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Surface Engineering - Application on Wear

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Abstract: In this article, engineering surface application is introduced as a new concept. The basis of this concept is the understanding that different surface technologies are applied to the design of existing engineering components, but, it is necessary to know that surface engineering would cover only part of the design of the component, the surface treatment to be applied should also be known. This is because, surfaces with a high index of hardening due to deformation, are resistant to severe adhesive wear, abrasion and pickling, but they should not have the same resistance to other types of wear. It means that a correlation must be established between the surface quality and the pickling resistance. In this article, it is shown that the use of high compatibility metallic materials is preferred and that a correlation can be established between the surface quality and the pickling resistance by a simple number. The selection of materials and methods of obtaining the engineering surfaces for tribological applications, depends to a large extent on the mechanism and particular type of predominant wear. Therefore, the selection of materials resistant to wear will be analyzed depending on the type of wear in question.

Key words: tribology; wear resistance; design; surface treatment; pickling

1. Introduction

In the early 1980s, people realized that the vast majority of engineering components may undergo degradation or catastrophic failures due to surface related phenomena such as wear, corrosion, or fatigue during use, thus proposing the interdisciplinary topic of surface engineering. The advancement of this development was stimulated by the increasing use of a wide range of surface technologies: laser beam and electron beam processes, plasma thermochemical techniques, and novel engineering coatings (for example, electroless nickel plating), ion implantation and, more recently, duplex methods of surface modification. However, it is within the traditional technologies of thermal treatment of surfaces, such as hardening by tempering, nitrating and carburization, where the origins and fundamental principles of surface engineering can be found.

Engineering components generally fail when their surface cannot adequately withstand external forces or the environment to which they are subjected. The choice of a surface material with adequate thermal, optical, magnetic and electrical properties and sufficient resistance to wear, corrosion and degradation is crucial for its functionality.

Surface engineering includes the application of traditional and innovative surface technologies in components and engineering materials in order to produce a composite material with properties not obtainable in the base or surface material. Frequently, the different surface technologies are applied to the design of existing engineering components, but ideally, surface engineering would encompass the design of the component, knowing the surface treatment to be applied.

This innovative multidisciplinary branch of engineering, through a final tribological analysis of the phenomena of wear, other superficial damages such as corrosion and materials science, allows to optimize the surfaces exposed to these processes in valves, evaporators, heat exchangers, pumps and centrifugal compressors, parts and mechanical parts, etc., in order to significantly prolong their service life. The types of wear most frequently present in industrial or service processes are the following: abrasion adhesion, pitting corrosion, fretting erosion, impact cavitation.

Generally, an interaction of these mechanisms occurs and this is why in a suction system we can find erosion and cavitation, thermal fatigue and erosion of steam turbine blades, or abrasion and corrosion in a pulp pump screw affected by the presence of chlorine ions.

Corrosion itself is a complex interaction of physico-chemical variables, which always requires a rigorous analysis due to the different ways in which it occurs, such as corrosion under tension, differential aeration, vibro-corrosion, etc.

Once the specialist engineer has determined (diagnosed) the types and forms of wear present in an equipment or component, he uses materials science to determine which alloy or coating, be it metallic, polymeric, ceramic or a mixture of they (composites), can extend its service life. The engineer must also determine the procedure for applying alloys to resist existing types of wear.

2. Development

The selection of appropriate materials for the preparation of friction pairs' components is often limited to factors that have little to do with tribology, such as their cost. The weight is a factor that can be important and also the resistance to corrosion. The mechanical properties, the rigidity and the tenacity are of great importance, also, in the engineering applications. Although these factors may limit the range of materials to be used, they also serve to establish a spectrum of feasible solutions. The most convenient will always be the most comprehensive selection, for which it is convenient to use selection maps, such as those by Kostetskii, 1972; Ashby & Jones, 2012; Chowdhury, 2019.

However, most of the properties listed, perhaps in addition to the corrosion resistance, are properties of the material volume, making it possible to focus on different surface properties that are more important to tribology through a range of feasible approaches. The modification or coating of a surface, in order to achieve combinations of properties on the surface and the sub layer, belonging to the volume of the material, leads to the so-called surface engineering.

