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REVIEW ARTICLE

Application of MoS_2 in the space environment: a review

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ABSTRACT A considerable portion of space mechanism failures are related to space tribological problems. Cold welding in high vacuum; surface erosion and collision damage caused by various radiations, high temperature oxidation under atomic oxygen (AO) bombardment; and thermal stress caused by temperature alternation all alter the physical, chemical, and friction properties of materials. In particular, the space vibration caused by alternating temperatures and microgravity environments can alter the motion of the contact body, further affecting its friction properties. Improving the friction properties of contact surfaces in the space environment is an important way to extend the service life of spacecraft. Traditional lubricants can no longer meet the lubrication requirements of the space environment. This study describes the characteristics of the space environment and the applications of solid lubricants. The friction properties of MoS_2, a solid lubricant widely used in space, are discussed. The synergistic lubrication of MoS_2 with surface textures or metals is presented. Advances in research on the friction properties of collision sliding contacts in the space environment are reviewed. The combination of MoS_2 and soft metals with surface textures is introduced to reduce the effects of vibration environments on the friction properties of moving parts in space mechanisms. Finally, the challenges and future research interests of MoS_2 films in space tribology are presented.

KEYWORDS MoS_2, soft metal, space environment, surface texture, synergistic effect, vibration

1 Introduction

With the development of space technology, the expected range and lifetime of space activities are gradually increasing, and the complexity of spacecraft is also increasing. Moving parts are widely used in the space mechanisms of spacecraft, such as artificial satellite antenna mechanisms, solar panel drive mechanisms, antenna and sensor pointing mechanisms, attitude control mechanisms, and mechanisms connecting rockets and satellites [1–3]. The lifetime of these moving parts could be a key factor limiting the lifetime of spacecraft [4–6]. According to reports from the National Aeronautics and Space Administration (NASA), many failures of the moving parts that occur on the spacecraft are caused by tribological problems [7]. Given that they operate in a space environment, there is usually no opportunity to replace or replenish lubricants once they are launched. The complex space environment also leads to difficulties in providing long-lasting and reliable lubrication for the spacecraft. Thus, designing lubricants with long service lives is a considerable challenge.

Spacecraft operate in complex environments and usually undergo ground testing, ground storage, transportation, launch, space operations, and even re-entry and return. Most spacecraft are typically tested on the ground before launch and stored in a controlled environment for several years. They may operate in space for 10–30 years after launch. Spacecraft in low Earth orbit (LEO) are exposed to highly reactive atomic oxygen (AO) [8]. AO is highly corrosive and can lead to oxidation and damage to the material. Harsh conditions in high orbits, including high vacuum, microgravity, alternating operating temperatures, and intense radiation, cause material deterioration or even destruction. High vacuum and high temperatures can cause severe adhesion at the contact interface and increase wear. In a microgravity environment, irregular vibration is generated due to the disturbance of friction torque or thermal deformation [2]. Vibration can affect the precise control of velocity and position by precision opto-electromechanical instruments and orientation mechanisms. The docking and

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separation of spacecraft and the deployment of solar panels and antennas can also be affected by vibration. Space radiation may considerably influence the properties of materials [9]. Among the various anomalies of spacecraft, more than 40% of the failures are caused by the influence of the space environment, and some examples are shown in Table 1 [10].

Moving parts in space mechanisms often perform complex motions, such as multiple start–stop operations and intermittent operations. Lubricants can reduce wear between the friction nodes of moving parts [11,12], whereas the lubricants used in space mechanisms are always subject to extreme space environments [13–15]. These extreme space environments present difficulties for the long-lasting and reliable lubrication of space mechanisms. The operating status of space mechanisms affects the mission or even results in the failure of the related systems or the mission. For example, the failure of the Kepler telescope stabilizing system was caused by high friction in the space environment [16]. In addition, the failure of the radar antenna of the Japan Earth Resources Satellite and the failure of the main antenna deployment mechanism of the Galileo Jupiter probe were associated with lubrication failures caused by the space environment [3,10,17]. Therefore, the lubrication condition of the moving parts in space mechanisms is a critical factor in determining the reliability and service life of spacecraft. Many studies have focused on the lubricants used in spacecraft and their friction properties.

The characteristics of the space environment and the application of solid lubricants are introduced in this study. The friction properties of molybdenum disulfide (MoS_2), a widely used solid lubricant in space, are discussed. The incorporation of MoS_2 and soft metals with surface texture is introduced to reduce the influence of the vibration environment on the friction properties of moving parts in space mechanisms. The soft metals can absorb part of the energy of the collision caused by the vibration, and the deformation of the surface texture can extrude the stored MoS_2 for secondary lubrication. In addition, multilayer or composite films formed by MoS_2 and metals can effectively improve the friction and wear properties. Therefore, the synergistic lubrication effects of MoS_2 with surface textures and metals are discussed in this study, and advances in the study of the friction properties of collision sliding contacts in the space environment are reviewed. The remaining studies on improving the friction properties of MoS_2 have been discussed in other review papers [18–23] and thus are not introduced in detail here. Finally, we present the challenges and future research interests of MoS_2 films in space tribology.

2 Lubricants in the space environment

Lubricants for space mechanisms are applied in complex and variable space environments. Their reliability is determined not only by their own structure but also by the operating environment; thus, serious unpredictability occurs. Under vacuum conditions, materials with low vapor pressure must be used, so liquid-based lubricants used in spacecraft are usually limited to those based on perfluoropolyethers, multiply alkylated cyclopentanes and polyalphaolefins oils [24]. Solid lubricants exhibit low vapor pressure in typical spacecraft operating environments. Solid lubricants are widely used due to their low evaporation rate and high radiation resistance [24–26]. The distribution of liquid lubricants and abrasive particles is affected in the microgravity environment. Traditional lubrication methods, such as gravity oil supply, or circulating oil supply fail in the state of microgravity [27]. However, microgravity has minimal effect on solid lubricants and can reduce the self-weight load of the friction pair, resulting in a low coefficient of friction (COF). For space mechanisms operating in extreme or variable temperature environments, solid lubricants are preferred. Liquid lubricants are too viscous to flow effectively at extremely low temperatures [24] and evaporate or creep at extremely high temperatures, leading to losses and even contamination [28]. Solid lubricants can be used in a wide temperature range [29]. For example, graphite, MoS_2, and Ag can be used in medium- and low-temperature environments, whereas oxides, fluorides, and Au are mainly used in high-temperature environments. Mechanical lubrication above 400 °C is generally limited to solid lubricants [29,30]. Torres et al. [31] summarized the effective lubrication

Table 1 Spacecraft failures caused by the space environment [10]

Spacecraft	Space environment	Anomaly description
Hubble space telescope	Thermal	Thermal expansion of the support poles was blamed for the vibrations, which interfered with deep-space observations
JERS-1	Thermal	The cold welding of the deployment pins due to faulty lubrication caused the radar antenna to fail to deploy
Galileo	Thermal	A lubricant used on the mechanical joints failed to function in the ambient thermal environment
GOES-7	Solar	The intense high-energy radiation permanently damaged solar panel electronics and caused an accelerated power degradation
ETS-6	Radiation	High radiation levels from the Van Allen belts quickly eroded the efficiency of the solar panels
Intelsat K	Plasma	The electrostatic discharge resulting from a geomagnetic storm disabled the momentum wheel control circuitry on the satellite

range of some high-temperature solid lubricants, as shown in Fig. 1. The temperature of the space environment varies greatly due to sunlight exposure [32], and solid lubricants exhibit stable properties during temperature changes, which are an important advantage for space applications. The space vibration collision in the microgravity environment [33] and the alternating high and low temperature environment [2] increase the indentation depth between the contact bodies. At this time, the contact state between the lubricating films is changed, further affecting the friction performance of the lubricating films.

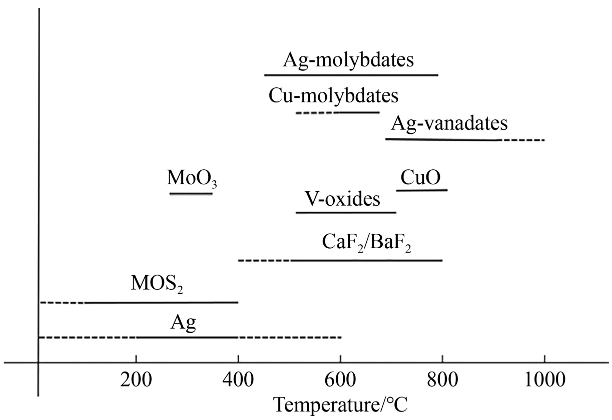

Fig. 1 Temperature ranges for effective lubrication for several solid lubricants, as reported in Ref. [31]. Reproduced with permission from Ref. [31] from Taylor & Francis.

Solid lubricants present excellent friction properties, bearing capacity, radiation resistance, and wear resistance. They can be used where grease cannot be used and where environments are harsh, although they have some shortcomings. Solid lubricants are usually applied as thin films, bonded, or sputter deposited on metal surfaces. In contrast to liquid lubrication, the wear track of solid lubricating films cannot be replenished after being worn [32]. Wear debris from solid lubricant films can be trapped and circulate back into the contact region as a third body activated by flow and rheology within the contact, providing additional life. Wear debris can also be permanently lost for contact [34,35]. Therefore, life and wear resistance are critical considerations when evaluating solid lubricants. In addition, given the lack of a cooling effect, the solid lubricating films cannot carry away the frictional heat generated during operation [36]. Solid lubricants have been shown to offer lubrication advantages in complex space environments [20,37–42]. They can be used where lubricating liquids or greases are inconvenient or unavailable [43]. Therefore, solid lubricants are one of the main lubricants used in space mechanisms to avoid cold welding and high friction between moving parts [44].

Solid lubricants, such as graphite and talc, have been used for a long time, and the demand for solid lubricants drives their development. MoS_2 was used in the United States in the 1880s, but minimal research was conducted on solid lubricants. Solid lubricants were not proposed as a research object until World War II and have developed rapidly since then [45]. MoS_2 was developed by the Max Planck Institute in Germany and the National Advisory Committee for Aeronautics, the predecessor of NASA, laying the foundation for its later applications. The successful launch of Soviet Sputnik Vostok-1 in 1957 marked the beginning of the human cosmic era and promoted the development of solid lubricants to a new level [46]. Solid lubricants have received extensive attention in the field of tribology due to their excellent performance even under harsh conditions, such as high temperatures and vacuum [20,38–40]. The United States, the Soviet Union, the United Kingdom, Germany, Japan, France, and other countries have invested many resources in the research of solid lubricants [45]. Japan's solid lubricant development program began in the 1960s, and solid lubricants have been applied to the rolling bearings of satellites and small rockets [47]. The rolling bearings of some US missile products, and the scanning mechanisms of space stations, space shuttles, and weather satellites, also used solid lubricants. Since its first artificial earth satellite, China has conducted extensive research on solid lubricants. Many types of space mechanisms have successfully used solid lubricants, including rod antennas, solar panel hinges and torsion spring devices, and gravity balance mechanisms for satellite attitude control [48].

Solid lubricants include soft metals (such as Au, Ag, Cu, and Pb [49]), polymers (such as polytetrafluoroethylene (PTFE) [5,50,51]), two-dimensional (2D) layered materials (such as graphite and MoS_2 [23,24,37,52]), and hard carbon-based materials (such as diamond-like carbon (DLC) [40,53–55]).

The primary physical property of soft metals suitable for lubrication is their low shear strength [29]. The shear strength of soft metals is further reduced at high temperatures, where most other solid lubricants fail [56]. In addition, soft metals have multiple slip surfaces and can effectively repair microstructural defects through frictional heat [37,56]. Although soft metals perform well at high temperatures, they also have limitations, such as the inability to achieve sufficiently low friction levels and poor adhesion to substrates compared with other solid lubricants. Some of these problems can be overcome by combining soft metals with surface textures [37].

In terms of cost, weight, and manufacturability, polymers show remarkable advantages. Polymers used as solid lubricants include PTFE, polyetheretherketone, polyimide, and polyethylene. PTFE is widely used among them due to its excellent friction properties [57]. PTFE consists of long "zigzag" chains or helixes that are held together by physical forces. These helixes do not easily form chemical bonds with other atoms or molecules; thus, PTFE has a low-energy, low-friction surface [5]. However, given its low shear strength, PTFE is only used under low load conditions. Furthermore, although polymeric solid lubricants are inexpensive and effective in reducing friction, they typically rely on a complex tribofilm formation process and provide limited wear resistance. Therefore, their long-term use is limited in cases where replacement parts are not available [37].

