Thin Films in Tribology

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Abstract

This article examines tribology. More emphasis is on the effect of wear on engineering materials as it is an important and costly aspect of engineering industries. Wear degradation is one of the most failure mode incurring millions of funds by maintenance and replacement in modern industries. Apart from lubricants, thin film deposition technologies are well established for the improvement of wear resistance in high friction operations. There have been a widespread of hard coatings such as diamond and diamond-like carbon coatings for tribological applications in the last decades. However, the limitation of such coatings is that plastic deformation of such hard coatings begins from the substrate material. This is because the wear mechanisms of the material will depend on the mechanical properties such as hardness and ductility of the substrate and the coating. In depth knowledge of the macro-mechanical mechanisms dominating the tribological process are discussed. Different wear mechanisms are briefly reviewed with respect to their effect on substrate-film system and hardness. The influence of the thin film deposition method employed and the surface treatment used on the tribological properties of the coated materials are discussed.

Keywords
Tribology, wear degradation, thin films

1. Introduction

1.1 Background

The term tribology refers to the science and technology of interacting surfaces in relative motion and the particles related thereto, this science covers friction, wear and lubrication for interacting machine elements(Dowson, 1993)(Menezes et al., 2013)(Bhushan, 2013). This science has been applied since the ancient times from the creation of wheels or rollers to the implementation of lubricants to avoid friction when pyramids where being built. Tribological principles were also applied during and after Roman Empire for war machinery and fortification methods (Bhushan, 2013). Many other developments followed particularly in the use of steel bearing materials instead of wood in 1500, later the understandings of lubricants by Sir Isaac Newton sans so forth. Wear however is a much younger subject than friction and lubricants, studies on wear became substantial after the use of steam power, development of railway, automobiles and the aircraft(Bhushan, 2013).In modern industries, tribology is applied for reliability, improved performance, cost saving and durability of moving parts in various industries all over the world.

Generally, in a tribological contact, the harder material scratches the softer material, as such soft and the hard coating may be used to reduce friction and or wear. When using soft coatings, friction losses are confined to a thin film of low shear strength and will persist as long as the film remains. However, this effect can be achieved better through the use of liquid lubricants, the best thin coating contribution in tribology can, therefore, be achieved through the use of hard coats. Thin film coatings can be achieved through a number of processes: ion beam assisted deposition, thermal spraying, chemical vapor depositions (CVD) and physical vapor deposition (PVD) methods such as sputtering.

1.2 Economic Aspect

Virtually every machine in operation experience material losses and consume a lot of energy due to tribological inefficiencies. Individually the losses may be small but for same loss repeated on many machines of similar types, the loss can be so enormously thereby incurring very high costs (Stachowiak, 1993). Using this aforementioned perspective, a simple estimate of costs or benefit from tribological practices can be summarized as follows (Stachowiak, 1993):

$$Total\ tribological\ cost/saving = sum\ of\ individual\ machine\ cost/saving\ x\ number\ of\ machines \quad (1)$$

In total, approximately 23% of the world energy consumption from tribological contact, it has been reported that 20% is used to resist friction and the remaining 3% to manufacture worn parts and spare equipment due to wear and wear related failures(Holmberg and Erdemir, 2017). Henceforth, by implementing surface modification techniques such as thin film technology worldwide, energy and cost losses due to friction and wear can be reduced by 40% in the long term. In 1966, the Jost report [Lubrication(Tribology)- Education and Research; published by Her Majesty's stationery office, London] indicated potential savings of over $800 million per year for the industry by better application of tribological principles(Mang, Bobzin, and Bartels, 2010) (Shaffer, 2013). Some estimates have shown that losses due to ignorance of tribology cost the united states about $200 billion per year in 1966 as such the importance of friction and wear reduction should be more emphasized for economic reasons as well as long time reliability(Bhushan, 2013). All estimated losses due to wear and friction are tremendous therefore understanding the problems of tribological economics is very crucial for engineers, but to do that one has to also have the fundamental knowledge of the failure itself. According to Stachowiak, the analysis of wear and friction can have a direct commercial implication, for instance, insurance companies might not cover the cost of the equipment whose wear damage was due to a certain mechanism which could have been easily prevented (Stachowiak, 1993). The minimization of losses due to wear and friction has the potential to save significant and substantial savings without the use of large capital investment but through mere surface modification techniques such as thin film deposition. Table 1 depicts potential savings by correct application of tribological applications in US$ billion for major industrial countries.

