



Full Length Article

Wear and neutron shielding resilience of titanium-hexagonal boron nitride coatings against extreme lunar radiation and thermal cycles

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ABSTRACT

Ti6Al4V and Al6061 are aerospace alloys used in lunar structural components and rovers owing to their high specific strength. However, they deteriorate rapidly when subjected to demanding conditions of the lunar environment, such as extreme thermal cycles, solar particle radiation, and abrasive regolith. Cryo-milled powders were employed to deposit hBN-reinforced protective titanium coatings through plasma spray (atmospheric-APS and vacuum-VPS) with 2 and 10 vol% of hBN on Ti6Al4V and Al6061 substrates. These coatings were evaluated for durability under extreme lunar-like conditions, including thermal cycling, electron radiation, and synergistic (electron radiation-thermal cycle) exposure. The coatings exhibited radiation-induced hardening, resulting in a substantial increase in their microhardness ~20–40 % compared to virgin condition. Bright-field transmission electron microscopy (TEM) analysis reveals the presence of high dislocation densities, black dot defects, and dislocation clusters, providing evidence of the severe impact of synergistic environmental stresses. Ball-on-disk tribological tests were conducted in the presence of JSC-1 A lunar regolith simulant to evaluate the wear performance of coatings. Compared to conventional Ti6Al4V substrate, 50 %, 90 %, and 70 % reductions in wear volume were observed in the Ti/2 vol% hBN coatings in thermal-only, radiation-only, and synergistic environments. Neutron shielding tests indicate that the synergistic coatings offer higher neutron shielding performance by up to 28 % compared to virgin coatings, attributed to improved neutron capture by ¹⁰B isotopes. Upon a comprehensive assessment and ranking of multiple coatings under varying conditions, the VPS Ti/2 vol% hBN coating emerges as the top choice for protection against extreme radiation and thermal cycles for future lunar explorations.

1. Introduction

Ti6Al4V and Al6061 are the critical aerospace alloys used in lunar

structural components, landers, and rovers due to their high specific strength and workability [1–6]. However, the lifespan of these alloys deteriorates significantly due to the extreme conditions of lunar

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environments, such as prolonged thermal cycles (-196°C – 150°C) [7], harsh radiation exposures [8,9], and abrasive lunar regolith particles [10–13]. The high abrasiveness of lunar regolith particles is characterized by their sharp edges and bi-modal particle size distribution [14–16]. The structural parts are vulnerable to catastrophic damage when these particles rub against or get caught between alloy components. Additionally, the high-velocity impact of regolith particles during lunar lander ascent and descent causes permanent erosive wear on these alloys [17–19]. Furthermore, the durability of these components is threatened by extreme space radiation such as galactic cosmic rays (GCR), solar particle events (SPE), and secondary albedo radiation. Sustained exposure to these radiations leads to brittle fracture and eventual failure of structural systems and microelectronics [8,9,20].

A protective composite coating of titanium-hexagonal boron nitride for these structural alloys is proposed in this research to synergistically enhance the wear and radiation shielding properties in the austere lunar environment. Hexagonal boron nitride (hBN) is known for its outstanding properties in thermal conductivity (550 W/mK), friction reduction (low friction coefficients between 0.1 and 0.7), high wear resistance, and radiation protection. The atomic structure of hBN resembles graphene, with covalent solid bonds within planes and weaker Van der Waals forces between them, facilitating reduced friction during sliding. hBN excels in radiation shielding due to its boron content, which has an exceptionally high thermal neutron absorption cross-section of $B \approx 760 \text{ b}$, and significantly higher than graphene ($C \approx 0.0035 \text{ b}$) [21] and 500 times more than concrete [20].

Boron-containing nanomaterials and polymer composites have been explored previously in several studies to counter the radiation and thermal hazards. Recent studies explored using boron nitride nanotubes (BNNTs) for effective radiation shielding [22]. The computer code OLTARIS (On-Line Tool for the Assessment of Radiation in Space) [23] used to assess the space radiation properties showed that BNNTs offer effective radiation shielding against GCR and SPE and BNNTs act as carriers of hydrogen absorption [23]. A recent study demonstrated reinforcing hBN nanoflakes on a polyimide matrix enhanced the wear resistance by 70 % and the mass absorption coefficient of after-radiation shielding by 2.2 times [24]. BNNTs-reinforced Ti composites, produced through spark plasma sintering, exhibited a significant boost in wear resistance (26 %) and neutron shielding (50 %) with the addition of 1 wt % BNNT [9]. A multilayer polyethylene/hBN composite, created via hot pressing, achieved remarkable neutron shielding efficiency compared to the random composite (up to 40 % with 30 wt% hBN) and effective heat dissipation during neutron collisions [25]. In our recent study, novel Ti-hBN composite coatings deposited by APS (atmospheric plasma spray) and VPS (vacuum plasma spray) were analyzed for their wear performance against JSC-1 A lunar simulant and neutron shielding performance at virgin conditions where coatings were not subjected to thermal fluctuations/radiation. The coatings with 2 vol% hBN concentration revealed a substantial 90 % reduction in wear volume for the Ti/2 vol% hBN coatings compared to the unreinforced coatings by synergistic action of harder secondary phases and solid lubrication effect of hBN. Additionally, we investigated the neutron radiation shielding capability of the developed coatings. The VPS Ti-2 vol% hBN coatings exhibited an effective 27 % mass absorption coefficient for neutron shielding, showcasing their potential as protective layers in such scenarios.

It is imperative to study the wear and radiation performance of these protective coatings subjected to this extreme lunar environment scenario to mimic the conditions as closely as possible in analyzing and assessing their durability. Assessing their response to radiation and thermal attacks is vital in developing novel materials for lunar structural protection. Also, no research is singularly dedicated to assessing the wear and radiation performance of structural materials and protective coatings, when exposed to the harsh lunar environment encompassing its extreme thermal fluctuations and radiation exposure. Hence, this study aims to evaluate the wear and radiation performance of APS and VPS-deposited Ti-hBN composite coatings subjected to harsh thermal

fluctuations and radiation exposure in the simulated lunar environment. The microstructural, phase transformation, wear, and neutron shielding response of the coatings against these conditions are critically evaluated, and their efficacy against wear and neutron shielding in lunar conditions is probed.

2. Experimental details

2.1. Materials and preparation

The composite Ti-hBN powders were prepared in 2 and 10 vol% concentrations of hBN from as-received powders (hBN: average size = 5 μm , surface area = 7.5 m^2/g , density = 2.1 g/cm^3 , graphene super-market, Ti6Al4V: average size <30 μm , density = 4.5 g/cm^3 , Tekna TEKMAT™ Ti64–45/16-G5; Fig. S1) by cryomilling. The comprehensive cryo-milling parameters and coating synthesis are provided in (supplementary information 1.1) our previous publication [26]. Conventionally manufactured (CM) Al6061 and Ti6Al4V machined to $\Phi 3.81 \times (\text{t}) 0.64 \text{ cm}$ circular pucks were used as substrates for APS and VPS coating deposition. APS coating deposition was conducted at the Plasma Forming Laboratory of Florida International University, while VPS coatings were deposited at Plasma Processes, LLC in Huntsville, Alabama. SG-100 plasma gun (Praxair Surface Technologies, Indianapolis, Indiana) was used for coating deposition. All coatings were deposited to have a minimum thickness of 150 μm . The detailed process parameters of the coating deposition are provided in Table 1.

2.2. Exposure testing for the coatings

To simulate the harsh space conditions, the coatings were exposed to three different conditions: pelletron radiation, thermal cycle, and synergistic (radiation exposure followed by thermal cycle) (Fig. 1). These tests were conducted at NASA Marshall Space Flight Centre, Huntsville, AL.

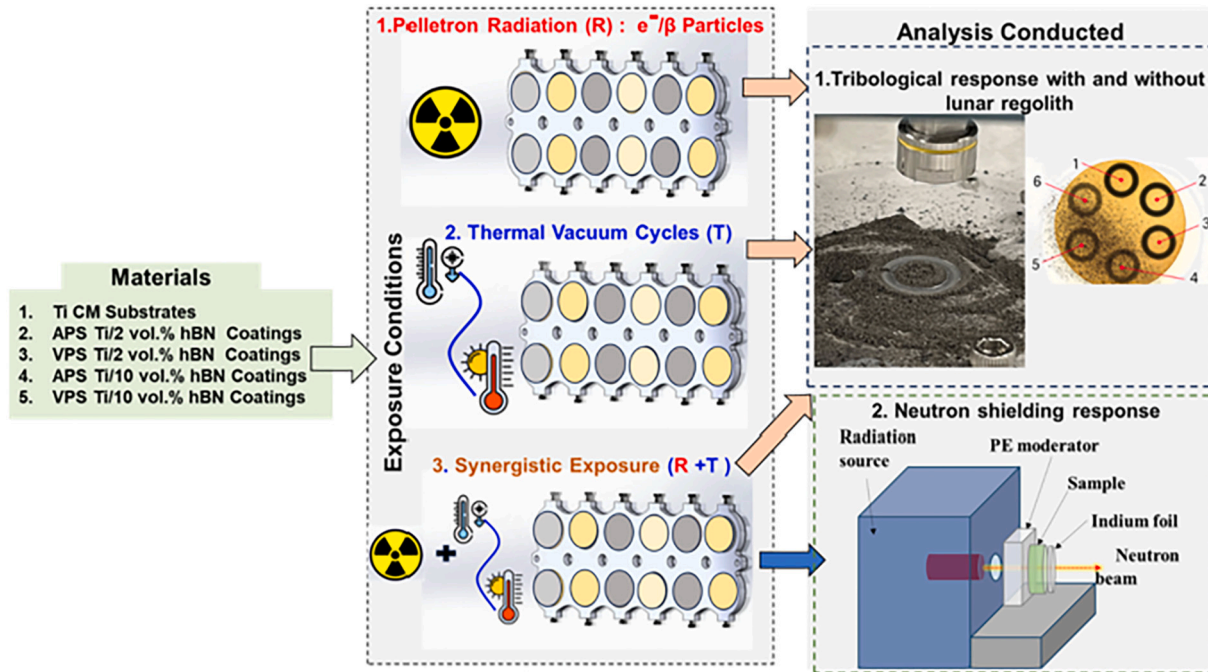
The APS & VPS Ti/2 vol% hBN and Ti/10 vol% hBN coatings were arranged inside the NASA MSFC Pelletron particle accelerator radiation chamber for the radiation exposures (Fig. S2 A). The pelletron was pumped down to a vacuum range of 1×10^{-6} Torr. The electron beam source is then energized to a voltage of 620 keV to achieve a target energy of 400 keV at the coatings. Since the absorbed dose of the samples is material dependent, the samples were exposed to a calculated dose of 6 Mrad at a fluence of $1.13 \times 10^{14} \text{ J}/\text{cm}^2$. The detailed exposure conditions are provided in Table 2. The chosen exposure conditions are designed to replicate the actual lunar environment as closely as possible. The thermal cycle range in our study, spanning from -170°C to 120°C , is representative of the lunar temperature extremes. Regarding radiation, the dosage conditions in our study are comparatively higher than those typically encountered on the Moon. While the average radiation dose on the lunar surface is about 1–2 mSv per day, our exposure conditions involve a much higher dosage, reflecting extreme scenarios beyond the usual lunar environment. This approach ensures that the coatings are tested under more rigorous conditions to assess their performance and durability comprehensively in a short, simulated period.