2D layered materials are widely used as solid lubricants for satellites and space probe bearings or as components of metal-based or polymer-based composite solid lubricants to improve substrate friction performance [39,53,58]. In some cases, 2D layered materials can achieve low COF and good wear resistance. Graphite and MoS_2 are the two most typical 2D layered solid lubricants. Graphite requires a certain level of humidity to provide effective lubrication and has good lubricity in air while failing in a vacuum. MoS_2 exhibits low friction and wear in a vacuum, whereas its lubricity is affected by temperature and humidity and deteriorates rapidly in the presence of ambient gases, such as H_2O and O_2 [24,37].

Since its first synthesis in 1971, DLC has been widely used in industry for its high hardness, wear resistance, corrosion resistance, low friction, and low surface roughness [40,53]. Depending on the chemical composition and environmental factors, DLC exhibits a wide range of COFs, i.e., from 0.001 to 0.70. Hydrogen-free DLC films (a-C) and hydrogenated DLC films (a-C:H) are two types of DLC. On the one hand, the wear resistance of a-C is better than that of a-C:H. On the other hand, a-C obtains good friction properties in wet environments and performs poorly under dry conditions or inert environments, whereas a-C:H provides lower COFs under dry conditions [37]. Moreover, DLC films perform poorly on soft substrates or when coated under high contact loads. The AO environment is also detrimental to the friction properties of DLC films. AO exposure leads to continuous oxidation of surface carbon atoms, resulting in greatly reduced wear life [5].

For complex space environments, different solid lubricants can be combined to form hybrid/composite solid lubricant systems that couple the advantages of their respective components [22,59]. In addition, solid lubricants can also be combined with surface textures to mitigate their inherent disadvantages [37].

3 Lubrication mechanism of MoS_2 and influence of the environment

3.1 Lubrication mechanism of MoS_2

Most of the moving parts in spacecraft operate at low velocities, and they are lubricated with solid lubricants. Among solid lubricants, MoS_2 is widely used due to its excellent friction properties in a vacuum environment.

MoS_2 is more resistant to vacuum cold welding and radiation than ordinary liquids and greases. It has a higher load-carrying capacity and a wider operating temperature range [18,60]. At the normal temperature (293 K) in a vacuum environment, MoS_2 has a lower COF and a longer service life compared with solid lubricants, such as graphite and PTFE, and the higher the vacuum level, the lower the COF. At low temperatures (20 K) in a vacuum environment, the COFs of almost all solid lubricating films increased in comparison with the normal temperature environment, whereas MoS_2 still showed good lubricity and wear resistance [39]. Most solid lubricants, such as graphite, are more suitable for the ground environment and tend to fail in the space environment [24]. MoS_2 has a lower COF in space than in air and is an ideal vacuum lubricant with a larger temperature range in a vacuum [61,62]. Therefore, MoS_2 has become one of the most effective space lubricants due to its excellent friction properties in the space environment [24,63–65]. It has been widely used in the bearings of various drive mechanisms, scanning mechanisms, and rotating mechanisms [19,43,66].

One of the drawbacks of MoS_2 that cannot be ignored is the formation of MoO_3 in ground applications or when oxygen is present in space environments, causing damage to its lifetime and friction behavior. MoO_3 oxides are covalently bonded and brittle, resulting in a susceptibility to exfoliation and abrasion, which destroy the lubricity of MoS_2 [67–69]. Based on first-principles calculations, the friction force between MoO_3 interfaces increases in comparison with that between MoS_2 interfaces, and the resulting increase in adhesion prevents the interface from sliding. Wong et al. [70] investigated the friction properties of MoS_2 films at high temperatures. When the temperature was 20 °C, the COF remained at 0.065. When the temperature reached 400 °C, the MoS_2 film began to be oxidized to MoO_3, which induced a decreased lubricating ability, and the COF increased to 0.35 [70]. Spalvins [21] believed that the oxidation products of MoS_2, such as MoO_3, were poor lubricants that worsened friction and wear. Lince et al. [71–73] also found that the chemical composition and structure of MoS_2 films were closely related to their friction and wear properties. In addition to oxygen, which can oxidize MoS_2 to form MoO_3 at high temperatures, oxidation may occur in the presence of AO due to its extreme reactivity [74]. Detailed studies of the effect of oxygen and AO on the frictional properties of MoS_2 on the ground or in space are presented in Subsections 3.2 and 3.3.

The application of MoS_2 as a thin film on frictional surfaces is common, and its preparation methods include bonding, spraying, physical vapor deposition (PVD), chemical vapor deposition (CVD), atomic layer deposition (ALD), and other techniques. The bonding method uses an adhesive to bond MoS_2 to the surface of the substrate. This method is widely used due to its ease of application and low cost, but it produces thick films and is limited by the adhesive strength. It is suited for mechanisms with low sliding velocities, moderate to high contact stresses, and large clearances [5]. The spray coating method involves spraying dissolved MoS_2 nanoparticles onto a substrate by using techniques, such as thermal spraying and plasma spraying. For example, Khare and Burris [75] used ethanol as a carrier to prepare MoS_2 films on 440C stainless-steel substrates by spray coating technology. In recent studies, the tribological properties of films obtained by cospraying MoS_2 with other materials were improved. Wu et al. [76] combined *in-situ* synthesis of MoS_2/C with plasma spraying technology to improve the friction and mechanical properties of the film. PVD is a method of preparing MoS_2 films by evaporating the MoS_2 target material under vacuum conditions using an arc or electron beam and depositing the vapor onto the substrate to form a film. The method is fast and allows for control of the composition and thickness of the film. PVD can produce pure and stable films with good density and adhesion [77,78]. CVD involves the decomposition of MoS_2 gas precursors on the substrate to form a film [19]. ALD is a type of CVD that involves the introduction of MoS_2 gas precursors to the substrate surface, which then undergoes a chemical reaction to deposit the film layer by layer [19]. ALD allows for precise control of film thickness and composition, which can produce high-quality films, whereas the preparation process is long. Most MoS_2 films used in space mechanisms are prepared by PVD, and sputtering is the most widely used preparation method [39].

In 1969, MoS_2 films were prepared by Spalvins [79,80] through sputter coating technology, and excellent friction properties could be obtained with MoS_2 films prepared by sputtering. Sputtered MoS_2 films exhibit excellent friction properties, and the COF can reach 0.01. Most lubricating films based on soft metals (Ag, Au, Pb, etc.) and PTFE-based films present COFs in the order of 0.05 and 0.1 [19,21]. In a vacuum environment, the sputtered MoS_2 film has a low COF, but its friction properties deteriorate under humid air conditions. As a result, MoS_2 films formed by sputtering can provide low COFs and strong adhesion under suitable operating conditions [81]. Fleischauer and Hilton [1] noted that space precision bearings lubricated with sputtered MoS_2 films have low and stable friction torque and long wear life. Sputtered MoS_2 films also provide good lubrication to other precision moving parts and could be one of the main lubricants used in space mechanisms [82]. Since the pioneering research of Spalvins [79], sputtered MoS_2 films have been successfully used in space mechanisms operating under high vacuum, high temperature, and space radiation, such as solar panel drive mechanisms, harmonic driven gears and bearings, and antenna pointing and control systems [5,24,83–85].

MoS_2 has a Mohs hardness value of 1.0–1.5 and a COF of 0.01–0.08 [86,87]. Its excellent friction properties are derived from its layered hexagonal crystal structure [88,89]. As shown in Fig. 2 [90], MoS_2 has a highly anisotropic crystal layer structure, and the Mo atoms in each interlayer are arranged in a hexagonal arrangement located between the two layers of S atoms [21,90,91]. The layered structure of MoS_2 is caused by the polarization effect of Mo atoms on S atoms. This polarization effect leads to the formation of strong covalent Mo–S bonds within the MoS_2 layers, whereas the interaction between the layers is a weak van der Waals force, and the interlayer bonds are so weak that only a small shearing force is required for MoS_2 to be exfoliated [87,91,92]. Furthermore, as shown in Fig. 3 [21], the MoS_2 layer structure can have two regular crystallite orientations:

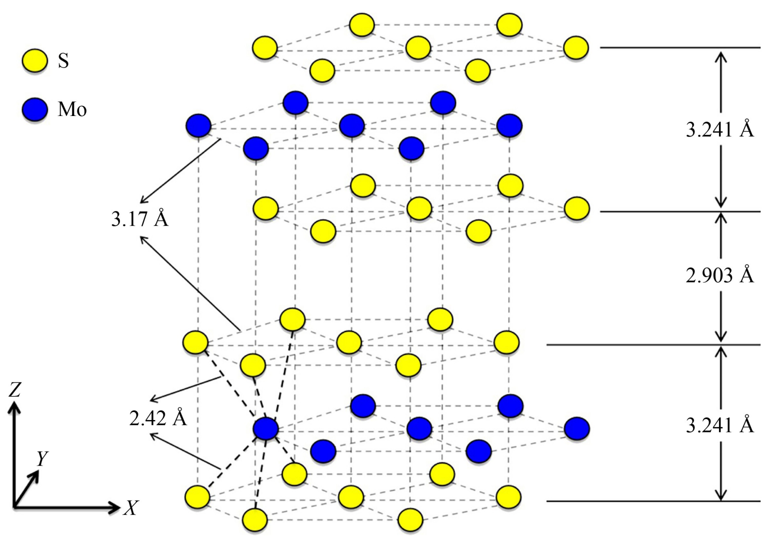

Fig. 2 Structure of MoS_2 [90]. Reproduced with permission from Ref. [90] from IOP Publishing Ltd.

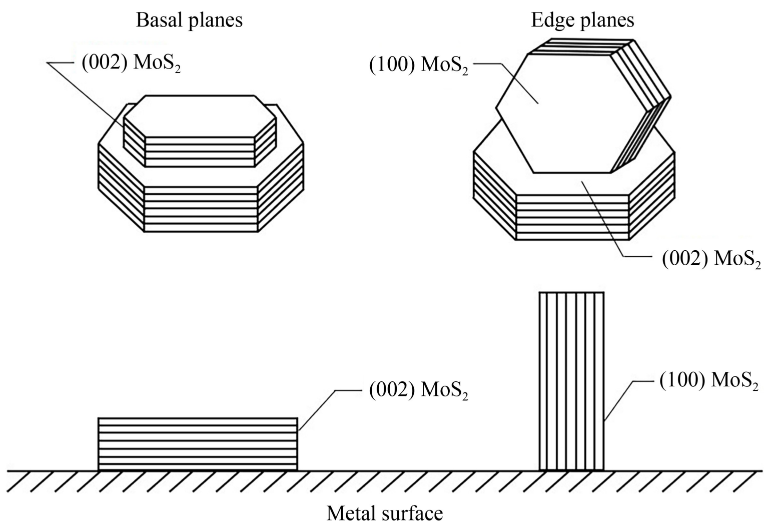

Fig. 3 Parallel basal plane orientation and vertical basal plane orientation structure of MoS_2 crystal [21]. Reproduced with permission from Ref. [21] from Springer Nature.

parallel to the substrate or perpendicular to the substrate. When MoS_2 is in the parallel substrate direction, shearing is prone to occur along the substrate direction, resulting in low friction [21,90].

Holinski and Gänsheimer [92] investigated the lubrication mechanism of MoS_2 using scanning electron microscopy. They described the lubrication mechanism of MoS_2 in terms of the polarity of S atoms and the good adhesion of S atoms to metals and attributed the excellent friction properties of MoS_2 to the strong polarization of S atoms [92]. Fusaro [93] studied the lubrication mechanism of MoS_2 films coated on polished, sanded, and sandblasted surfaces using an optical microscope. The lubrication mechanism was found to be the plastic flow of the MoS_2 film between the slider and the metal substrate [93]. Spalvins [94] found that the low shear strength between the MoS_2 crystal layers ensured low friction. Zhang et al. [62] noted that the ionic bonding between the Mo and S atoms induced a high strength of the MoS_2 film so that the lubricating film on the metal surface could not penetrate. S atoms were exposed on the surface of the MoS_2 crystal layer and had strong adhesion with the metal surface so that the MoS_2 film could not be peeled off easily when it was covered on the metal surface [62]. According to Barton and Pepper [95], single crystals of MoS_2 form transfer films on the surfaces of Cu, Ni, Au, and stainless steel. Only one slip was required to form a transfer film on the contact surface, and the thickness of the transfer film increased with the number of slips. When the direction of the MoS_2 single crystal was parallel to the substrate, the transfer film was smooth and flat. When the transfer film was formed, the transfer rate of the MoS_2 film was slowed down, increasing the wear life of the film. However, a low COF could be obtained only when a properly oriented MoS_2 transfer film was formed on both moving surfaces [95]. Ye et al. [96] investigated the friction and wear properties of MoS_2 films under micromotion conditions. They concluded that the formation of transfer films was the main reason for the high load-bearing capacity and good wear resistance of MoS_2 [96]. Cao et al. [97] concluded that MoS_2 nanosheets had a high elastic modulus, which resulted in a small contact area and thus induced friction reduction.

