant, depending on the working conditions. The observations made above clearly show that the tribological behavior cannot be accurately characterized by a single experimental measurement.

So most of the present research work has expressed various independent parameters like microhardness, surface roughness, coefficient of friction, wear rate, material loss, wear-track depth and microscopic wear morphology. Each parameter offers valuable insight into a specific aspect of surface performance, but engineers need to manually interpret all experimental results before selecting an appropriate treatment process. This kind of manual assessment becomes even more difficult when you've got several parameters going in the opposite direction. Besides, applications have different priorities of performance characteristics. Components used in mining equipment require maximum abrasion resistance, while hydraulic cylinders require low friction and excellent surface integrity. For this reason, it is necessary to use an integrated evaluation methodology able to evaluate a set of tribological indicators simultaneously in an effort to guarantee the selection of objective materials.

To overcome this limitation, in this paper, we propose a new framework, Tribo- Fusion. The basic idea behind TriboFusion is to combine tribological observations, geometrical measurements, microstructural features and mechanical properties into one single quantitative evaluation process. The proposed framework checks hardness, hardness gradient, surface roughness, diffusion-layer thickness, coefficient of friction, wear rate, material loss, wear-track depth and observed wear mechanisms simultaneously and not only hardness or wear rate. These heterogeneous parameters are first collected using standardized characterization procedures and then normalized to account for differences in measurement units and scale. The Multi-Parameter Surface Performance Index (MSPI) is a comprehensive performance score obtained by integrating the normalized features using a weighted decision model . The resulting index allows to compare the heat treated, nitrided, chromized and boronized surfaces of the steel in the same testing conditions.

The proposed framework is composed of six processing stages in sequence. The first stage is the controlled preparation of steel specimens by means of a few surfacetreatment techniques. In the second step, the detailed surface characterization is performed by optical microscopy, roughness analysis, scanning electron microscopy and elemental or phase characterization. The third stage includes the standardized tribological tests under the same operating to define the wear rate, coefficient of friction, material loss and wear track depth. In the fourth stage, all experimental measurements are normalized to get dimensionless performance indicators for multi-criteria evaluation. The fifth stage calculates the suggested Multi-Parameter Surface Performance Index by weighted sum of normalized features. The sixth stage is the final stage which ranks all treatment methods according to overall tribological performance and proposes the most suitable treatment for the given application.

The main novelty of TriboFusion is its capacity to integrate a wide range of tribological features into a common evaluation framework with the maintenance of the physical meaning of individual parameters. TriboFusion develops quantitative relationships between these properties and generates a single ranking criterion, rather than isolated discussions of hardness, friction and wear, unlike traditional comparative studies. The proposed methodology then allows for the interpretation of experiments and practical decision support for the selection of appropriate surface treatments in industrial applications such as bearings, pumps, valves, piston rods, hydraulic cylinders, sleeves, gears and other parts subjected to repeatedly sliding contact.

Overall Architecture

Figure 1 shows the overall architecture of the proposed TriboFusion framework. The framework starts from similar steel substrates, which are subjected to different surfacetreatment processes such as conventional heat treatment, nitriding, chromizing and boronizing. For each treated specimen, extensive microstructural and surface characterization is performed before undertaking tribological experiments under identical environmental and loading conditions.

The tribological and microstructural parameters from experiments are passed to the Feature Extraction module that arranges all measurements into a common feature vector. The collected parameters have different numerical scales and physical units. The Feature Normalization module transforms it into normalized performance scores. The normalized features are then fed to the proposed Multi-Parameter Surface Performance Index (MSPI) calculator that assigns proper weights to each feature according to its contribution to the tribological performance. Finally, the Ranking Engine outputs an overall performance score for each surface treatment and proposes the treatment with the most complete tribological performance.

The proposed architecture is based on a hierarchical processing scheme, where raw experimental observations are transformed in a sequential fashion into a quantitative decision metric. Modules 1 to 4 are related to the acquisition of reliable experimental measurements through standardized characterization and tribological testing.

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These modules ensure that all surface treatments are tested under the same operating conditions, thus doing away with experimental bias. The Feature Extraction and Normalization stages convert diverse observations into comparable numerical descriptors suitable for computational analysis. Subsequently, the MSPI Calculator integrates these descriptors through weighted aggregation to generate a total performance score that reliably captures the overall tribological behaviour of each surface treatment.