The coatings were subjected to TVAC (Thermal vacuum cycles) on the NASA MSFC ET V3 (Marshall Space Flight Center Environment Testing Version 3) Thermal Cycle Vacuum Chamber. The sample exposure envelope in the chamber measures $1.5 \times 0.3 \times 0.05 \text{ m}$, and a lift bar, equipped with motors on both ends, aids in raising and lowering samples, with an 11.5-kg lift capacity, ensuring even weight distribution for optimal operation. The samples were loaded onto the mounting bar positioned vertically. The yellow arrow (Fig. S2B) shows the mounting bar at the bottom of the cold box. The red arrow shows the quartz lamp array and radiator plate. The quartz lamp array and radiator plate facilitate radiative heating, operating under a low vacuum of $1.3 \times 10^{-10} \text{ MPa}$. Temperatures as low as $-170 \pm 10^{\circ}\text{C}$ are achieved when samples are elevated into the cold box and around $+120 \pm 10^{\circ}\text{C}$ when

Table 1

Plasma spray process parameters.

Process Type	Spray distance (mm)	Feeding Type	Primary gas pressure (MPa)	Secondary gas pressure (MPa)	Carrier gas pressure (MPa)	Plasma power (kW)	Deposition time (s)	Vacuum level (MPa)
APS	140	External	0.28 (Ar)	0.55 (He)	0.21 (Ar)	22	90	NA
VPS	100	External	0.69(Ar)	0.34 (He)	0.24 (N ₂)	24	90	0.07

**Fig. 1.** The detailed flowchart of the methodology of the study showing exposure conditions. and analysis**Table 2**

Pelletron accelerator radiation exposure details.

Duration (hrs.)	Dose (MRad)	Upstream Energy (KeV)	Flux (nA/cm ²)	Aluminum Scatter Foil Thickness(mm)	Estimated Energy loss(keV)	Target Energy (keV)
4.8	6	620	1	20	232	400

lowered in front of the radiator plate and lamp array. Notably, due to the design of the cold box, samples mounted horizontally during irradiation exposure are positioned vertically during thermal exposure. Additionally, materials undergo a pre-testing baking process to prevent potential contamination. The coatings were subjected to synergistic exposure (thermal cycle followed by radiation immediately) to understand their behavior in the harshest lunar conditions possible that can be simulated. Coatings subjected to all these three exposure conditions were examined by microstructural and tribological characterizations. Synergistic samples were exposed to additional neutron shielding tests to understand their shielding response to secondary neutron radiation from the lunar surface.

2.3. Coating characterization

The as-sprayed coatings were sectioned, cold-mounted in epoxy resin, and then ground down to a 1200-grit SiC paper. Subsequently, polishing was carried out using 1 μm alumina suspension and 0.05 μm colloidal silica suspension for microstructural characterization. The microstructural, cross-sectional analysis of the coatings was conducted using a Schottky field emission scanning electron microscope (FESEM, JEOL-F100, JEOL Ltd., Tokyo, Japan) equipped with a secondary electron detector and backscatter detector, along with energy dispersive spectroscopy (EDS) capabilities. ImageJ was used to examine ten

randomly selected images of the coatings from the polished cross-sections to assess the thickness and area percentage porosity of the composite coatings.

The structure and phase fractions of the as-sprayed coatings were assessed via X-ray diffraction (XRD, Rigaku Smart lab instrument) with Cu Kα radiation ($\lambda = 1.54 \text{ \AA}$) at a scan rate of $2^\circ/\text{min}$. The XRD instrument was set at an operating voltage of 40 kV and a current of 40 mA, scanning in the 2θ range of 10° to 90° . The phase fractions were further determined through Rietveld refinement. Additionally, the identification of chemical compositions and secondary phases in the coatings was accomplished using Raman spectroscopy. Raman microscopy was carried out (Thermo Scientific DXR2, Langley Research Center, Hampton, Virginia) with a laser excitation source of 532/785 nm under a $50\times$ objective lens. The Raman spectra were corrected for spectral background using a smart subtraction technique provided by the Raman microscope. Specimens for TEM investigations were prepared using a focused ion beam (FIB, JEOL JIB 4500, USA) with a sample size of $10 \mu\text{m} \times 6 \mu\text{m}$ and a sample thickness of approximately $1 \mu\text{m}$. The samples were then milled to a thickness of 100 nm using an ion beam.

The microhardness of the as-sprayed coatings was measured employing a Vickers microhardness tester (LM810AT, LeCO, USA) with an indentation load of 100 gf and a dwell time of 15 s. To obtain an average microhardness value, a minimum of ten indentations were carried out across the polished cross-sections of the samples, which were

mounted in resin and polished to a surface finish of 0.05 μm beforehand.

2.4. Tribological and neutron shielding analysis

The tribological assessments of the coatings were conducted using a ball-on-disk tribometer in two distinct conditions: one with the presence of JSC-1 A lunar mare simulant and the other without it. JSC-1 A represents the lunar mare regions, characterized by their high silica, iron oxide, alumina, magnesium oxide, and calcium oxide content. Simulant particles were continuously introduced between the contact pair throughout the testing period. Table 3 provides comprehensive details on the specific test parameters chosen.

These parameters were carefully selected to mimic the abrasive conditions observed in lunar environments, drawing inspiration from previous studies on lunar regolith abrasion. Prior research in this domain has typically employed a load range of 5–10 N [6,9,27]. A normal load of 9 N was employed to replicate the contact pressure experienced by lunar and Martian rovers in their components, such as rims, sprockets, and grousers [27–33]. The acting contact pressure for the experiment was calculated using Hertzian contact pressure generated between the mating surfaces defined as [34],

$$P_{max} \cong 0.4 \left(\frac{E^* F}{R^2} \right)^{1/3} \quad (1)$$

where E is the effective elastic modulus of contacting surfaces, R is the radius of the contacting sphere, and F is the applied load. For mating pairs, the contact pressures were calculated as SS440C–Al 6061: 975 MPa and SS440C–Ti6Al4V: 1220 MPa. The tests underwent 30 min to ensure accurate wear quantification, especially considering the tendency of simulants to fracture and fragment during prolonged sliding. The mass loss from the coatings was measured using a precision balance with a sensitivity of 0.1 mg. The wear track profiles and volume losses were determined using a non-contact surface profilometer (Keyence VK-X 1100) equipped with confocal microscopy. The wear volume was calculated by averaging five distinct wear profiles, encompassing wear width, depth, and area, obtained from wear scar profilometry. The specific wear rate was calculated using Eq. (2).

$$W_s = \frac{V}{F \times L} \quad (2)$$

where W_s is the specific wear rate (mm^3/Nm), V is the total friction volume (mm^3), F is the normal load (N), and L is the overall sliding distance (m).

Neutrons are secondary radiations off the lunar surface that have been shown to induce brittle fractures in material systems due to prolonged exposure. Neutron radiation shielding tests were conducted at NASA Langley Research Center to assess the shielding response of synergistic exposure coatings against virgin (control samples not subjected to any exposure) coatings, as seen in Fig. 1. Unlike wear, which can occur independently in various environments (thermal cycle and particle radiation), neutron shielding specifically takes place within the combined radiation and thermal cycle conditions of the lunar environment. To induce neutron activation, a circular piece of pure indium (In) foil, measuring 25 mm in diameter and approximately 1.0 mm in thickness, was used as a reference target. This indium foil was exposed to neutron radiation, both with and without the presence of a test sample. Neutron activation was achieved by subjecting the In foil to a one-Curie

Americium (^{241}Am)–Beryllium (^9Be) neutron source, as depicted in Fig. S3A. To moderate the neutron emission, a polyethylene (PE) block, approximately 2.5 cm thick, was positioned in front of the Am–Be neutron source. This served to slow down the fast neutrons (4.5 MeV) emitted from the Am–Be source (1 Ci). The neutron dose rate was reduced from 800 mrem/h to 320 mrem/h by the PE block moderator. The In foil, along with the test material, was placed behind the PE block and exposed to neutron irradiation at a dose rate of 320 mrem/h. This exposure continued overnight, over 6 h, to ensure that the activation equilibrium was reached with the activation of ^{115}In to ^{116}In by neutrons. The next day, the activated Indium foil was removed from the test sample and counted using a Geiger-Mueller (GM) meter (Spectrum Techniques, GM35 Geiger-Mueller tube) with a digital counter (Spectrum Techniques, ST360 counter). The neutron shielding effectiveness was determined based on the linear absorption cross-section (or coefficient, μ_x ; Eq. (3)) and the mass absorption cross-section (or coefficient, μ_m ; Eq. (4)) of the material.

$$\mu_x = -\frac{1}{t} \ln \left(\frac{A}{A_0} \right) \quad (3)$$

$$\mu_m = \frac{\mu_x}{d} = -\frac{1}{d \cdot t} \ln \left(\frac{A}{A_0} \right) \quad (4)$$

where t is the sample thickness, d is the sample density, A_0 is the average initial activity of unshielded Indium foil, and A is the average initial activity of shielded foil.

3. Results and discussions

3.1. Powder properties, coating microstructure and porosity

The detailed description of powder morphology and its effect on reduction in powder flowability during coating deposition, coating microstructure, and microhardness are described in detail in our recent work [26] and in supplementary Fig. S1. The initial high flowability of pure Ti6Al4V powder was 28 g/min, diminished to 22 g/min with the addition of 2 vol% hBN, and it further decreased to 14 g/min when the hBN concentration reached 10 vol%. This reduction in flowability can be attributed to the increased cohesion between particles due to the agglomeration of hBN during the powder dispersion. This reduction in powder flowability was reflected in the virgin coating properties.

