June 2025| Vol. 5| Issue 2

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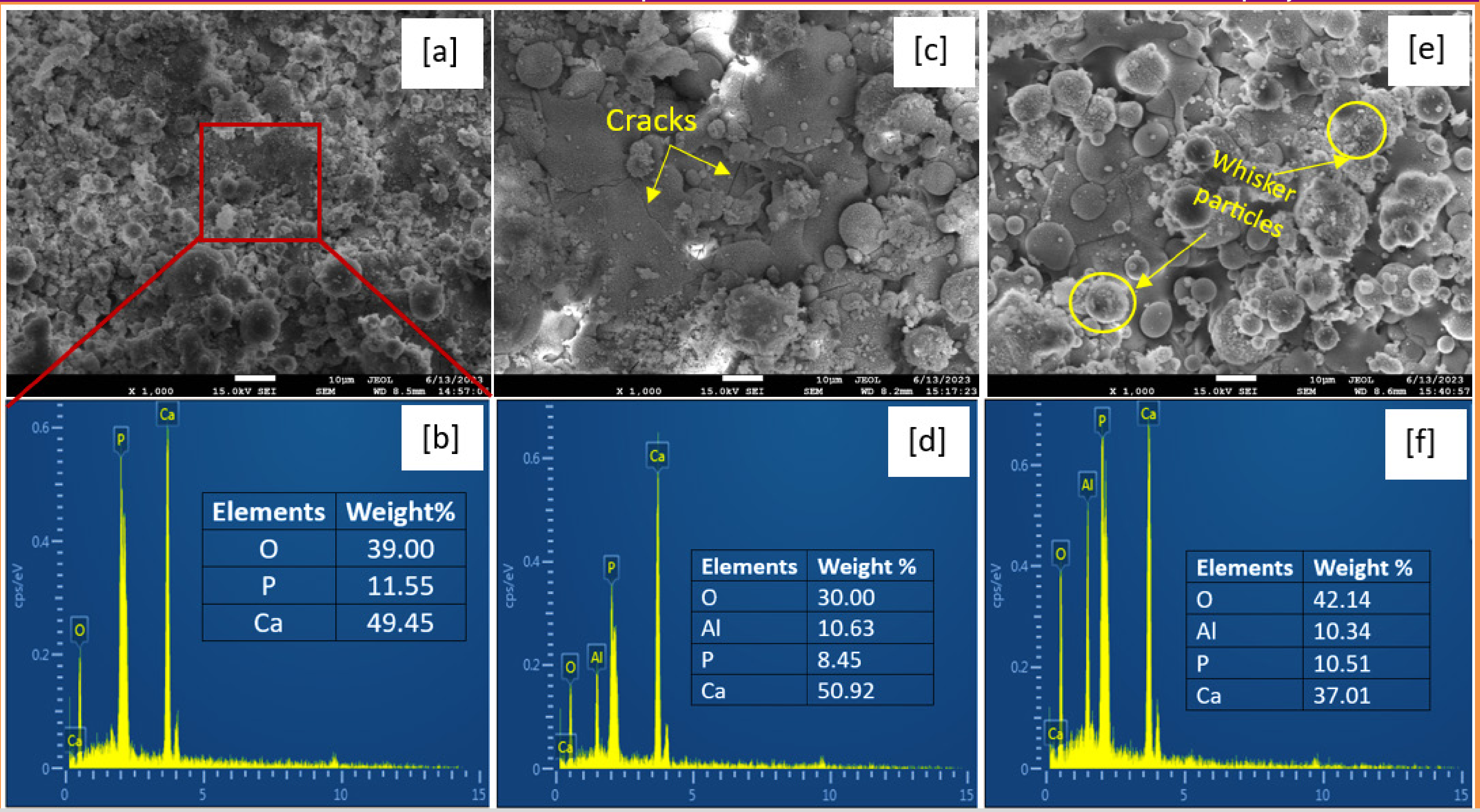

Issue Highlights

- Extreme Condition Tribology: An Overview of Friction, Wear, and Lubrication
- Biocompatibility and Corrosion Performance of HA-Based LVOF Sprayed and Post-Annealed Coatings on SS 254 Surgical Grade Bio-Implant Material
- Thermal Spray Coatings for Biomedical Applications: A Brief Overview
- Call for Papers - International Cold Spray Conference & Expo 2026

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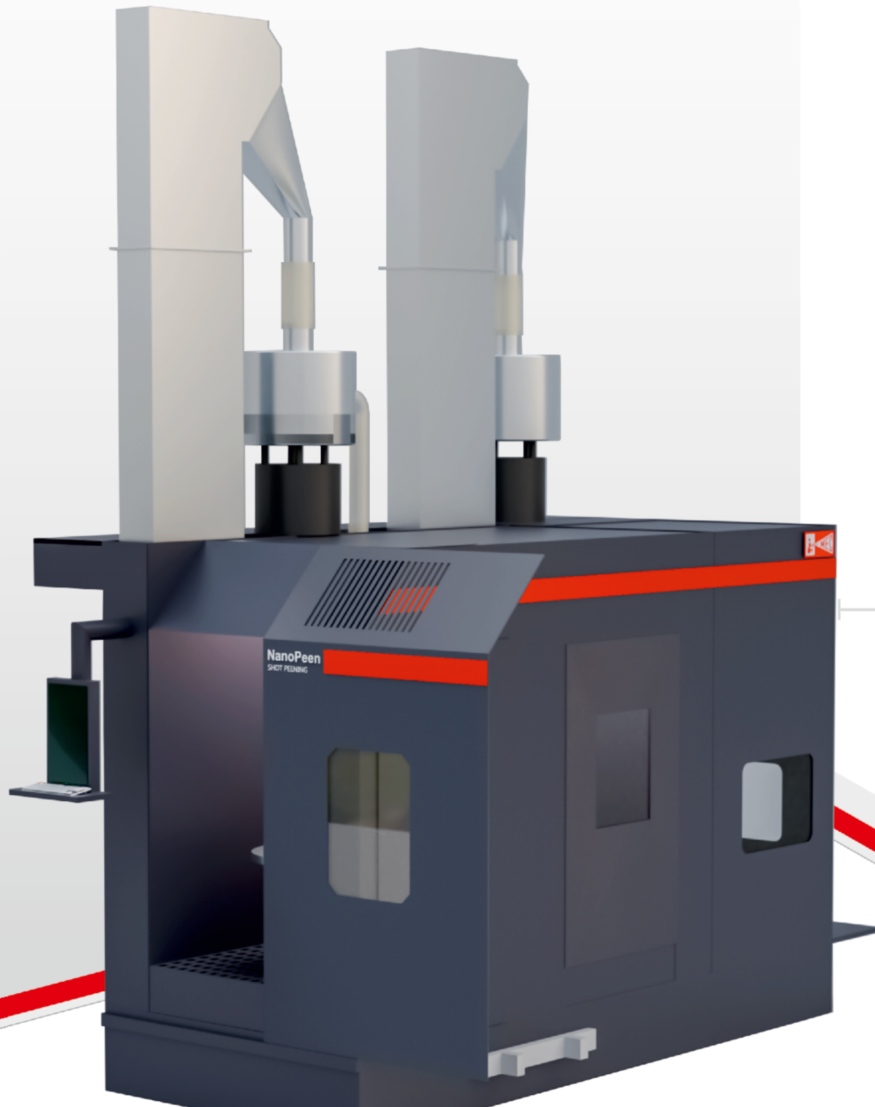

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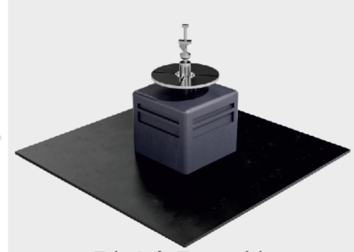

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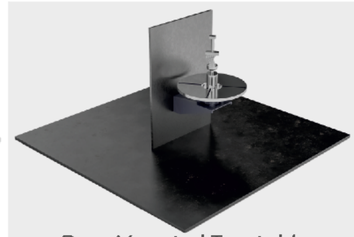

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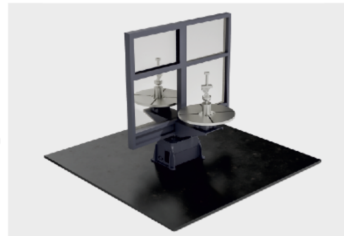

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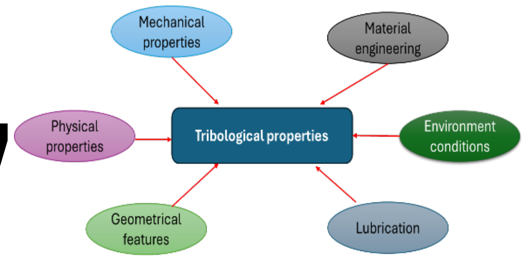

