VIEW POINTS

Surface Engineering. Application on Wear

Ingeniería de Superficies. Aplicación en el desgaste

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Francisco Martínez-Pérez*

Universidad Tecnológica de La Habana-CUJAE, Centro de Estudios de Ingeniería de Mantenimiento, Marianao, La Habana, Cuba.

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 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 the 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.

Keywords: Tribology, Wear Resistance, Design, Surface Treatment, Pickling.

RESUMEN: En este artículo se introduce un nuevo concepto: La aplicación de la ingeniería de superficies. La base de este concepto es el comprender que diferentes tecnologías superficiales son aplicadas en el diseño de los componentes de ingeniería que existen, pero es necesario conocer que las superficies de ingeniería cubrirán parte del diseño del elemento, pero debe conocerse también sobre el tratamiento superficial a aplicar. Esto se debe, que las superficies con un alto grado de endurecimiento debido a la deformación son resistentes a un severo desgate adhesivo, a abrasión y al decapado, pero no deben tener la misma resistencia a otros tipos de desgate. Esto significa que debe establecerse una correlación entre la calidad superficial y la resistencia al decapado. En este artículo se muestra que el empleo de materiales metálicos de alta compatibilidad es preferible y que siempre debe establecerse una correlación entre la calidad superficial y la resistencia al decapado mediante un simple valor numérico. La selección de materiales y los métodos de obtención de las superficies ingenieras, para las aplicaciones tribológicas, depende en gran medida del mecanismo y el tipo particular de desgaste predominante. Así, la selección de materiales resistentes al desgaste será analizado en función del tipo de desgate.

Palabras clave: tribología, resistencia al desgate, diseño, tratamiento superficial, decapado.

INTRODUCTION

Recognizing that the vast majority of engineering components could be degraded or fail catastrophically in service due to surface-related phenomena, such as wear, corrosion or fatigue, led in the early 1980s to develop 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, electric plating without nickel), 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.

An engineering component generally fails when its surface cannot adequately withstand external forces or the environment to which it is 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.

*Author for correspondence: Francisco Martínez-Pérez, e-mail: fmartinezperez2013@gmail.com

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"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 by the surface of ordinary materials." Frequently, the different surface technologies are applied to designs of existing engineering components but, ideally, surface engineering does not include that design knowing the surface treatment to be applied.

This innovative multidisciplinary branch of engineering, through a final tribological analysis of the phenomena of wear and other superficial damages, such as corrosion, and the use of science of materials, allows optimizing the surfaces exposed to these processes in valves, evaporators, heat exchangers, pumps, 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 how in a suction system, it is possible to find erosion and cavitation, thermal fatigue and erosion in the blades of a steam turbine or abrasion and corrosion in a pulp pump screw affected by the presence of chlorine ions.

Corrosion is itself a complex interaction of physical-chemical variables, which always requires a rigorous analysis due to the different ways in which it occurs, such as corrosion under tension, differential aeration, vibration-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 them (composites), allows prolonging its duration in service. The engineer must also determine the procedure by which the alloy will be applied and its resistance to the type of wear present.

DEVELOPMENT

The selection of appropriate materials for the preparation of components for friction pairs is often limited by factors that have little to do with Tribology, such as their cost, for example. 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, except perhaps the corrosion resistance, are properties of the volume of the material and this gives the possibility of concentrating on varying surface properties of greater importance to Tribology, through a spectrum of different methods feasible to employ. 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 machines. All this, according to Rabinowicz & Tanner (1966); Ron & Conway (2002); Ludema & Ajayi (2018) can represent more than 2% of a country's GDP.

The designers or maintainers must take into account two very important considerations: to establish the magnitude of wear that will occur in service and knowing this, take the necessary measures for its reduction, taking into account, of course, the economic aspects they imply. In order to establish the amount of wear, which can be calculated, the mechanism of wear that will take place must be known; this can be done through specialized calculation (Hebda & Chichinadze (1989); Martínez (2010); Hutchings & Shipway (2017), as well as determining the factors that affect this, which can be done through physical mathematical modeling (Stolarski, 1990; Martínez, 2010).

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

The selection of materials and the methods of obtaining engineering surfaces, for tribological applications, depends to a large extent on the mechanism and particular type of predominant wear. 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 such parameters for the operation of the system. 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. That is why knowing the values of the magnitude of the wear produced is essential for this stage of the design or the redesign of the friction pairs.