The SEM micrographs in Figs. 2 and 3 show the microstructural properties, porosity distribution, and defects in the composite coatings deposited on Ti6Al4V substrates subjected to virgin, radiation, thermal, and synergistic exposures. The microstructure of APS and VPS Ti/2 vol% hBN coatings (Fig. 2A, Fig. 3A) is characterized by its density, lack of microcracks, and defects, ensuring strong coating integrity and adhesion to substrate materials. These coatings exhibit minimal unmelted particles in both cross-sections and the top surface after the spraying process, resulting in uniform melting of powder particles and enhanced inter-layer strength. Both Ti/2 vol% hBN display minimal porosity, measuring <1 %, and achieve high levels of densification, attributed to improved powder flow and a reduction in particle agglomeration compared to Ti/10 vol% hBN (Fig. 4). However, when the hBN concentration is raised to 10 vol%, microstructure exhibits various defects, including unmelted particles as shown in both cross-sections and the top surface, microcracks from the substrate to the surface, chipping at the coating's top edges, and isolated delamination areas (Fig. 2B, Fig. 3B). It is worth noting that the APS coating shows more chipping and delamination due to a higher concentration of hard secondary phases like TiO, TiO₂, TiN and TiB [26] (Fig. S4) resulting from reactions in atmospheric conditions. This results in a higher porosity in the 10 vol% hBN APS coatings of 5–7 % (Fig. 4). Despite the increased hBN content, the porosity of VPS coatings remains below 1 % due to the vacuum spraying environment. However, reducing the powder feed rate at elevated hBN concentrations

Table 3
Ball-on disk test parameters.

Counter Surface	Counter surface diameter (mm)	Load	Speed	Wear Scar Diameter	Duration
SS440C	5 mm	9 N	0.021 m/s	8 mm	30 min

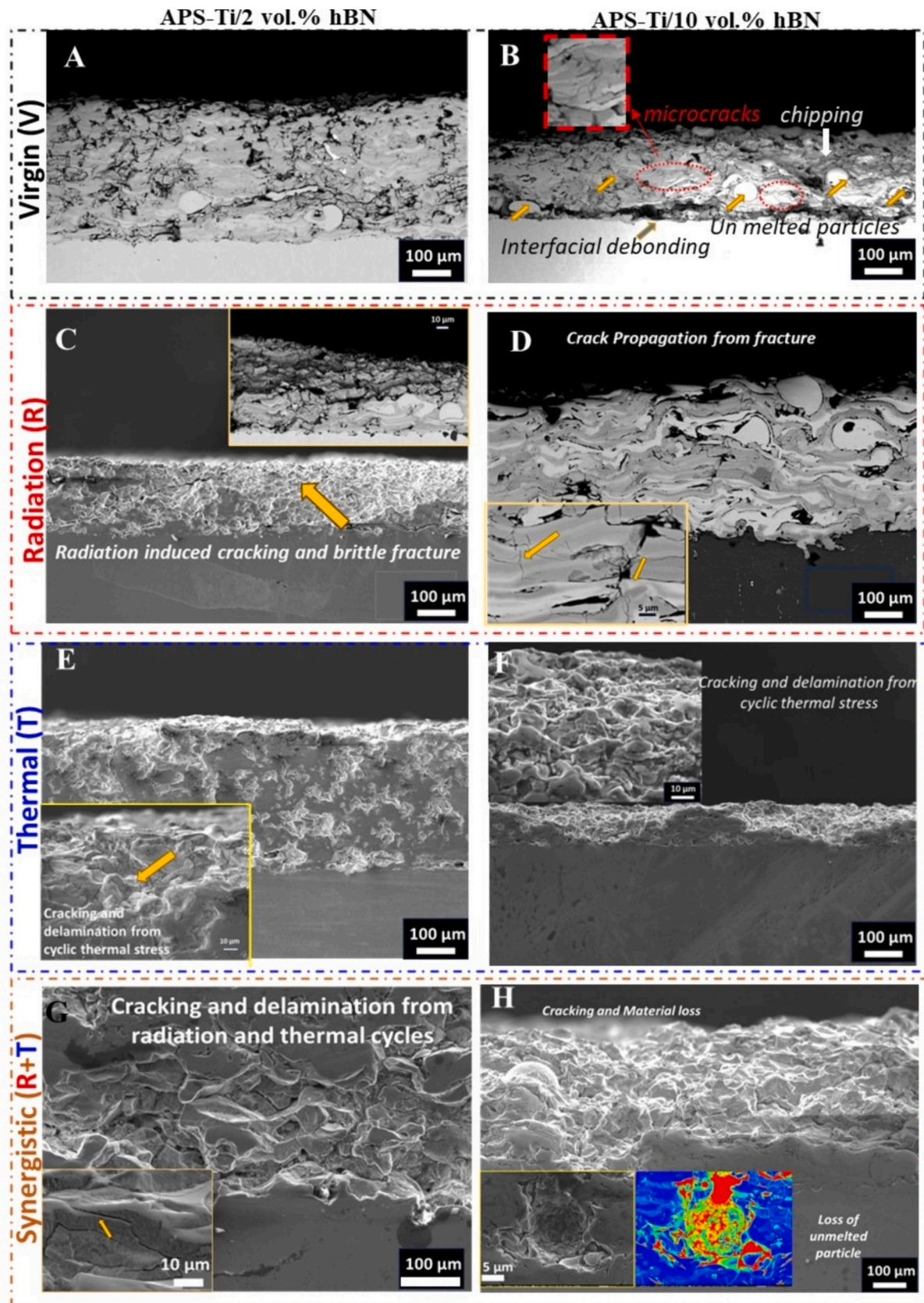


Fig. 2. SEM micrographs of APS Ti/2 vol% hBN and Ti/10 vol% hBN coatings on Ti substrates subjected to (A-B) virgin (C–D) radiation exposures (E–F) thermal exposure (G–H) synergistic exposure.

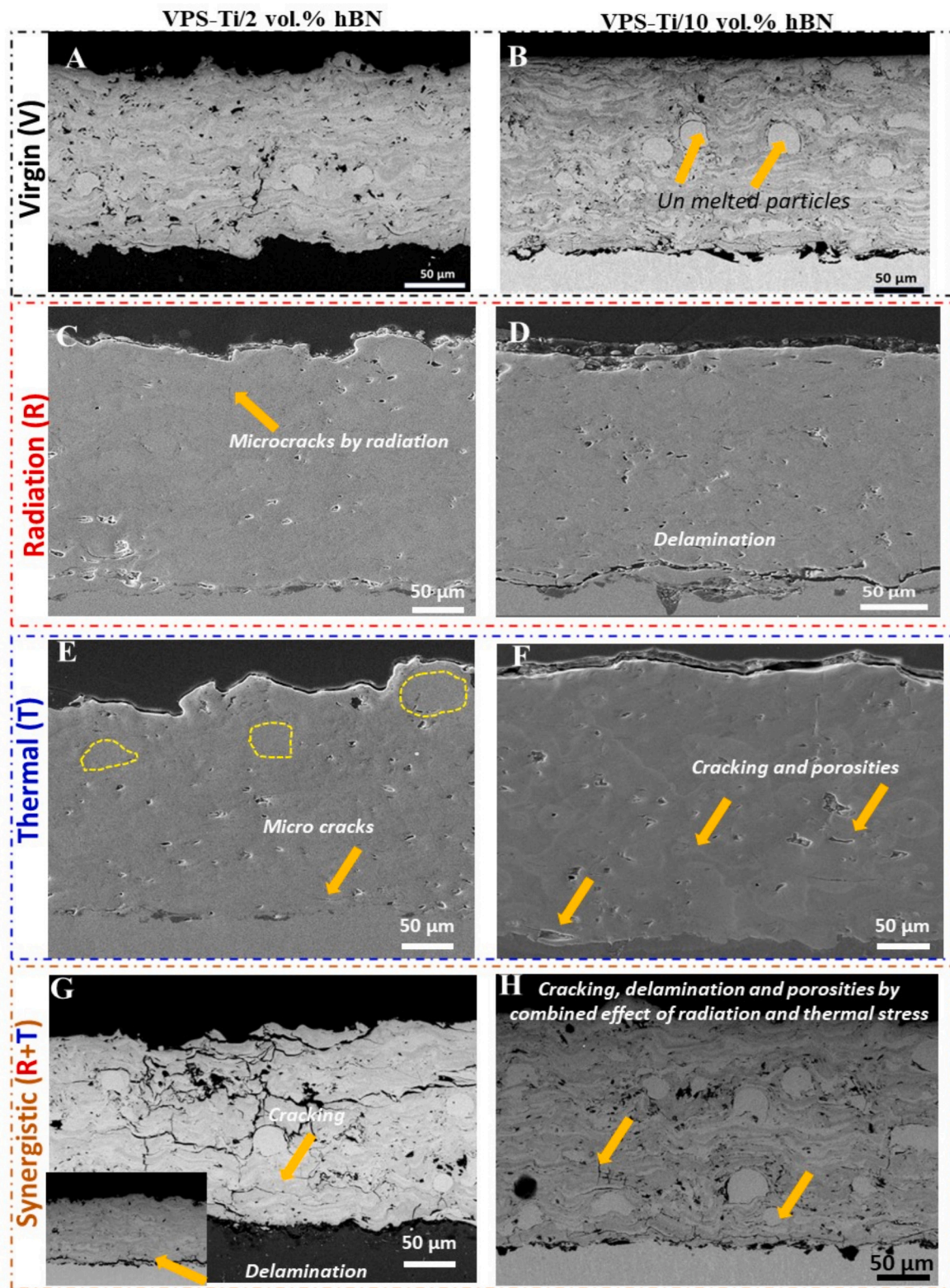


Fig. 3. SEM micrographs of VPS Ti/2 vol% hBN and Ti/10 vol% hBN coatings on Ti substrates subjected to (A-B) virgin (C–D) radiation exposures (E–F) thermal exposure (G–H) synergistic exposure.

leads to an uptick in unmelted particles and delamination within the coatings, as evident in Figs. 2B & 3B.

The same trend is repeated with the coatings exposed to exposure conditions. The effect of radiation is reflected in the coating microstructure with enhanced crack propagation and brittle fracture (Fig. 2C).

Several micro-cracks (Figs. 2D, 3C), enlarged porosities, and delamination (Fig. 3D) from the coating surface can be seen in both APS and VPS composite coatings in both concentrations.