Wear, as an adequate function factor of engineering systems, is obvious in the design. However, the wear leads to major expenses in maintenance, due to costs for replacement of elements, production capacity, energy efficiency losses and consequently of the machine. All this, according to professors Rabinowicz & Tanner, 1966; Ron & Conway, 2002; Ludema & Ajayi, 2018 can represent more than 2% of a country's GDP.

The designer or maintainer must take into account two very important factors; determine the degree of wear that will occur in use and, knowing this, take the necessary measures to reduce it and, of course, take into account the economic aspects this implies. In order to determine the amount of wear that can be calculated, it is necessary to know the wear mechanism that will occur. This can be achieved through specialized computational literature (Hebda & Chichinadze, 1989; Martínez, 2010; Hutchings & Shipway, 2017), as well as determining the factors that affect this, or through physical and mathematical modeling to determine the factors that affect this (Stolarski, 1990; Martínez, 2010).

The various possible processes to apply must be considered as an essential part in the design of tribological systems. In Fig. 1 an algorithm is shown that shows the sequence of steps to follow in the design of a tribological system.

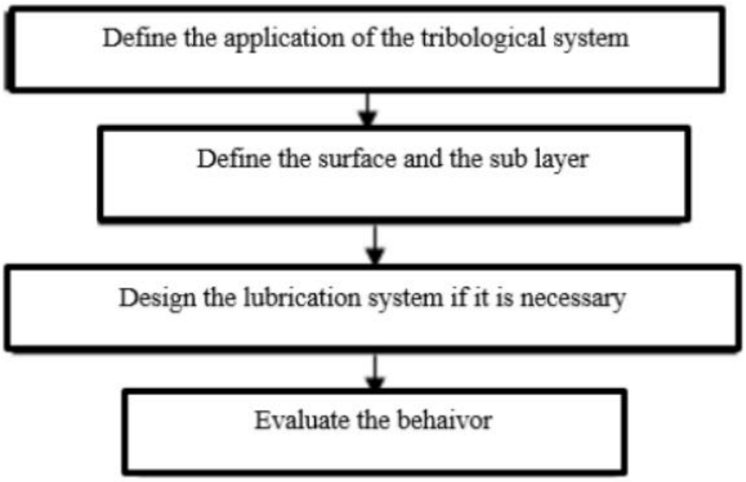

Figure 1. Algorithm that shows the system of steps to follow in the design of a tribological system.

Metals and their alloys are among the most commonly selected materials for mechanical components. Their compositions and micro structures are normalized, sometimes even internationally and therefore their mechanical properties are easier to predict. Non-metallic materials are less regulated and, therefore, their properties, even with identical compositions, tend to vary. However, in materials, even when their mechanical and physical properties are equal, their response to tribological applications cannot be given by a simple number.

For tribological applications, the selection of materials and the method of obtaining engineering surfaces largely depend on the main wear mechanisms and specific types. Therefore, the selections of materials to resist wear will be analyzed depending on the type of wear in question.

The variation of the operating parameters of any tribological system will be limited by the values of mentioned parameters for the system operation. Thus, the decrease in the acting pressures on the interaction surfaces will depend on the applied load, but this, in turn, will depend on design factors. However, the pressure will depend on the actual contact area and this will depend on the surface qualities of both tribological elements. Variations of the pressure or the speed of displacement can vary the wear mechanism, so these aspects must all be taken into account. This is why knowing the value of the resulting wear level is essential for this stage of designing or redesigning the friction pair.

When the type of wear is friction, the displacement parameters and forces between surfaces must be considered. In addition, the entry of oxygen as an environment medium must be controlled. When optimizing the design of such systems, in addition to the factors analyzed, it is also necessary to consider the forces acting on the connection between two components to avoid displacement of one component relative to the other, possible temperature, thermal expansion differences between the two torque components, and possible vibration sources.

If the displacement occurs between sliding surfaces, such as in the case of bearings, the displacement itself cannot be eliminated because it is inherent in torque. In this case, a fundamental factor is the surface tension that one torque element may generate relative to another. In this case, analysis must be conducted to reduce the force in the torque generated.