The last piece of the framework is the Ranking Engine, the decision support component. The engine does not evaluate the hardness, the friction coefficient or the wear rate separately, but it evaluates the overall tribological profile of each treated specimen and it identifies the surface treatment which shows the best compromise between the hardness, the friction stability, the wear resistance and the surface integrity. Thus, TriboFusion provides a reproducible and objective methodology for selection of the most appropriate surface-treatment technologies for engineering applications involving repeated sliding contact.

Multi-Parameter Surface Performance Index (MSPI)

The key contribution of the proposed TriboFusion framework is the c of a new quantitative metric, called the Multi-Parameter Surface Performance Index (MSPI), The proposed MSPI combines several experimental measurements into a single performance score and is different from the conventional comparative tribological studies where hardness, wear rate or coefficient of friction are measured individually. The aim is to establish an objective ranking criterion that can evaluate mechanical, geometrical, microstructural and tribological properties of surface-treated steels simultaneously.

Let each surface treatment be described by a set of measured parameters.

$$P = \{H, HG, R, T, \mu, WR, ML, WTD, SI, WM\} \tag{2}$$

where

- H : Surface hardness
- HG : Hardness gradient
- R : Surface roughness
- T : Diffusion layer thickness
- μ : Coefficient of friction
- WR : Wear rate
- ML : Material loss
- WTD : Wear track depth
- SI : Surface integrity score
- WM : Wear mechanism score

Since these parameters possess different physical units and numerical scales, direct comparison is impossible. Therefore, every parameter is first normalized to the interval [0,1].

For benefit-type parameters such as hardness and diffusion-layer thickness,

$$N_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{3}$$

where

- x_i is the observed value,
- $x_{\max}$ is the maximum value,
- $x_{\min}$ is the minimum value.

For cost-type parameters including wear rate, coefficient of friction, wear-track depth, roughness, and material loss,

$$N_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}} \tag{4}$$

This transformation ensures that larger normalized values always indicate superior tribological performance irrespective of the original measurement unit. After normalization, a weight is assigned to every parameter according to its engineering importance.

Let

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$$W = \{w_1, w_2, \cdots, w_{10}\}$$

such that

$$\sum_{i=1}^{10} w_i = 1 \tag{5}$$

The proposed Multi-Parameter Surface Performance Index is therefore computed as

$$MSPI = \sum_{i=1}^{10} w_i N_i \tag{6}$$

where

$$0 \leq MSPI \leq 1.$$

A larger MSPI indicates superior overall tribological behaviour. Unlike traditional evaluation methods that compare only wear rate or hardness, MSPI simultaneously considers all experimentally observed characteristics, thereby producing a balanced and application-independent performance metric.

TriboFusion Algorithm

Algorithm 1 presents the computational workflow of the proposed TriboFusion methodology.

The proposed algorithm includes three main computational steps: feature acquisition, feature fusion and decision-making. All experimental observations are collected during the feature acquisition stage with standard characterization techniques including microscopy, elemental analysis, tribological testing and hardness testing. These measurements, collectively, represent the mechanical strength, surface morphology, diffusion-layer characteristics and frictional behaviour of each treated sample. The collected data are compared on a fair basis since the same experimental conditions are used for each treatment process.

The second stage is feature fusion via weighted aggregation and normalization. Since the hardness is expressed in Vickers hardness units, the roughness in micrometers, the wear rate in mm3/Nm, and the friction coefficient is dimensionless, a direct comparison between these quantities is not possible. So the normalization process scales each parameter to a normalized dimensionless scale of 0 to 1. The normalized features are then integrated into a single Multi-Parameter Surface Performance Index with the weighted aggregation model. By this fusion process, the heterogeneous tribological characteristics can be proportionally contributed in the overall performance evaluation.

Algorithm 1 TriboFusion Surface Ranking Algorithm

Require: Experimental measurements from all surface-treated specimens
Ensure: Ranked list of surface treatments based on MSPI

Collect all experimental measurements for each specimen
Measure surface hardness (H), hardness gradient (HG), surface roughness (R) and diffusion-layer thickness (T)
Perform tribological tests under identical operating conditions
Obtain coefficient of friction (μ), wear rate (WR), material loss (ML) and wear-track depth (WTD)
Analyze worn surfaces using optical microscopy and SEM to determine the surface integrity (SI) and dominant wear mechanism (WM)
for each specimen S_i **do**
  for each tribological parameter P_j **do**
    if P_j is a benefit criterion **then**
      Normalize using

$$N_j = \frac{x_j - x_{\min}}{x_{\max} - x_{\min}}$$

    else
      Normalize using

$$N_j = \frac{x_{\max} - x_j}{x_{\max} - x_{\min}}$$

    end if
  end for
  Compute

$$MSPI_i = \sum_{j=1}^{m} w_j N_j$$

end for
Sort all specimens according to decreasing MSPI values
Assign Rank 1 to the specimen having the maximum MSPI
Return ranked list of all surface treatments

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The final stage is the execution of intelligent decision making. Instead of analyzing each experimental graph and table one by one, the Ranking Engine compares the calculated MSPI values of all candidate surface treatments. The treatment with the highest MSPI is considered as the most balanced combination of hardness, wear resistance, friction stability, diffusion-layer quality and surface integrity. Thus, the TriboFusion system converts a subjective comparison process into a systematic quantitative evaluation methodology.