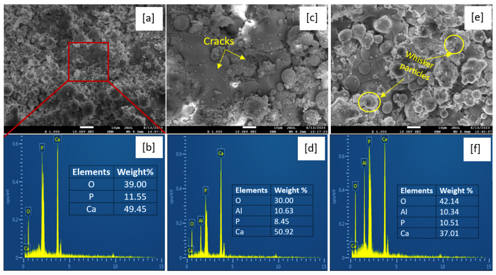

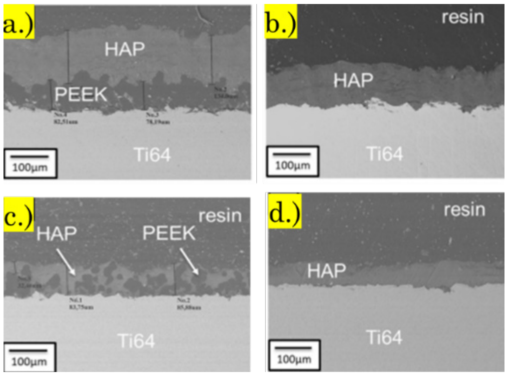

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ABOUT THE COVER

FESEM and EDAX micrographs of as-sprayed coatings (a&b) HA (c&d) HALM and (e&f) HALN

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Editor’s Note

Dear Readers,

Welcome to the latest edition of SPRAYTODAY Magazine, your premier source for all things related to thermal spray technology. We are excited to bring you this issue, which reflects the latest advancements and trends in the thermal spray field.

I am particularly pleased to be allowed to recommend to you the latest issue of SPRAYTODAY. This issue includes invited innovative featured articles on “Extreme Condition Tribology: An Overview of Friction, Wear, and Lubrication; Biocompatibility and Corrosion Performance of HA-Based LVOF Sprayed and Post-Annealed Coatings on SS 254 Surgical Grade Bio-Implant Material; Thermal Spray Coatings for Biomedical Applications: A Brief Overview, that illustrate current research trends in thermal spray development.

We are excited to announce our upcoming event on cold spray: The international cold Spray Conference and Expo (ICSC 2026), will be held on Jan 23-25, 2026, at the IITM Research Park IIT Madras, Chennai. This conference will serve as a hub of innovation and collaboration for cold spray technology. More than 350+delegates, including leading experts, researchers, and industry professionals from around the globe will attend the ICSC2026 to discuss cutting-edge developments, share insights, and explore the future of cold spray technology in the world. With a robust lineup of keynote speeches, technical sessions, and an expansive expo will be showcasing the latest equipment, materials and recent developments. The conference significantly will contribute to learning about the latest advancements and understanding the new applications of Cold spray technology. ICSC2026 website https://www.indtsa.org/icsc-2026

As we navigate the pages of this magazine, let's collectively embrace the spirit of innovation and collaboration. The thermal spray community in India is not just witnessing change; it is driving it. We hope this edition sparks inspiration, fosters knowledge exchange, and fuels the passion for pushing the boundaries of thermal spray technology.

Thank you for being part of our journey.

Be healthy, active, and curious! Happy Spraying!

Best Regards,

(Satish Tailor | PhD)


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Extreme Condition Tribology: An Overview of Friction, Wear, and Lubrication

by ***Amit Kumar[1], Satish Tailor[2]***

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Abstract
With the rapid industrialization there is an increase in demand for energy efficient mechanical systems. Within extreme environments like high temperatures, cryogenic conditions, vacuum conditions, and high-load conditions present multifaceted tribological challenges. In such rigorous circumstances, traditional materials and lubricants are unable to exhibit its efficacy, leading to rise in friction, accelerated wear, and an increased likelihood of failure. High temperatures lead to oxidation, thermal expansion, and material softening, while cold environments cause brittleness and lubricant failure. This review highlights the influence of such environments on friction, wear, and lubrication behaviours. Approaches such as minimum quantity lubrication (MQL), the utilization of cryogenically stable materials, and solid lubricants are used as viable solutions. Understanding the tribology in these conditions will help in the development of advanced materials and methods to improve the efficacy of the components and the system.

Introduction
In recent years, industrialization has seen rapid growth in terms of material advancement and technical advancement along with energy efficiency. With these, mechanical systems frequently encounter extreme conditions that exceed conventional design parameters. This harsh environment possesses significant risks to the efficacy and durability of the systems. Tribology plays an important role in mitigating these risks by investigating the friction, wear and lubrication among the mating surfaces in relative motion. Initially articulated by Dr. H. Peter Jost in 1964, tribology constitutes an interdisciplinary field that integrates principles from mechanical engineering, materials science, and surface chemistry. Its importance turns especially evident under conditions where traditional materials and lubrications methods are susceptible to failure. These not only are a threat to system efficacy but also play a substantial role in global energy consumption. About 23% of the energy are lost due to friction and the degradation of the material.[1] This loss figure of energy shows the significant need inn enhancing the energy efficiency by the implementation of advanced tribological methodologies. These improvements consist of wear-resistant coatings, materials with long durability, and novel lubrication techniques. Figure 1 shows the important aspects of tribological properties. These collectively influence the friction, wear and lubrication dynamics and show the interdisciplinary aspects of tribology. Among them, environmental conditions play an important role in determining the methods and materials for improving the efficiency of the system. Subsequently, the enhancement of tribological systems not only fosters improved operational efficiency but also aligns with broader objectives of sustainability and economic viability.

Nevertheless, extreme environmental conditions present unique challenges that often undermine traditional tribological principles. In vacuum environments, the lack of atmospheric moisture can lead to lubricant evaporation and increased surface adhesion, thereby elevating the risk of cold welding and component seizure. In cryogenic environments, materials demonstrate a heightened susceptibility to brittleness, while conventional lubricants may either solidify or completely lose their lubricative performance. Elevated temperature conditions accelerate oxidation and thermal degradation, thus compromising the functionality of both lubricants and structural materials, which in turn hastens wear. Additionally, when facing major mechanical stress, the stresses at contact points could exceed the yield strength of the materials involved, leading to plastic deformation, surface deterioration, and the start of subsurface crack formation.[2] To alleviate these challenges, modern tribology incorporates sophisticated materials and surface engineering techniques. Selection of suitable lubricants like such as molybdenum disulfide, graphite, and diamond-like carbon is key to minimizing friction and thermal wear. Moreover, pioneering methodologies such as minimal quantity lubrication (MQL), cryogenic cooling, and the utilization of ionic or nano-lubricants offer sustainable approaches for the management of friction and wear across a variety of industrial applications. This article examines how scientific progress in the field of tribology effectively addresses these challenges, thereby facilitating the optimal performance of machinery under critical operational conditions.

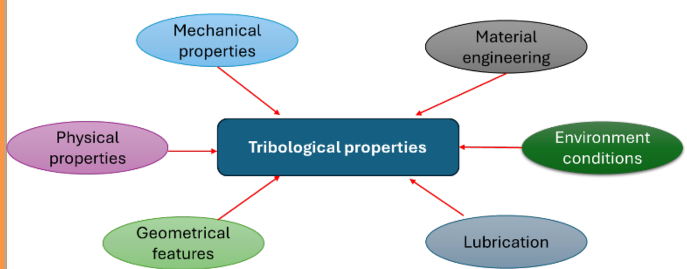

Figure 1: A schematic representation illustrating the various tribological properties

Friction in extreme conditions

Friction represents a fundamental force within all mechanical systems that exhibit relative motion. Although it frequently contributes to energy dissipation and the degradation of components, it also assumes a crucial function in the regulation of movement—evident in braking systems or gripping mechanisms across a diverse array of engineering applications. Under typical environmental conditions, the behaviour of friction generally adheres to well-established theoretical principles, influenced by variables such as surface roughness, normal load, and the presence of lubrication. Nevertheless, in extreme operational environments, including outer space, cryogenic temperatures, high-temperature industrial processes, or heavily loaded interfaces, the characteristics of friction can undergo significant alterations. These severe conditions engender intricate surface interactions and material responses that transcend the parameters of classical friction models, thereby necessitating specialized analytical approaches and engineering solutions.