When the type of wear is the friction (fretting), the parameters of displacement between the surfaces and the forces acting, are essential to be taken into account. Additionally, the control of oxygen access as an environmental medium must be controlled. In an optimal design for this type of system, in addition to the analyzed factors, it is necessary to consider the force that acts on the union of both elements to avoid the displacement of one with respect to the other, the temperature that can be generated, the difference in the thermal expansion of both elements of the pair and the probable sources of vibrations.

If the displacement takes place between sliding surfaces, as is the case with the bearings, the displacement itself cannot be eliminated, since it is intrinsic to the pair; in this case a fundamental parameter is that of the traction of the surface that can generate one element of the pair on the other. In this case, the analysis should be based on the decrease in the normal acting force or the friction that occurs in the torque.

If the working wear mechanism is that of contact fatigue, as is the case of gears, cam followers and bearings, three factors are essential, the number of active load cycles, which cannot be varied, and contact efforts, where not only their possible reduction should be considered, but the value of resistance to them from the materials of the pair, especially that of more probable wear. For the reduction of the acting forces, the value of the load and the surfaces geometry 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. Such, for example, will be the case of polluting or wear particles in the lubricant. 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, essential parameters are the speed of impact of the particles on the surface, their angle of incidence, as well as the density of the impacted material. In hydro erosive wear, the avoidance of acute angle of variation in fluid movement is an aspect to be taken into account.

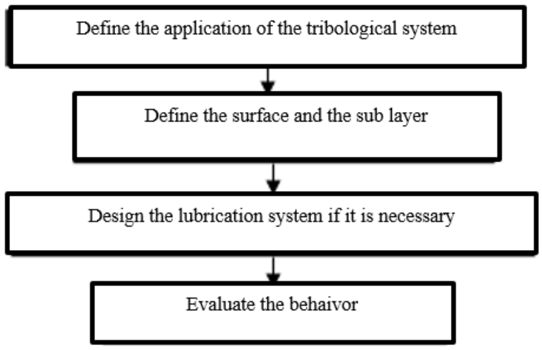

FIGURE 1. Algorithm that shows the system of steps to follow in the design of a tribological system.

Lubrication is a powerful method to reduce the amount of wear on bearings and other friction pairs. Considering K, a constant that represents a coefficient of wear in the case of lubricated slip, its value can be significantly low if hydrodynamic conditions of lubrication are achieved. But the hydrodynamic conditions cannot always be maintained, and when they pass to limit lubrication, the value of K can reach values of the order of 10^{-6}, depending on the properties of the lubricant used. K is a constant, which in the Archard equation, for sliding wear, is:

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

Q being the magnitude of wear that depends on the contact between all the asperities; P the contact pressure that can be replaced by the hardness of the material that wears and W the normal load applied. Acceptable values of K according to ASM manuals of Kostetskii (1972); Blau (1992); Hutchings & Shipway, (2017); Chowdhury (2019) and Ron & Conway (2002) [6], are given in Table 1.

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

Type of lubrication	K
Hydrodinamic	$< 10^{-13}$
Elastohydrodinamics	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; 2017; Martinez, 2011).

MATERIALS AND METHODS

For the evaluation of the different formulas for the calculation of wear according to the type of wear at work, the algorithm developed in this respect can be consulted (Martínez, 2010).

In general, the highest values of K occur in metal-metal sliding conditions, lower than those 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 Figure 2, a map is shown in which the mutual solubility of friction pairs formed by two pure metals can be appreciated.

Both the combinations indicated as completely insoluble, showing a negligible solubility in the solid state (▲), as well as those indicated as two coexisting phases in the liquid state (●), give 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).

	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).

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 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, therefore, 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, but 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; 2017).

The resistance of metals to severe conditions of adhesive wear and surface damage under high normal loads, cannot always be correlated with their resistance to wear under less severe conditions. Several factors influence the resistance of materials to surface damage by sliding: the effectiveness of the surface layer to prevent adhesion, the resistance of the adhesion, once the film is broken, and the extent of the bond formed. The mutual solid solubility as an indicator of the strength of the adhesive force, plays some role; metals that bind strongly are more prone to surface damage by sliding. Hexagonal metals with a limited number of landslide planes have a lower tendency to this type of damage than metals of cubic structure, presumably due to their lower ductility.

