New Generation of MoS_x Based Solid Lubricant Coatings: Recent Developments and Applications

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Abstract. In recent times, there is a growing interest in applying Molybdenum disulphide (MoS_x) solid lubricant coatings on components to improve the tribological performance (i.e. lower friction coefficient and wear rate). The tribological performance of MoS_x coating is strongly dependent on coating properties and tribological environment. MoS_x coatings are highly successful in certain applications such as in space/vacuum technology, but its effectiveness is questioned in other terrestrial applications such as in cutting tool industry due to its lower hardness and poor oxidation resistance leading to shorter life. In order to circumvent this drawback, the paper identifies that current research is being concentrated on developing MoS_x based coatings using three different approaches: (1) Metal or compound addition in MoS_x coating (2) MoS_x layer on hard coating and (3) MoS_x addition in hard coating matrix. Although the primary objective is same in all three cases, the third approach is considered to be more effective in improving the tribological properties of the coating. Finally, the potential applications of MoS_x based coatings in different industrial sectors have been briefly outlined.

Keywords: Molybdenum disulphide, Solid lubricant, Coating, Sputtering.
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INTRODUCTION

Molybdenum disulphide (MoS_x) is the most appropriate solid lubricant coating in tribological applications, where the traditional liquid lubrication is not suitable (e.g., devices used in space) and where there is a need to fully or partially eliminate liquid lubricant. Sputtered MoS_x coating is an attractive choice due to its low co-efficient of friction (usually in the range of 0.01 - 0.25) and its ability to retain the favourable tribological properties in extreme environments (cryogenic temperature up to a maximum temperature of 300-400 ^oC in air and up to 800 ^oC in high vacuum). Sputtered MoS_x coating obtained at optimum deposition conditions can display the lowest coefficient of friction (0.002) among the currently known solid materials under favourable operating conditions (i.e., ultra-high vacuum) [1]. MoS_x coating is also regarded as a true solid lubricant as it can form a sacrificial transfer layer between the two mating surfaces, which helps to reduce friction and wear. Fundamental knowledge, historical development, lubrication mechanism, deposition methods and applications of MoS_x coating have been reviewed by many authors [2, 3].

SPUTTERED MOS_X: PROPERTIES AND PERFORMANCE

Pioneering work by Spalvins during late 1960's has established that sputtering is a remarkable technique for depositing high quality MoS_x coating [4]. The tribological performance of MoS_x coating is strongly dependent on tribological environment and coating properties, which are controlled by sputtering conditions as shown in Figure 1.

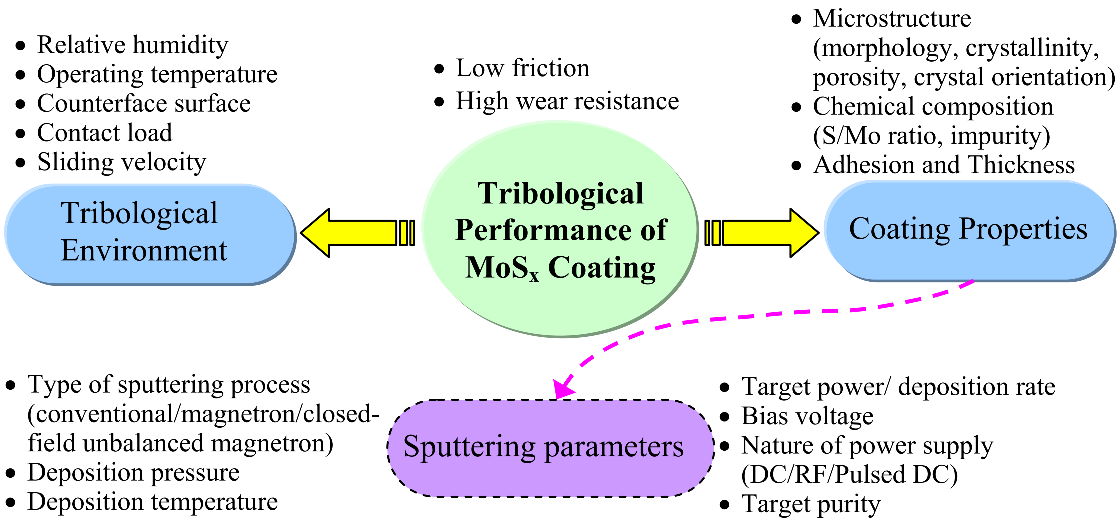

FIGURE 1. Factors affecting the performance of MoS_x coating.