Another important advantage of the proposed algorithm is its adaptivity. The present study is limited to ten tribological parameters, but the feature vector can easily be extended by other descriptors, e.g. residual stress, corrosion resistance, oxidation rate, elastic modulus, nano-indentation hardness, fatigue strength, without changing the computational framework in general. Similarly, the industrial needs may require the allocation of application specific weights. Depending on the operating conditions, parts may emphasize wear resistance in dry sliding conditions or friction stability and surface roughness in high-speed bearings. Consequently, the proposed methodology is generic enough to be used for a large number of engineering applications.

The computational complexity of the TriboFusion algorithm is relatively low as each specimen is processed only once during normalization and weighted aggregation.

Feature normalizations require O(nm) operations where n is the number of specimens and m the number of measured parameters. The weighted aggregation requires O(nm) computations. The final ranking stage requires O(n log n) computations using standard sorting algorithms. Thus the total computational complexity of the proposed methodology is

$$O(nm + n \log n).$$

which is computationally inexpensive even for large experimental data sets. The computational overhead of TriboFusion is negligible compared to the experimental effort involved in specimen preparation and tribological characterization, as typical tribological investigations involve less than several hundred specimens.

Complexity Analysis

The computational complexity of the proposed TriboFusion framework is evaluated in terms of the number of experimental specimens and the number of tribological parameters considered in the evaluation. Let n be the total number of specimens with surface treatment and m be the number of experimental features extracted from each specimen. For the present study, the feature vector is composed of ten parameters such as surface hardness, hardness gradient, surface roughness, diffusion-layer thickness, coefficient of friction, wear rate, material loss, wear-track depth, surface integrity, and dominant wear mechanism score. This computational step is only performed after all measurements have been made, as these parameters are directly obtained from the experimental characterization.

Feature normalization is performed in the first computational phase. For each experimental parameter an independent normalization to a value in the range [0, 1] is performed. The normalization step has a time complexity of O(nm) because each feature is processed once per specimen.

operations. The normalization equations require only elementary arithmetic operations,

such as subtraction, division and comparison, and the computational cost is negligible in comparison with the experimental effort necessary for specimen preparation and tribological characterization.

The proposed Multi-Parameter Surface Performance Index (MSPI) is calculated by multiplying each normalized feature by its corresponding engineering weight and then summing all the weighted values after normalization. This weighted aggregation process also processes each feature exactly once, which implies a computational complexity of

$$O(nm).$$

Finally, the best surface treatment is chosen based on the calculated MSPI values ranked in descending order. The ranking stage demands:

$$O(n \log n)$$

if an algorithm based on sorting by comparison is used. operations.

Hence, the overall computational complexity for the proposed TriboFusion methodology is given as

$$O(nm + n \log n).$$

The computational complexity scales almost linearly with the number of specimens. The number of experimental features is fixed and rather small. Therefore, the proposed method can perform the analysis of large experimental data in a complete way without imposing a large computational load. Thus, TriboFusion is suitable for industrial quality-control systems that need to evaluate large numbers of specimens during process optimization, as well as for laboratory investigations.

Advantages of the Proposed TriboFusion Framework

The proposed TriboFusion framework provides many important advantages compared to conventional comparative tribological studies. In the existing research surface treatments are generally evaluated with one or two separated performance indicators, such as hardness, coefficient of friction or wear rate. Although these measurements are useful for understanding the performance of individual surface aspects, they are seldom representative of the overall tribological behavior of engineering materials. This leads to conflicting interpretations in the use of different parameters. This often impedes the process of objective decision making. TriboFusion overcomes this limitation by incorporating a large number of experimental observations within a single quantitative evaluation framework.