If the working wear mechanism is contact fatigue, just like in the case of gears, cam followers, and bearings, then three factors are essential, namely the number of effective load cycles that cannot be changed and the contact force. Among these three factors, not only should their possible reduction be considered, and it is necessary to consider the resistance value of a pair of materials to them, especially the more likely wear. For the reduction of the acting forces, the value of the load and the geometry thereof will be essential.

If the type of wear is abrasive or erosive, caused by hard particles, a parameter to be considered will be the removal of the particles from the system. For example, contamination or wear particles may appear in lubricants. As the size of the large particles has a greater effect on these wear than the small ones, the elimination of these particles will be of great importance, either through filtering or their separation by inertia. However, the ratio between the hardness of the material Hm and the hardness of the abrasive Ha must exceed the value of 0.85 ($Hm/Ha \geq 0.85$). In erosion, an essential parameter is the speed of particles' impact on the surface. The same angle of incidence and the density of the impacted material are also essential. In hydro erosive wear, the avoidance of acute angle of variation in fluid movement is an aspect to be taken into account.

Lubrication is a powerful method to reduce the amount of wear on bearings and other friction pairs. Considering K, a constant represents the wear coefficient under lubrication sliding conditions, and if the hydrodynamic lubrication conditions are maintained, its value may greatly decrease. But they are not always maintainable, and when they limit lubrication, the K value may reach $10^{-6,}$ depending on the characteristics of the lubricant used. K is a constant, which in the Archard equation, for sliding wear, is:

$$K = QH/W \quad (1)$$

Q is the magnitude of wear that depends on the contact between all the projections; P is the contact pressure that can be replaced by the hardness of the worn material and W is the applied normal load. Acceptable values of K according to ASM manuals of Kostetskii, 1972; Blau, 1992; Hutchings & Shipway, 2017; Chowdhury, 2019 and Ron & Conway, 2002, are given in Table 1.

Table 1. Typical values of the coefficient K for wear lubricated by sliding

Type of lubrication	K
Hydrodynamic	$< 10^{-13}$
Elastohydrodynamics	$10^{-13} – 10^{-9}$
Limit	$10^{-10} – 10^{-6}$
Solid lubrication	$\approx 10^{-6}$
Without lubrication (severe wear)	10^{-4} - 10^{-2}

It is evident that the sliding wear in conditions of hydrodynamic lubrication, is the most desirable state and in the design, all the measures must be taken to propitiate it in the operating conditions. The most important factor that determines the lubrication regime, is the minimum thickness of the lubricant layer compared with the surface roughness, which can be calculated by specialized monograms, taking into account another factor λ, integrating all the influential parameters (Hebda & Chichinadze, 1989; Stolarski, 1990; Ron & Conway, 2002; Martínez, 2010; Martinez, P.F., 2011, 2017).

3. Materials and Methods

For the evaluation of the different wear calculation formulas based on the types of wear in work, the algorithm developed in this respect can be referred to (Martínez, 2010).

In general, the highest values of K occur in metal-metal sliding conditions, which is lower than the values that occur in sliding conditions between non-metal-metal and non-metal-non-metal. If the conditions are metal-metal slip, with the same characteristics, the value of K is even higher. If the conditions of both metals of the pair differ, the value of K decreases and depends, essentially, on the tribological compatibility of both metals, understanding by tribological compatibility, the ease of establishing between both metals high values of the molecular component of friction (Martínez, 2010). This possibility is strongly related to the molecular and crystalline structure of both elements of the pair, as well as to the value of its solubility in the solid state, which is inferred from the characteristics of the equilibrium diagram formed by the interaction of both metals. In Fig. 2 a map is shown in which the mutual solubility of friction pairs formed by two pure metals can be appreciated.