A primary challenge encountered within these extreme environments is that friction demonstrates an increased susceptibility to fluctuations in material properties and environmental conditions. For instance, under elevated thermal conditions, frictional behaviour is considerably affected by mechanisms such as thermal expansion, material degradation, and oxidation reactions. As the temperatures of surfaces increase, there is a potential loss of hardness, which may lead to an augmented real contact area and, in numerous instances, enhanced adhesion. This phenomenon frequently culminates in unstable friction coefficients. Notably, certain high-temperature scenarios experience an initial decline in friction due to material softening, followed by a precipitous increase as surface degradation advances. Oxide layers that form at high temperatures may either reduce or intensify friction, depending on their thickness, composition, and how they interact with the opposing surface.[3]

On the other hand, extremely low temperatures such as those encountered in cryogenic or polar environments present their own challenges. Most metals undergo a ductile-to-brittle transition, meaning that instead of deforming plastically under stress, they tend to fracture. This brittleness affects surface behaviour during contact, increasing the likelihood of cracking and material removal. In addition, many lubricants either become too viscous to flow or freeze entirely at such low temperatures, leaving surfaces exposed to dry contact. In some cases, even the presence of frost or condensed moisture can alter friction unpredictably, depending on the sliding speed and the type of materials in contact.

Vacuum conditions, like those found in outer space, bring yet another layer of complexity. In the absence of atmospheric gases, protective surface films such as oxides and water vapor cannot form. This increases the likelihood of cold welding—where two metal surfaces adhere strongly due to atom-to-atom contact at asperities. As a result, friction levels rise significantly, and components may seize. Traditional lubricants cannot be used in vacuum because they tend to evaporate or degrade rapidly. [4]

With this understanding, selection of materials and coating should be done with utmost care, which mostly relies on self-lubricating surfaces and solid lubricants to mitigate these issues.

In scenarios characterized by extreme mechanical loads, such as those present in rail-wheel interfaces or high-velocity rotating machinery, the contact pressures can attain magnitudes sufficient to surpass the yield strength of the constituent materials. This phenomenon engenders plastic deformation, an elevation in interfacial shear

stress, and an augmented propensity for micro-welding between the contacting surfaces.[5] Consequently, the outcome frequently manifests as a non-linear frictional response, wherein surface damage accrues rapidly, particularly when debris resulting from wear becomes lodged within the contact zone.
Furthermore, it is essential to acknowledge that extreme environments rarely involve a solitary stressor. For example, a component of a satellite may simultaneously experience both vacuum conditions and significant thermal variations. Similarly, elements within jet engines may encounter both high thermal loads and mechanical stress. Therefore, the understanding of friction in such contexts requires a comprehensive approach, integrating material science, surface chemistry, thermal dynamics, and mechanical loading.

Wear in extreme conditions

The occurrence of wear under extreme operational conditions presents a complex challenge, fundamentally altering the conventional mechanisms and behaviours that are typically observed under standard operational environments. In scenarios involving elevated heat, materials frequently undergo thermal softening, resulting in a drop in hardness and a heightened risk of wear. However, temperature also assumes a crucial role in the formation of protective oxide layers, which may serve to alleviate wear rates. Within the framework of metals and composites, transitions from abrasive wear to oxidative and delamination wear mechanisms are frequently recorded as temperature levels rise. The presence of boron nitride or carbide particles in aluminum composites results in better wear resistance at high temperatures, which is associated with the protective oxidation layers formed.[6]
In a similar vein, specialized coatings such as tungsten carbide-cobalt and CoCrMo-based composites employ tribochemical films to enhance wear resistance at thermal conditions nearing 1000°C. Advanced materials, including high-entropy alloys and MCrAlY coatings, also demonstrate promising wear performance at high temperatures, owing to their oxidation-resistant surface layers. However, at excessively high temperatures, these protective layers may undergo degradation, resulting in significant wear and material failure.

Conversely, the wear exhibited at extremely low temperatures presents unique challenges. With mechanical stress, materials frequently exhibit a rise in brittleness, resulting in micro-cracking and fractures that are brittle. Cryogenic environments, as encountered in space or polar applications, necessitate materials and surface treatments that can endure embrittlement and reduce plasticity. In metals, the ductile-to-brittle transition becomes a dominant failure mechanism. In polymers, increased hardness at low temperatures can improve wear resistance, but surface embrittlement remains a major concern. Certain polymers like PTFE and composites filled with MoS_2 maintain favourable friction and wear properties even at cryogenic temperatures, making them suitable for space and deep-cold applications. [7]

In vacuum environments, the absence of protective surface films accelerates adhesive and fatigue wear. When surfaces come into contact in a vacuum, the lack of moisture and gaseous layers increases direct metal-to-metal adhesion. This leads to stronger junction formation, higher friction forces, and more severe material transfer and surface damage. Dissimilar material pairs may reduce wear severity, and alloying elements that promote the formation of thin protective layers can mitigate adhesive wear. Fatigue wear plays a critical role in a vacuum environment, where cyclic stresses instigate subsurface fissures, ultimately culminating in material detachment. [4]

The wear characteristics under conditions of extreme mechanical loading, as observed in bearings, rail-wheel systems, and heavy-duty machinery, hold equal importance. Elevated contact stresses can provoke subsurface fatigue, leading to the initiation and propagation of cracks. Recurrent stress cycles ultimately result in phenomena such as material spalling, pitting, or delamination. In rail systems, for example, the combination of cyclic loading with contaminants such as sand intensifies abrasive wear and accelerates the onset of fatigue damage. For polymers subjected to cyclic loads, fatigue wear is manifested through microcracking and surface roughening, significantly influenced by thermal effects occurring at the tips of cracks.[8,9]

To alleviate wear in demanding environments, strategies that integrate wear-resistant coatings, high-entropy alloys, solid lubricants, and surface treatments are extremely important. A solid insight into the elaborate dynamics among material features, working environments, and surface interactions is necessary for refining the durability and operational effectiveness of components that endure extreme scenarios. Ongoing research and innovation within the fields of material science and tribological engineering are instrumental in advancing dependable solutions for these challenging applications.

Lubrication in extreme conditions

Lubrication is fundamental in mitigating friction, diminishing wear, and augmenting the operational efficiency and lifespan of mechanical systems. Although typical lubricants, including oils, greases, and synthetic fluids, can show satisfactory functioning in usual operating scenarios, their effectiveness is often undermined in extreme conditions defined by elevated temperatures, cryogenic states, vacuum, and large mechanical loads. Under such rigorous circumstances, the functionality of traditional lubricants is adversely affected due to phenomena such as thermal degradation, solidification, evaporation, or chemical instability, thereby necessitating the formulation of specialized lubrication methodologies.[10]

In scenarios involving elevated temperatures, fluid lubricants encounter formidable challenges. Mineral oils and greases generally exhibit degradation, oxidation, or viscosity loss when subjected to temperatures exceeding 150–300°C, resulting in a significant reduction in film strength and protective capabilities. [11] Solid lubricants, specifically molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), graphite, and hexagonal boron nitride (h-BN), demonstrate exceptional stability when subjected to high-temperature environments, thus preserving their lubrication capabilities even more than 500°C. In particular extreme applications, composite materials that integrate solid lubricants, such as silver and fluoride-based eutectics, provide lubrication across an extraordinarily broad temperature spectrum. Also, innovative coatings, which consist of metal matrix composites and ceramic layers, reveal remarkable durability against both oxidation and wear at high temperatures during operation. [12]

Cryogenic environments introduce an entirely distinct array of challenges. Under conditions of extreme low temperatures, lubricants frequently undergo solidification or exhibit increased viscosity, thereby impairing their capacity to sustain a fluid film between interacting surfaces. In these contexts, solid lubricants once again emerge as critical components. Molybdenum disulfide (MoS_2) demonstrates noteworthy lubricating efficiency even at temperatures beneath –60°C, surpassing the functionality of numerous conventional polymer materials. Certain polymers, such as PTFE and polycarbonates, demonstrate effective functionality under dry, low temperature sliding conditions; while naturally occurring ice layers may serve as passive lubricants in humid cryogenic environments. Specialized synthetic oils, including fluorinated oils and perfluoropolyether (PFPE), are also employed for their stability at low temperatures, although these may encounter volatility issues in vacuum or radiation-exposed environments.[13]

Lubrication strategies under conditions of extreme mechanical loading necessitate approaches capable of withstanding elevated contact pressures and high shear forces. Boundary lubrication and extreme-pressure (EP) additives, encompassing phosphorus- or sulphur-based compounds, are routinely utilized to establish protective films that avert direct surface contact under stress. Current innovations spotlight the integration of gallium-based liquid metals (GBLMs) as lubricants, exhibiting extraordinary performance in high-load environments due to their exceptional thermal conductivity and low melting points.[13] Additionally, solid lubricants incorporated within metal or ceramic matrices are increasingly deployed in scenarios where liquid lubricants fail due to evaporation or degradation.