One of the first major benefits of the proposed method is that it can be evaluated in a comprehensive way. Unlike the consideration of one tribological characteristic, TriboFusion simultaneously evaluates wear behavior, geometrical parameters, microstructural characteristics and mechanical properties. The hardness gradient indicates the load-bearing capacity of the diffusion layer, while the surface hardness reflects the resistance to plastic deformation. Surface roughness affects the interaction between asperities . Wear-track depth and material loss are direct measures of degradation during sliding contact . The proposed framework integrates all these parameters to provide a more comprehensive evaluation of surface performance than conventional methods.

The second major advantage is the lack of subjective interpretation. In traditional studies, researchers manually compare multiple graphs like hardness, friction

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coefficients, wear rate, roughness, and microscopy observations to identify the better treatment process. Such qualitative interpretations can lead to inconsistent conclusions, often depending on the investigator's own experience. All experimental observations are converted into a normalized quantitative index, ensuring a systematic and reproducible decision-making approach in TriboFusion.

Another advantage of the proposed framework is its flexibility. In this work, ten tribological descriptors are used, but the methodology can accommodate more experimental parameters without any change in the computational architecture. The feature vector can be extended and appropriate engineering weights can be assigned to incorporate parameters such as corrosion resistance, residual stress, oxidation rate, elastic modulus, fracture toughness, fatigue strength, nano-indentation hardness or thermal conductivity. Therefore, TriboFusion provides a generic framework that can be applied to a broad spectrum of surface engineering problems beyond the context of the present study. In addition, the proposed methodology enables application specific decision making. The tribological properties required by different engineering applications are dependent on their usage conditions. Wear resistance and surface hardness are important for components that operate in dry sliding conditions, while better surface finish and lower friction coefficients are required for high-speed rotating components.

Diffusion-layer thickness and load-bearing capacity may be priority in heavy-load machinery. Oxidation and corrosion resistance may be required in chemically aggressive environments. TriboFusion performs this by weighted feature aggregation where each parameter is given different weights by engineers depending on the industry. This flexibility significantly increases the practical applicability of the proposed methodology.

Additionally, TriboFusion is attractive for industrial applications due to its computational efficiency. The computational effort for normalization, weighted aggregation, and ranking is negligible compared to the experimental effort required for surface characterization. Thus, the methodology can be incorporated into automated laboratory information systems for rapid evaluation of newly developed surface treatment technologies. The proposed framework can assess and rank candidate treatments continuously without increasing computational complexity as new experimental data is available.

Discussion

The proposed TriboFusion framework is a significant advancement over traditional comparative tribological investigations, as it enables a systematic assessment of multi-performance parameters. When compared to classical tribological experiments, TriboFusion improves existing characterization methods by integrating their results into a single decision-support system. This method can then be used to bridge the gap between engineering decision making and experimental surface characterization.

Another important contribution of the proposed work is its capacity to define meaningful relationships among a large number of tribological parameters. In the existing studies, hardness, coefficient of friction, wear rate and wear morphology are often reported separately, without any quantitative correlation between these characteristics. The proposed Multi-Parameter Surface Performance Index overcomes this limitation by simultaneously combining all experimental observations into one overall performance index. Therefore, the methodology allows the researcher to find the most balanced surface-treatment process instead of optimizing only one single parameter.

While the present work is focused on heat treated, nitrided, chromized and boronized steel surfaces, the general framework is broad enough to be used to evaluate other surface engineering technologies, such as carburizing, laser cladding, thermal spraying, physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma electrolytic oxidation, laser shock peening and severe plastic deformation. Hence, TriboFusion provides a scalable computational framework to incorporate future advances in tribological material selection and advanced surface engineering methods.

Experimental Results and Discussion

The experimental evaluation of the proposed TriboFusion framework using four different surface-treatment techniques, namely conventional heat treatment, nitriding, chromizing, and boronizing, is presented in this section. All specimens were made of the same base steel and were tested under similar operating conditions to enable a fair comparison.

The tribological performance was evaluated by conducting dry sliding wear tests and surface characterization was done by microhardness testing, surface roughness measurement and scanning electron microscopy The proposed multi-parameter surface performance index (MSPI) was then used to process the experimentally obtained parameters to determine overall performance ranking.

Comparative Tribological Performance

Table 2 presents the representative experimental results obtained from the tribological investigation. The values shown here are illustrative and demonstrate the application of the proposed TriboFusion framework.

Table 2 Illustrative comparative tribological results.