Some investigations have shown that those metals and alloys with a high degree of deformation hardening, presents lower tendency to superficial damage during the sliding; however, this factor is not infallible in its prognosis. For example, austenitic steels, although they have highly deformational hardening, show high surface damage in this type of process, when their structure is transformed into martensite. Hardness alone is a poor indicator of the

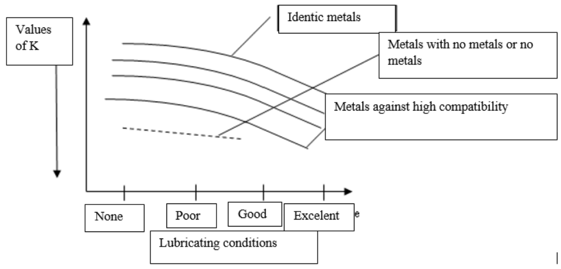

FIGURE 3. Typical values of wear coefficients K of different materials in slip pairs under different lubrication conditions.

resistance to surface damage during sliding processes: in steels, for example, a high concentration of carbides or nitrides show a high resistance to the process of surface damage by sliding, higher than when it obtains a similar hardness, but with a lower concentration of these hard and brittle particles.

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

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, greater probably to the damage.

Ceramic materials subjected to moderate sliding may show wear coefficients as low or even lower than 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 the appropriate forms (which would have to be done by powder metallurgy, generally with high costs, and also the possibility of surface fractures of small scales but leading to severe wear, which requires great care in the design. However, components of integrally ceramic materials can be very durable for some tribological processes: for example, alumina bushings and seals in water pumps, silicon nitride valve components and alumina femoral heads and cups in hip implants.

Some of the disadvantages of the volumetric use of ceramic materials in elements of friction pairs, can be avoided using the material in the form of deposits in a metallic substrate, or by ceramic coatings projected by powders in the form of plasma or by physical deposition to the vacuum (PVD) or vacuum chemistry (CVD), which are methods that conform 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 and, therefore, of local fracture that leads to severe wear. However, the possible chemical reaction of an unsuitable lubricant with the surface must be taken into account.

In polymeric materials little is intended for use as wear resistant materials, being commonly used as slip bearings, sometimes in conditions of dry or boundary slip. However, some polymeric materials of sufficient strength can be used as volumetric elements in tribological applications, being significant the use of nylon (polyamides) and polyester sulfides; besides these materials, in most of the times, are used as polymeric base composites, 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, which combine low weight and good tribological properties compared to similar elements made of forged steel.

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

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

From Figure 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 using 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 like 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, which can significantly lengthen the shelf life in cutting elements.

In other cases, where the contact forces penetrate deep into the component, towards the entire surface layer or even below it (negative gradients), methods that generate thicker surface layers are needed. In a highly loaded sprocket, for example, the material of the surface used must have a high yield strength, so as to maintain elastic interaction conditions during work, exposed to high contact stresses when contact slippage occurs. However, the core of the gear tooth and the rest of the gear require high fracture toughness and

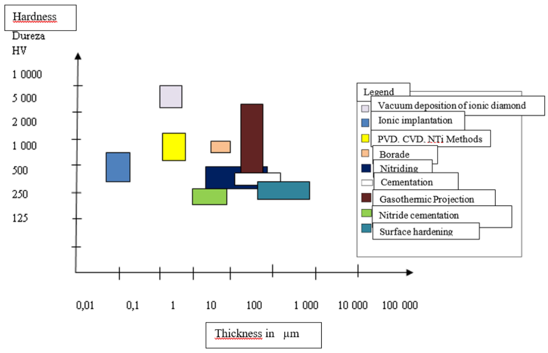

FIGURE 4. Depths and hardness typical of different forms of coatings and surface hardening.

resistance to the appearance of fatigue cracks, being subjected to high cyclical loads and sometimes impact loads, during service. In this case, for the combination of such properties, it is preferable to use steel elements, with thermal or chemical thermal surface treatments.

CONCLUSIONS

- Frequently, the different surface technologies are applied to designs 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 be present as a third body or as constituent of one of the elements of the pair (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, that is to say that they present in their equilibrium diagrams very little or no solubility in the solid state.
- 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 steels, it is convenient the presence of carbides or nitrides in the outer layer, even if the surface hardness is reduced somewhat.
- 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 the erosive wear are important factors of density of the impacted material, the speed of impact and the angle of incidence in the collision.
- 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.

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Francisco Martínez-Pérez, Profesor Titular, Universidad Tecnológica de La Habana, Centro de Estudios de Ingeniería de Mantenimiento, Marianao La Habana, Cuba, Tel. 78 335577, e-mail: fmartinezperez2013@gmail.com.