Vacuum conditions, such as those experienced in space applications, present additional lubrication challenges. The absence of atmospheric pressure results in lubricant evaporation and cold welding of contacting surfaces. Lubricants in solid form, such as MoS_2, WS_2, and diamond-like carbon (DLC) coatings, find widespread use due to their minimal vapor pressures and impressive longevity. Furthermore, innovative lubrication solutions, such as ionic liquids, hybrid greases, and tribo-coatings, are currently being investigated for vacuum applications, offering enhanced longevity. [14-16]

In conclusion, the provision of lubrication under extreme conditions necessitates a comprehensive comprehension of material dynamics, environmental interactions, and the formulation of pioneering solutions. Progressions in solid lubricants, specialized lubricating oils, composite coatings, and intelligent lubrication technologies persist in enhancing the dependability and efficacy of mechanical systems functioning within the most arduous environments.

Challenges and future scope

Tribology under extreme conditions faces major challenges such as rapid material degradation, lubricant breakdown, unpredictable wear behaviour, and instability of protective surface films. Real-time monitoring and maintenance in inaccessible environments like space or deep-sea settings remain difficult. Additionally, environmental concerns arise from the use of non-sustainable lubricants and coatings. Looking ahead, the future of tribology will focus on developing smart self-healing materials, nanostructured coatings, and high-entropy alloys that withstand harsh environments. Advances in cryogenic tribology, solid lubricants for vacuum and radiation settings, and sensor-embedded systems for real-time wear monitoring are promising areas. Moreover, eco-friendly lubricants and advanced modelling techniques will be critical for creating sustainable, high-performance tribological solutions.

Summary

In conclusion, the evaluation of tribological performance under extreme conditions—such as elevated thermal environments, cryogenic settings, vacuum conditions, and substantial mechanical stresses—necessitates specialized methodologies that transcend traditional material and lubrication techniques. Such environments expedite wear mechanisms, modify frictional characteristics, and pose significant challenges to the efficacy of standard lubricants. As previously articulated, the implementation of solid lubricants, advanced coatings, cryo-compatible materials, and nano-enhanced lubricants offers promising avenues for enhancing durability and operational efficiency. Furthermore, the integration of tribological design with sustainable engineering practices is imperative for the progression of applications within the aerospace, nuclear, deep-sea, and precision manufacturing domains. Ongoing research into intelligent materials, in-situ monitoring methodologies, and environmentally resilient lubrication systems will be essential for addressing existing constraints and ensuring dependable performance in demanding operational contexts.

References

1. R. Shah, R. Chen, M. Woydt, The effects of energy efficiency and resource consumption on environmental sustainability, Lubricants 9 (2021) 1–8. https://doi.org/10.3390/lubricants9120117.
2. W. Cui, H. Chen, J. Zhao, Q. Ma, Q. Xu, T. Ma, Progresses on cryo-tribology: lubrication mechanisms, detection methods and applications, Int. J. Extrem. Manuf. 5 (2023). https://doi.org/10.1088/2631-7990/acc2fa.
3. C.-H. Yang, J. Natarajan, Friction, Lubrication, and Wear, in: A. Patnaik, T. Singh, V. Kukshal (Eds.), IntechOpen, Rijeka, 2020. https://doi.org/10.5772/intechopen.93796.
4. Q. Wang, F. Zheng, T. Wang, Tribological properties of polymers PI, PTFE and PEEK at cryogenic temperature in vacuum, Cryogenics (Guildf). 75 (2016) 19–25. https://doi.org/10.1016/j.cryogenics.2016.01.001.
5. Y. Lyu, Y. Zhu, U. Olofsson, Wear between wheel and rail: A pin-on-disc study of environmental conditions and iron oxides, Wear 328–329 (2015) 277–285. https://doi.org/10.1016/j.wear.2015.02.057.
6. S.R. Schmid, ed., Wear, Schey's Tribol. Metalwork. Frict. Lubr. Wear (2023) 0. https://doi.org/10.31399/asm.tb.stmflw.t59390039.
7. J. Li, X. Yan, X. Liang, H. Guo, D.Y. Li, Influence of different cryogenic treatments on high-temperature wear behavior of M2 steel, Wear 376–377 (2017) 1112–1121. https://doi.org/10.1016/j.wear.2016.11.041.
8. Y.B. Huang, L.B. Shi, X.J. Zhao, Z.B. Cai, Q.Y. Liu, W.J. Wang, On the formation and damage mechanism of rolling contact fatigue surface cracks of wheel/rail under the dry condition, Wear 400–401 (2018) 62–73. https://doi.org/10.1016/j.wear.2017.12.020.
9. W.J. Wang, J. Guo, Q.Y. Liu, M.H. Zhu, Z.R. Zhou, Study on relationship between oblique fatigue crack and rail wear in curve track and prevention, Wear 267 (2009) 540–544. https://doi.org/10.1016/j.wear.2008.12.100.
10. M. John, P.L. Menezes, Self-Lubricating Materials for Extreme Condition Applications, Materials (Basel). 14 (2021) 5588. https://doi.org/10.3390/MA14195588.
11. A. Kumar, M. Kumar, S. Tailor, Tribological behaviour of HVOF-sprayed Ni-based self-lubricating composite coatings, Trans. Inst. Met. Finish. 101 (2023) 320–328. https://doi.org/10.1080/00202967.2023.2185974.
12. A. Kumar, M. Kumar, S. Tailor, Self-lubricating composite coatings: A review of deposition techniques and material advancement, Mater. Today Proc. (2023). https://doi.org/10.1016/j.matpr.2023.01.035.
13. N.L. McCook, D.L. Burris, P.L. Dickrell, W.G. Sawyer, Cryogenic friction behavior of PTFE based solid lubricant composites, Tribol. Lett. 20 (2005) 109–113. https://doi.org/10.1007/s11249-005-8300-4.
14. X.M. Lai, J.C. Han, P. Gao, J.J. Qu, Y. Li, C.L. Tan, J. Jiang, Research on Wear Mechanism of Solid Lubrication Bearing in Vacuum Environment, Appl. Mech. Mater. 798 (2015) 424–429. https://doi.org/10.4028/www.scientific.net/AMM.798.424.
15. Y. Li, S. Zhang, Q. Ding, L. Hu, Effect of cation nature on vacuum tribo-degradation and lubrication performances of two tetrafluoroborate ionic liquids, Tribol. Int. 150 (2020). https://doi.org/10.1016/j.triboint.2020.106360.
16. C. Xiao, J. Li, L. Chen, C. Zhang, N. Zhou, T. Qing, L. Qian, J. Zhang, J. Luo, Water-based superlubricity in vacuum, Friction 7 (2019) 192–198. https://doi.org/10.1007/s40544-018-0212-z.

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Biocompatibility and Corrosion Performance of HA-Based LVOF Sprayed and Post-Annealed Coatings on SS 254 Surgical Grade Bio-Implant Material

by ***Praveen Kumar Verma, Hitesh Vasudev, and Vinod Kumar***

Department of Mechanical Engineering Punjabi University Patiala, School of Mechanical Engineering, Lovely Professional University, Punjab, India.

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Abstract

The UNS 31254 (SS 254) stainless steel has extensive medical applications. Nevertheless, its poor biomedical and corrosion resistance restricts its application in the medical field. To counteract this issue, the Low-Velocity Oxy-Fuel (LVOF) method was employed to deposit coatings of hydroxyapatite (HA), HA+10 wt% micrometric - Al2O3 (HALM), and HA+10 wt% nanometric-Al2O3 (HALN) on the SS 254 substrate. The HA-reinforced coatings were annealed at 400°C and 800°C for 2 hours. Field emission scanning electron microscopy (FE-SEM), X-ray diffraction (XRD), electrochemical corrosion tests, and in-vitro bioactivity studies investigated the performance of the coatings. The XRD study determined the phases available and determined the crystallinity of the coatings. Further, the effect of sintering brought about by annealing also showed a significant reduction in porosity. HALN annealing at 800°C for 2 hours has reduced the unwanted phases (α-TCP and β-TCP) formed during coating thus resulting in enhanced crystallinity and densification of the coatings. Increased annealing temperature improved the corrosion resistance of the coating and decreased the bioactivity of the coatings.

Introduction

The demand for medical implants is increasing due to aging populations and injuries that compromise biological functions. Surgical-grade stainless steels, particularly UNS S31254 (SS 254), have been widely used for orthopedic and biomedical implants due to their superior mechanical properties. However, their clinical application is limited by poor biocompatibility and the release of toxic metallic ions during corrosion in the human body. To enhance implant performance, hydroxyapatite (HA) coatings are widely applied due to their excellent biocompatibility and bioactivity, closely resembling the mineral composition of natural bone. However, HA's brittleness reduces its mechanical reliability, necessitating reinforcement with aluminum oxide (Al_2O_3), which improves both biocompatibility and mechanical strength.

