VIEW POINTS

The Concept of Tribodesign. Its Application

El concepto de Tribodiseño. Su aplicación

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ABSTRACT: The behavior of the influence of forces on materials is a recognized basic study in design engineering. The interaction of surfaces in contact in relative motion should not be ignored as a special study, since, like the resistance of materials, this is a basic element in any engineering design. Tribology, the name given to the science and technology of interacting surfaces in motion, is one of the most important and basic concepts in engineering and especially in design engineering. This should, without doubt, be used in the designation of a new term "Tribodesign". Thus, the Tribodesign concerns all the machine elements that are designed where friction, lubrication and wear play a fundamental role. It is an obvious, but fundamental fact that today, the assistance or practical help of Tribology is based not only on maintenance, but also on its application in the design of machine elements and machinery.

Keywords: Design, Tribology, Engineering, Science, Technology.

RESUMEN: El comportamiento de la influencia de las fuerzas en los materiales es un reconocido estudio básico en la ingeniería de diseño. La interacción de las superficies en contacto en movimiento relativo no debe ser obviada como un estudio especial, ya que, al igual que la resistencia de materiales, esto es un elemento básico en cualquier ingeniería de diseño. La Tribología, nombre con que se ha designado a la ciencia y tecnología de las superficies interactuantes en movimiento, es uno de los más importantes y básicos conceptos en ingeniería y especialmente en la ingeniería del diseño. Este debe, sin dudas, ser empleado en la designación de un nuevo término "Tribodiseño". Así el Tribodiseño concierne a todos los elementos de máquina que se diseñen donde la fricción, la lubricación y el desgaste juegan un papel fundamental. Es un hecho obvio, pero fundamental, que hoy en día, la asistencia o ayuda práctica de la Tribología se basa no solo en el mantenimiento, sino también en su aplicación en el diseño de los elementos de máquina y la maquinaria.

Palabras clave: diseño, tribología, ingeniería, ciencia, tecnología.

INTRODUCTION

The behavior of the influence of forces on materials is a recognized basic study in design engineering. The interaction of surfaces in contact in relative motion should not be ignored as a special study, since, like the resistance of materials, this is a basic element in any engineering design.

Tribology, the name given to the science and technology of interacting surfaces in motion, is one of the most important and basic concepts in engineering and especially in design engineering. This should, without doubt, be used in the designation of a new term "Tribodesign" (Martínez, 2010). This does not include various types of mechanical wear, such as: erosion and cavitation. Thus the Tribodesign concerns all the machine elements where friction, lubrication and wear play a fundamental role. It is an obvious but fundamental fact that the practical assistance or help of Tribology is based on its application in the design of machine elements and machinery.

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In order to achieve the integration of Tribology and Tribodesign in mechanical engineering and mechanical design, it is advantageous to visualize the task of controlling, in an adequate way, the flow of forces, energy and matter, including the interaction of these different forms of flow. Movement is also essential when considering kinetic energy as a time variation controlled in the position of some elements.

In general, load transmission is associated with the concentration of the contact pressure, regardless of where it is concentrated, whether on a shaped surface, such as the support of a lathe or in the case of a sleeve bearing; or where the surface is not shaped, as in the case of contact between two convex gear teeth or cams. In the first case, the contact, due to the quality of the surfaces, will be confined first in the rough edges of greater height and later it will be dispersed in the process of wear. On non-shaped surfaces, even when both are perfectly smooth, the contact will tend to concentrate on its own. This contact area is called Hertzian, because it is an elastic regime.

It is clear to be able to establish that the shaped or non-shaped areas of the surfaces in contact, where the flow of forces is established to transmit the movement, will be much smaller than the apparent area in which the deformation of the bodies in contact is generated. This is similar to saying that a stress concentration is determined. Thus, even if the load to be transmitted is small, the stress concentration will be large in dry working conditions. This stress concentration can be mitigated, or even effectively avoided, by the flow of a total lubricant layer (Stolarski, 1990; Bayer, 2008; Martínez, 2010).