3.2 MoS_2 in the space environment

The lubrication of spacecraft mechanisms faces numerous challenges in space. These complex environments produce a considerable influence on the friction properties of MoS_2, possibly affecting the lubrication of spacecraft mechanisms, leading to mechanism failure or even catastrophic consequences [86,98–100].

A high vacuum environment is the most essential operating environment for spacecraft. In a high vacuum environment, the oxide film on the metal surface is worn away quickly, and regeneration is difficult. The “bare” metal surfaces have a remarkable adhesion effect, and even cold welding can occur, which affects the relative motion of the friction pairs [32]. In addition, in a high vacuum environment, given the lack of gas diffusion and convection, the frictional heat cannot be removed in time [36]. Most of the frictional heat at the contact interface is transferred by heat conduction, and high friction temperatures increase wear [32,101,102]. Ashby et al. [101] noted that majority of the friction power during a sliding contact was converted into frictional heat. Meng et al. [103] found that the COFs of MoS_2 films increased dramatically in a high-temperature environment.

In the space environment, spacecraft are inevitably exposed to a combination of various electromagnetic radiations (such as Gamma ray, X-ray, and ultraviolet

(UV) radiation) and particle radiation (such as high-energy electrons, protons, and solar wind). This radiation can considerably alter the structure of materials, causing erosion and collision damage. For example, UV radiation can alter the chemical properties of materials and lead to their degradation [104–106]. Dever [105] found that UV radiation might promote the breakage of important organic structural bonds (e.g., C–C and C–O), as well as functional groups. UV radiation might also lead to the cross-linking of polymer surfaces, which could lead to embrittlement and even surface cracking [105]. Nicholson et al. [9] investigated the changes in the friction properties of MoS_2 lubricating films under proton irradiation with an energy of 500 eV. Results showed that proton irradiation compromised the friction properties of MoS_2 lubricating films, as shown in Fig. 4 [9]. Radiation can affect the properties of MoS_2; therefore, protection and shielding must be considered for MoS_2 [107]. Shielding lubricated mechanisms can be designed using materials, such as high-density polyethylene, to protect against radiation [46].

Most lubricated surfaces are contained within spacecraft and not directly exposed to the AO environment. However, materials of equipment located on the front surface of LEO spacecraft inevitably experience degradation due to collisions with AO [104]. AO erosion in a LEO environment leads to the oxidation of MoS_2 and the formation of an oxide layer on its surface [108,109]. This oxide layer is thin, but it can well prevent further oxidation of MoS_2. The formation of the surface oxide layer increases the initial COF of MoS_2, but when it is fully exfoliated, the recovered COF is almost the same as that of the unexposed samples [110–112]. Gao et al. [113] conducted direct exposure of radio frequency sputtered MoS_2 films in a LEO environment and analyzed the structure and properties of MoS_2 films before and after space exposure on the ground. They found that AO oxidized the surface layer of the films and slightly increased the COF in the early stages of sliding [113]. Arita et al. [114] discovered that AO erosion resulted in a higher initial COF than the corresponding unexposed samples, regardless of whether the films were sputtered, inorganically bound, or organically bound. Cross et al. [115] and Tagawa et al. [116] demonstrated that under continuous sliding conditions with AO irradiation, the wear lives of MoS_2 films were greatly reduced due to the exfoliation of the oxide layer. The oxide layer was continuously generated and exfoliated during the sliding contact process, resulting in a high COF, high friction noise, and high wear [116]. Gao et al. [117] found that the hardness of MoS_2 films dropped drastically after being irradiated by AO, leading to their rapid wear under high contact stress. To reduce the influence of the AO environment on lubrication materials and structures, exposed surfaces must be coated with protective coatings, as in the case of radiation environments. This coating helps protect the surfaces from the effects of AO [13,104].

Spacecraft experience high, low, and even alternating temperatures and are alternately exposed to sunlight and Earth's shadow region in orbit; moreover, external heat sources cause uneven heating of the space orbit. The surface temperature of spacecraft can reach 200 °C when exposed to direct sunlight and −200 °C when flying into the shadow zone of Earth. The International Space Station orbits Earth once every 90 min, which means that it experiences alternating temperature environments approximately 5800 times during each year of service. The alternating temperatures stimulate the random vibration of the space mechanism [2], increasing the indentation depth between the contact bodies, and the friction properties of the lubricating film in the contact interface are also affected. In addition, MoS_2 films are coated on the substrate surface, and the thermomechanical

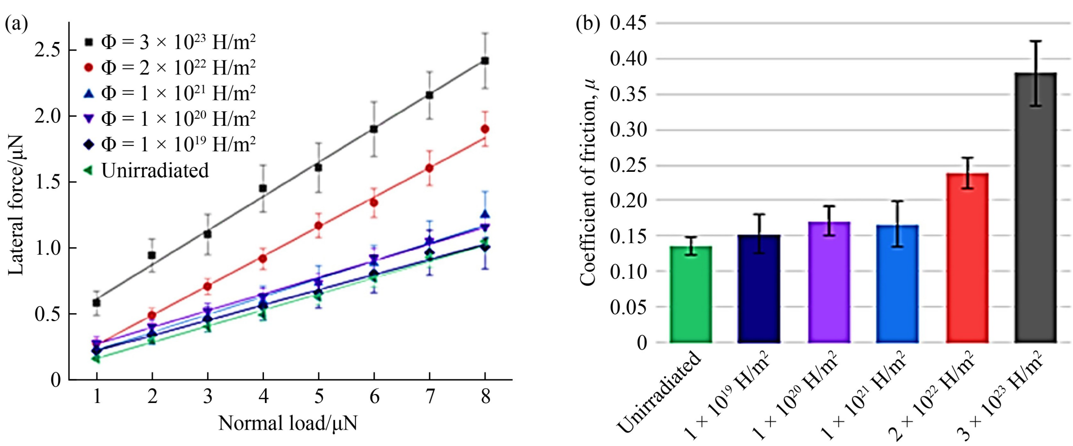

Fig. 4 (a) Lateral force of the MoS_2 coating following proton irradiation to five fluences from 10^{19} to 3×10^{23} H/m^2 and the unirradiated condition and (b) average coefficient of friction for each irradiation condition, which tends to increase with dose [9]. Reproduced with permission from Ref. [9] from Elsevier.

properties of the two materials are usually different. The alternation of high and low temperatures can generate remarkable interfacial stresses in the material, which can lead to wear and exfoliation of the lubricating film [118,119].

3.3 MoS_2 in the ground environment

In addition to the various space environments described in Subsection 3.2, the ground environment has an important influence on MoS_2.

Space mechanisms are assembled and tested on Earth. Even one-off mechanisms must be tested [120]. Given the high cost of launching spacecraft and the high requirements for equipment life, operations and testing must be performed on the ground prior to launch. Given their large size, most spacecraft cannot be fully tested in a vacuum chamber and must be tested in a clean room [82]. Furthermore, the spacecraft are stored on Earth for months or even years before launch. The COF of the MoS_2 film in air increases with storage time, and the wear life decreases. Therefore, the adaptability of the lubricating film to the ground storage environment must be considered [121,122]. When launching a spacecraft, sea launches have flexible launch azimuths that can accommodate any orbital inclination. Considering the potential hazards of ground launches to surrounding buildings, sea launches can reduce the risk of launching over populated areas, conflicts with other launch systems or air traffic, and damage due to malfunctions [123]. In addition, a sea launch has the advantages of safety, high capacity, and ease of spacecraft transportation, which is an important component of space technology. However, for sea launches, the lubricants used in the spacecraft inevitably meet the challenge of the high humidity, temperature, and salt spray of the ocean air during preactivity [124]. These issues mean that, in addition to the ability to work in the space environment, the ability of the lubricant to work during assembly, testing, storage, and transportation on the ground or at sea is also critical [4].

3.3.1 Oxidation during storage

During storage periods of several months or even years prior to spacecraft launch, oxidation is the main factor that leads to MoS_2 degradation and affects its friction performance.

Several scholars have noted that MoS_2 is oxidized in air [17,96,111,125–129], and the presence of water vapor promotes this reaction [83,130–132]. According to their results, MoS_2 films are prone to failure in air, especially in humid air [133–136], and oxidation is the main cause of degradation, increased COF, and wear. Pope et al. [84,137] compared the friction coefficient of MoS_2 stored under different conditions, as shown in Fig. 5, and found that MoS_2 films stored in laboratory air or high humidity environments had an increased COF and reduced wear life. They associated this phenomenon with the oxidation of the films, suggesting that MoS_2 was oxidized to produce MoO_3, which changed the microstructure and hindered the reorientation of the substrate planes with sliding [84,137]. Lince et al. [138] observed the oxidation and degradation of MoS_2 powders when stored in different air humidity for more than three years. Gao et al. [139] and Yao et al. [140] focused on MoS_2 thin films grown by CVD, which experienced degradation after being exposed to ambient environments at room temperature for a period. Budania et al. [141] also found the same phenomenon in MoS_2 prepared by exfoliation. These findings indicate that CVD-grown and exfoliated MoS_2 layers show degradation effects after being left in ambient air at room temperature for extended periods. Protective measures are needed to improve the stability and performance of MoS_2 in various environments. Afanasiev and Lorentz [142] found that MoS_2 particles exposed to ambient air at room temperature for one year showed considerable degradation and liquefaction. They proposed that after a few minutes to several hours of exposure, the edges of the particles oxidized and bonded with hydroxyl groups. Then, chemical reactions occurred with adsorbed H_2O and dissolved the oxide. Moreover, in subsequent exposure, the edges were further oxidized, leading to a self-propelled degradation process.

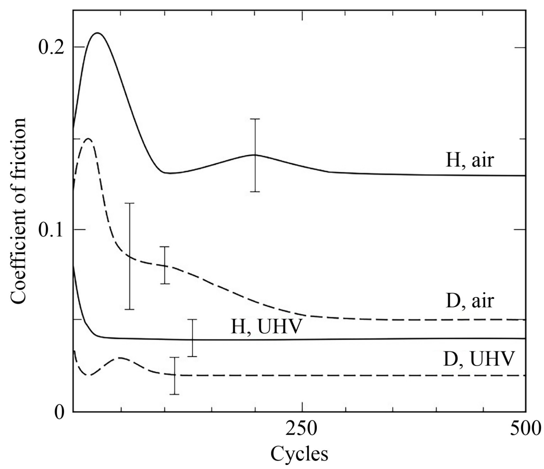

Fig. 5 Average coefficient of friction vs. number of cycles for MoS_2 coatings tested in air and ultrahigh vacuum (UHV). D refers to samples stored in 2% relative humidity for less than 100 days after deposition; H refers to storage for 150 days in 25%–35% relative humidity followed by 190 days in an atmosphere of 98% relative humidity after deposition [84]. Reproduced with permission from Ref. [84] from Elsevier.

3.3.2 Effect of water and oxygen on operating contacts

In addition to oxidation during storage, the effects of water and oxygen on operating contacts during spacecraft ground operations and testing must be considered. The main obstacle to the use of MoS_2 films in ground environments is their high sensitivity to humidity [84,143]. The COFs of MoS_2 films vary greatly depending on the environment. MoS_2 films tested in the laboratory under vacuum and inert gas environments have low COFs and wear rates [22,144,145], but the COFs of MoS_2 films increase with increasing air humidity [84,130,146–148].

The increase in the COF with humidity can be attributed to the oxidation of MoS_2 or the interaction of water molecules between MoS_2 layers. Ross and Sussman [149] concluded that water would accelerate the oxidation of MoS_2, especially when the system was heated, and that frictional heat would also accelerate the oxidation process. Haltner and Oliver [150] investigated the effect of water vapor on the friction properties of MoS_2, discovered that the COF in humid air was higher than that in humid N_2 at the same relative humidity, and proposed the hypothesis of water-induced oxidation. Fusaro [111] conducted a comparative study on the friction properties of MoS_2 films in humid air, dry air, and dry Ar. Results showed that the friction force was greatest in humid air and that the oxidation of MoS_2 films in humid air was the cause of the increased friction.