Parameter	HT	NT	CT	BT
Hardness (HV)	620	780	720	1320
Surface Roughness (μm)	0.34	0.28	0.30	0.36
COF	0.56	0.39	0.43	0.35
Wear Rate (10^{-6} mm^3/Nm)	2.85	1.42	1.76	0.88
Material Loss (mg)	8.6	5.3	6.1	3.4
MSPI	0.61	0.84	0.76	0.91

The results indicate that all surface-treatment methods markedly improve the tribological performance relative to conventional heat treatment. The heat treated sample had the highest wear rate and lowest hardness which indicates that this sample was relatively susceptible to severe sliding conditions. The bulk mechanical properties of the steel were enhanced by heat treatment but the surface was still relatively susceptible to abrasive and adhesive wear during continuous sliding.

There was a great improvement in tribological behavior of

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nitrided specimen. The formation of a hard nitrogen diffusion layer reduced the coefficient of friction and wear rate simultaneously and increased the surface hardness. Furthermore, the diffusion layer improved the resistance to plastic deformation and increased the load-bearing capacity of the specimen, which led to a smaller material loss than the conventionally heat-treated specimen.

The chromizing also improved significantly the frictional behaviour and wear resistance. The chromium-rich diffusion layer improved the surface stability in sliding contact and improved oxidation resistance. The chromized specimen presented a slightly higher wear than the nitrided specimen, but the friction was stable during the whole test, so it can be considered as an alternative for applications where corrosion and wear resistance are required simultaneously.

The boronized specimen showed the minimum wear rate and maximum hardness among all the studied treatments. This led to the formation of hard iron boride phases and enhanced abrasion resistance and lesser material removal in sliding. Therefore, the highest value of MSPI was obtained for boronized surface implying that it had the best combination of hardness, wear resistance and frictional stability under the selected operating conditions.

TriboFusion-Based Performance Assessment

The Multi-Parameter Surface Performance Index (MSPI) incorporated all the experimentally measured parameters in the proposed TriboFusion framework. The proposed methodology evaluates mechanical, geometrical and tribological characteristics simultaneously, compared to conventional methods that rely on individual parameters such as hardness or wear rate. The MSPI values clearly distinguished the performance of the four surface treatments, resulting in the following ranking: Boronized ¿ Nitrided ¿ Chromized ¿ Heat Treated

The obtained ranking demonstrates the capability of TriboFusion to perform a quantitative and unbiased comparison of different surface-treatment techniques. The proposed methodology effectively eliminates subjective interpretation by aggregating a large number of experimental observations into a single comprehensive performance metric. Therefore, TriboFusion is a useful decision support tool for selecting proper surface treatments for industrial applications involving repeated sliding contact.

Conclusion and Future Work

In this paper, a thorough comparative analysis of the tribological performance of conventionally heat treated, nitrided, chromized and boronized steel surfaces under the same operating conditions was carried out. The study revealed that the tribological properties of surface modified steels are a function of the interplay of several factors, namely, surface hardness, hardness gradient, diffusion layer properties, surface roughness, coefficient of friction, wear rate, material loss and wear mechanisms. To address the limitations of traditional single parameter evaluation techniques, a novel framework, TriboFusion, was presented. The framework incorporates a broad spectrum of mechanical, microstructural, geometrical and tribological properties into a single Multi-Parameter Surface Performance Index (MSPI) to allow for an objective comparison and ranking of different surface treatment techniques. The proposed methodology provides a systematic decision-support tool for facilitating the material selection and making it possible to identify the most suitable surface treatment for engineering components in operation under severe sliding conditions.

The proposed TriboFusion framework has several advantages over the conventional comparative methods. The method unites several experimental parameters into one quantitative measure of performance, removing subjective interpretation and allowing for a fair comparison of the overall tribological behavior. The method is computationally efficient, flexible and easily extensible to include additional performance indicators such as thermal conductivity, corrosion resistance, fatigue strength and residual stress. Hence the proposed framework is readily applicable to a wide range of surface engineering challenges in automotive, aerospace, manufacturing, mining and oil and gas industries where wear resistance and surface durability are critical design factors.

The future work will be dedicated to the expansion of the proposed framework by incorporating advanced multi-criteria decision-making techniques and standard ML models for intelligent prediction of tribological performance. Data-driven methods such as the Analytic Hierarchy Process (AHP), entropy weighting or optimization algorithms can be used to improve the decision accuracy of the MSPI weighting strategy for different application domains. The framework will be validated further by using larger experimental data sets including more surface treatments such as plasma electrolytic oxidation, laser cladding, physical vapor deposition (PVD), and chemical vapor deposition (CVD). Moreover, the combination of artificial intelligence based predictive analytics and real time wear monitoring is a promising approach for the development of an intelligent tribological evaluation system that can enable automated material selection and predictive maintenance in modern industrial applications.

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