The objective of the work is to provide the necessary elements to acquire the main knowledge concerning Tribodesign and analyze its application to several of the most important machine elements.

DEVELOPMENT OF THE TOPIC

Specific Principles of Tribodesign

Two principles, specific to the Tribodesign, are to prevent contact between moving surfaces and to consider the lubricant film as one more element of the machine and, accordingly, to consider that lubricants are engineering materials.

In its most general form, the principle of preventing contact between moving surfaces is not to avoid contact, but to take into account its consequences, such as risk of overstressing the surface of the moving body material, that is, mechanical wear. This principle, very important in the Tribodesign, can be executed in different ways. When this is combined with other principles, such as optimally grouping functions, it leads to the conclusion of the need for a protective layer. Such a layer, which covers the sliding surface, is frequently used as a wear substrate. The protective action can be, for example, to decrease the contact pressure by using a relatively low layer and with a low coefficient of friction, of a soft solid, thus reducing the risk of over-concentration of stresses in the sliding surface layer. This is a principle related to the novel science of Surface Engineering (Martínez, 2012).

The protective layer has various forms and is one of the most important aspects in terms of the principle of attenuating the contact between the sliding surfaces. At the same time, the principle of grouping the functions must be employed, since the substrate of the sliding surface has its own functions. Protection is assigned to the layer and the structural strength depends on the substrate material. In fact, the substrate serves in most cases as the softest material in the layer, thus allowing the transmission of external load. As the protective layer is an element interposed to the flow of forces, it must be designed so as not to fail in transmitting the load to the substrate (Martínez, 2016). From this point of view, a distinction must be made between protective layers made of a solid material (by heat, thermochemical, deposition treatments) and those consisting of fluids, which can either be a liquid or a gaseous lubricant.

Solid protective layers must be conceived first. On particularly shaped solid surfaces, it is often preferred to use protective layers weaker than the substrate material and the other surface of the pair. Such a protective layer can be used without great risks of structural failure of the relatively softer material. In the case of shaped surfaces, this can be explained by a slight penetration of the roughness of the harder material of the pair into the protective layer. In fact, the depth of penetration is comparable to the size of micro contacts formed by surface roughness. This is characteristic in contact surfaces of shaped surfaces. Unless the protective layer is extremely soft and thick, the areas of contact, and the depth of penetration, will never be greater than those of the two surfaces of the moving contact pair.

Other factors to consider are the strengthening and rigidity effects that the substrate material exerts on the protective layer. In a thin protective layer, the support exerted by the resistant substrate, particularly when the bond between layer and substrate is strong, will give the layer great resistance. The thinner the layer, the greater the stiffening effect of the substrate. However, this stiffness will cause a decrease in the bond between the protective layer and the substrate. For the effect of strengthening of the substrate to the protective layer to be effective, its thickness must not exceed the depth of penetration. Furthermore, the thickness of the layer must be greater than the penetration depth to withstand misalignment or deformation of at least one of the two bodies in contact, as well as to assimilate the effects of hard particles that have been trapped between the two surfaces in contact.

The situation of solid protective layers in non-conformed layers, such as gears, is slightly different, since the depth of penetration is much greater, not preventing the flow of the penetration of forces. The reason for this lies in the fact that the Hertzian contact area is much larger than the small contact areas between the asperities of the two non-shaped surface bodies. Therefore, the volumetric strength of the protective layer should be equal to or greater than that of the substrate. Both of these effects can be achieved when the protective layer of the gear is achieved through surface treatments such as cementing. Sometimes it is thought that protective soft coatings achieved on non-shaped surfaces, such as copper deposition on gears, are sometimes thought to be effective; but this is only true for the settling process and not for durability.

Liquids and gases form protective layers that are synonymous with total fluid layers. From the point of view of the Tribodesign and the design of machine elements, these layers show several interesting aspects since they constitute the most complete embodiment of protective layers. In any total fluid layer, the pressures must be formed hydrodynamically, in such a way as to balance the load transmitted through the fluid film from the boundary of the surface of one body to the other (Jost, 1990). These two surfaces must be kept separate in such a way that contact between the two bodies is totally avoided. This will only be possible to fully achieve on shaped surfaces. This will always be better achieved with full flowing coats than with any other solid coat. Even on non-shaped surfaces where the extremely thin fluid layer has an elastohydrodynamic character, avoiding contact pressures should be avoided.