Windom et al. [68] investigated the oxidation of MoS_2 in various environments. They found that the presence of water vapor in humid O_2 or N_2 had no additional effect in comparison with dry O_2 or N_2. This finding led them to conclude that humidity has no effect on the oxidation of MoS_2 [68]. Khare and Burris [75] questioned the hypothesis that "humidity and thermal energy facilitate oxidation, which increases the shear strength of the sliding interface". Their study demonstrated that water does not promote oxidation at room temperature. Below the transition temperature, the friction force increased with the addition of humidity, regardless of the presence of O_2. The environmental sensitivity of the friction properties of MoS_2 at this time was caused by the physical binding of water to the near surface, which hindered interlayer shear. Above the transition temperature, friction increased with increasing O_2 and decreasing humidity due to oxidation. At this point, water could help mitigate the effects of high-temperature oxidation by displacing O_2 from the environment or preferentially adsorbing to the surface [75]. Dreva et al. [151] found that water molecules at room temperature could hinder the alignment direction of MoS_2 layers, exposing some active edge locations to contact and leading to high friction and wear. Serpini et al. [152] performed tribological tests on sputtered MoS_2 films in humid air and vacuum using a ball-on-disk tribometer. They concluded that the well-attached transfer film provided better friction properties than wear debris recirculation. However, the formation of the MoS_2 transfer film was hindered in a humid environment. The negative effect of water did not cause excessive oxidation of the MoS_2 film; by contrast, the physisorption of water impaired the good friction properties of MoS_2 [152].

Yang et al. [133] investigated the effect of undissociated and dissociated water molecules on the COFs of MoS_2 films. As shown in Fig. 6 [133], the COF of the MoS_2 film in an N_2 environment with a relative humidity of 40% was comparable with that in air with a relative humidity of 43%. The introduction of H_2O molecules increased the COFs of the MoS_2 films in N_2 and air environments, but the effect of air oxidation was not as remarkable. They proposed that the influence of water molecules was an important reason for the elevated COF of MoS_2 in a humid environment. On the one hand, the transfer layer caused by sliding gradually formed during the increase in relative humidity. The reduced interlayer spacing of MoS_2 in this transfer layer increased interlayer adhesion, resulting in an elevated COF. On the other hand, the defects in the MoS_2 films could affect the dissociation and adsorption behavior of H_2O molecules. Although the COF of MoS_2 single crystals is hardly affected by air humidity [153], MoS_2 films, particularly those prepared by vapor deposition, usually contain various defects [154–156]. These defects could affect the dissociation and adsorption behavior of H_2O molecules [157]. The interlayer adsorption of dissociated water molecules did not change the interlayer binding energy and had minimal effect. However, the physisorption of H_2O on MoS_2 layers with original defects and new slip-induced defects formed hydrogen bonds that increased the interlayer binding energy and increased the COF of MoS_2 in humid environments [133].

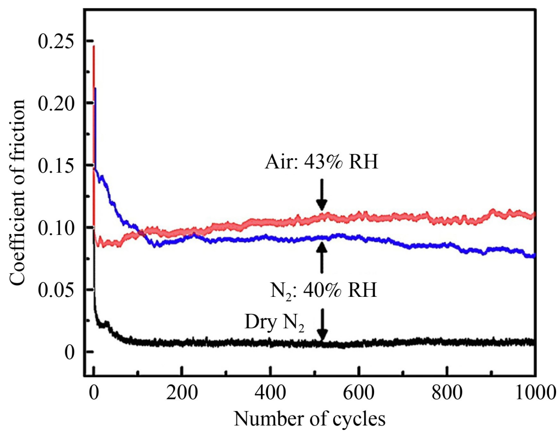

Fig. 6 Comparison of the variation in the coefficient of friction values of MoS_2 during sliding tests in an ambient air atmosphere with 43% relative humidity (RH), a N_2 atmosphere with 40% RH, and a dry N_2 (< 2% RH) atmosphere [133]. Reproduced with permission from Ref. [133] from Elsevier.

These assembly tests and storage requirements revealed the shortcoming of MoS_2 films: Despite their low friction and long life in vacuum and dry environments, they are sensitive to air and hot and humid environments. Pure

MoS_2 films in air, particularly in humid air, have low hardness, high COF, and short service life. It can be damaged before entering the space environment, posing challenges to the long-term service of spacecraft [21,111,158,159].

4 Synergistic effects of MoS_2 with surface textures or metals

Numerous studies have been conducted to improve the friction properties of MoS_2, such as MoS_2 films combined with textures [93,160,161], metal-doped MoS_2 films [138,162–164], metal–MoS_2 multilayer films [165–167], MoS_2/a-C:H composite films with good resistance to AO radiation [168], MoS_2–WS_2 composite films that show improved adaptability to thermal cycling and AO radiation environments [169], PbO–MoS_2 films with improved temperature adaptability [170], LaF_3–MoS_2 composites for humidity resistance [171], and Sb_2O_3-containing MoS_2 films (i.e., Au–Sb_2O_3–MoS_2 and Sb_2O_3–MoS_2) for durability in long-term storage in humid air [138]. The encapsulation of MoS_2 and other 2D materials can improve the applicability, longevity, and lubricity behavior of MoS_2 under vacuum and ambient conditions, providing good operational stability under various ambient conditions [172]. The encapsulation of MoS_2 between two layers of graphene can remarkably reduce defects and improve stability [173], whereas the encapsulation of MoS_2 within h-BN can reduce surface contamination caused by the environment [174]. Using urea formaldehyde encapsulation to synthesize microcapsules and prepare composite materials can reduce the environmental sensitivity of MoS_2 and improve its friction properties [175]. The multicomponent synergy of the composite and multilayer films could considerably improve the friction properties of MoS_2. Alternating high and low temperatures and microgravity in space can cause moving parts to vibrate and operate in collision sliding contact. When combined with textures, MoS_2 films maintain a low adhesion component in the vibration environment, and surface textures can continuously provide lubricant to the contact interface, resulting in a synergistic friction reduction effect. In addition, metallic materials tend to form dislocations in the vibration environment, which can absorb some of the collision energy of contact bodies. Therefore, in the space environment, MoS_2 combined with surface textures or metals may achieve improved synergistic lubrication effects. This section focuses on the properties of MoS_2 and surface textures, as well as the properties of composite and multilayer films formed by MoS_2 and metals, and their synergistic lubrication effects are discussed. The rest of the studies on the friction properties of MoS_2 is not presented here.

4.1 Synergistic effect of MoS_2 with surface textures

The surface morphology of mechanical parts has a considerable influence on their tribological behavior. Surface textures with specific distribution morphologies on the contact surfaces of mechanical parts can be used to capture abrasive particles and reduce the plowing effect. When combined with liquid or solid lubricants, surface textures can also provide lubricants to the contact surfaces, effectively improving the friction and wear reduction properties of the friction subsurface and extending the service life of the parts [176–187]. Therefore, the friction properties of the material can be improved by proper surface textures rather than simple smoothing [37,188]. Surface texture technology is widely used in mechanical seals [189,190], piston rings [191–193], thrust bearings [194], and microelectromechanical systems [195–197].

High contact pressures occurring at the edges of the texture under dry conditions are considerable disadvantages of the surface texture [198,199]. A disadvantage of solid lubricating films is that they are easily removed from the substrate and provide a short service life [37,200]. Surface textures and solid lubricating films wear rapidly under high load and low velocity conditions and no longer serve to reduce friction and wear [201–204]. The combination of surface textures and solid lubricating films can help overcome these drawbacks [205,206]. As a typical solid lubricating film, MoS_2 film can be combined with surface textures to form a reliable solid lubricating film, resulting in a synergistic friction-reducing effect [207]. Oksanen et al. [208] demonstrated that surface textures could store solid lubricants, provide a “secondary lubrication supplement” for friction pairs, and reduce friction and wear, producing considerable synergistic lubrication effects [209]. Qin et al. [210] demonstrated that a composite film combined with substrate textures could maintain a low friction level for a long period because the solid lubricant stored in the microdimples was squeezed and replenished to the contact region during the sliding friction process, as shown in Fig. 7. Rapoport et al. [63] demonstrated that laser textured steel surfaces covered with MoS_2 films had a lower COF and increased wear life than polished steel surfaces covered with MoS_2 films. Wu et al. [211] found that the textured surface filled with MoS_2 could reduce the COF and temperature during a sliding contact and reduce the width of wear scars on cemented carbide disks and the wear loss of titanium alloy balls.

Fusaro [93,161] noted that the rougher the substrate surface is, the longer the lifetime of the MoS_2 film. Xu et al. [160] concluded that the rough surface could improve the bond strength between the MoS_2 film and the substrate, which promoted lubrication in the later stages of fretting friction. This was because the residual MoS_2 film could be retained in the dimples maximally [160].

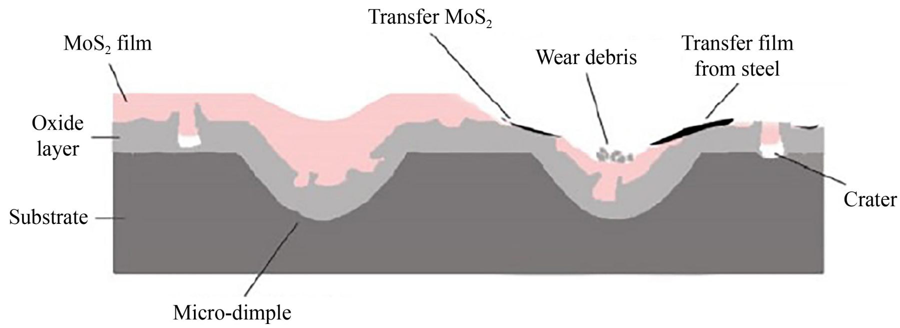

Fig. 7 Friction schematic of the laser surface texturing/plasma electrolytic oxidation (PEO)/MoS_2 coating [210]. Reproduced with permission from Ref. [210] from Elsevier.

The lifetime-versus-roughness curve reaches a maximum and then begins dropping. According to the rule of thumb, the upper limit of surface roughness should be less than half of the coating thickness based on *Ra* values. Different types of coatings have their own maximum and optimal roughness [5,212,213]. This is the reason for the controversy over the introduction of surface textures. Properly designed surface textures can remarkably improve friction and wear properties [211,214], whereas inappropriate texture parameters may lead to higher friction and wear and make the lubricating film more prone to failure [215–219].

The main parameters affecting the friction properties of surface textures are density [220–225], shape [226,227], size [228–230], and orientation [231–233]. As the texture density increases, more solid lubricant can be stored. However, an increase in texture density also leads to an increase in surface roughness and a reduction in the hard surface area available to support contact loading and resist abrasive wear. Therefore, friction properties do not vary monotonically with density [206,219,234–236]. Furthermore, the range of optimal texture density varies among different studies [234,237–241]. Different surface texture shapes affect the contact pressure and are found to have different stages of running in; thus, different texture shapes and orientations may exhibit different properties [225,242–246]. Maldonado-Cortés et al. [243] conducted a comparative study of the properties of various texture shapes, such as line, crosshatch, circle, triangle, square, and "S" shapes. The friction properties were found to vary with the applied pressure. Yu et al. [247] compared the load-bearing properties of circular, elliptical, and triangular textured dimples in different sliding directions. The elliptical dimples perpendicular to the sliding direction were found to have the best load-bearing capacity [247]. Geometric parameters, such as the width and intersection angle of the microgroove texture, also have a considerable influence on friction reduction [225,248,249]. The friction properties of composite films combining solid lubricants and surface textures are influenced not only by the parameters of the surface textures but also by the operating conditions [11,177,250]. In addition, the type of lubrication, contact conditions, and lubrication state should be considered [202]. These conditions could explain why the results of studies on texture parameters vary so much [37].