Coating Properties

Depending on the sputtering conditions, purely amorphous or quasi-amorphous (i.e., poorly crystallined) and crystalline MoS_x coating can be resulted. The latter one is more favourable for low friction properties. Two types of crystallite orientations are generally observed in sputtered MoS_x coating: basal planes perpendicular to the substrate (Type I) and (2) basal planes parallel to the substrate (Type II) as shown in Figure 2 [1]. Type I coating is characterised by needle-like topography, high shear strength and loosely packed columnar structure compared to the cluster shape topography, low shear strength and dense non-columnar structure in Type II coating. Furthermore, the exposed reactive edge sites (100) Type I coating easily oxidise in humid environment leading to higher coefficient of friction and poor wear resistance. On the other hand, Type II coating having basal plane (002) parallel to sliding direction can provide low shear strength and hence, low friction and wear result. In addition, the protected edge sites in Type II coating can offer higher resistance to oxidation.

MoS_x coatings produced by conventional sputtering process (DC or RF) exhibit typical of Type I coating. MoS_x coating deposited by closed-field unbalanced magnetron sputtering exhibits long life, low coefficient of friction and high resistance to humidity due to a good combination dense non-columnar microstructure, favourable basal plane orientation and excellent adhesion to the substrate. Only a very thin coating of about 0.2 μm is required for effective lubrication [1]. Coating properties do not vary considerably with the thickness within the range from 0.15 to 3.0 μm [5].

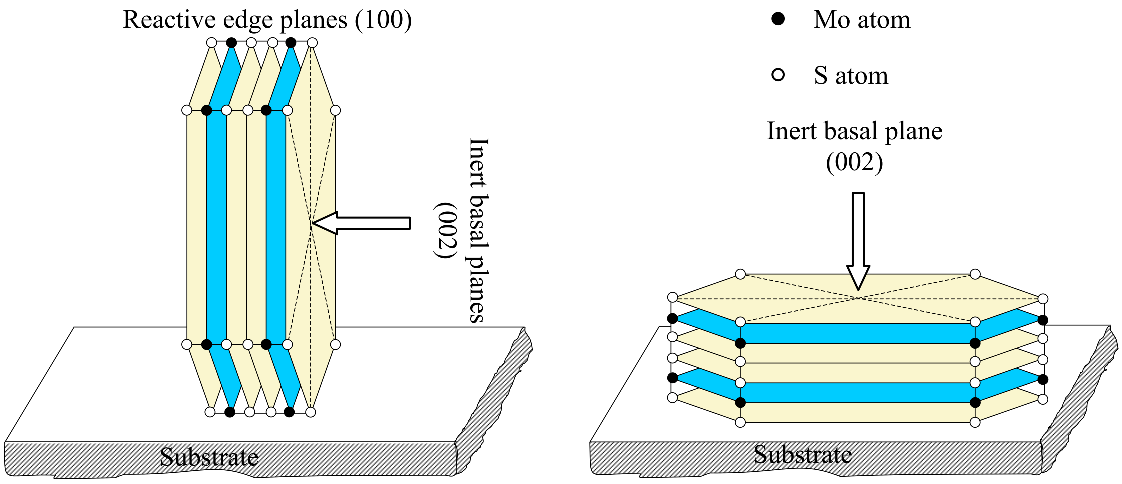

FIGURE 2. Schematic diagram of orientations of MoS_2 crystallites.

MoS_x coating with higher ratio of basal plane to edge plane (002)/(100) yields lower friction and wear rate and exhibits increased resistance to degradation in reactive environments. It has been shown that negative bias voltage (-50 to -100 V), unbalanced mode of the magnetron, pulsed power supply, deposition rate, deposition pressure and temperature have significant influence on the crystal growth with (002) orientation [5, 6]. The low friction properties of MoS_x coating are strongly dependent on the stoichiometry (S/Mo ratio = x), which can vary from low to high sulphur content ($0.8 < x < 2.2$). However, an optimum combination of wear and friction properties can be obtained with a deficiency of sulphur in the coating (x values in the range of 1.2-1.8). The content of crystalline structure increases with increasing the x value, which will improve the lubrication property of MoS_x coating and a minimum x value of 1.1 is required to maintain the hexagonal crystal structure in the coating [1]. Sulphur deficiency in MoS_x coating is generally occurred due to resputtering of sulphur atoms from the growing coating by the energetic ion bombardment under low pressure, high negative bias voltage or strong unbalanced condition of the magnetron.

Tribological Environment

Operating conditions and environment have profound impact on the durability and friction properties of MoS_x coating. Under ultra high vacuum and dry nitrogen environments MoS_x coating exhibits super-lubricant properties with coefficient of friction as low as 0.002 [7]. The super low friction properties of MoS_x coating in vacuum could be related to the specific structural properties (e.g., stoichiometricity, crystallinity etc.), development of transfer film on the matting counter face and friction induced basal plane orientation during sliding leading to very low interfacial shear strength. It has also been demonstrated that friction coefficient and wear rate increase with the increasing relative humidity level during wear testing. However, the rate of increasing friction coefficient and wear with the relative humidity is much higher in random/edge oriented MoS_x coating than basal oriented MoS_x coating due to the fact that random-oriented MoS_x coating oxidises more easily [6].