The synthesis and processing of HA significantly influence its phase stability and structural integrity. Post-coating heat treatment is an effective strategy to enhance crystallinity and eliminate undesirable amorphous phases, thereby improving corrosion resistance and bioactivity. Various deposition techniques, including plasma spraying, high-velocity oxy-fuel (HVOF) spraying, and flame spraying, impact the coating's microstructure and performance. Among these, low-velocity oxy-fuel (LVOF) spraying presents a cost-effective, energy-efficient alternative, producing denser coatings with higher crystallinity than plasma-sprayed HA. However, studies on LVOF-sprayed HA coatings remain limited.

This study investigates the electrochemical corrosion resistance and in-vitro bioactivity of heat-treated LVOF-sprayed HA coatings, including HA with micrometric (HALM) and nanometric (HALN) Al_2O_3 reinforcement, on SS 254 substrates. The findings aim to optimize coating performance for improved durability and biocompatibility in biomedical applications.

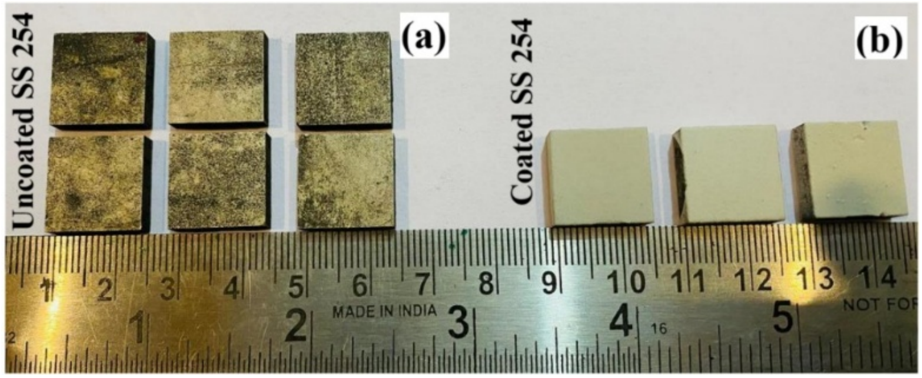

Figure 1: (a) Uncoated and (b) Coated samples

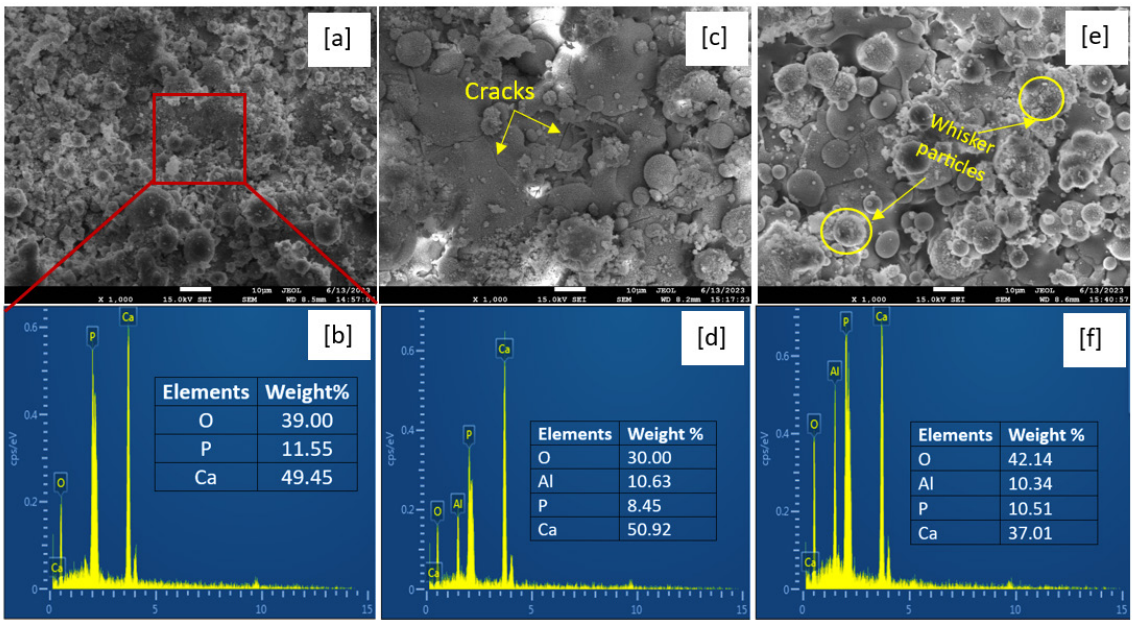

Figure 2: FESEM and EDAX micrographs of as-sprayed coatings (a&b) HA (c&d) HALM and (e&f) HALN