The combination of surface textures and MoS_2 is a promising approach that can produce synergistic effects to improve friction and wear performance remarkably. Textures were prepared on the surfaces of various substrates (such as stainless steel [241], Ti-based alloys [209,234,236,251], Ag–Ni-based alloys [252], and Al–Si alloys [253,254]), and they were filled with MoS_2 to improve the friction properties [255]. Regarding the design of surface texture, as discussed by Chouquet et al. [256], it must be tailored to specific application conditions to produce positive results. Therefore, when designing spacecraft lubrication, the appropriate texture size and density should be determined on the basis of the substrate material, contact surface, and operating conditions so that the texture does not unduly affect the surface stresses when storing MoS_2. In some literature, the surface texture density is usually chosen between 10% and 30% [236–238,240]. The appropriate texture shape is determined on the basis of the lubrication and sealing conditions. Open microgrooves provide good lubricity under liquid lubrication conditions, whereas closed, structured pits retain lubricant better than microgrooves under solid or paste lubrication conditions [257]. Experiments under specific conditions based on the operating position of the spacecraft, the specific needs of the space mechanisms, and the direction of contact surface movement are conducted to aid lubrication design.

4.2 Synergistic effect of MoS_2 with metals

MoS_2 has excellent friction properties in vacuum [34,258,259] and has been widely used for space lubrication [260,261]. However, pure MoS_2 films are loosely structured, poorly resistant to moisture, easily oxidized, and have a limited lifetime [20,109,262,263]. Using molecular dynamics (MD) simulations, Fig. 8 [109] shows the relevant oxidation processes between

MoS_2 and AO [109]. As shown in Figs. 8(a) and 8(b), MoS_2 is easily oxidized when its structure is sparse and disordered. The (002)-oriented MoS_2 has a dense and highly ordered structure with good oxidation resistance, as shown in Figs. 8(c) and 8(d). The doping of metals can induce the growth of MoS_2 along the (002) basal plane and create a synergistic effect with MoS_2 [164,264], showing better friction and wear properties than undoped MoS_2 in vacuum and exhibiting excellent oxidation resistance performance and improved performance and storage capacity in air [124,163,265–267].

Stupp [162] discovered that the addition of less than 10% (atomic fraction) of metallic elements (e.g., Cr, Co, Ni, Ta, or Au) to MoS_2 films could produce a synergistic effect. The doping elements were uniformly distributed within the films, and the hardness and density of MoS_2 films were effectively improved, which reduced the COFs and wear rates of MoS_2 films in the ground environment. Ding et al. [268] demonstrated that appropriate Cr or Ti doping can improve the hardness of MoS_2 films, as shown in Fig. 9. Spalvins [94] found that the dispersion of Au in MoS_2 films contributed to the compactness and strength of the film structure. In studies of MoS_2–Au composite films, Simmonds et al. [269] discovered that the addition of Au considerably affected the crystallinity of MoS_2 and guided the growth of MoS_2 on the substrate along the (002) direction, thus improving its friction properties. Lince [270] investigated the sliding contacts of cosputtered Au–MoS_2 films in N_2. Results showed that the properties were better than those of pure MoS_2-sputtered films and pure Au-sputtered films [270]. Gao et al. [271] exposed sputtered MoS_2–Au composite films to the LEO space environment and investigated their resistance to AO. They found that the exposed films exhibited no considerable difference in friction properties but had better resistance to oxidation than unexposed

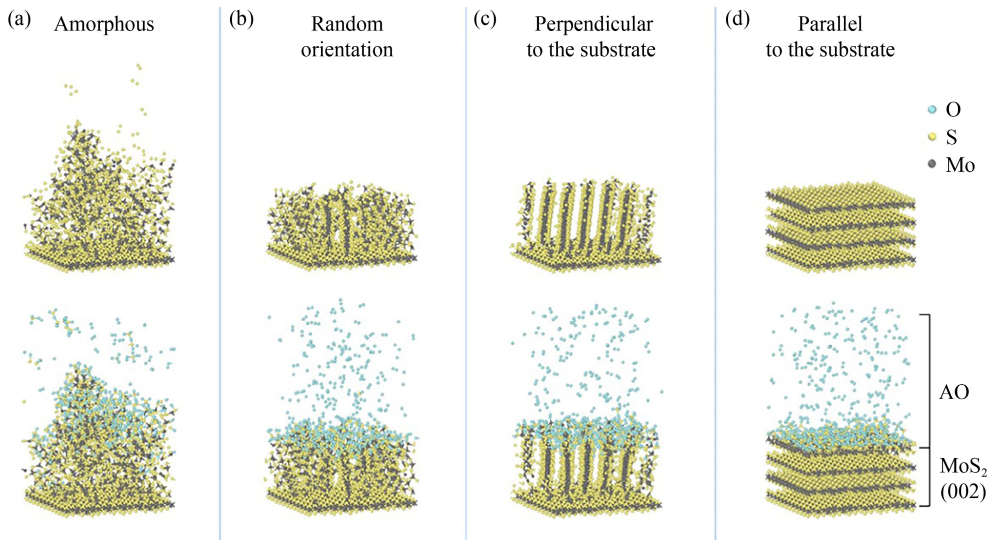

Fig. 8 Oxidation kinetic process of simulated MoS_2 structures including (a) amorphous, (b) random orientation, (c) MoS_2 (002) perpendicular to the substrate, and (d) MoS_2 (002) parallel to the substrate under atomic oxygen (AO) irradiation [109]. Reproduced with permission from Ref. [109] from American Chemical Society.

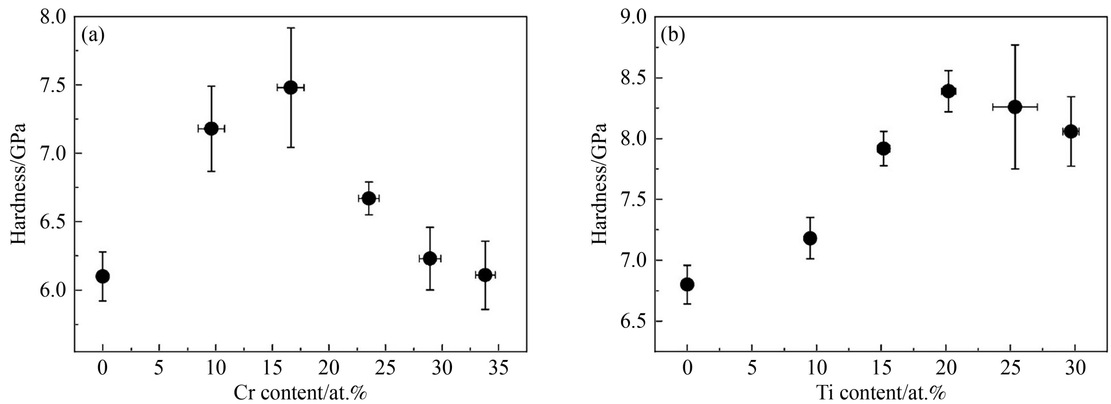

Fig. 9 Hardness of the as-deposited (a) MoS_2–Cr and (b) MoS_2–Ti composite coatings as a function of Cr or Ti content in the coatings [268]. Reproduced with permission from Ref. [268] from Elsevier.

films. This result was attributed to their compact microstructure and the passivation of the dangling bonds at the edges of the MoS_2 platelets, which might be partially occupied by doped atoms [271]. Liu et al. [272] discovered that a MoS_2–Ta film doped with approximately 20% Ta had a stable COF. Baran [273] investigated the adhesion and fatigue resistance of MoS_2–Ta composite films and discovered that the films had good stiffness, adhesion, and load-bearing capacity. Serles et al. [4] investigated composite films codeposited by MoS_2 and Ta, which exhibited sustainable lubricity regardless of the environment, as shown in Fig. 10. The composite films formed by MoS_2 and Ta exhibited different friction mechanisms under UHV and air conditions. Completely different small particles and compact sheet lubricating films were noted in air and UHV environments, as shown in Fig. 11 [4], resulting in adaptive lubrication in air and UHV environments.

In addition to the composite films mentioned above,

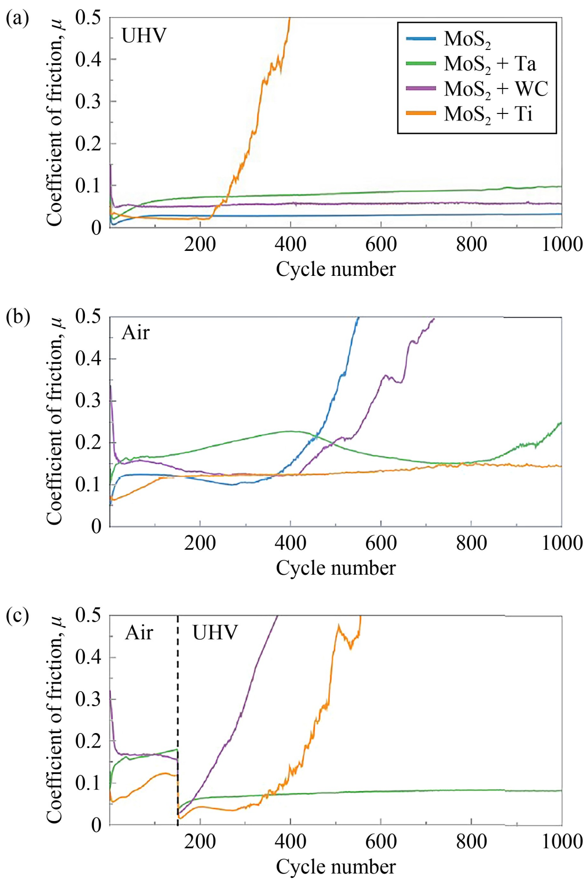

Fig. 10 Tribological testing of the pure and codeposited MoS_2 coatings. Per-cycle averaged friction coefficient under (a) ultrahigh vacuum ((2.7 ± 2.2) ×10^{-6} Pa), (b) humid clean room air (ISO 5 Clean Room, RH 43% ± 5%), and (c) transition from 150 cycles under air conditions followed by pumping down the chamber and 850 cycles in ultrahigh vacuum [4]. UHV: ultrahigh vacuum. Reproduced with permission from Ref. [4] from John Wiley and Sons.

multilayer films formed by MoS_2 and metallic materials can play a synergistic role in improving friction properties. Multilayer films are formed by the alternating deposition of materials with different compositions or structures, each with a thickness on the nanoscale. One part of multilayer structures provides high corrosion and oxidation resistance and even thermal conductivity, and the other part provides excellent friction and wear properties. The synergistic effect of multiple components can effectively improve friction properties, and multilayer film structures can be used to optimize various properties [274–281]. As mentioned by Holmberg et al. [203], to obtain excellent friction properties, each part of the coating and substrate must have specific functions, as shown in Fig. 12(a). Multilayer films offer the possibility of designing surfaces according to functional requirements. Functionally graded multilayer films, as shown in Fig. 12(b) [203], which are designed to provide different functions with specific material layers, are a promising strategy for multilayer films. Holmberg et al. [203] found that the mechanical properties of multilayer films with alternating deposited high- and low-shear-modulus layers were remarkably improved. The soft layer with low shear modulus acted as a shear band in an alternating soft and hard multilayer film. It allowed some "relative sliding" with the high-shear-modulus hard layer while maintaining low stress levels, as shown in Fig. 13 [203]. As a result, the mechanical and friction properties of the multilayer films were improved [203]. Given the crystal structures with multiple slip planes of soft metals, no considerable process work hardening is detected during sliding contacts. Dislocations and point defects from shear deformation are quickly offset by the frictional heat generated during sliding contacts. Therefore, soft metals are suitable as "soft layers" that can be combined with other lubricating films to form multilayer films [20].