Tribological Problems in the Design of Machine Elements

Some of the tribological problems found in the most common machine elements are the following:

Sleeve Bearings

When a sleeve bearing operates under hydrodynamic lubrication conditions, a hydrodynamic lubricant layer develops. Under these conditions the shaped surfaces are completely separated and a copious flow of lubricant prevents overheating. Under these conditions, of total separation of the surfaces, mechanical wear does not occur. However, this ideal situation is not always guaranteed (Kragelski, 1965).

Sometimes, misalignment, poor assembly or transient problems like elastic or thermal distortion, can be the cause of metal-metal contact. Contact can arise at startup (before the lubricant layer has had a chance to fully form), the bearing can become overloaded from time to time and the penetration of wear particles from elsewhere occur, carried by the lubricant, without having been filtered.

In particular cases, such as internal combustion engines, the formation of acids or other corrosive substances can occur during combustion, especially when it is incomplete, which are transmitted to the lubricant, causing chemical wear. The variations of hydrodynamic pressures in the shaft can cause detachment of particles; which constitutes the fundamental cause of the appearance of foreign particles in the lubricant (Bowden & Tabor, 1954). These particles can be trapped between the bearing support and the latter or be embedded in the softer material, leading to an abrasive wear process (scratching) in the hard material of the shaft. Chrome plating processes on crankshaft bearings are sometimes successful in combating abrasive or chemical wear.

Bearings

Bearings are the highest class of machine elements with Hertzian contact characteristics and the characteristics of this type of interaction. From a practical point of view, they can be divided into two classes: ball bearings and roller bearings, although the nature of contact and the laws governing friction and wear is common to both.

Any type of bearing is characterized by two numbers, the static load rating and the service life. Static load capacity is the load that can be applied to the bearing, which is either stationary or subjected to a slight rotational movement that does not limit its rotational properties. In practice, the maximum load is taken as that for which the combined deformation of the ball or roller and the raceway at any point does not exceed 0.001 of the diameter of the rolling element. L10 is represents the dynamic load capacity of the bearing; which is the load for which the bearing life is 10^6 revolutions and the probability of failure is no greater than 10%.

As in most engineering applications, the lubrication of a bearing is considered for two reasons: to control friction forces and to decrease the probability of contact failure (pitting or fatigue). It is universally accepted that lubrication is capable of promoting operation without the likelihood of bearing contact failure. The analysis and study of bearing contact failure methods will allow engineers to introduce design modifications to machines and, in particular, to improve lubrication to avoid bearing contact failure (Ashby, 2011). This is why, the combined study of bearing lubrication and failure methods, is an attractive research topic.

Pistons, Piston Rings and Cylinder Liners

One of the most common tribological knots in mechanics is the one formed by a piston inside a

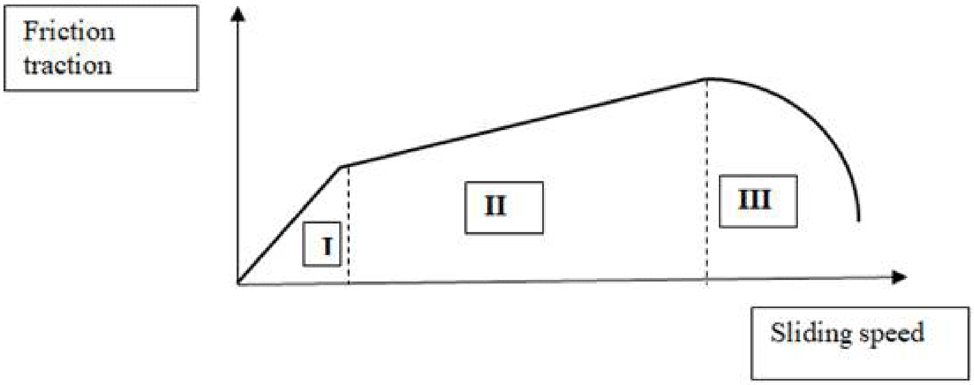

FIGURE 1. Forms of the dependence of friction traction with sliding speed.