ADVANCES IN MOS_X BASED COATINGS

MoS_x coating exhibits low friction and long life in vacuum or inert environment, it struggles to provide the same in terrestrial environment due to its low hardness and susceptibility to oxidation. To address this issue, research is being undertaken on developing MoS_x based coatings using three different approaches (Figure 3).

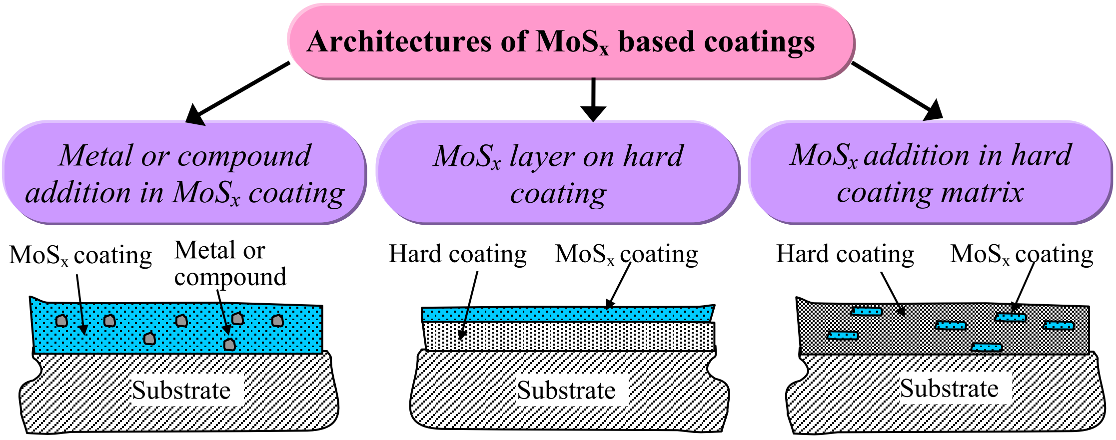

FIGURE 3. Classification of MoS_x based coating architectures.

Metal or Compound Addition in MoS_x Coating

Efforts have been devoted to improve the tribological properties of pure MoS_x coating by incorporating metals (Au, Pb, Ti, Cr etc.) or compounds (e.g., PbO, SbO_x) into the coating in the form of composite or multilayer structure [8, 9, 10]. It has been evidenced that the improvement comes through structural modifications such as formation of densified structure, tribologically favoured basal oriented structure, higher hardness and preferential oxidation of metal protecting the MoS_x from oxidation during wear. A 5-20% concentration of metal/compound in MoS_x coating could give optimum tribological properties. Ti is most frequently used as an inclusion in MoS_x coating due to its good adhesive properties and compatibility with MoS_2. The metal-doped MoS_x coating has showed potential improvement over pure MoS_x, but lifetime is still limited owing to the soft MoS_x matrix.

MoS_x Layer on Hard Coating

In this architecture, MoS_x coating is deposited on top of hard coatings (e.g., TiN, CrN, TiCN, TiAlN, DLC, Si_3N_4) [10, 11]. This double layer approach can enhance the performance of the coating in tribological applications by the combined effect of friction reducing MoS_x top layer and hard and load bearing under layer. The solid lubrication property of MoS_x coating could be fully developed by a strong support from the underneath hard coating. The hard coating layer could be produced either in the form of multilayer or graded structure and the soft layer on top of that either as pure MoS_x or MoS_x/Ti [10]. Although soft MoS_x coating could be removed very quickly, the lubrication effect could still be maintained for extended periods of time.

MoS_x Addition in Hard Coating Matrix

Recently, combined hard-solid lubricant coatings have been produced by adding MoS_x into hard coating matrix (TiN, TiAlN, TiSiN, TiB_2, CrN, CrB_2 etc.) [12, 13]. These coatings can provide both high wear resistance and low friction coming from the hard and soft parts respectively. Again, the low friction properties can be maintained throughout the entire lifetime of the coating as MoS_x is uniformly distributed across the whole thickness of the coating. MoS_x concentrations from 7-11% are suggested to achieve optimum tribological properties. TiN+MoS_x coating deposited by closed-field magnetron sputtering demonstrated a significant reduction of coefficient of friction (~ 45%) and wear rate compared to pure TiN coating as shown in Figure 4.