Mikhailov et al. [165] prepared MoS_2–metal (Pb, Ni, Au, etc.) multilayer films and pure MoS_2 sputtered films. The results of pin-on-disk tribometer tests at two different loads of 5 and 1 N are summarized in Tables 2 and 3 [165]. At a low load (1 N), which corresponded to an average Hertzian contact pressure of approximately 400 MPa, the COFs of the various films were comparable. At a high load (5 N), which corresponded to an average Hertzian contact pressure of approximately 700 MPa, the average COFs of MoS_2–metal multilayer films were lower than those of pure MoS_2 films [165]. Wang et al. [282] used an unbalanced magnetron sputtering technique to synthesize multilayer films consisting of Ti metal layers and MoS_2 layers. The experimental results showed that the Ti interlayer in the MoS_2–Ti multilayer film considerably improved the compactness and stability of the film structure. The oxidation of MoS_2 was also effectively inhibited due to the preferential reaction of the Ti interlayer with O_2 to form TiO_2 [282]. Therefore, MoS_2–Ti multilayer films

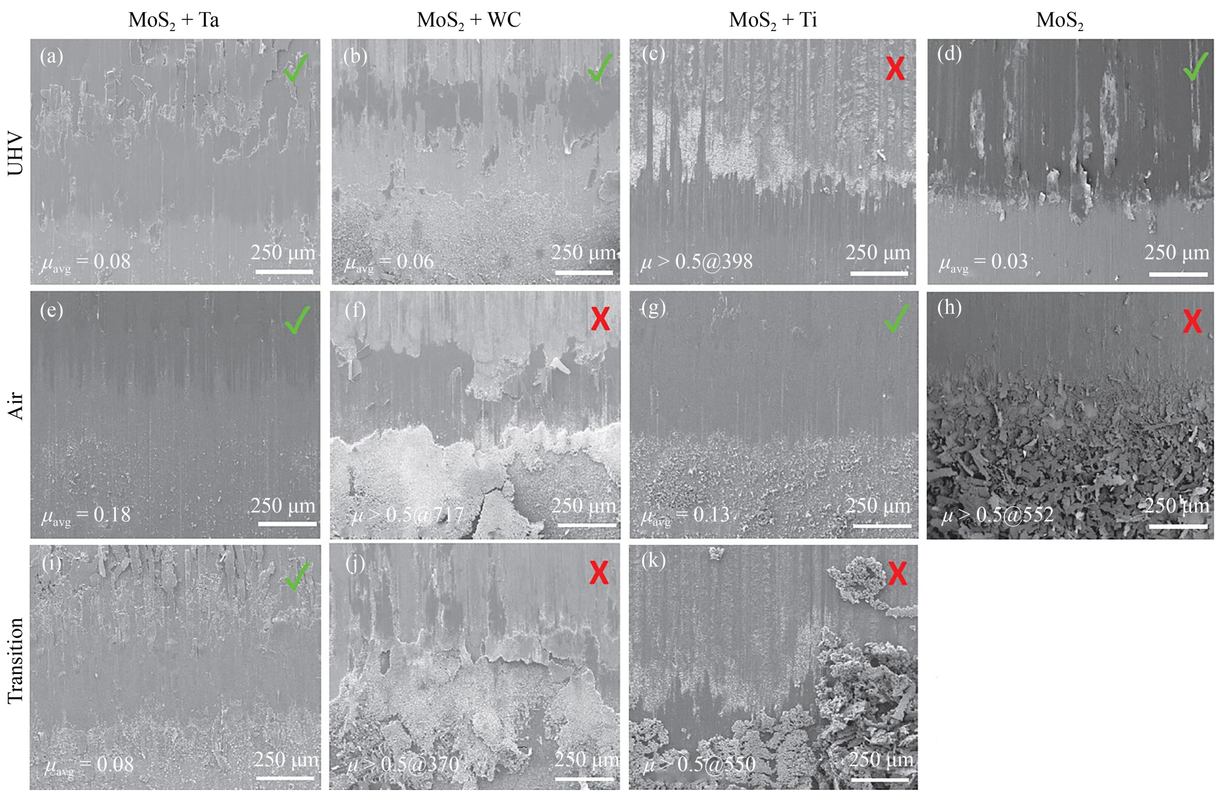

Fig. 11 Scanning electron microscope images of four coatings of MoS_2 + Ta, MoS_2 + WC, MoS_2 + Ti, and MoS_2 after cycling or failure (μ > 0.5) in (a–d) ultrahigh vacuum (UHV), (e–h) air, and (i–k) transition from air to ultrahigh vacuum environments [4]. Reproduced with permission from Ref. [4] from John Wiley and Sons.

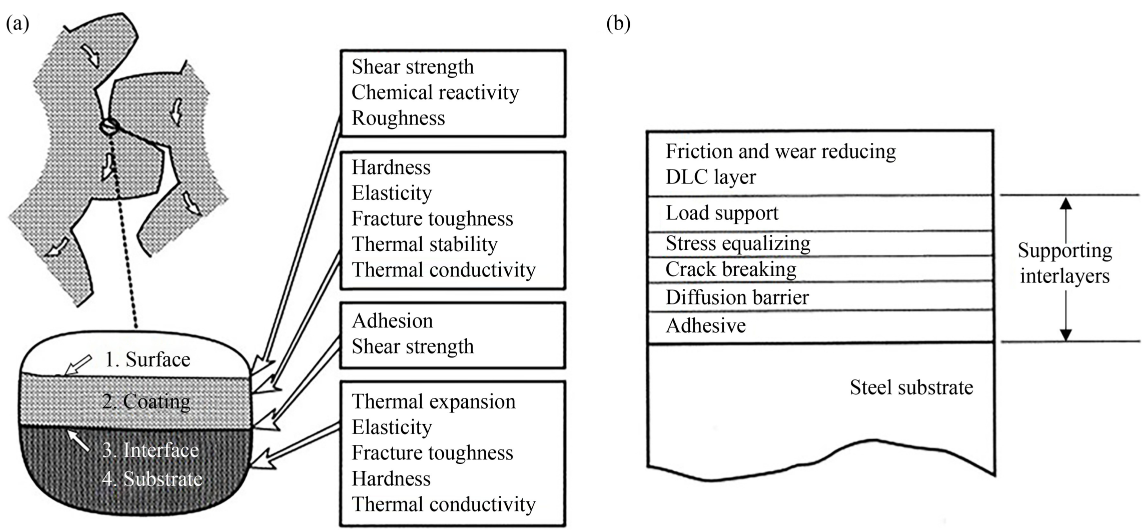

Fig. 12 (a) Tribologically important properties in different zones of the coated surface and (b) functionally graded multilayer coating design to utilize specific layers for distinct properties [203]. Reproduced with permission from Ref. [203] from Elsevier.

exhibit good wear and oxidation resistance and present promising applications as solid lubricants in humid environments. Zhang et al. [167] synthesized MoS_2–Ti multilayer films and investigated the effect of various modulation periods on the mechanical and friction properties of multilayer films. They found that multilayer structures closely related to the modulation period could improve the mechanical and friction properties of multilayer films [167]. Qin et al. [283] deposited Ag and MoS_2 films on the surface of a plasma electrolytically oxidized Ti–6Al–4V alloy to form multilayer films (PEO/Ag/MoS_2) and discovered that the multilayer films could effectively reduce COFs. Tian et al. [166] designed a periodic multilayer MoS_2–Ag film based on ion beam-

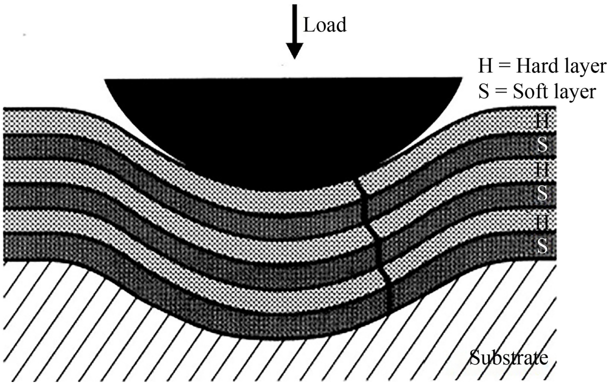

Fig. 13 Multilayer coatings with alternating hard and soft layers can allow deflection to occur under load without yielding of the hard layers. They effectively slide over each other, with shear occurring in the soft layer. The pattern of shear is illustrated by the line through the film, which was initially straight in the unloaded condition [203]. Reproduced with permission from Ref. [203] from Elsevier.

assisted deposition. The film had a distinct nanoperiodic structure with a multilayer composite structure in the MoS_2-enriched region, allowing for ultralow friction [166]. Chien et al. [284] coated the MoS_2 surface with a layer of Au. The Au film was found to effectively prevent O_2 or humidity from reacting with MoS_2, and the durability of the MoS_2/Au coating was remarkably improved [284]. Gao et al. [285] exposed the MoS_2–Au/Au multilayer film in a space environment on the Shenzhou VII manned spacecraft and then conducted tribological experimental studies in a vacuum environment after the samples were returned to Earth. Results showed that the multilayer film still had good friction properties, attributed to the compactness of the multilayer film and the inhibition of the transport of Au elements from the surface to the interior of the film, as shown in Fig. 14 [285].

Many studies have shown that the doping of metals, such as Ti, Cr, Zr, Au, Ta, Pb, Ni, and Ag [4,85,162,165,166,209,268–270,286–288], in MoS_2 can considerably improve the friction and wear properties. Compared with a pure MoS_2 film, the doped film has the advantages of high bond strength with the substrate, long wear life, resistance to moisture and heat, and oxidation resistance. Metal doping has a concentration limit, beyond which the solubility limit will be reached, resulting in poor friction properties. For example, the concentration limit of Ti is 18% [260]. The optimum concentration of Cr is 16.6% for improving hardness and 10% for improving friction properties [268]. The optimum concentration of Zr is 10% [259]. Au still has good tribological properties at high concentrations of > 42%. The optimum amount of Au addition depends on the contact stress, and a lower concentration of Au is better at high stress and a higher concentration of Au is better at low stress [270,289]. The appropriate amount of metal doping can produce a synergistic lubrication effect with MoS_2, which is an important direction for the lubrication design of spacecraft space devices.

Subsection 4.1.1 demonstrated that surface textures and MoS_2 films can form a synergistic friction reduction effect. In this section, the synergistic effect of MoS_2 films

Table 2 Mean COF (μ) of the MoS_2 pure and multilayer coatings after different numbers of revolutions in humid air (50%) for a load of 5 N [165]

MoS_2–metal multilayer	Mean COF, μ			X-ray diffraction (XRD) (002) peak relative value/%
	500 revolutions	5000 revolutions	20000 revolutions	
600-nm MoS_2 pure	0.21	0.25	0.31	0
17×33-nm MoS_2–16×3-nm PbO	0.15	0.17	0.17	20
17×33-nm MoS_2–16×3-nm Pb	0.10	0.17	0.20	40
17×33-nm MoS_2–16×1.5-nm Ni	0.17	0.17	0.20	60
15×33-nm MoS_2–14×7-nm Au	0.12	0.15	0.15	100

Notes: The last column presents relative values of the XRD (002) peak of MoS_2 in the films.

Table 3 Mean COF (μ) of the MoS_2 pure and multilayer coatings after different numbers of revolutions in humid air (50%) for a load of 1 N [165]

MoS_2–metal multilayer	Mean COF, μ		XRD (002) peak relative value/%
	5000 revolutions	50000 revolutions	
600-nm MoS_2 pure	0.35	0.33	0
17×33-nm MoS_2–16×3-nm Pb	0.32	0.30	40
17×33-nm MoS_2–16×1.5-nm Ni	0.28	0.27	60
15×33-nm MoS_2–14×7-nm Au	0.20	0.21	100

Note: The last column presents relative values of the XRD (002) peak of MoS_2 in the films.

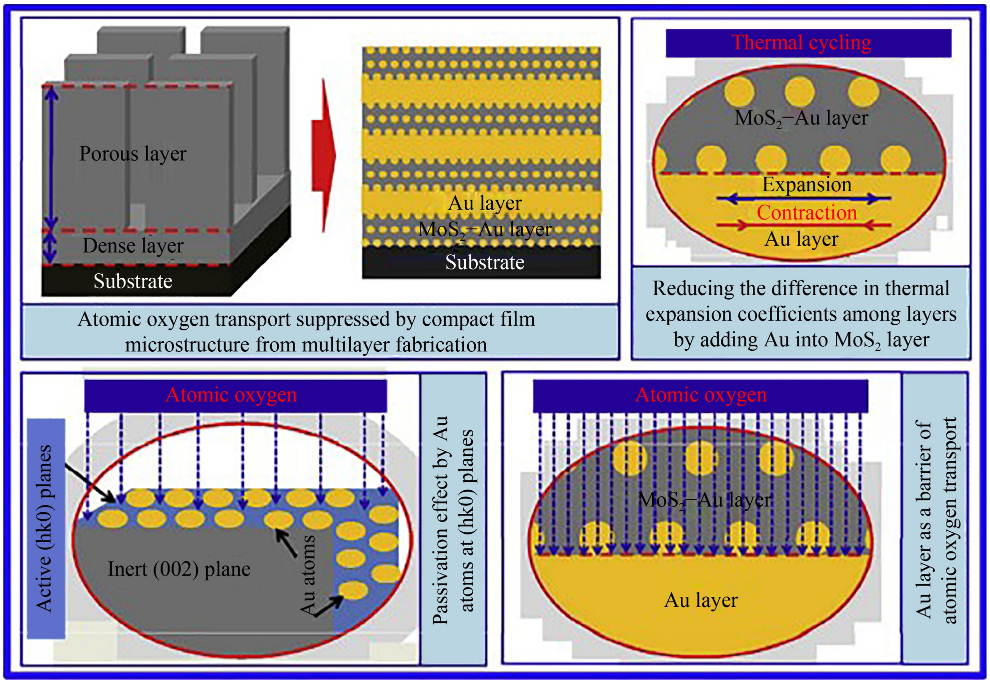

Fig. 14 Mechanisms of MoS_2–Au/Au multilayer film with a good capability resistant to space-environmental exposure [285]. Reproduced with permission from Ref. [285] from Elsevier.

with metals is introduced. Based on these two effective ways to improve friction properties, combining composite or multilayer films with surface textures to form a solid lubricant system is also an important trend. In the combination of surface textures with multilayer films, textures can be prepared on the surface of the lubricating film in addition to the surface of the substrate [37]. For example, Voevodin et al. [290] processed groove textures on Ti–TiC–TiC/DLC functionally graded coating surfaces and coated the textured surfaces with MoS_2 films. The wear life was improved by at least one order of magnitude over the untextured surface covered with MoS_2 film on the coated surface [290]. Solid lubricants that combine composite or multilayer films with surface textures can provide effective "secondary lubrication" and extend the service life of the lubricating film. In addition, the advantages of each individual component can be combined to produce a synergistic friction reduction effect, resulting in a stable and reliable solid lubricating film with excellent friction properties.