Table 1. Potential savings by the correct tribological application in the industry (1.6% of GDP 2008) *(Mang, Bobzin, and Bartels, 2010)*

Region	**Potential savings (in US$ billion)**
European Union	303
United States	186
China	68
Japan	63
Germany	50
France	48
United Kingdom	36

2. Surface modification

Many surface treatment and thin film deposition are utilized to modify material surfaces for tribological performance. Figure 1 shows different surface treatment and thin film deposition techniques. Thin film deposition involves the addition of a material to the surface of the other whilst surface treatment is the alteration of the surface microstructure or chemistry(Podgornik and Vižintin, 2002).

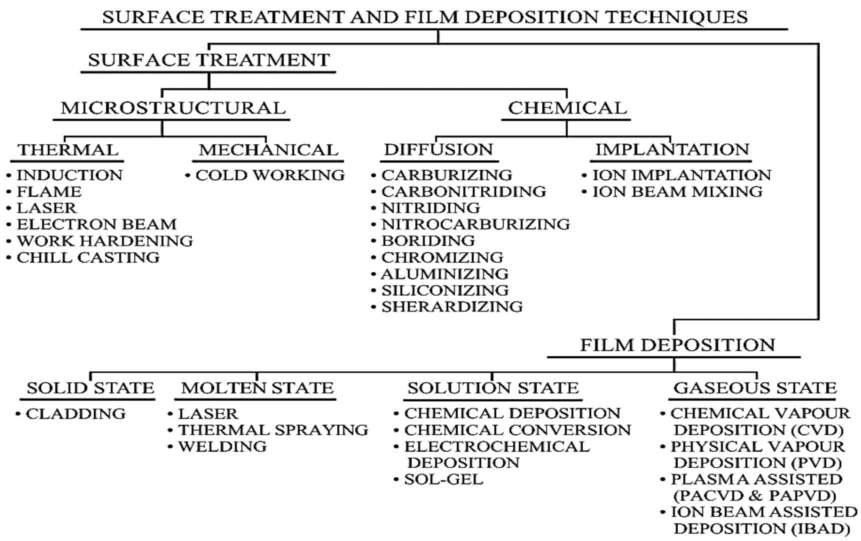

Figure 1: Classification of surface treatment and film deposition techniques(Podgornik and Vižintin, 2002)

When selecting the method of surface modification, be it surface treatment or film deposition, there are many different factors to consider. The factors affecting the choice of method used include but not limited to application requirement, availability, adhesion, film adaptability and most importantly also the cost of the materials and processing (Oshida, 2013) (Holmberg, 1994). To produce materials of good tribological properties, the modified surface must posses a good combination of properties such as adhesion, hardness and strenth depending on the targeted application. It is therefore empirical that one understand the advantages and shortcomings of the method to be used to effectively predict the perfect combination of a desired surface microstructure and properties. A simplified basic guide of material selection guide for wear control with respect to likely mechanical properties is given in table 1.

Table 2: Basic material selection guide for wear control

Material property	Wear Mechanism				
	Abrasive	**Adhesive**	**Erosive**	**Corrosive**	**Surface fatigue**
Hardness	*important*	*important*	*important*	*Semi-important*	*important*
Toughness	*Semi-important*	*Semi-important*	*important*	*Semi-important*	*Semi-important*
Fatigue resistance	*important*	*Semi-important*	*important*	*Semi-important*	*important*
Inertness	*Semi-important*	*Semi-important*	*Semi-important*	*important*	*Semi-important*
High melting point	*Semi-important*	*important*	*Semi-important*	*Semi-important*	*Semi-important*

3. Wear mechanisms

Wear is the progressive damage involving material loss, which takes place on two solid surfaces as a result of sliding or rolling motion relative to one another(Kato and Adachi, 2001). The interaction of asperities of surfaces in contact causes wears based on the mechanical behavior and chemical nature of these surfaces. It is important to note that wear process is not always undesirable like in the case of machine elements such as bearing and gears, it is used in many industries for many applications such as grinding and polishing. The processes that may lead to wear of a surface are categorized into four common types(Bhushan, 2013):

- Abrasive wear
- Adhesive wear
- Corrosive wear
- Fatigue wear

3.1 Abrasive wear

When two material surfaces have interlocking interfaces, a harder material will plow into a softer one removing a certain volume of the soft material when sliding. This is called abrasive wear. In this wear mode, we assume a single contact point model where a hard sharp abrasive pierces thorough a flat soft surface forming a groove by plowing. During abrasive wear, there is a possibility of having a hard particle or worn hard debris trapped between two sliding surfaces that may result in severe wear called three-body abrasion(Kato and Adachi, 2001). The mineral processing industries, mining, and excavation are the ones facing this type of wear where material deterioration is experienced in a wide range of components (Lancaster, 1989). Abrasive wear volume can be approached using Archard equation (Rebai, 2014).