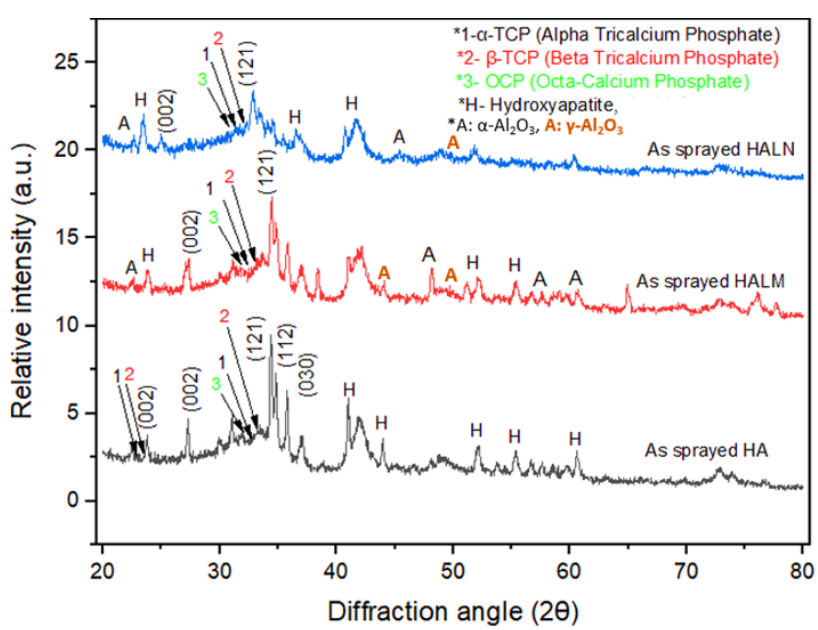

Figure 3: XRD profile of the as-sprayed coatings

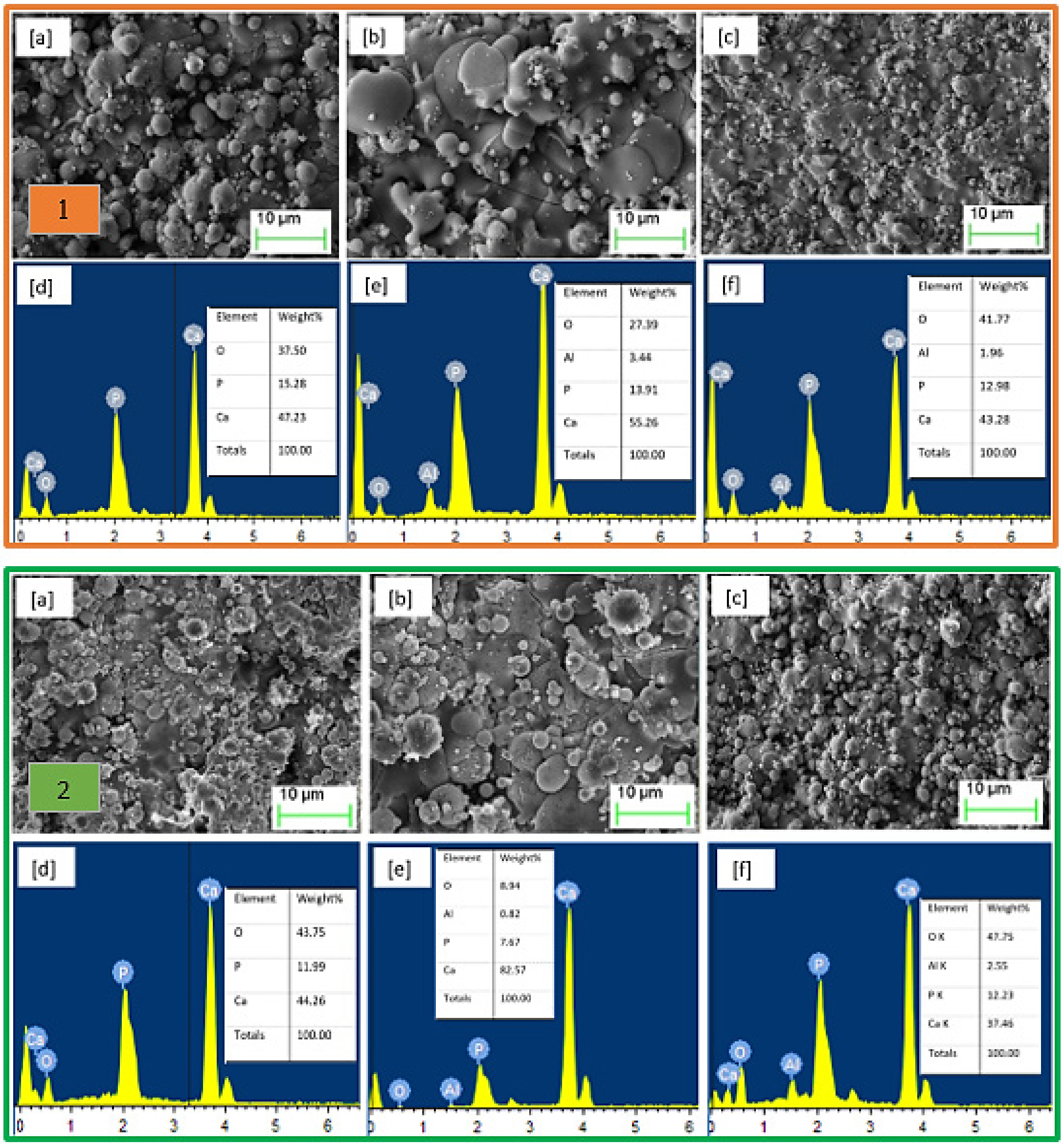

Figure 4: FE-SEM and EDX micrographs of annealed coatings: (a, d) HA, (b, e) HALM, and (c, f) HALN at (1) 400°C and (2) 800°C.

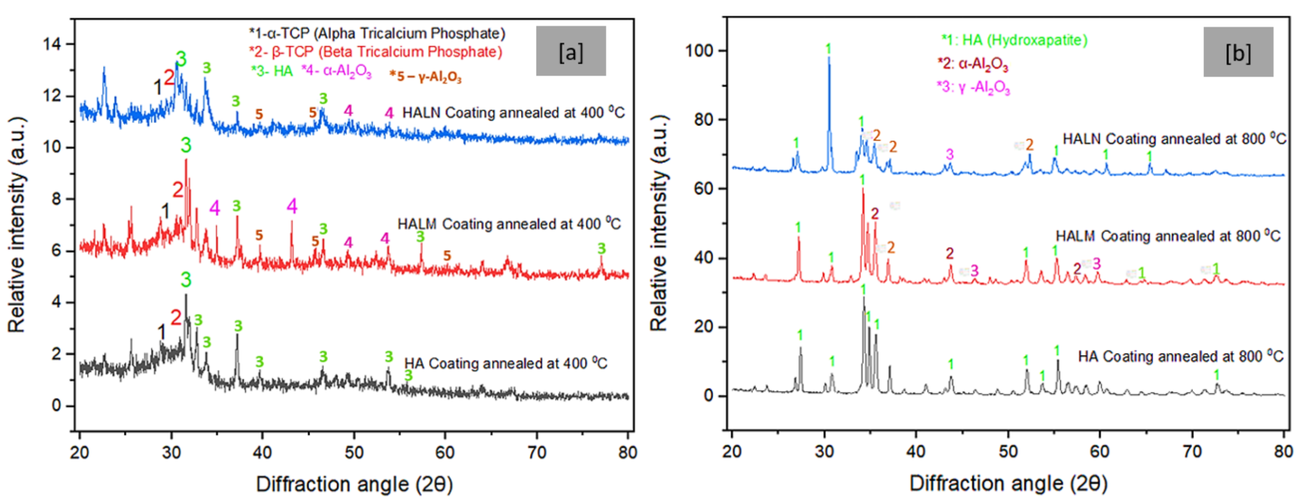

Figure 5: XRD profile of the annealed coatings at temperatures 400 0C and 800 0C

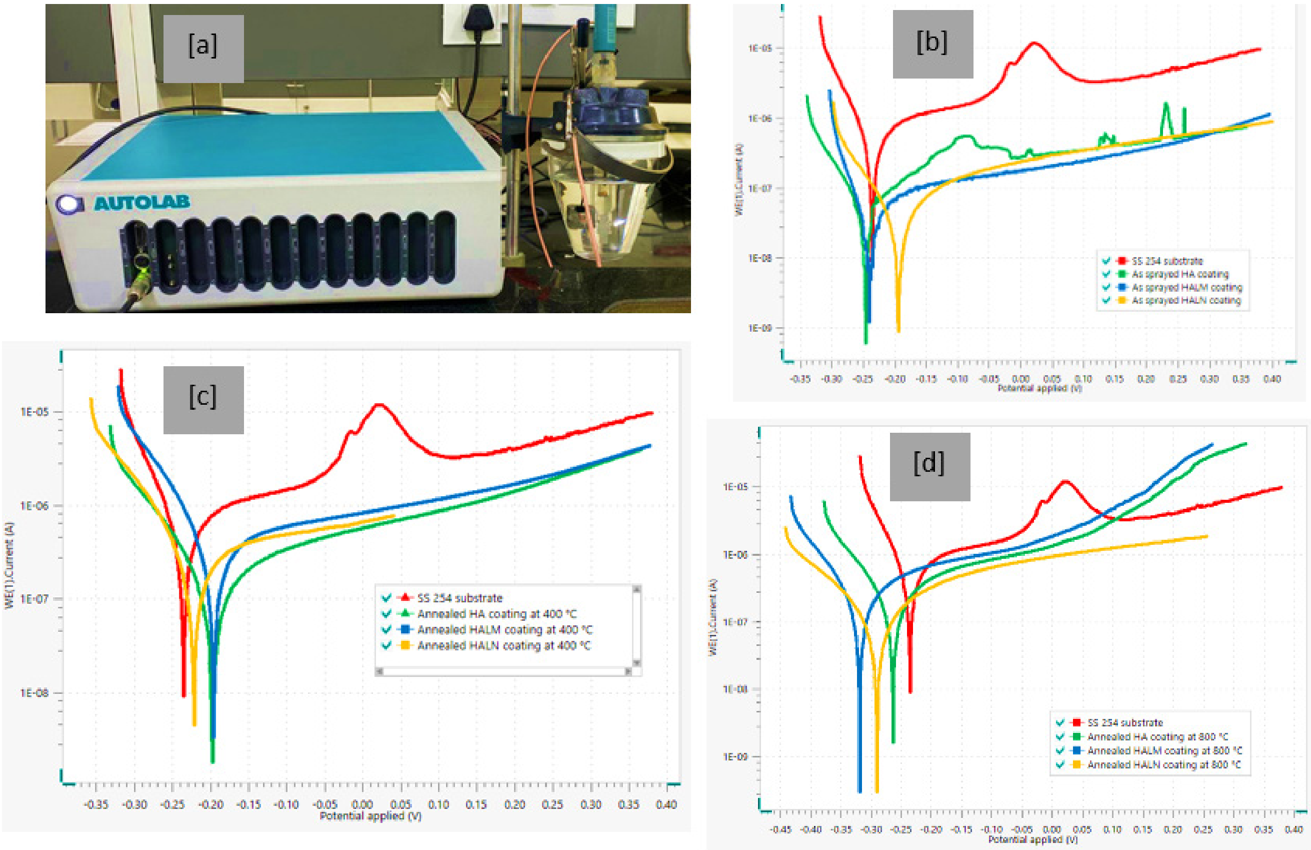

Figure 6: (a) Electrochemical corrosion setup and (b–d) Tafel plots of uncoated SS 254, as-sprayed, and annealed (400°C, 800°C) HA, HALM, and HALN coatings

Experimental & Results

The study investigates hydroxyapatite (HA) and alumina (Al_2O_3) coatings, using commercially available powders. HA was blended with 10 wt% micrometric (HALM) and nanometric (HALN) alumina. Characterization using SEM/EDS and XRD confirmed the composition and particle sizes (HA: 40 µm, HALM: 40–50 µm, HALN: 200 nm). XRD analysis revealed that adding nano-alumina improved crystallinity and phase stability, with HALN showing broader HA peaks, suggesting reduced crystallinity and enhanced corrosion resistance.

FE-SEM analysis showed HA had a smooth, uniform surface, while HALM exhibited irregularities and cracks due to micrometric alumina. HALN displayed a refined, dense microstructure with whisker-like particles, enhancing structural integrity. Annealing at 400°C and 800°C improved coating uniformity, reduced porosity, and enhanced adhesion. XRD results indicated improved crystallinity with increased annealing temperature, with HALN reaching the highest crystallinity at 800°C, ensuring phase stability without significant HA decomposition.