The effect of radiation plays an important role in microstructural damage of metallic [35–37] and ceramic materials [38–40]. Radiation

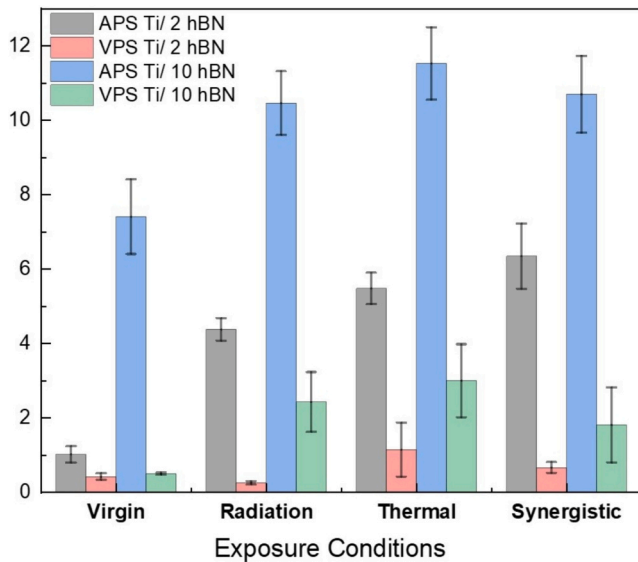


Fig. 4. Porosity of APS and VPS Ti-hBN composite coatings against various exposure conditions. The porosity increases as the concentration of hBN increases.

tends to cause point defects and defect clusters, such as black-dot defects [39,40] (point defects caused by missing atoms from their regular lattice sites due to exposure to radiation, creating dark spots when observed under bright field transmission electron microscopy) and dislocation loops [39]. These defect clusters get larger over exposure time, which induces high hardness and brittleness in the material. This irradiation damage in coatings tends to open porosities and accelerates crack growth and propagation, which is attributed to a higher porosity. Both APS and VPS coatings show a higher porosity (4 % for APS Ti/2 vol% hBN and 1 % for VPS Ti/2 vol% hBN) in the irradiated samples compared to the virgin conditions. Since porosity is higher in 10 vol% hBN concentrations even in unexposed conditions, upon exposure, the porosity level further increases (10 % for APS and 2.5 % for VPS) due to fracture and crack growth, as evident from the microstructural images (Fig. 2D & 3D). The porosity further increases slightly in thermal-only exposure, where cyclic thermal stresses in the material expand and compress the material, which opens micro-cracks and crack propagation [41,42]. This is evident in both coating conditions and hBN concentrations (Fig. 4, 6 % for APS Ti/2 vol% hBN and 1.5 % for VPS Ti/2 vol% hBN; 11 % for APS Ti/10 vol% hBN and 2 % for VPS Ti/10 vol% hBN). Porosity levels increase in the synergistic conditions due to the

synergistic effect of radiation and thermal cycles.

Crack formation could be initiated by radiation-induced brittle fracture due to the formation of dislocation clusters. At the same time, thermal cycling induces stresses that further expand and compress materials for crack widening and propagation in synergistic conditions (Fig. 5A, B) [42]. Propagating cracks merge to form a network of cracks, which results in crack coalescence (Fig. 5C) and ultimately increases the crack density and porosity in the coatings [41,42]. Heavy cracking and delamination are observed for synergistic coating due to the synergistic effect of radiation and thermal cycles (Figs. 2G and 3G). This is attributed to the porosity increment to 7 % for APS Ti/2 vol% hBN and 2 % for VPS Ti/2 vol% hBN; 12 % for APS Ti/10 vol% hBN and 3 % for VPS Ti/10 vol% hBN in the case of coatings exposed to synergistic environment.

3.2. Microhardness variation of the composite coatings apropos to exposures

The microhardness behavior of the coatings subjected to exposures and compared against the virgin coatings is represented in Fig. 6A. Compared to the Ti and Al substrates, at all exposure conditions, the hardness increases significantly due to the formation of secondary phases like TiO, TiN, and TiO₂ during plasma spray [26]. Pure Ti6Al4V APS coatings show 39 % higher microhardness than the Ti6Al4V substrate and a 326 % improvement over the Al6061 substrate. Pure VPS Ti/2 vol% hBN coatings exhibit a reduced enhancement of 184 % for the Al6061 substrate and no improvement for the Ti6Al4V substrate due to forming a metastable TiO phase during the APS process [26]. VPS control samples also contain the TiO phase but to a lesser extent due to vacuum conditions. Microhardness is enhanced by 157 % and 772 % for APS Ti/2 vol% hBN coatings compared to Ti6Al4V and Al6061 substrates, while VPS Ti/2 vol% hBN coatings show a decrease to 70 % and 527 %, respectively [26]. The significant improvement is attributed to low porosity, uniform melting of powder particles, and the formation of hard secondary phases such as TiO, TiN, and TiB. Increasing hBN concentration to 10 vol% does not further improve microhardness and instead reduces the enhancement compared to Ti/2 vol% hBN coatings. APS Ti/10 vol% hBN coatings demonstrate a hardness enhancement of 466 % and 75 %, while VPS coatings show enhancements of 390 % and 51 % on Al CM and Ti CM substrates, respectively, attributed to high porosity, non-uniform melting, and defects from hBN agglomeration. It is anticipated that the improved hardness of the composite coatings when compared to both the substrates and the control samples, will enhance their ability to resist abrasive wear when subjected to lunar simulant JSC-1 A.

Irradiated coatings exhibit a significant increase in hardness, with a 24 % improvement for Ti/2hBN APS, a 40 % increase for Ti/2hBN VPS, a

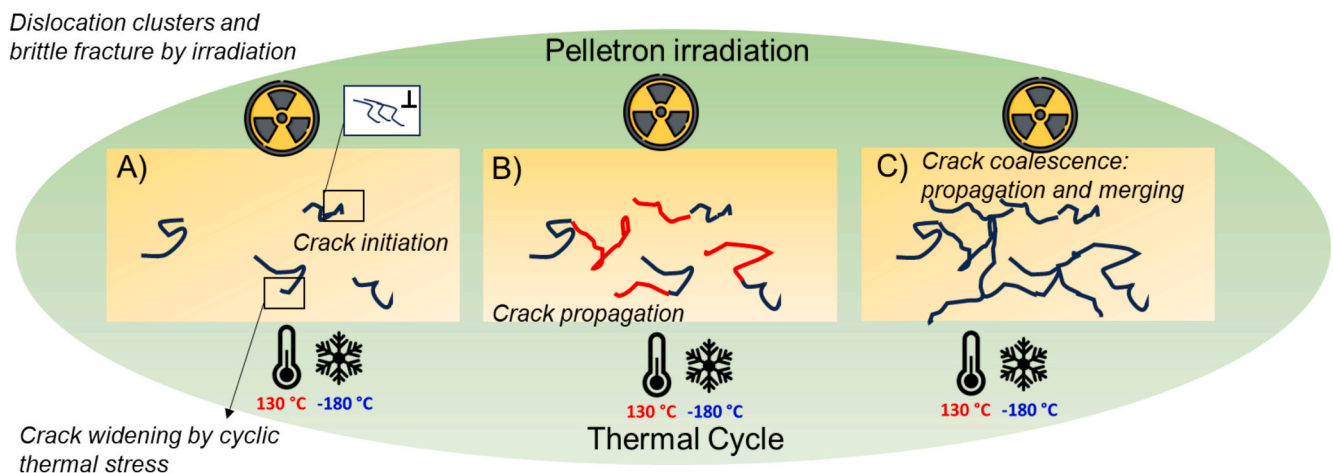


Fig. 5. Mechanism of crack formation and propagation in coatings in a synergistic environment (a) crack initiation (b) crack propagation (c) crack coalescence.

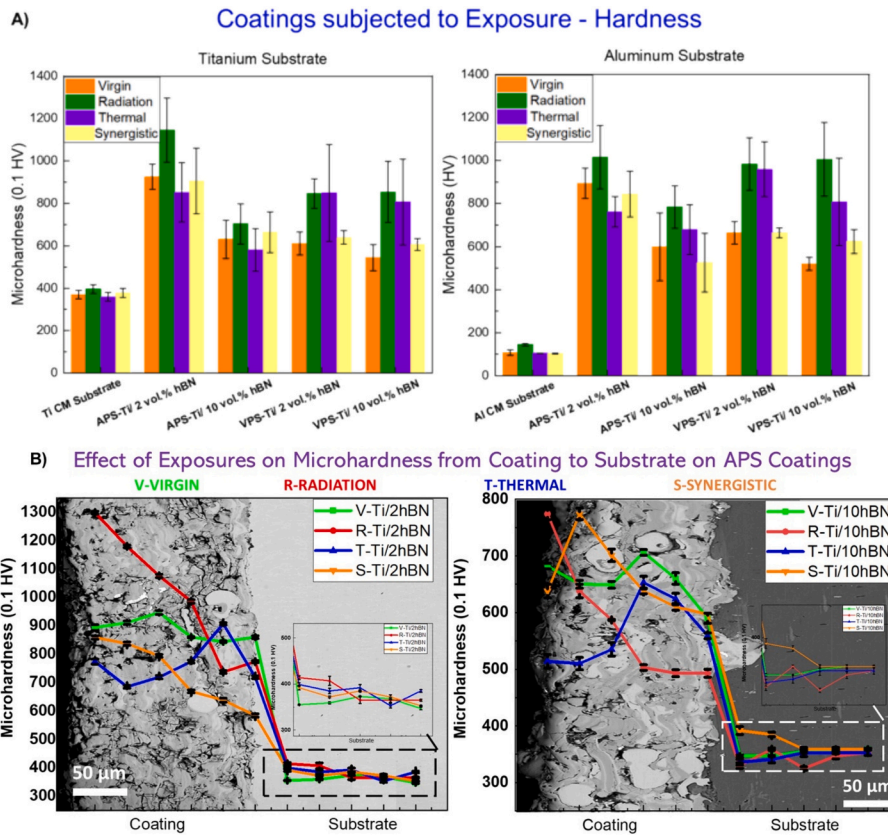


Fig. 6. (A) Effect of exposures on microhardness response of APS and VPS composite coatings (B) Effect of radiation exposure on microhardness from coating to the substrate on APS Coatings on titanium substrates (INSET: magnified hardness response on the substrate).