cylinder; piston that in turn contains rings that form, the three, the tribological set. This set is found in engines, gas compressors and vacuum systems. The main function of a piston is to act as a seal and to counterbalance the action of fluid forces acting on the piston head. In most cases, it is the rings that perform the sealing function. To achieve this in hydraulic machines, this is compensated with a high degree of precision.

Although pistons are normally lubricated, in the chemical industry they use special piston rings that work without lubrication. They are made of polymeric materials that possess self-lubricating properties. System failures are generally due to loss of compression. The designs of these systems have to consider a high compromise, since a very effective lubrication that avoids compression losses and low friction can lead to a high consumption of lubricant in internal combustion engines. On the other hand, wear mainly occurs in the upper part of the piston (compression ring) where the combination of speed, pressure and temperature lead to the need for hydrodynamic lubrication (ASME, 1980). The conditions in the pistons where high corrosivity, due to the presence of sulfur and other harmful elements present in the fuel and in the oil. Alkaline oils are less prone to abrasive wear on cylinders.

Cams and Followers

Although the elastohydrodynamic theory of lubrication can help to understand how the contact takes place in the followers, from the point of view of its lubrication, a clear concept in its design cannot yet be offered.

Track systems are used extensively in engineering. The automotive valve trains are a system that includes the possible complications in the contact of followers. In the automotive cam contact, the maximum Hertz stresses (between 650 and 1300 MPa) and the maximum sliding speeds occur, which can reach 10 m/s. The expected lubricant film values are comparable to the best surface finish that can be obtained by normal engineering machining processes. And, of course, the surface finish has a decisive effect on the behavior of this element, in which, the contact and its behavior have a marked effect on heating, so the lowest possible value of friction is desired. Thus, the requirements of the design of these elements are that the contact surfaces and the lubricant film support the imposed loads with minimal wear or other forms of surface failure (Sinatora, 2003). It can thus be concluded that, in the tri-design these elements it is necessary to avoid superficial failure.

The fundamental thing in the design of the cams and followers is to ensure an adequate selection of the lubricant and the thickness of the layer. It is known that the decrease in the radius of the nose of the follower increases the Hertzian forces, the relative speed and also the thickness of the lubricating layer. A cam or follower with the greatest layer thickness in operation operates satisfactorily, while smaller thicknesses lead to premature failure. Temperature limitations are important to avoid surface filing failure modes on cams operating under high pressure and speed conditions. The working conditions on the cams and followers are not constant and this aspect is important when designing these elements.

Friction Drives

Friction transmissions, whose use has been growing in different transmission variants, are the opposite of hypoid transmissions since they start from the principle that the friction elements must move without sliding and are capable of transmitting a peripheral force from one to the other. These transmissions normally work in elastohydrodynamic lubrication regimes. If friction traction is analyzed on a graph as a function of sliding speed, three different forms of dependence can be identified (Figure 1).

In the first stage I, the dependence is linear in that the frictional traction is proportional to the sliding speed. After which, a second stage II is obtained, of increasing friction traction, until a maximum is reached after which, a third stage III occurs in which a fall is observed.

The initial stage I can be related to the rheological properties of the oil where the viscosity is the predominant parameter. However, the maximum that is reached in the second stage is somewhat surprising. Today, it is estimated that under appropriate circumstances the lubricant layer, under the high Hertzian contact pressures, becomes a kind of solid crystal, which is common with other solids that present a limit stress that corresponds to the maximum value reached in that stage. With respect to the third stage III, the drop in traction is fundamentally attributed to the decrease in viscosity associated with the increase in temperature in the lubricant. This type of transmission has not received enough attention and the articles published are mainly related to the principles of operation and the kinematics of the process (Bhushan & Gupta, 1991).