Porosity analysis revealed a decrease with annealing: as-sprayed coatings had porosities of 7.4% (HA), 6.8% (HALM), and 6.2% (HALN), reducing to 3.6% for HALN at 800°C. Microhardness tests showed HALN had the highest hardness (475.5 $HV_{0.1}$) post-annealing, indicating superior mechanical properties. The electrochemical analysis demonstrated HALN exhibited the lowest corrosion rate and highest corrosion resistance, improving with annealing at 800°C.

Bioactivity tests in simulated body fluid (SBF) revealed apatite formation, with HALN showing the most significant weight gain, indicating superior bioactivity. The study concludes that HALN coatings, due to their refined microstructure, improved hardness, and corrosion resistance, are the most promising for biomedical applications.

Conclusions

In this study, HA, HALM, and HALN coatings were developed using LVOF spraying and annealed at 400°C and 800°C. Annealing at 800°C eliminated the amorphous phase, enhancing crystallinity, which reached 91.84% for HALN. Hardness increased with temperature, peaking in HALN at 800°C, which also exhibited the lowest porosity.

Electrochemical tests in simulated body fluid showed the highest corrosion rate for HALN at 800°C. In-vitro bioactivity analysis indicated the highest weight gain in as-sprayed HA and the lowest in annealed HALM at 800°C. These findings highlight the impact of annealing on coating properties for biomedical applications.

References

1. Tiwari S, Mishra SB. Low velocity oxy fuel spraying of hydroxyapatite coating on a multifunctional UNS S31254 austenitic stainless steel. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine. 2021 Aug;235(8):958-72.
2. Balani K, Chen Y, Harimkar SP, Dahotre NB, Agarwal A. Tribological behavior of plasma-sprayed carbon nanotube-reinforced hydroxyapatite coating in physiological solution. Acta Biomaterialia. 2007 Nov 1;3(6):944-51.
3. Tailor S, Vashishtha N, Modi A, Modi SC. High-performance Al2O3 coating by hybrid-Lvof (low-velocity oxyfuel) process. Journal of Thermal Spray Technology. 2020 Jun;29(5):1134-43.
4. Singh A, Singh G, Chawla V. Influence of post coating heat treatment on microstructural, mechanical and electrochemical corrosion behaviour of vacuum plasma sprayed reinforced hydroxyapatite coatings. Journal of the mechanical behavior of biomedical materials. 2018 Sep 1;85:20-36.
5. Tiwari S, Mishra SB. Post annealing effect on corrosion behavior, bacterial adhesion, and bioactivity of LVOF sprayed hydroxyapatite coating. Surface and Coatings Technology. 2021 Jan 15;405:126500.
6. Fernández J, Gaona M, Guilemany JM. Effect of heat treatments on HVOF hydroxyapatite coatings. Journal of Thermal Spray Technology. 2007 Jun;16:220-8.
7. Jha AK, Das B, Saha P. Influence of Al2O3 nanoparticle addition on the properties of hydroxyapatite coatings. Surf Coat Technol. 2021;415:127121.
8. Rattan V, Sidhu TS, Mittal M. Study and characterization of mechanical and electrochemical corrosion properties of plasma sprayed hydroxyapatite coatings on AISI 304L stainless steel. Journal of Biomimetics, Biomaterials and Biomedical Engineering. 2018 Mar 1;35:20-34.
9. Morks MF, Kobayashi A. Effect of gun current on the microstructure and crystallinity of plasma sprayed hydroxyapatite coatings. Applied Surface Science. 2007 Jun 30;253(17):7136-42.
10. Lee, H., Park, C., Kim, J., & Choi, S. (2020). Effect of micro and nano alumina addition on the mechanical properties and microstructure of hydroxyapatite coatings. *Surface and Coatings Technology*, 385, 125421.
11. Kumar, R., Singh, D., & Rajesh, B. (2019). Thermal stability and structural integrity of hydroxyapatite-alumina composite coatings: An annealing study. *Ceramics International*, 45(11), 14123-14131.

Thermal Spray Coatings for Biomedical Applications: A Brief Overview

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Abstract

Biomaterials are used extensively in the development of implants and medical devices in the modern world. Thermal spray is an emerging surface treatment method that offers coatings with improved biocompatibility, wear resistance, and corrosion resistance for different biomaterials. This brief review paper is intended to offer an overview of thermal spraying of biomaterials, advantages, challenges and the latest developments in biomedical applications. Pioneers have employed key thermal spray processes such as plasma spraying, HVOF (High-Velocity Oxy-Fuel) spraying, and cold spraying for direct application of the coatings on biomaterials. These coatings enhance the performance of the implant by improving osseointegration, corrosion resistance and mechanical strength. However, some challenges including coating adhesion, degradation of the biomaterials by the induced temperature, and the long-term biological compatibility are still an issue.

Introduction

Biomaterials used in bioimplant for increasing biocompatibility, mechanical strength and functionality [1]. But the interaction between biomaterials and the human body is still a challenge. Presently biomaterials struggle inside the human body because of corrosion, wear, osseointegration and cell growth [2]. To overcome these issues surface modifications, show the potential for enhancing the biocompatibility of biomaterials. There are many types of surfaces coatings techniques, but thermal spraying shows the potential of coating by impacting the melted materials on substrate using kinetic energy [3]. It gives freedom to deposit ceramic, metallic coating on bioimplants.

This review paper aims to give an overview of thermal spray coatings for biomedical applications. It will explore different thermal spray techniques and biomaterials for biomedical applications.

Thermal Spray Techniques

Biomaterial coatings over bioimplant should have certain bio-compatible properties which can show in Table 1. Below.

Table 1: Coating properties [2]

Coating	Properties
Bioactive coatings	· Bone cells can grow on the surface of implant · Triggers biological responses like tissue regeneration
Antimicrobial coatings	· Bacterial contamination occurs in ventilators, catheters and frequently touched surfaces
Anticorrosive coatings	· Release of ions from biomaterial can cause toxicity in body.
Wear resistant coatings	· Wear debris causes inflammation and aseptic loosening.

In thermal spray coatings, high velocity oxy fuel (HOVF) spraying, plasma spraying and cold spraying shows the potential of coating biomaterials [4].

Plasma spraying uses a high-temperature plasma arc to melt and propel powdered material onto a substrate, forming a protective or functional coating [5]. HVOF (High-Velocity Oxy-Fuel) is a thermal spray technique that uses a high-speed combustion jet to deposit dense, wear-resistant coatings with strong adhesion [6]. Cold Spray is a high-rate material deposition process which involves spraying micro-sized metallic and composite powders at supersonic velocities on to a suitably prepared substrate [7].

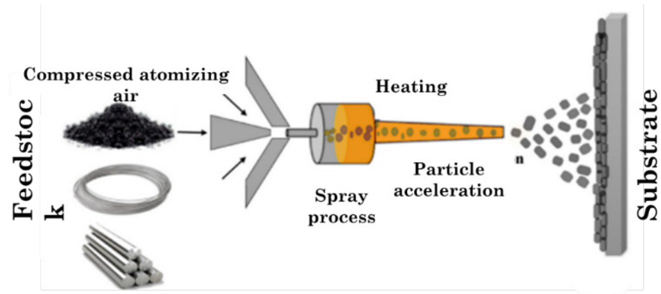

Figure 1: Schematic Diagram Of thermal spray [8].

Biomaterial coatings using Thermal Spray

Metallic implants, such as hip joints, are commonly used to replace damaged or deteriorated body parts due to wear, disease, or injury. Typically made from titanium or stainless-steel alloys, these materials offer excellent mechanical strength and biocompatibility. However, being bioinert, they lack the ability to form a direct bond with bone cells (osteoblasts), which is essential for successful osseointegration [9]. To enhance implant integration with surrounding bone tissue, biomaterial coatings are applied using thermal spray techniques, providing a bioactive surface that promotes cell attachment and long-term stability.

Gadow et al. [10] studied hydroxyapatite (HAp) coatings for biomedical implants using High-Velocity Suspension Flame Spraying (HVSFS), Atmospheric Plasma Spraying (APS), and High-Velocity Oxy-Fuel (HVOF) spraying. Coatings were analyzed for surface roughness, microhardness, porosity, and bond strength using XRD and SEM. HVSFS produced refined microstructures with nanoscale HAp suspensions, while APS and HVOF showed variations in crystallinity and adhesion. This study shows the importance of feedstock powder composition and process parameters on coating deposition.