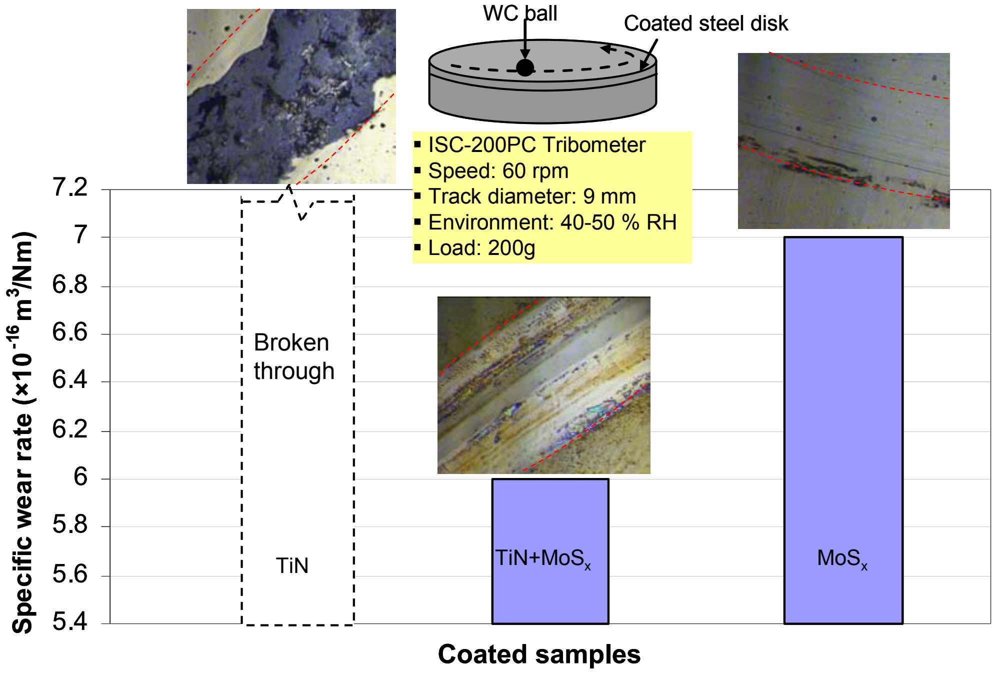

FIGURE 4. Comparison of wear rates among TiN, TiN+MoS_x and MoS_x coatings.

APPLICATIONS OF MOS_X BASED COATINGS

Pure MoS_x coating is most commonly used in space/vacuum applications. Lately, it has been reported that significant improvement in tool life (2-5 times) could be achieved in milling, drilling, punching, hobing etc. with MoS_x based coatings either as a top layer on hard coatings (TiN, TiAlN etc.) [14] or in a composite form (e.g., TiN-MoS_2) [12]. Figure 5 shows MoST (MoS_2/Ti) coated circular saw and hob for machining applications. The MoS_x based coatings allow improved chip flow with a lowered coefficient of friction, reduced cutting force, heat generation and built-up edge formation in the cutting tool. Hence, improved tool performance, higher productivity and better workpiece quality result. MoS_x based coatings have also found applications in plastic moulds, extrusion dies, stamping tools etc. and in automotive parts such as pistons and piston rings.

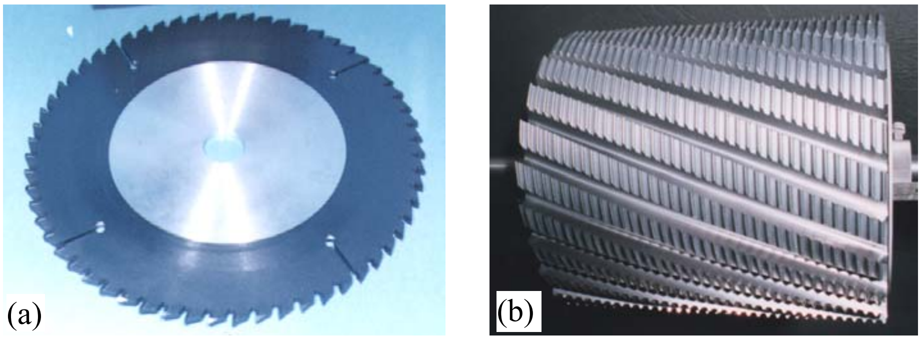

FIGURE 5. MoST™ coated (a) Circular saw and (b) Hob (Teer Coatings Ltd., UK; with permission).

CONCLUDING REMARKS

Sputtered MoS_x coating has come a long way since its first successful use in space applications. Technological improvement in sputtering process such as the development of closed-field unbalanced magnetron has contributed towards the deposition of MoS_x coating with improved properties and longer life. Nevertheless, such improvement is still not satisfactory for terrestrial applications. Therefore, new generation MoS_x based hard and solid lubricant coatings has been developed by modifying coating structure and architecture in order to broaden the application range. Coating companies have already started commercial production of MoS_x based coatings (MoST™ by Teer Coatings Ltd., UK and MolyGlide® by Guhring, Germany). In future, a widespread use of MoS_x based coatings can be anticipated.

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