40 % rise for Ti/10 hBN APS, and a remarkable 57 % enhancement for Ti/10 hBN VPS. This consistent trend is also observed in coatings applied to aluminum substrates. This phenomenon is speculated to be a result of irradiation-induced hardening, possibly due to the penetration of radiation through the coatings and the introduction of dislocations in the atomic structure. Previous studies on irradiation effects in metals and ceramic materials show the presence of point defects, dislocation clusters, and dislocation loops [36,39,43]. Hardness exhibits an upward trend in thermal cycle samples for VPS coatings, which can likely be attributed to the oxidation of titanium at elevated temperatures. The synergistic samples show a slight decrease after both exposures, speculated to be because of microcrack crack formation and propagation. XRD of VPS coatings in Fig. 7 represents a higher peak intensity of TiO compared to virgin coatings. Additionally, cryogenic temperatures enhance the mechanical properties and material hardness by alleviating internal stresses within the material and promoting the development of a fine-grain structure [44–47].

The hardness increases by 39 % and 49 % for 2 vol% and 10 vol%, respectively, on Ti substrates, while a minor reduction in hardness of 8 % and 5 % is observed for APS coatings, possibly due to the enhanced crack formation by cyclic thermal stresses and larger pore distribution. The synergistic exposure coatings also show a minor rising trend in hardness after consecutive exposures by 2 % and 5 % for 2 vol% hBN, APS, and VPS, respectively, and 5 % and 12 % for 10 vol% hBN coatings. The reduction in hardness improvement in synergistic exposure could be attributed to the crack propagation and crack coalescence in the coatings due to radiation-induced brittle fracture and thermal stresses.

To understand the effect of radiation penetration into the substrates from coatings, microhardness measurements were done on APS coatings from coating to substrates across the cross-section (Fig. 6B). The results show that in the case of virgin coatings, the hardness follows a stable trend from the top layers to the bottom layers (layer closes to substrate)

and then decreases steeply to substrate hardness. Irradiated coatings show a decreasing trend in hardness from the top to the bottom layers. This shows that radiation penetrates initial layers, induces dislocations in the material, and increases the hardness. The radiation could be absorbed by the B¹⁰ isotopes in the subsequent layers, thereby gradually ebbing away the formation of dislocations [20]. The same trend is observed in synergistic exposure coatings as well, which indicates that radiation effects predominate over thermal cycles. The thermal cycle indicates a rising-declining hardness trend across the cross-section, which shows that the effect of the thermal cycle is location-specific. Higher hardness is observed across the cross-section devoid of cracks, while hardness decreases as the indentation areas cover cracks and porosities due to thermal stresses.

To investigate the effect of dislocation due to irradiations, dislocation densities were calculated using crystallite sizes obtained from the Williamson-Hall method (Eq. (5)). The full-width half maxima for each peak were measured by fitting the XRD pattern using the Pseudo-Voigt function to quantify peak broadening. Fitting the graph obtained by plotting $\beta_{hkl}\cos\theta$ and $4\sin\theta$ are used to obtain average crystallite size.

$$\beta_{hkl}\cos\theta = \frac{0.9\lambda}{D} + 4\epsilon\sin\theta \quad (5)$$

where, β_{hkl} is FWHM, θ is the diffraction angle, λ is the wavelength of CuK α ($\lambda = 0.154056\text{ nm}$), D is average crystallite size, and ϵ is the lattice strain. The results of dislocation densities from the linear fitting in the WH-plot (Fig. S5) for feedstock and deposits are shown in Fig. 7B. Estimation of the dislocation density (ρ) is done using Eq. (6).

$$\rho = \frac{1}{D^2} \quad (6)$$

The dislocation densities in coatings irradiated with 2 vol% hBN show a notable increase, with a two-order-of-magnitude rise in APS

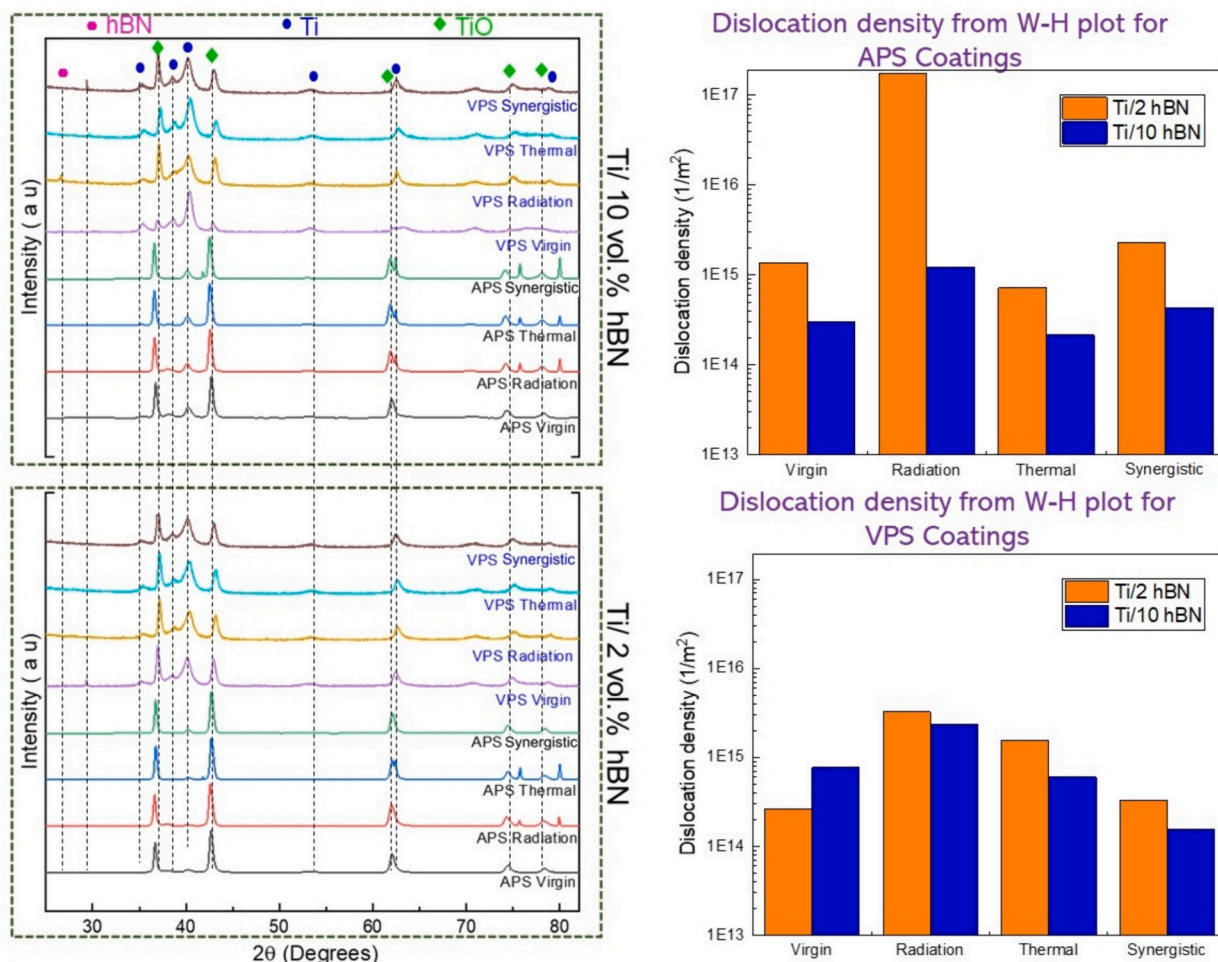


Fig. 7. (A) X-ray diffraction patterns of the composite as-sprayed and exposed coatings (B) Dislocation densities of the coatings calculated using the Williamson-Hall method.

conditions and a one-order-of-magnitude increase in VPS conditions. This could be attributed to the vacuum spraying conditions, which could retain a higher concentration of hBN in the final coating. The XRD (Fig. 7) and Raman Spectrum (Fig. S4) of VPS coatings show higher intensity hBN peaks (26.7°), and the Raman spectrum indicates the presence of high-intensity hBN (1365 cm^{-1}) TiB (570 cm^{-1}) and TiN ($300\text{--}500\text{ cm}^{-1}$) phases in VPS coatings compared to high-intensity TiO peaks in the APS coatings. Thermal cycles for VPS 2 vol% coating show higher (1 order of magnitude) dislocation densities compared to virgin coatings, while synergistic exposure coatings display a 25 % rise in dislocation densities for APS and VPS 2 vol% hBN concentrations, thereby justifying the similar trend in hardness response. This can be attributed to the effect of radiation in the first exposure, which induces dislocations in the coating. The investigation of radiation-induced hardening in the coating was analyzed by bright field TEM on APS Ti/2 vol% hBN coating, which showed the highest dislocation density by XRD. The TEM images.

Fig. 8 showcases evidence of black-dot defects, accumulated dislocation clusters, Moire dislocation fringes, and dislocation loops [35,37–40,48,49] in the coating, indicating high-dislocation density in the radiated APS-Ti/2 vol% hBN. Fig. 8A represents black-dot defects with an average size of $\sim 3.26\text{ nm}$. Black-dot defects are formed by displacements of atoms in the material lattice due to high-energy radiation and occupying interstitial sites to form a point defect. Over time, the atoms migrate and recombine, forming dislocation clusters (Fig. 8A and B). Moire dislocation fringes in Fig. 8C represent the misalignment of a line/half plane of crystal lattices in titanium after radiation

exposure, which generates edge dislocation loops (blue arrows). The polygonal shape of the loop in Fig. 8D represents the magnified image of these edge dislocations created in the coating. The high density of the dislocation clusters and loops contributed to the enhanced coating microhardness, which resists deformation and induces brittleness in the material. The control sample in Fig. 7E represents an area of Ti/2 vol% hBN coatings with low dislocation density. Fig. 8F represents an alternate area of APS Ti/2 vol% hBN coating with hBN flakes. Our previous work has shown the amount of hBN retained in coatings based on Rietveld analysis (APS and VPS Ti/2 vol% hBN $< 1\text{ wt}\%$; VPS/Ti/10 wt% hBN $< 3\text{ wt}\%$) from XRD [26]. The crystal structure of the hBN flake shows an ordered atomic arrangement without any observable dislocation loops or clusters. This could be attributed to the effectiveness of boron nitride in alleviating radiation-induced brittle fracture and keeping its structural integrity. This property of hBN is expected to influence/enhance the wear and radiation behavior of the coatings subjected to exposure.