	Mo	Cr	Co	Ni	Fe	Nb	Zr	Ti	Cu	Al	Zn	Mg	W	Sn	Pb
Pb	▲	●	●	●	●	●	X	X	●	●	●	▽	▲	X	○
Sn		●	▽	▽	▲	▽	▽	X	▽	▲	▽	▲	▽	○	
W	X	X	X	X	X	X	▽	X	▲	X			○		
Mg	▽		▽	▲	▲	●	X	▲	X	X	▽	○			
Zn	▽	X	X	X	X	▲	▲	▽	X	X	○				
Al	▽	X	▽	X	X	X	▽	X	X	○					
Cu	●	●	X	X	▽	▲	X	▽	○						
Ti	X	X	▽	X	X	X	X	○							
Zr	X	▽	X	▽	▲	X	○								
Nb	X	X	X	X	X	○									
Fe	X	X	X	X	○										
Ni	X	X	X	○											
Co	X	X	○												
Cr	X	○													
Mo	X														

LEGEND:
● Two liquid phases
▲ One liquid phase, solubility in solid less than 0,1%
▽ Solubility in solid between 0,1 y 1,0%
X Solubility in solid more than 1,0%
○ Identic metals

Figure 2. Map showing the relative mutual solubility of pure metal pairs, defined from their binary phase diagram (According to Rabinowicz & Tanner, 1966).

Both the combinations are completely insoluble, showing a negligible solubility in the solid state (▲), as well as those showing up as two coexisting phases in the liquid state (●), and giving rise to tribologically compatible pairs. The identical metal pairs (○) are, of course, completely and mutually soluble and show little compatibility. Other pairs show different solubility ratios, as shown on the map. In general, slip pairs with high mutual solubility show low tribological compatibility and therefore relatively high values of K; a low mutual solubility, which leads to good tribological compatibility, is needed to obtain low values of K (Totten, 2016; Ludema & Ajayi, 2018).

Mutual solubility is not the only factor that influences compatibility, which is also associated with the properties of surface films (usually oxides) in slip pairs. The absence of significant oxide films in noble metals such as gold, platinum silver and rhodium tends to be associated with low K values, demonstrating that oxidative mechanisms play an important role.

Some metals with a compact hexagonal structure also show an abnormal behavior, associated with their limited ductility, compared with metals of cubic structure and also with chemical factors. Titanium, Zirconium and Hafnium, for example, show a relatively low reduction in K value, when lubricated with any hydrocarbon lubricant, compared to what they have when working against each other without lubrication.

The hardness of the steels and other metals that form layers of oxide during the sliding process, is of importance in determining the stability of that layer and the predominant wear mechanism. If the metal is hard enough to provide sufficient mechanical support to the oxide layer, medium wear will occur with low K values through an oxidation mechanism. Thus, the hardness can have a strong influence on the adhesive wear resistance of some metals, although the increase in the hardness of a particle of an alloy can have a decrease in the value of its wear, the hardness does not serve as a prediction factor of the wear resistance of the different alloys. Other factors, especially the presence of micro structural components such as carbides in steels and graphite in cast iron, are sometimes of greater importance (Martínez, 2010; Martinez, P.F., 2011, 2017).

The resistance of metals to severe adhesive wear and surface damage under normally high loads cannot always be correlated with their wear resistance under less severe conditions. Several factors affect the resistance of a material to surface sliding damage: the effectiveness of the surface layer in maintaining adhesion, the adhesion of the oxide film after it breaks, and the durability of the bond formation. Reciprocal solubility plays a role as an indicator of bond strength and metals with high bond strength are more susceptible to surface sliding damage. Hexagonal metals with limited sliding surfaces have a lower propensity to damage than metals with cubic structures, probably because they are less ductile.

Some investigations have shown that those metals and alloys with a high degree of deformation hardening, presenting a lower tendency to superficial damage during the sliding. However, this factor is not infallible in its prognosis. For example, austenitic steels, although they are highly deformational hardening, show a high surface damage in this type of process, when their structure is transformed into martensite. Simple hardness does not indicate resistance to surface damage during sliding: for example, in steel, high concentrations of carbides or nitrides exhibit high resistance to sliding surface damage, higher than when it achieves similar hardness, but with lower concentrations of these hard and brittle particles.

Fig. 3 shows a comparative diagram of typical values of wear coefficients K of different materials under sliding conditions under different forms of lubrication.