$$V_{ab} = k_{ab}\frac{W}{H}L \quad (2)$$

Where V_{an} is the volume removed, W is the normal load, L is the sliding distance, H is the hardness of the softer material in contact and k_{ab} is the wear coefficient of values between ranges 10^{-6} and 10^{-1} due to the geometry of the asperity

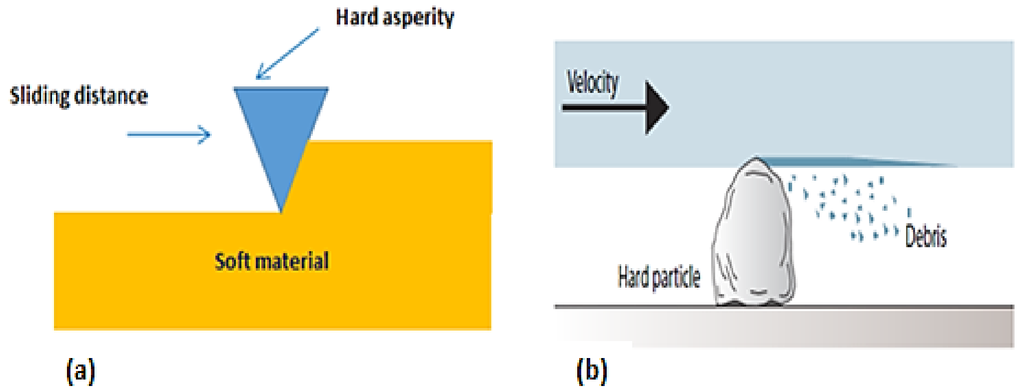

Figure 2. Schematics images of (a) simplified abrasive wear mechanism and (b) three body abrasion

3.2 Adhesive wear

During adhesion wear, the adhesive junction (bonded asperities) created in the contact area are sheared by sliding resulting in the material transfer from one body to the other(Kato and Adachi, 2001)(Bhushan, 2013). Continued sliding causes contact junctions to be sheared resulting in more transferred fragments which can also be transferred back to the original surface depending on the mechanical properties of the two bodies involved and the loading conditions. Adhesive wear is the one of the most common types of wear encountered. This wear mechanism can be estimated using the Archard model (Rebai, 2014)

$$V_{ad} = k\frac{W}{H}L \quad (3)$$

Where k is the coefficient of wear and W, H, L are the same as previous.

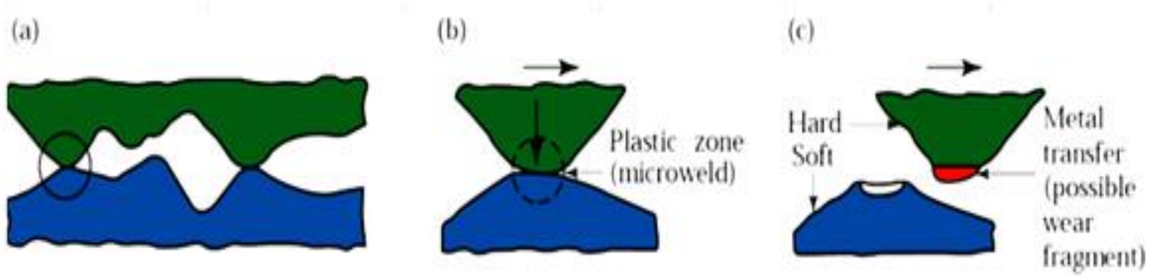

Figure 3. Adhesive wear mechanism overview

3.3 Fatigue wear

During repeated rolling and sliding, materials may induce surface cracks which will break up the surface after a critical number of cycles(Bhushan, 2013). This mode of wear is called fatigue wear. Wear defects formed by this mechanism are characterized by large pits in the surface. Bearings, gears and friction drives are more susceptible to fatigue wear since they operate under constant different loads repeatedly. The volume of wear due to fatigue is calculated as

$$V_f = C\frac{\eta\gamma}{\varepsilon^2 H}WL \quad (4)$$

W, H, L are same, γ is the particle size, $\eta$is the distribution asperity heights and $\varepsilon$is the strain failure during one cycle(Rebai, 2014)

3.4 Corrosive wear

Corrosive wear occurs when sliding surfaces in contact are in a corrosive environment. Corrosion occurs generally due to chemical or electrochemical interactions of the interface with the environment such as air. For static components or surfaces only corrosion will take place forming an oxide layer which might slow down the corrosion, but when the surfaces slide against one another the formed oxide layer wears away and the chemical attack continue forming cracks and abrasions(Bhushan, 2013). This wear mode is characterized by a uniformly worn surface. Thee wear volume of corrosion is estimated by(Rebai, 2014)

$$V_c = L\frac{kdW}{\xi^2\rho^2 VH} \quad (5)$$

Where W, H are same, d represents the diameter of asperity, L is the contact distance, V is the speed, k is a factor of oxidation, ξ is the critical thickness of the layer and ρ is the critical thickness of reaction layer.