3.3. Tribological performance of the composite coatings subjected to exposures

The abrasive wear performance of the Ti substrates and deposited coatings in the presence of JSC-1 A lunar regolith and no-regolith conditions are shown in Fig. S6 and Fig. 9 in terms of the average coefficient of friction and wear rate, respectively. The wear performance of Ti substrates and coatings is only represented in this section since the substrate effect did not affect wear properties. The uncoated Ti

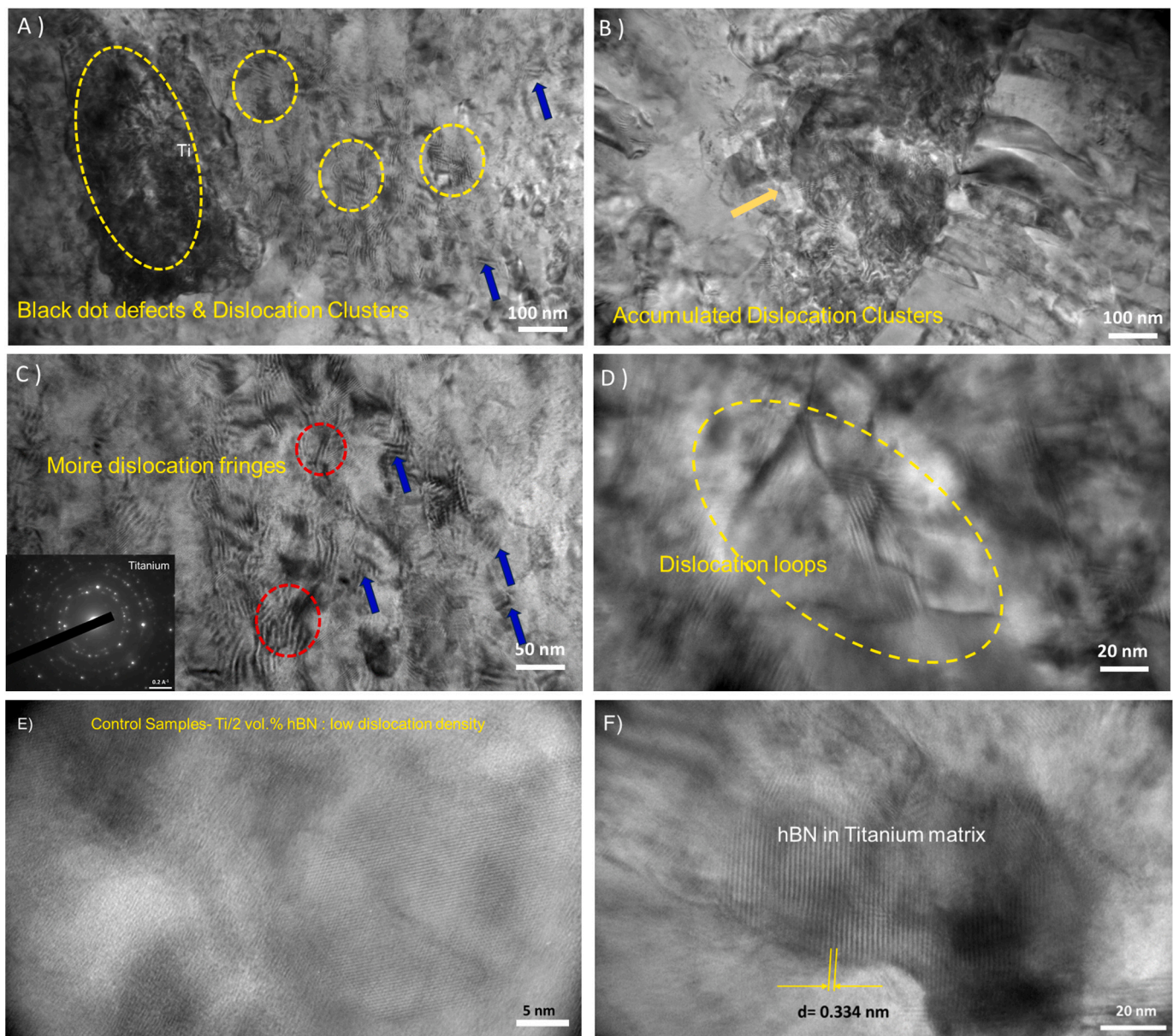


Fig. 8. Bright-field TEM images of APS Ti/2 vol% hBN coatings showing (A) Black-dot defects and dislocation clusters, edge dislocation loops. (blue arrows), (B) accumulated dislocation clusters in interlamellar of coating, (C) Moire dislocation fringes, (D) Dislocation loops at high-magnification, (E) Control sample with low dislocation density, (F) APS Ti/2 vol% hBN coatings showing (A) hBN flakes with d-spacing of ~ 0.334 nm without any dislocation clusters.

substrates show no definite differences in coefficient of friction (COF) subjected to different exposures; however, they show a low coefficient of friction at all conditions compared to coatings due to a low initial roughness. In the presence of lunar regolith, the COF indicates a slightly decreasing trend from virgin to synergistic conditions. However, when sliding with JSC-1 A, the COF does not indicate a definite trend due to the simultaneous embedding and removal of particles for all coatings and exposure conditions [26]. The coatings exposed to radiation show a lower COF compared to the other exposed coatings under both conditions. After exposure to the irradiation, the APS Ti/2 vol% hBN, VPS Ti/2 vol% hBN, and VPS Ti/10 vol% hBN coatings exhibit decreases in the COF by 40 %, 19 %, and 27 %, respectively, when compared to Ti CM substrates. The COF for both APS and VPS Ti/10 vol% hBN coatings has increased with the values ranging between 0.5 and 0.8 due to the poor surface integrity of coatings resulting from agglomeration, unmelted particles, and porosity in the final coatings. The JSC-1 A simulant exhibits a high Vickers Hardness (900 HV), surpassing that of VPS 2 vol%

hBN coatings while falling short of the hardness of APS 2 vol% hBN coatings. During tribological testing, the JSC-1 A simulants undergo deformation and fragmentation when subjected to the contacting surfaces, resulting in the generation of third-body fragments. The concurrent processes of embedding and material removal caused by these third-body particles have a pronounced impact on the vertical movement of the tribometer spindle and load cell. Consequently, the COF behavior of the coatings demonstrates a lack of discernible and consistent trends in sliding tests with lunar simulants. This complex interplay underscores the intricate nature of tribological interactions and the multifaceted influences on frictional behavior, as shown in Fig. S6.

The wear rate of the coatings deposited on Ti substrate and subjected to various exposure conditions are depicted in Fig. 9. Reduced wear rates are consistently observed in exposed Ti CM substrates compared to their virgin counterparts, irrespective of the presence or absence of regolith. The introduction of virgin coatings amplifies wear rate reduction by 65 % and 40 % for APS and VPS Ti/2 vol% hBN, respectively, under no-

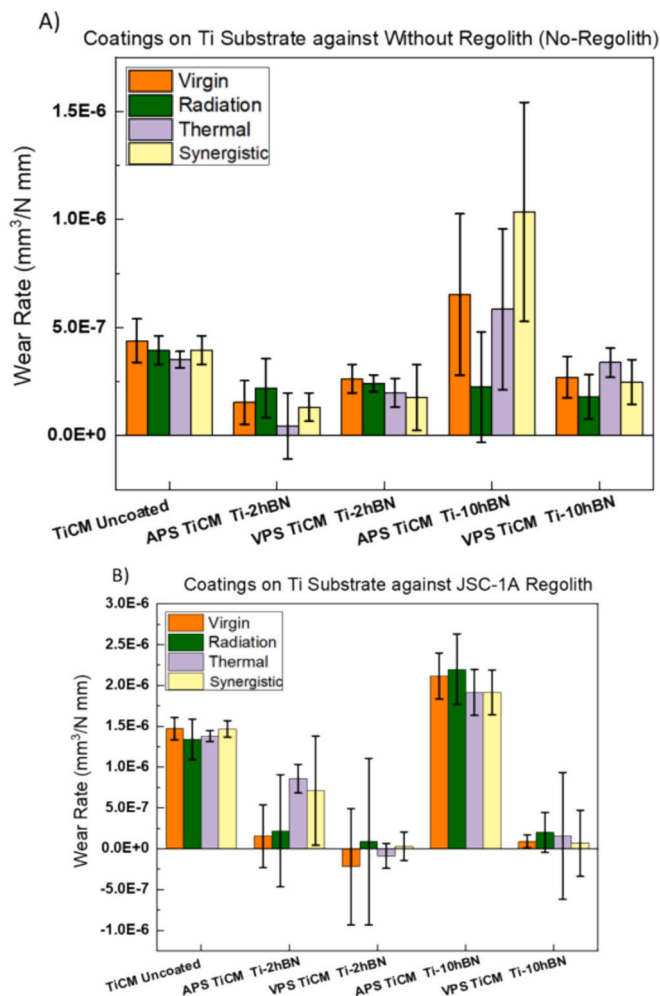


Fig. 9. Wear rate of the composite coatings subjected to exposures calculated based on mass-loss from tribometer tests (A) No-regolith condition (B) With JSC-1 A.

regolith test conditions (Fig. 9A). This phenomenon can be attributed to the synergistic effect of hBN retention within the coatings and the incorporation of hard secondary phases (TiO, TiN and TiB), leading to an overall increase in the cumulative surface hardness of the coatings [26]. The hBN layers are prone to shearing under the applied normal force applied by the counter surface due to the weak van der Waals bonds, allowing these layers to slide over each other. This results in a solid lubrication effect, wherein a thin hBN film becomes attached to the ball countersurface, resulting in a low shear force contact.

It is noted that despite the observed enhancement in microhardness due to hBN retention in APS Ti/10 vol% hBN coatings, the presence of coating defects such as agglomeration, porosities, and unmelted particles negatively impacts wear performance. In this regard, APS 10 vol% hBN coatings demonstrate a 48 % increase in wear rate. In contrast, VPS Ti/10 vol% hBN coatings exhibit superior performance compared to APS coatings. This is attributed to the reduction in the concentration of TiO secondary phase, minimizing pull-outs from the coating during sliding, and achieving maximum hBN retention in the coatings for a solid lubrication effect. VPS coatings display a remarkable 40 % improvement in wear reduction.

Moreover, both exposed substrates and coatings demonstrate a reduction in wear rates when compared to their virgin counterparts. This reduction can be attributed to radiation-induced hardening of the material, resulting in an increase in hardness for both irradiated and synergistic samples. APS and VPS Ti/2 vol% hBN coatings consistently

exhibit significantly improved wear rates across all exposure conditions. For APS Ti/2 vol% hBN coatings, a substantial 44 %, 87 %, and 66 % reduction in wear rates is observed in the context of radiation thermal synergistic exposure, compared to Ti CM substrates under no-regolith test conditions. In the case of VPS 2 vol% coatings, a notable 40 %, 44 %, and 55 % reduction in wear rates is observed under similar radiation-thermal synergistic exposure conditions compared to Ti CM substrates in no-regolith tests. However, the irradiation and thermal cycle effects, such as crack propagation, brittle fracture, and delamination of the coatings, resulted in a high wear rate (66 % and 160 % increment in thermal and synergistic exposure) in the APS Ti/10 vol% hBN coatings. However, because of their 40 % enhancement in hardness, the irradiation-only coatings showed a significant 40 % reduction in wear rate in no-regolith test conditions. The VPS Ti/ 10 vol% hBN coatings have 54 %, 3 %, and 37 % reduction in wear rate compared to substrates due to a reduction in secondary phase formation in the vacuum spraying conditions and the higher hBN retention. A detailed description of wear behavior and mechanism on coating surfaces is provided in our previous publication [26].