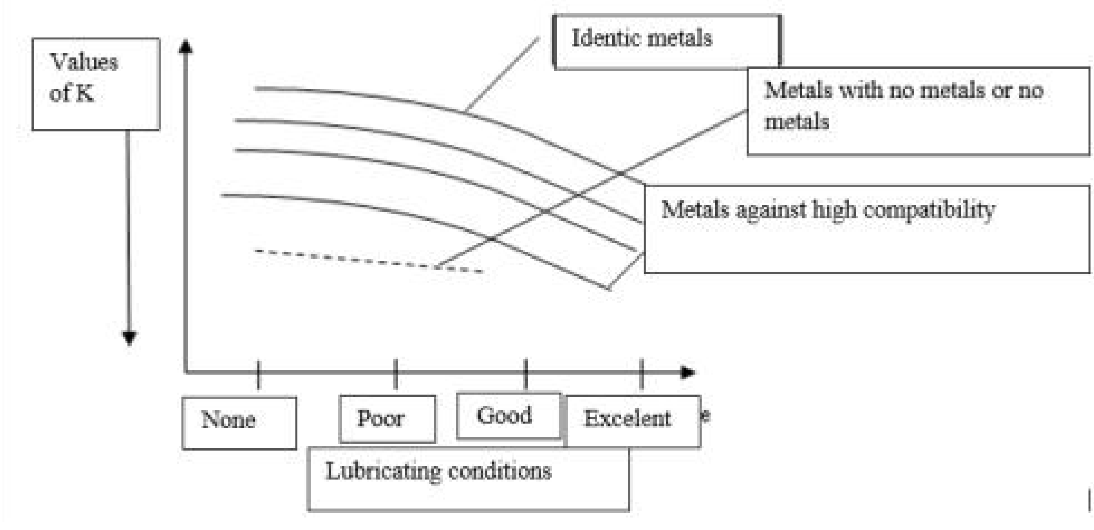

Figure 3. Typical values of wear coefficient K of different materials in slip pairs under different lubrication conditions.

The hard coatings or the layers deposited by diffusion, which are also of a very limited ductility, present a good resistance to this type of process. Rough surfaces, preferably those of random structuring, (for example, those generated by sand blasting), generally increase the resistance to damage, probably because the growth of the joint is limited and the probability of damage is greater.

Ceramic materials subjected to moderate sliding may show wear coefficients as low or even lower as dissimilar metals. This fact, together with its high hardness, shows that ceramic materials can present significantly lower wear values than metals. However, the volumetric use of ceramic materials presents some limitations for tribological applications. Their mechanical properties (especially the fracture toughness) may not be adequate for the requirements that are needed, such as producing them in a proper form of powder metallurgy, which is usually very expensive, and may cause small-scale surface fracture and serious wear, which requires great care in design. However, the overall ceramic components may be very durable during the tribological process: for example, aluminum bushings and seals on water pumps, silicon nitride valve components and alumina femoral ends, as well as components in hip joint implants.

Some drawbacks of the volume use of ceramic materials in friction pair components can be avoided by using deposited materials in metal substrates or ceramic deposits projected through plasma powder or physical vacuum deposition (PVD) or chemical vacuum deposition (CVD), which are methods that confirm an important group of surface engineering. In all tribological uses of ceramic materials, the use of lubrication is very convenient, since it reduces the surface traction, thereby reducing local fractures that lead to severe wear. However, the possible chemical reaction of an unsuitable lubricant with the surface must be taken into account.

In polymeric materials, they are rarely intended as wear-resistant materials and are typically used as sliding bearings, sometimes under dry or boundary sliding conditions. However, some polymeric materials, with sufficient strength, can be used as volumetric elements in tribological applications, among which the use of nylon (polyamide) and polyester sulfides is very important. In addition to these materials, in most of the times they are used as polymeric base composites and strengthened with suitable fillers. These materials are used as low-loaded gears, although polymers reinforced with carbon fibers are used in some gears for racing cars. Compared to similar components made of forged steel, these materials have the characteristics of light weight and good friction properties.

The wide diversity of existing surface materials engineers, allow the designer to select them, at least to a certain extent, instead of using materials volumetrically equal to its surface.

Fig. 4 shows the wide range of combination of layer depth and hardness that can be obtained on surfaces by these methods.