5 Lubrication of collision sliding contacts in a space environment

Spacecraft operate in harsh space environments, in which alternating temperatures and microgravity environments cause irregular vibrations of the space mechanism. Foster et al. [2] studied the vibrations that occurred shortly after the Hubble Space Telescope was deployed in orbit, and the vibrations were found to be particularly pronounced during the orbital day–night crossings, with amplitudes much larger than the amount of vibrations predicted at design time. Alternating temperatures in space can cause irregular vibrations in the space mechanism, causing collisions in the clearance joints of the spacecraft's moving parts. Under a microgravity environment, the disturbance of friction torque tends to cause vibrations in the relevant mechanism. When a slight disturbance is applied to one of the moving parts, the part does not quickly return to its equilibrium position but continues to vibrate in its vicinity, causing collision friction [291]. Precision opto-electromechanical instruments are extremely sensitive to mechanical disturbances, which can disrupt the proper operation of the instruments [292]. Kleiman et al. [104] found that the ends of spacecraft mechanisms were prone to vibrating in microgravity, causing the mechanisms for precise velocity and position control to not work properly.

As mentioned above, the oxide film on the metal surface is easily worn and difficult to regenerate in a vacuum environment. The atomic bonding between the surfaces of the parts of the space mechanism leads to a remarkable increase in adhesion components, producing adhesion effects and even cold welding, which greatly affects the relative motion of the parts [32]. Collisions between contacting bodies in a vibration environment convert their kinetic energy into deformation energy, which increases the indentation depth between contact bodies and increases the plowing component [2,33]. A friction force is mainly composed of an adhesion component and a plowing component [293]. The increase in the plowing component and the high adhesion effects in vacuum can lead to a dramatic increase in the friction force, which challenges the life of spacecraft. For example, the Galileo spacecraft operates in a high vacuum and microgravity environment, and the inaccurate deployment of its high-gain antenna is mainly due to cold welding caused by microvibration abrasion [3]. In addition, the increase in friction force leads to an increase in frictional heat. Especially in a high vacuum environment, no gas diffusion and convection occur to remove the frictional heat in time. The material softens at high friction temperatures, further increasing wear [101]. Therefore, vibrations in a space environment should not be ignored [33,294].

5.1 Simulation of collision friction in a space environment

Macroscopic mechanical vibrations can affect the sliding and stick–slip modes of friction, sometimes leading to a considerable reduction in friction [295–299]. Atomic force microscopy tests have confirmed that vibrations also affect microscopic friction processes [300–302]. The adhesion effects in a high vacuum environment highlight the intermolecular forces. The collision and friction processes of contact bodies involve various physical quantities, such as acceleration, velocity, position, and collision energy. The friction process also involves molecular interactions between materials, material migration, and the generation and evolution of dislocations. To understand the lubrication mechanism of lubricating films further, numerous experimental studies are required to study the mechanical behavior of contact problems at the atomic scale from an experimental view. However, opportunities to conduct tribological tests in space are few. The effects of a vacuum environment and a microgravity environment are difficult to balance when performing space tribological tests on Earth.

MD simulations have been widely used in nanotribology to study friction [303–305], indentation [306–308], contact [309], wear [310], and lubricant design at the atomic scale [311]. MD simulations can capture the forces among all the atoms and simulate the migration of materials and the evolution of dislocations. Many microscopic details that are difficult to observe in experiments, such as interfacial stress distribution [312] and atomic trajectories [102], can be easily observed in MD simulations [313–315]. Indeed, MD simulations can be used to study the friction properties and mechanical behavior of materials used in space exploration from an atomic-scale perspective. For example, MD simulations can effectively simulate the forces between MoS_2 atoms and obtain friction properties that are consistent with experimental results [316]. Using quasistatic MD simulations, Vazirisereshk et al. [317] found that the friction properties of MoS_2 were closely related to its energy barriers during a sliding contact. Onodera et al. [318,319] used MD simulations to point out that the lubrication of MoS_2 depended on the atomic-scale mechanical behavior of the MoS_2 interlayer contact.

For vacuum and microgravity environments that are difficult to balance in Earth-based experiments, MD simulations can explain the adhesion effect in the vacuum environment by interatomic forces, and the effect of the microgravity environment can be studied by the principle of energy conservation or by setting up vibrations of contacting bodies. It is suitable for the study of friction behavior in a space environment and provides an effective way to reveal the friction mechanism. In addition, the collision and friction of lubricating films can be simulated to help the design of lubricating films for spacecraft. Considering the vacuum adhesion effect and the collision between contacting bodies in a microgravity environment, Tong et al. [33,320] proposed an MD modeling method for a nanoscale collision sliding contact problem under microgravity and investigated the friction properties of lubrication methods, such as Au film [291], Ag film [294], MoS_2 film [321], and a textured surface [322], based on the motion characteristics of the space mechanism.

5.2 Au/MoS_2 composite film combined with surface textures

Considering complex environments, such as high vacuum and microgravity, especially the adverse effects of space vibration on the friction and thermal properties of space mechanisms, Au is a solid lubricant worth considering in the space environment with low shear strength and good thermal conductivity. Au and Ag can be used as solid lubricants. They have a face-centered cubic lattice structure without low-temperature brittleness and can maintain good friction properties in low-temperature environments. The durability of the Ag film is higher than that of the Au film, but the resistance to oxidation and AO erosion of the Ag film is lower. The Au film has excellent chemical stability and can maintain friction properties in harsh space environments. Banks et al. [49] demonstrated that the main effects of AO on metallic materials were oxidation and erosion. Among several soft metals with face-centered cubic structures, such as Au, Ag, Cu, and Pb, Au is insensitive to AO due to its chemical inertness. By contrast, other soft metals show different degrees of oxidation and erosion effects in the AO erosion environment. Except for oxides and Au, most lubricants are damaged in no more than a decade by the synergistic effects of high-temperature oxidation with high-velocity collisions of AO [323]. For example, space flight experiments demonstrated that Ag and Cu films were considerably oxidized in the AO erosion environment, whereas Au films exhibited good oxidation resistance [49,324].

Considering the advantage of the Au film, Tong et al.

[291] introduced textures on the Au film surface and the effects on the friction and thermal properties of Au film were investigated. As shown in Fig. 15 [291], the textures on the Au film surface effectively reduced the friction forces during the collision sliding contacts, and the surface temperature decreased with increasing texture depth. Although the introduction of textures on the Au film can reduce the friction force to some extent, a large clearance in friction properties remains in comparison with the MoS_2 film [16]. Combining MoS_2 with soft metals to form a bilayer or multilayer film structure can improve its friction properties [20]. The combination of soft metals and layered materials can maintain a good performance of the lubricating film over a wide temperature range [37].

Stoyanov et al. [325] investigated the friction and wear properties of a pure Au film, a MoS_2–Au cosputtered film, and a MoS_2–Au bilayer film in the ground environment. Results showed that the MoS_2–Au bilayer film could effectively improve friction and wear properties [325]. Whether the combination of MoS_2 film and Au film can still improve friction and wear properties in the space environment is a topic worthy of exploration.

In the space environment, the low interlayer force or low shear strength of the lubricating film at the contact interface can contribute to the reduction of friction. The low interlayer force of the MoS_2 film reduces the adhesion component. The puckering effect of the MoS_2 film during a sliding contact can dominate friction in some cases [326]. The vibration collision process exacerbates the puckering effect and increases the plowing component. In addition, the frictional heat increases with increasing friction force, negatively affecting the friction properties of the MoS_2 film. Given the low shear strength of the Au film, dislocations or point defects are formed during friction and are rapidly eliminated in the subsequent sliding contact [20], which can absorb part of the collision energy in the vibration environment. However, in a vacuum environment, the adhesion effect between the metal surfaces is evident, which affects the friction reduction effect of the Au film. When the MoS_2 film is combined with the Au film, the MoS_2 film on the contact interface can reduce the adhesion component to achieve low friction. The Au film at the contact subsurface absorbs the kinetic energy in the form of dislocation during the collision, which weakens the puckering effect of the MoS_2 film and thus reduces the plowing component. At the same time, MoS_2 has strong adhesion to the metal surface, and frictional heat can be quickly conducted through the Au film, which can maintain the lubricating ability of MoS_2. To reduce the influence of collision on friction further, textures can be introduced on the surface of the Au film. It can promote the generation of dislocations inside the Au film to absorb the collision energy, reduce the adhesion component and the plowing component of friction, and improve the friction properties [291]. Furthermore, the dimple region of the surface textures can store MoS_2, thus extending the wear life of MoS_2 films.

Du et al. [327] investigated the friction properties of MoS_2/Ag films and discovered that they exhibited good friction properties from 100 to 500 K. When the temperature reached 600 K, the friction properties deteriorated, and the MoS_2 film was destroyed, as shown in Fig. 16 [327]. The latest study found that MoS_2/Au films can exhibit good friction properties when the temperature reaches 600 K, and the MoS_2 films are less damaged than MoS_2/Ag films, as shown in Fig. 17.

On the basis of these phenomena, MD models of collision sliding contacts are developed for different bilayer/multilayer films composed of two materials, Au and MoS_2, as shown in Fig. 18. The average friction forces are shown in Fig. 19. Compared with the pure Au film, the average friction forces of different bilayer/multilayer films are greatly reduced. Among them, the MoS_2/Au/MoS_2/Au film with the sandwich structure has

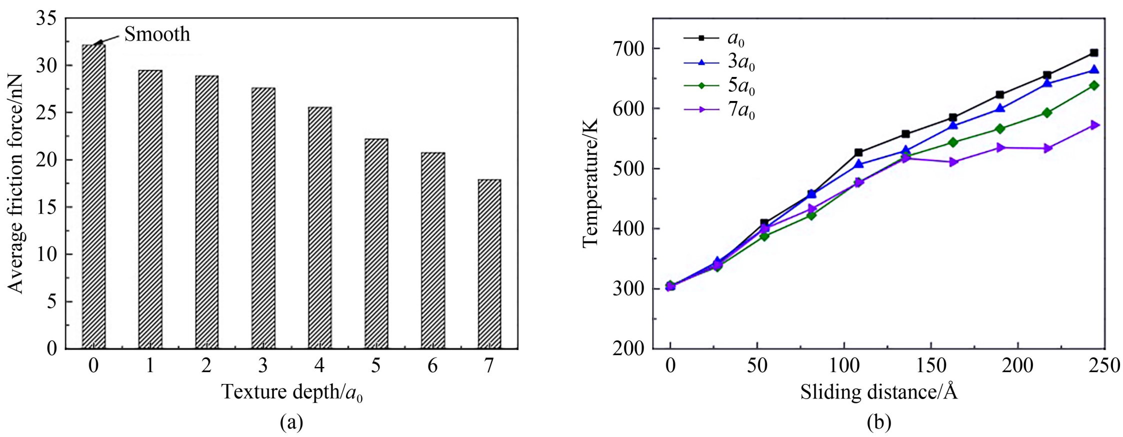

Fig. 15 Comparison of the average friction forces and the surface temperatures for different texture depths, where a_0 is the lattice constant of Au: (a) average friction force and (b) surface temperature [291]. Reproduced with permission from Ref. [291] from Elsevier.