When sliding with lunar simulant JSC-1 A, a significantly higher wear rate was observed on the substrates and coatings compared to scenarios without regolith (Fig. 9B). This can be attributed to the contact pressure between the mating surfaces, causing the simulants to fracture and fragment.

The high microhardness (900 HV) of the JSC-1 A simulant enabled sharp-edged particles to cut into the material, removing surface layers during sliding. As a result, regolith embedding and covering (Fig. 10 A & B) were observed on the worn surfaces of substrates and coatings. Fig. 11 A & B shows the top surface wear scar images of irradiated VPS Ti/2 vol% hBN coatings without and with regolith conditions. In without regolith condition, the scar is smooth and devoid of defects and third-body particles, and the EDS map shows elements rich in Ti, B, and N. However, the test with regolith shows even covering and embedding of JSC particles as identified by elements like Si, Al, and O. The virgin coatings indicate a significant improvement of 90 %, 116 %, and 94 % reduction wear rate of APS 2 vol%, VPS 2 vol% and VPS 10 vol% hBN respectively from the substrate. For APS 10 vol% hBN coatings, the wear performance deteriorated by 43 %, 64 %, 38 %, and 29 %, respectively, in virgin, radiation, thermal, and synergistic exposures because of the poor coating integrity of the APS 10 vol% hBN coatings and the crack coalescence due to radiation and thermal stresses. Both APS and VPS 2 vol% hBN coatings enhance wear performance considerably, with VPS coatings slightly outperforming APS coatings.

Compared to Ti CM substrates in all exposed samples, an astounding 90–95 % reduction in wear rate is observed. This can be attributed to higher hBN retention and high densification in vacuum plasma sprayed coatings. Fig. 10 C represents hBN flakes in VPS Ti/2 vol% hBN coatings in a magnified image of the wear track contributing to solid lubrication effect and resistance to deformation. Fig. 10 D & E represents the prevalent wear mechanisms in the VPS Ti/2 vol% hBN coatings. Irradiated coatings are shown for representation, while the mechanisms remain similar for all exposure conditions. The panoramic wear track cross-section is distinguished by the flattening of repeated sliding by the third-body particles in the mating pair. JSC particles upon repeated sliding fragments and plows into material surface. Upon repeated sliding, fragments get embedded in the material surface by filling and pavement. This is indicated by the slight mass gain ion VPS Ti/ 2 vol% hBN coatings (Fig. 10B). This embedding effect is severe in Ti substrates due to its low microhardness (335 HV), while the Ti/2 vol% hBN coatings with hardness >1200 HV only shows embedding and filling in isolated areas, as shown in Fig. 10 D & E. This phenomenon shows that coatings can protect the structural components and critical parts of material systems that are expected to last for several years without failure even in extreme, radiation, thermal and synergistic exposure environments.

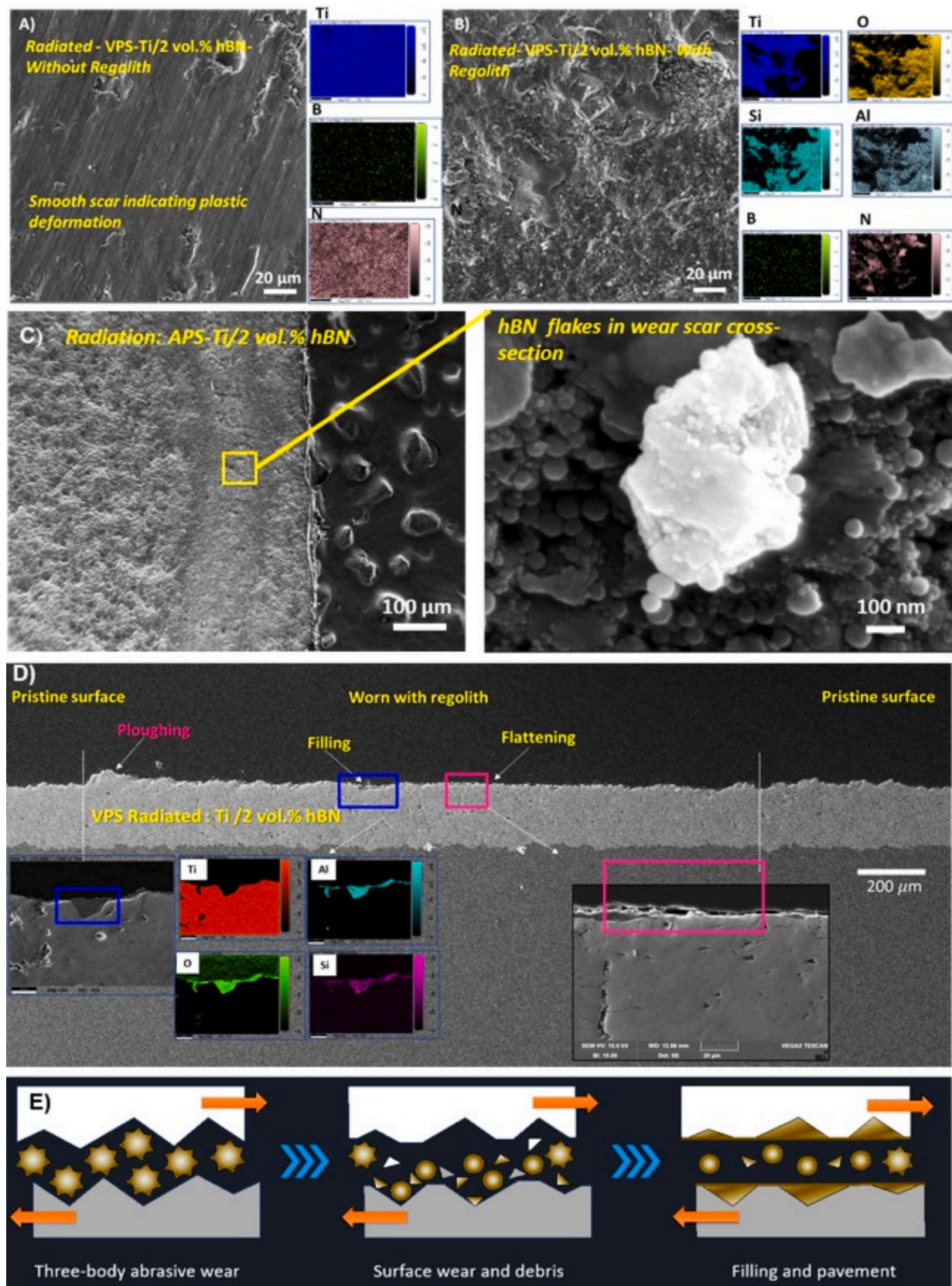


Fig. 10. Wear mechanisms in Ti-hBN composite coating A) Radiated VPS-Ti/2 vol% hBN without regolith (B) with regolith indicating embedding (C) Radiated APS-Ti/2 vol% hBN indicating smooth wear scar with hBN flakes imparting solid lubrication effect D) Panoramic wear scar cross-section of radiated VPS-Ti/2 vol% hBN E) Schematic representation of three-body abrasive wear with JSC-1 A.

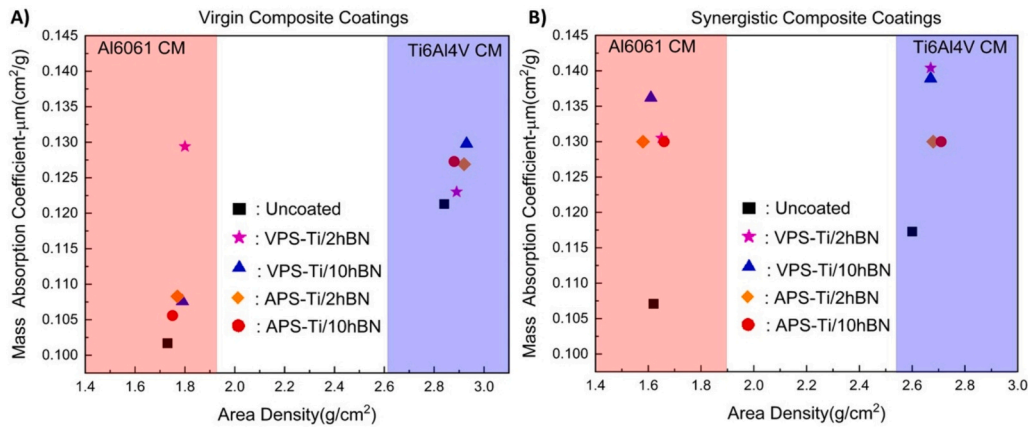


Fig. 11. Neutron shielding capacity of coatings deposited on Al 6061 and Ti6Al4V substrates subjected to (A) Virgin condition (B) Synergistic exposure.

3.4. Neutron shielding performance: virgin vs. synergistic composite coatings

Our previous study on the radiation shielding of coatings for Al6061 and Ti6Al4V substrates revealed that adding hexagonal boron nitride (hBN) significantly enhances the mass absorption coefficient (μ_m) and linear absorption coefficient (μ_x) [26]. In contrast to wear experiments, where substrates have minimal/no influence on coating wear, neutron shielding results are evaluated based on the material's density. As a result, neutron shielding analysis encompasses coatings on both substrates. Compared to uncoated Al6061 CM substrate, VPS Ti/2 vol% hBN and Ti/10 vol% hBN coatings exhibit a 27 % and 6 % increase in μ_m , making them the preferred shielding materials. For APS coatings, the improvements are 7 % and 4 %, respectively. On the Ti6Al4V substrate, VPS Ti/2 vol% hBN and Ti/10 vol% hBN coatings increase μ_m by 1 % and 7 %, while APS coatings show a 5 % improvement. This enhancement is notable given the low hBN concentrations (2 and 10 vol%) and the thin 200- μ m coating thickness, which is only 3 % of the 6.5 mm sample thickness. The actual hBN concentration in Ti/2 vol% hBN is just about 0.06 %, with a boron content of 0.03 %, including a 0.006 % weight concentration of the ^{10}B isotope. Yet, even with these minimal hBN concentrations, the coating substantially improves radiation shielding. The effectiveness of neutron shielding by Boron atoms is due to its *boron capture mechanism*, where neutrons interact with boron nuclei, leading to the emission of alpha particles and lithium nuclei [50]. These secondary particles, having lower penetration power, are absorbed by other secondary phases, thus reducing the harmful effects of radiation [51,52]. A detailed description of the results and mechanism is provided in our previous study [26].