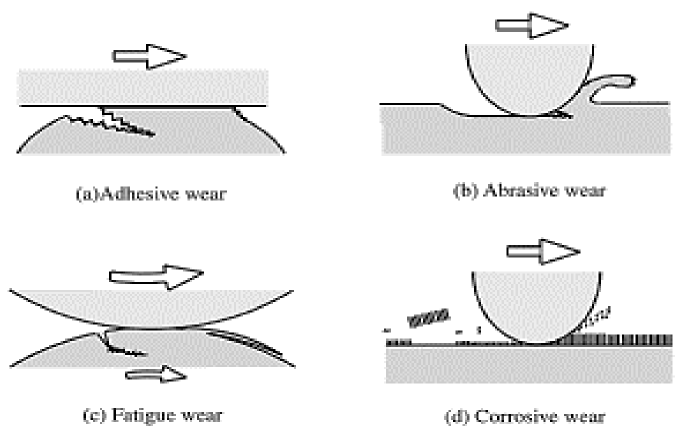

Figure 4. Schematic images of wear mechanisms*(Kato and Adachi, 2001)*

During wear failure of materials and components many complex phenomena occurs resulting in specific wear scars and deformations (Zhou *et al.*, 2013) describing the wear mechanisms stated in table 3. Wear mechanism can also be described from the shape of the cross section of the wear scar obtained as shown in figure 5. Positive wear volumes indicate that material has been lost from the surface leaving pits, cavities or valleys beneath the original surface, negative wear volume indicate addition of material to the surface in the case of adhesive wear mode

Table 3. Overview of wear modes

Wear type	Definition	Evidence	Susceptible application
Adhesive (sliding wear)	Wear due to localized bonding between contacting surfaces leading to material transfer between the two surfaces or the loss from either surface.	- Large lumps of debris - Heavy teared surface	- Bearings - Sliders - Gears - Camshafts
Abrasive	Wear of a solid surface due to hard particles protruding against a softer surface.	- Chip like debris - Scratched surface	- Mining operations - Sliding surfaces
Fatigue	Wear of a solid surface caused by fracture arising from recurring loading on the material.	- Large pits in the surface	- Rollers - Ball bearings - Friction drives
Erosive	Wear due to mechanical interaction between solid surface and a fluid impacting at high velocities.	- Small pits in material surface	- Turbines - Coal slurry pipes - Dam slipways
Corrosive	Wear due to chemical interactions of surfaces in contact,	- Uniformly worn surface. - Fine sized debris -Oxide layer on the solid surface	- Water pipes - Marine equipment

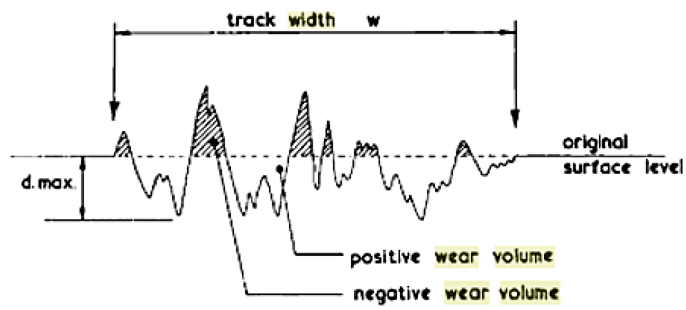

Figure 5.Schematic drawing of cross section of wear scar (Buckley, 1981)

4. Conclusion

Application and implementation of good tribological practices provide high economic benefits by reducing energy losses due to friction, loss due to the depreciation of machines and breakdowns. Surface modification methods are amongst other methods of improving materials against wear degradation. These methods influence the properties and applicability of the thin film depending on the environment of operation. A wide range of thin film deposition methods is available also selected depending on the desired final properties. Wear mechanisms failure modes, susceptible environmental operations and factors affecting the tribological behavior of the films have to be taken into considerate during thin film deposition of coatings.

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Biographies

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