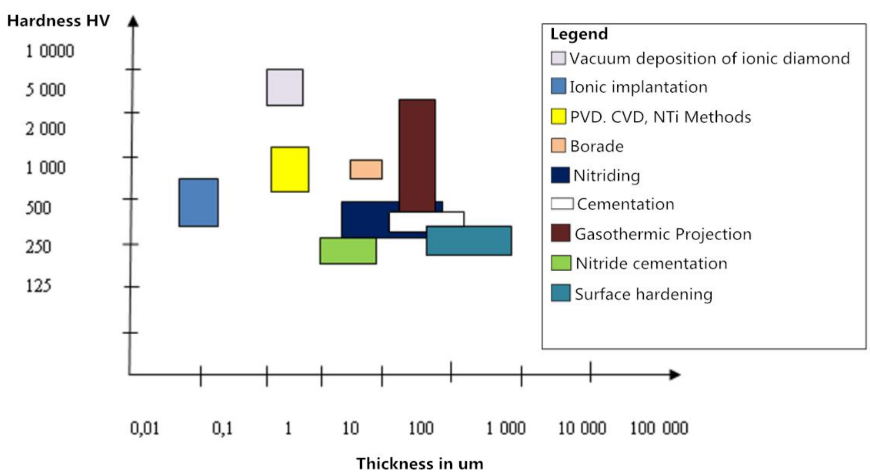

Figure 4. The typical depth and hardness of different deposition forms and engineering surfaces.

From Fig. 4, it can be concluded that different methods offer different possibilities of combination of depths and hardness of the surface layer. It is noteworthy that some methods are missing such as nickel chemistry, nickel plating, chrome plating and others. Those methods such as surface depositions with PVD, CVD or ionic implants that produce only very thin layers and great hardness, will be useful for use in applications with a minimum wear extension and where the surface acting force decreases rapidly during work, so that the thin surface layer is not eliminated. This is associated with the fact that the elastic interaction stage is reached quickly. In applications of precision engineering elements such as dies and some cutters by milling, these methods can offer great benefit in the work. Fundamentally the vacuum coating with NTi and the application of the cemented carbides, manufactured by PM, can significantly lengthen the shelf life in cutting elements.

In other cases where the contact forces penetrate deeply into the component, towards the entire surface layer or even below it (negative gradients), methods that generate thicker surface layers are needed. For example, in high load gears, the surface material must have high elastic strength in order to maintain elastic interaction conditions during operation. When sliding contact occurs, the elastic interaction conditions will be exposed to high contact forces. However, the core of the gear tooth and the rest of the gear require high fracture toughness and resistance to the appearance of fatigue cracks, being subjected to high cyclical loads and sometimes impact loads, during service. In this case, combining these characteristics, it is best to use metal materials that have undergone heat treatment and surface chemical treatment.

4. Conclusion

- Frequently, different surface technologies are applied to the design of existing engineering components, but ideally, surface engineering would cover the design of the component, knowing the surface treatment to be applied.
- There is no general correlation between the value of the wear and the coefficient of friction, although the lubricant may present as a third body or as a constituent of the paired elements (for example, the graphite in the melted irons or the molybdenum sulfide in some nylon base composition materials), tends to reduce both the value of wear and friction. Even poor lubrication is better than none to reduce the value of wear.
- The use of identical materials in sliding wear should be avoided. The use of high compatibility metallic materials is preferred, i.e., they have little or no solubility in solids in their equilibrium diagram.
- The high surface hardness is convenient in many occasions, which can be achieved by different surface engineering methods, such as PVD, CVD, thermal or chemical thermal surface treatments.
- In steel, the presence of carbides or nitrides in the outer layers is convenient, even if the surface hardness is reduced.
- Surfaces with a high index of hardening due to deformation, are resistant to severe adhesive wear, abrasive and pickling. A correlation can be established between the surface quality and the pickling resistance. The rough surfaces caused by surface bombardment are more resistant to pickling.
- In aggressive wear, the density of the impacted material, the impact velocity and the angle of incidence at the time of collision are important factors.
- Surface layers achieved by PVD, CVD, ion implantation, nitrating or cementing methods are resistant to sliding wear. The high hardness and low ductility are beneficial in these cases.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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