Chatelain et al. examined the use of PolyEtherEtherKetone (PEEK) as an intermediate layer in cold-sprayed hydroxyapatite (HAp) coatings. Comparing PEEK sublayers from flame spraying (FS) and atmospheric plasma spraying (APS), they found that the porous FS applied PEEK improved HAp anchorage, while the denser APS applied PEEK hindered deposition. The study highlighted the role of sublayer porosity in coating formation, showing that a porous structure facilitates HAp infiltration and enhances coating integrity, which informs optimization of cold spray for biomedical use.

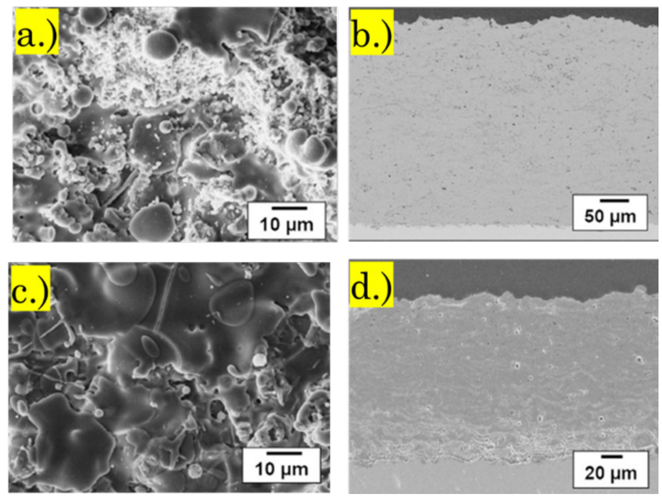

Figure 2: surface and cross-section SEM images of the of HVOF (a, b) and APS (c, d) coatings [10].

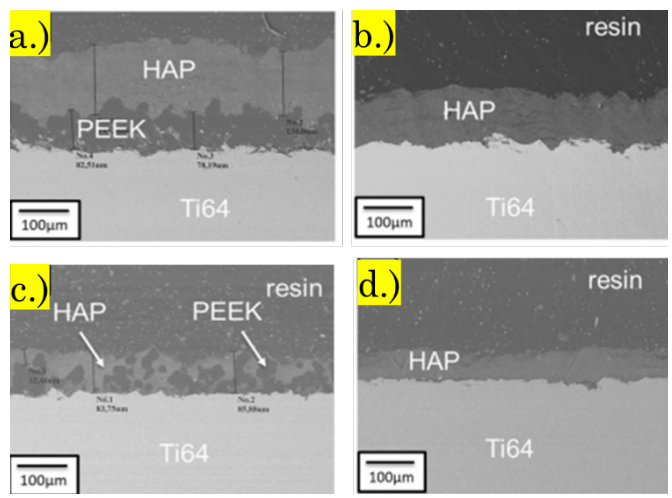

Figure 3: HAp coatings with and without a sublayer using Cold Spray (a, b) and heat-treated HAp coatings with and without a sublayer using Cold Spray (c, d) [11].

Kumar et al. investigated the effect of laser remelting on titanium-Baghdadite (Ti-Bag) composite coatings. Four compositions have been deposited on Austenitic 316L SS and analysed before and after laser remelting. It was found that the porosity has been reduced by laser remelting also electrochemical testing showed a decrease in corrosion current density, attributed to the formation of a protective oxide layer.

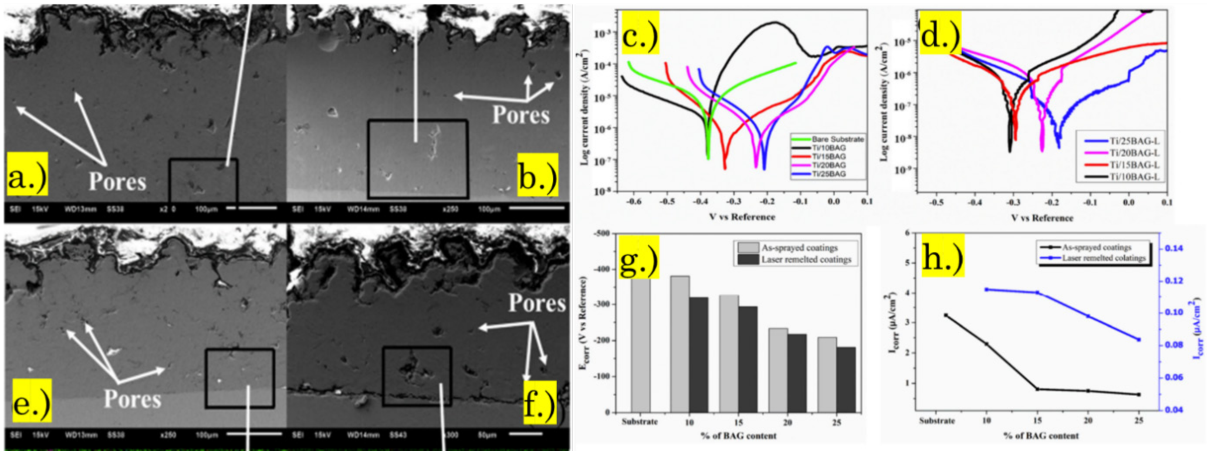

Figure 4: (a) Ti/10BAG-L, (b) Ti/15BAG-L, (e)Ti/20BAG-L, and (f) Ti/25BAG-L coating crossection. potentiodynamic scans of (c) as-sprayed and treated (d) laser- in Ringer's solution. electrochemical parameters such as (g) corrosion potential (Ecorr) and (h) corrosion current density (Icorr) [12].

Conclusions

Thermal spray coatings offer feasible and effective solutions for biomedical applications. These coatings improve mechanical properties such as hardness, wear resistance, and corrosion resistance, as well as biocompatibility of the bio implants. Optimization of parameters for coatings play an important role for good coating, also the post processing such as laser remelting reduces the porosity. Improving the surface characteristics and biocompatibility using thermal spray made a crucial advancement in medial material science.

References

1. Nouri, A., & Wen, C. (2015). Introduction to surface coating and modification for metallic biomaterials. Surface coating and modification of metallic biomaterials, 3-60.
2. Hashmi, A. W., Mali, H. S., Meena, A., Saxena, K. K., Ahmad, S., Agrawal, M. K., & Khan, M. I. (2023). A comprehensive review on surface post-treatments for freeform surfaces of bio-implants. Journal of Materials Research and Technology, 23, 4866-4908.
3. Talib, R. J., Saad, S., Toff, M. R. M., & Hashim, H. (2003). Thermal spray coating technology: A review. Solid State Sci Technol, 11(1), 109-117.
4. Prashar, G., & Vasudev, H. (2020). Thermal sprayed composite coatings for biomedical implants: a brief review. Journal of Thermal Spray and Engineering, 2(1), 50-55.
5. Kumar, D., Pandey, K. K., Kumari, S., Nair, A. M., Mirche, K. K., Maurya, S. S., & Keshri, A. K. (2022). Effect of nanodiamond concentration on the electrochemical behavior of plasma sprayed titanium-nanodiamond nanocomposite coatings. Diamond and Related Materials, 130, 109419.
6. Srikanth, A., & Bolleddu, V. (2023). High velocity oxy-fuel (HVOF) sprayed coating nanoarchitectonics: influence of reduced graphene oxide (rGO) on tribological characteristics. Applied Physics A, 129(5), 318.
7. Vollmer, K. C., Johnson, K., Dondelinger, M., & Jasthi, B. K. (2024). Microstructure, Mechanical, and Corrosion Properties of 304 Stainless Steel-H13 Tool Steel Composite Cold Spray Coatings. Journal of Thermal Spray Technology, 33(4), 931-950.
8. Ahmady, A. R., Ekhlasi, A., Nouri, A., Nazarpak, M. H., Gong, P., & Solouk, A. (2023). High entropy alloy coatings for biomedical applications: A review. Smart Materials in Manufacturing, 1, 100009.
9. Lima, R. S., & Marple, B. R. (2007). Thermal spray coatings engineered from nanostructured ceramic agglomerated powders for structural, thermal barrier and biomedical applications: a review. Journal of Thermal Spray Technology, 16, 40-63.
10. Gadow, R., Killinger, A., & Stiegler, N. (2010). Hydroxyapatite coatings for biomedical applications deposited by different thermal spray techniques. Surface and Coatings Technology, 205(4), 1157-1164.
11. Chatelain, D., Denoirjean, A., Guipont, V., Rossignol, F., & Tessier-Doyen, N. (2023). Role of PEEK as Intermediate Layer in the Cold Spray of Hydroxyapatite Coating. Journal of Thermal Spray Technology, 32(7), 2295-2306.
12. Kumar, A., Goyal, D. K., Kant, R., & Singh, H. (2022). Enhancing corrosion performance of cold-sprayed titanium/baghdadite (Ti/BAG) bio-composite coatings via laser treatment. Coatings, 12(7), 1010.

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