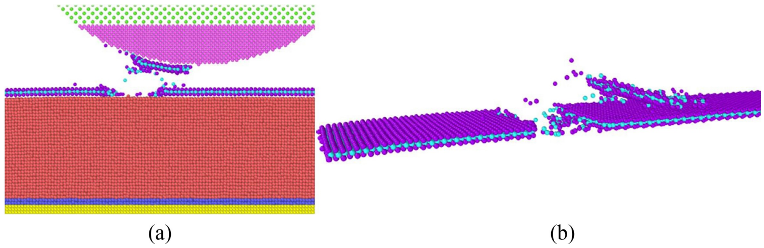

Fig. 16 Shape of MoS_2 film at 600 K: (a) collision process and (b) snapshot of the MoS_2 film [327]. Reproduced with permission from Ref. [327] from Tribology.

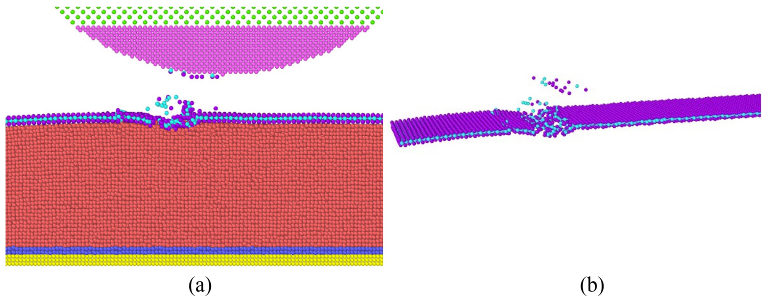

Fig. 17 Shape of MoS_2/Au film at 600 K: (a) collision process and (b) snapshot of the MoS_2 film.

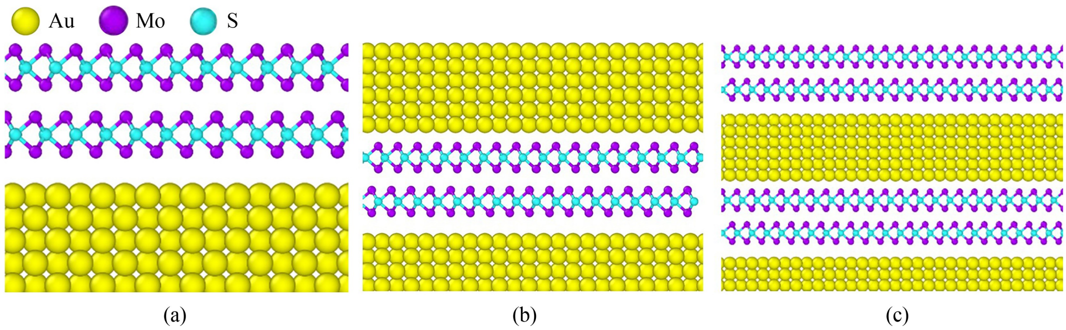

Fig. 18 Different bilayer/multilayer films composed of two materials, Au and MoS_2: (a) MoS_2/Au, (b) Au/MoS_2/Au, and (c) MoS_2/Au/MoS_2/Au.

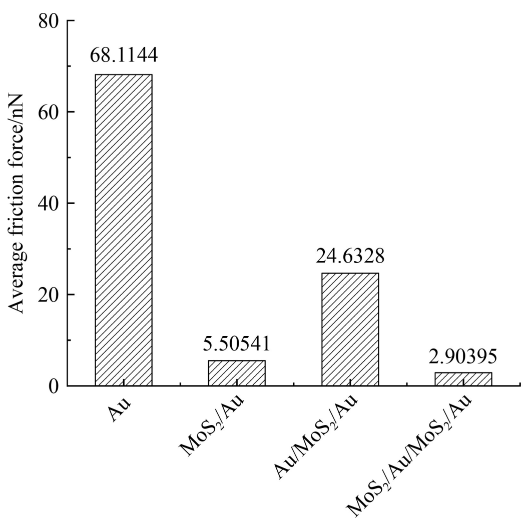

Fig. 19 Average friction forces of multilayer films composed of Au and MoS_2.

the lowest average friction force. The reason is that the Au film in the interlayer absorbs the energy of the collision process as a sacrificial layer during the collision sliding contact. Along with the generation of dislocations, the Au substrate is protected from the collision process, resulting in fewer failed atoms in the Au substrate compared with other multilayer films.

In the latest study, surface textures are introduced on Au substrates and combined with MoS_2/Au/MoS_2/Au films. The collision contacts of five types of lubrication combinations, including soft metal (SM), textured soft metal (TSM), multilayer film combined with soft metal (FSM), multilayer film combined with textured soft metal (empty) (FTSM-1), and multilayer film combined with textured soft metal (filled) (FTSM-2), as shown in Fig. 20, are modeled. Figure 21 shows the average friction forces for five types of lubrication combinations. Results show that TSM, FSM, FTSM-1, and FTSM-2 lubrication can effectively reduce the average friction

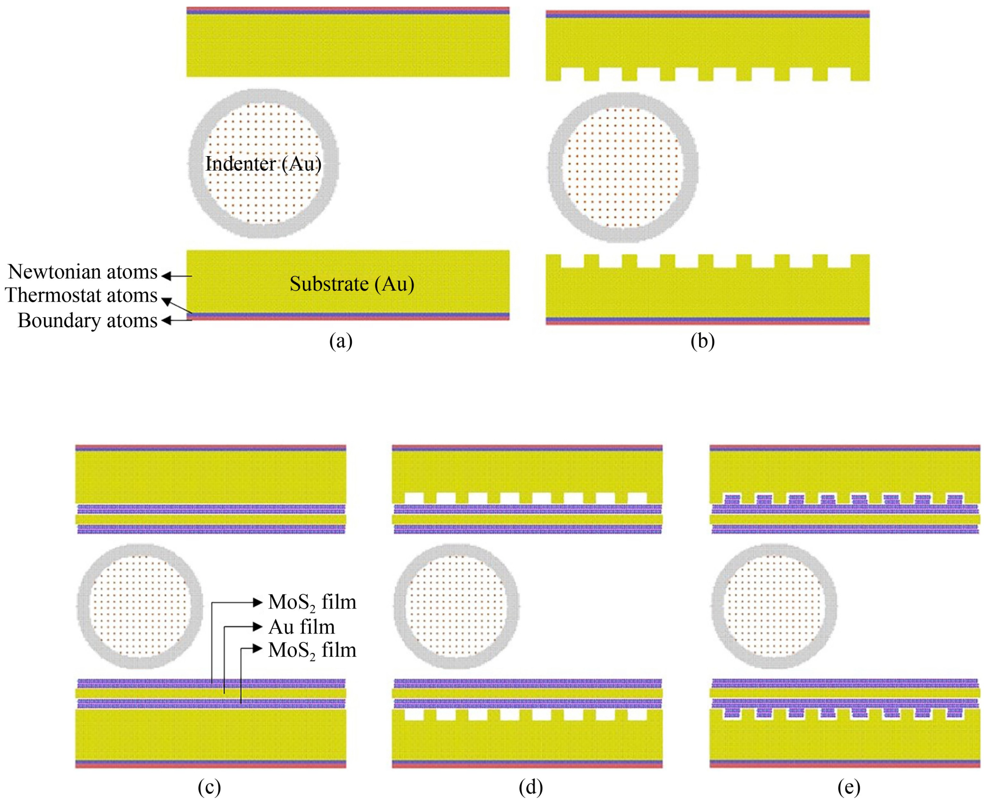

Fig. 20 Five types of lubrication combinations: (a) soft metal (SM), (b) textured soft metal (TSM), (c) multilayer film combined with a soft metal (FSM), (d) multilayer film combined with a textured soft metal (empty) (FTSM-1), and (e) multilayer film combined with a textured soft metal (filled) (FTSM-2).

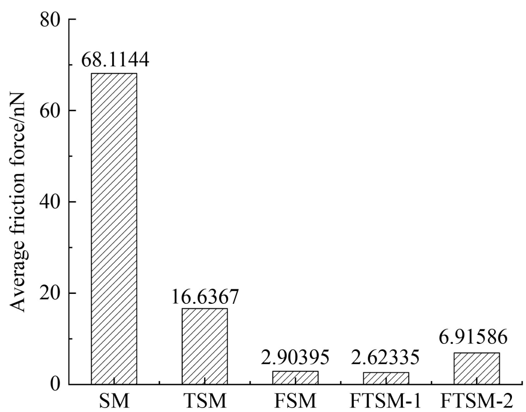

Fig. 21 Comparison of the average friction forces among different lubrication combinations.

forces during collision sliding contact. The friction reduction effect of FTSM-1 lubrication is limited in comparison with FSM lubrication. In addition, preparing textures in practical engineering applications increases the cost. As a result, FSM lubrication can be used in the case of low friction requirements. In the case of high requirements for wear life, FTSM-2 lubrication can be used.

In subsequent research, the influence of Au film surface texture parameters on the composite film composed of MoS_2 film and Au film should be further investigated. The introduction of other solid lubricating materials based on this composite film should be introduced to form a more desirable composite film structure. This research may contribute to the development of new solid lubricants to meet the requirements for lubrication in the space environment. It will prolong the service life of moving parts in space mechanisms and remarkably contribute to the long service life of spacecraft.

6 Conclusions and perspectives

This study reviews the characteristics of the space environment and the applications of solid lubricants and discusses the lubrication mechanism, environmental dependence, and performance improvement of MoS_2, which is widely used in the space environment. The extensive work conducted by scholars to improve the friction properties of MoS_2 and develop new lubricants for space applications is discussed in detail. Among them, MoS_2 films combined with surface textures and MoS_2 films combined with metals are two important research interests. Numerous studies have shown that combining MoS_2 films with surface textures or other materials with synergistic effects, such as metals, to form composite or multilayer films is an effective way to improve their friction and wear properties. The potential lubrication mechanisms of MoS_2 composite or multilayer films should still be further investigated in the future to guide the development of high-performance solid lubricating films. The potential research interests for the friction properties of MoS_2 lubricating films are summarized below.

1) Collisions in the ground environment and space environment should not be neglected. Given that spacecraft must be assembled, tested, stored, and transported on the ground prior to launch, the effect of air conditions, especially ambient humidity, on the friction properties of MoS_2 films deserves further investigation.

2) The combination of the surface texture and lubricant can improve friction properties. The design of surface texture should be based on the purpose of enhancing the retention and distribution of lubricant and reducing friction and wear. In addition to the surface texture parameters, the operating conditions of the target space mechanism, as well as the lubrication situation, can affect friction performance. Therefore, tailoring composite lubricating films with improved applicability for specific application scenarios is a promising direction.

3) Most of the current studies focus on the preparation of surface textures on substrates or solid lubricating films, whereas dual textures on the substrates and solid lubricating films have received less attention. The effect of dual textures on the friction properties of materials should be further studied.

4) Many experiments have been performed to investigate the friction mechanisms of MoS_2-surface textures and their bilayer/multilayer films. Further theoretical studies on the collision sliding contacts of composite films under the influence of space environments are required to investigate the friction mechanisms.

In summary, research on space solid lubricants is progressing rapidly. However, new high-property space lubricants or material combinations are still on the way to meet the demand for long service lives in space mechanisms. Friction properties and mechanisms in different environments should be investigated to help prolong the service life of spacecraft.

Nomenclature

2D	Two dimensional
a-C	Hydrogen-free diamond-like carbon film
a-C:H	Hydrogenated diamond-like carbon film
ALD	Atomic layer deposition
AO	Atomic oxygen
COF	Coefficient of friction
CVD	Chemical vapor deposition
DLC	Diamond-like carbon
FSM	Multilayer film combined with a soft metal
FTSM-1	Multilayer film combined with a textured soft metal (empty)
FTSM-2	Multilayer film combined with a textured soft metal (filled)
LEO	Low Earth orbit
MD	Molecular dynamics
MoS_2	Molybdenum disulfide
NASA	National Aeronautics and Space Administration
PEO	Plasma electrolytic oxidation
PTFE	Polytetrafluoroethylene
PVD	Physical vapor deposition
RH	Relative humidity
SM	Soft metal
TSM	Textured soft metal
UHV	Ultrahigh vacuum
UV	Ultraviolet
XRD	X-ray diffraction

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Conflict of Interest The authors declare that they have no conflict of interest.

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