In this study, the performance of virgin composite coatings is compared against the synergistic exposure coatings (Fig. 11 A & B) for their feasibility of use in a real-time scenario (simulated radiation-thermal cycles) of the space environment. The results show that the synergistic exposure coatings deposited on both substrates have an equal or higher neutron shielding performance than the virgin coatings. Both virgin and synergistic coatings have a higher μ_m than uncoated substrates. The uncoated synergistic exposure Al 6061 and Ti6Al4V substrates show a 5 % increase and a 10 % reduction in percent radiation shielded against virgin substrates, respectively, as referenced against indium foil.

For APS coatings, 18 % and 24 % improvement in shielding were obtained for Ti/2 vol% and Ti/10 vol% hBN synergistic coatings deposited on Al 6061 substrates compared to virgin condition. A marginal improvement in shielding efficiency of 4 % was observed for APS Ti/2 vol% hBN coatings deposited on Ti6Al4V substrates with respect to the virgin coatings. Similarly, APS Ti/10 vol% hBN coating exhibited a 3 % increase in shielding effectiveness. This improvement is higher for

VPS coatings, with 6 % and 28 % for Ti/2 vol% hBN and Ti/10 vol% hBN, respectively, on Al 6061 substrates and 14 % and 8 % on Ti6Al4V substrates. Also, compared to uncoated synergistic exposed Al6061 and Ti6Al4V substrates, a remarkable 21 % and 28 % improvement in mass absorption coefficient is observed for the VPS 2 and 10 vol% Ti-hBN composite coatings on Al substrates and 20 % on Ti substrates.

The improvement in the neutron shielding mechanism of the synergistic environment could be attributed to the increased hardness and resultant crack formation in the synergistic environment. Neutron radiation is found to scatter through cracks in a material [53]. Neutrons are uncharged particles that interact with atomic nuclei rather than electrons, which means they can penetrate matter relatively well, including materials with cracks or voids. An inelastic collision occurs when a fast neutron with energies greater than a few million electron volts collides with atomic nuclei [54]. This process is accompanied by the production of some secondary species (e.g., low-energy neutrons and γ -rays). Inelastic scattering is more common in heavy nuclei since they possess numerous energy levels that permit this type of interaction; when the energy of neutrons is lower than the threshold energy for inelastic scattering, they can only be decelerated through elastic scattering. High-energy neutron scattering is more likely to occur, and they may pass through cracks with minimal interaction [54]. On the other hand, low-energy or thermal neutrons are more prone to scattering and may experience more interactions as they pass through a material with cracks [53,54]. The scattering can change the direction and energy of the neutrons. Materials with voids or cracks are used to moderate or slow down fast neutrons (Fig. 12), making them more amenable to capture by materials with high neutron-absorbing properties, such as boron-containing materials (boron nitride) [52]. Also, cracks could increase the surface area, thereby exposing a higher area of boron atoms for neutron capture. Similar neutron shielding studies on different

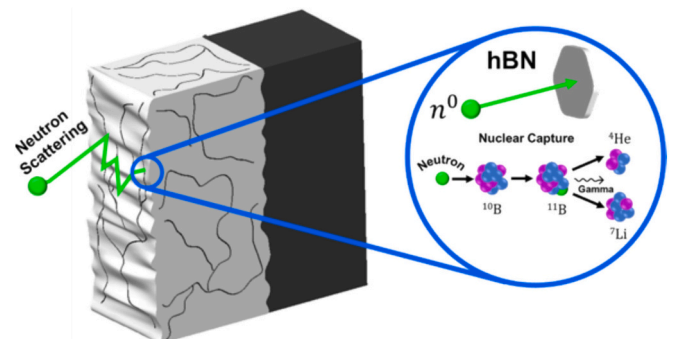


Fig. 12. Neutron scattering and shielding mechanism in the synergistic exposure coatings.

materials have made observations similar to those of the current study. However, it's important to note that this assertion requires further experimental design to control void and crack density in identical samples, such as foams or meshed structures. Future experiments with a more extensive statistical dataset are needed to verify these hypotheses conclusively.

3.5. Coating ranking and feasibility of use in harsh conditions

The high wear resistance exhibited against JSC-1 A lunar simulant and the exceptional neutron shielding capacity of these synergistic (radiation-thermal) coatings suggest their promising potential for effective utilization as a multifunctional protective coating in the challenging, abrasive, and radiation-rich lunar environment for structural components. The ranking of developed synergistic coatings against wear and radiation shielding of the lunar environment is depicted schematically in Fig. 13.

VPS Ti/2 vol% hBN coatings emerge as the optimal choice for aerospace applications, specifically in the context of wear and radiation challenges. The synergistic interplay between the hard secondary phases and the solid lubricity, bolstered by the high neutron absorption cross-section of the embedded hBN, significantly augments wear resistance and radiation shielding capabilities. These coatings safeguard against the rigors of harsh radiation, thermal, and synergistic environmental conditions. However, it is worth noting that APS coatings tend to deteriorate when hBN concentrations increase, leading to issues such as agglomeration, defects, and unmelted particles. Additionally, radiation-induced hardening can result in pronounced brittle fractures that can prematurely compromise the coating's lifespan. In contrast, VPS coatings maintain their integrity by minimizing the occurrence of secondary phases. The presence of retained hBN further elevates their wear and radiation resistance. Consequently, these coatings stand as highly promising candidates for aerospace applications, especially in lunar structural components, where they can effectively withstand the challenges posed by demanding environments.

4. Conclusions

This study investigated the effect of simulated lunar harsh conditions, including pelletron radiation exposure, thermal cycling, and synergistic exposure, on the titanium-hBN composite coatings. Radiation-induced hardening and subsequent brittle fracture increase the coatings' porosity and crack formation by cyclic thermal stresses. Enhancement in hardness is observed due to the formation of dislocation clusters, and thorough examination by XRD and TEM highlights the

existence of high dislocation densities, black dot defects, and dislocation clusters, indicating the severe impact of synergistic environmental stresses on these coatings.

Both APS and VPS 2 vol% hBN coatings exhibit substantial improvements in wear resistance, with VPS coatings showing a slight advantage over APS coatings. Remarkably, all exposed samples exhibit an impressive 90–95 % reduction in wear rate compared to the Ti CM substrates. This enhancement is attributed to the combined effect of solid lubrication and the presence of hard secondary phases within the coatings. The wear track cross-section reveals distinct features such as embedding, flattening, filling, and pavement of the wear tracks due to repeated sliding interactions with third-body particles in the mating pair. However, Ti/10 vol% hBN coatings experience degradation in wear performance due to hBN agglomeration, porosity, and defects.

Ti/2 vol% hBN coatings, when exposed to JSC-1 A lunar regolith, exhibit significant improvements in wear resistance, making them suitable for demanding lunar environments. Neutron shielding tests revealed that synergistic coatings show slightly higher neutron shielding performance due to enhanced neutron scattering and capture by crack formation induced by radiation-hardening. Compared to uncoated Al6061 and Ti6Al4V substrates exposed to a synergistic environment, the VPS 2 and 10 vol% Ti-hBN composite coatings exhibit a notable 28 % increase in mass absorption coefficient.

Upon a comprehensive assessment and ranking of different coatings under varying conditions, it becomes evident that the VPS Ti/2 vol% hBN and VPS Ti/10 vol% hBN coatings emerge as top choices for aerospace applications that involve extreme radiation and thermal cycles. Therefore, this study underscores the potential of harnessing the multifunctionality of hBN through its reinforcement in titanium powder using plasma spray techniques (APS and VPS). This approach allows for the creation of multifunctional coatings that substantially enhance wear resistance and radiation shielding for harsh conditions. These coatings hold great promise for future lunar structures and human landing systems.

CRediT authorship contribution statement

Abhijith Kunneparambil Sukumaran: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Kazuo Orikasa:** Software, Methodology, Investigation, Formal analysis, Data curation. **Sara Rengifo:** Resources, Project administration, Funding acquisition, Conceptualization. **Michael Renfro:** Methodology, Investigation, Formal analysis, Data curation. **William Scott:** Resources, Project administration, Methodology, Investigation, Data curation. **Annette Gray:** Investigation, Data curation. **Gia Garino:** Investigation, Data curation. **Alex Franco Hernandez:** Methodology, Investigation, Data curation. **Ambreen Nisar:** Methodology, Investigation, Formal analysis, Data curation. **Matthew Mazurkivich:** Supervision, Resources, Project administration. **Gabriel Demengehi:** Methodology, Investigation. **Ellen Rabenberg:** Methodology, Investigation. **Martin Volz:** Methodology, Investigation, Data curation. **Malik Thompson:** Methodology, Investigation. **Brandon Phillips:** Methodology, Investigation. **Nathan Jimenez:** Methodology, Investigation, Data curation. **Felipe Mora:** Methodology, Investigation. **Sang-Hyon Chu:** Methodology, Investigation, Data curation. **Cheol Park:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Arvind Agarwal:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

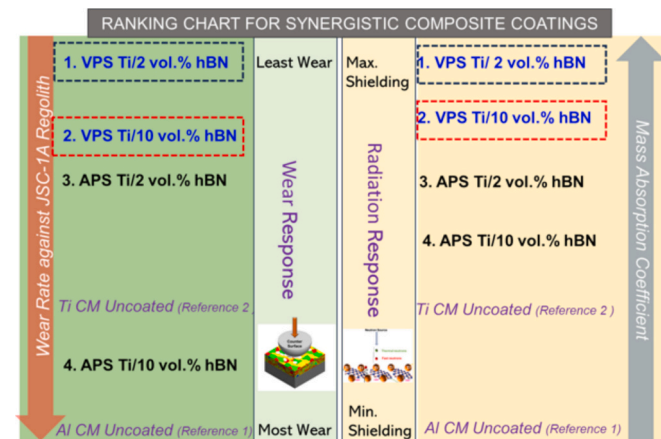


Fig. 13. Rankings of synergistic coatings based on their tribological performance against JSC-1A lunar simulant and neutron shielding effectiveness against Al and Ti substrates.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.surfcoat.2024.131185>.

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