In rolling friction drives, the maximum Hertzian contact stress values can exceed 2 600 MPa. Under normal operating conditions, the sliding speed is of the order of 1m / s which is, proportionally, a low value of the rolling speed. Frictional transmissions base their effectiveness on the traction friction that is transmitted through the lubricant and, therefore, the maximum coefficient of friction is required. As the sliding speeds are relatively small, it is possible to select materials for the work surfaces, resistant to pitting failure, and the optimization of the friction behavior becomes the most important parameter (Totten, 2018).

Involute Gears

The instant the contact line crosses the common tangent to the primitive diameters, the gear teeth roll one over the other without slippage. During the remaining period of contact, where the contact zone is at the addendum or the dedendum, some relative sliding takes place. In this way, the type of failure, called pitting, takes place at this time.

There is evidence that, in gears with good quality of surface hardening, material entrainment occurs in the deceleration zones combined with overload. However, before reaching this material drag, another type of damage occurs in areas located in the vicinity of the contact area of both gears (pinion and sprocket). The type of damage that occurs is that of abrasion by abrasive particles detached from the edge of the tooth. There are indications of subsurface fatigue due to Hertzian stresses. The growth of fatigue cracks may be related to lubricant trapped in the initial cracks that emerged during successive cycles. However, in transmission processes, where high stresses, speeds and high temperatures are present, the lubricant is truly an engineering material. A number of methods have emerged to predict the proper selection of gear lubricants Martínez (2010), which serve a design purpose, but with limitations in gear dimensions and operation. The selection of the lubricant must take into account the critical temperature criteria to determine the thickness of the lubricant film.

In low speed operating gears, operating at stresses above 2000 MPa with a lubricant film layer thickness of a few µm, no signs of wear have been seen after thousands of hours of operation. In high-speed operating gears working with a 150 µm lubricant layer thickness, they frequently fail due to scratches in gas turbine transmissions.

A second concept, gaining acceptance, is that scratching will occur when a critical temperature is reached, which is a combination of the inappropriate lubricant and materials on the tooth faces.

Hypoid Gears

Hypoid gears are typically used in right-angle transmission, associated with car shafts. The action on the teeth combines the rolling action, characteristic of spiral bevel gears, with a certain degree of sliding, which makes these gears critical from the point of view of surface load.

The successful operation of these gears depends on the use of so-called extreme pressure oils, typical in lubricants containing additives that form a protective layer at elevated temperatures. There are several additives that confer these properties. Additives called lead soap, with sulfur content, prevent scratching action in transmissions that have not yet had settling, particularly in gears that have not been phosphated. They are not satisfactory when there is high torque, but they are effective at high transmission speeds. Lead and sulfur chloride additives are good in high-torque, low-speed transmissions, but not when the speeds are high. The preventions of the failure modes are by pitting and grating.

Worm Screws

These transmissions are something special, because the degree of conformity is higher than in any other type of transmission. They can be classified as a pair of bolts. Transmissions of this type present a totally critical situation due to their high degree of slippage. From the point of view of wear, the most acceptable combination is the combination of phosphor bronze materials with hardened steel (Martínez, 2000). A good degree of surface finish and ensuring a precise mounting and rigid position are also important. The lubricants used for these transmissions generally have surface active additives and the prevailing mode of lubrication is mixed or limit. Therefore, the wear is medium and probably corrosive due to the action of the limit lubrication.

Lubrication is a powerful method of reducing the amount of wear on bearings and other friction torques. Considering K, a constant that represents a coefficient of wear in the case of lubricated sliding, its value can be significantly low if hydrodynamic lubrication conditions are achieved. But the hydrodynamic conditions cannot always be maintained, and when these 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 amount of wear that depends on the contact among all the roughness; P the contact pressure that can be substituted for the hardness of the material to wear and W the normal applied load. Acceptable values of K according to ASME manuals ASME (1980), are provided in Table 1.

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

Type of Lubrication	K
Hydrodynamics	$< 10^{-13}$
Elastohyrdrdynamics	10^{-13} - 10^{-9}
Limit	10^{-10} - 10^{-6}
Solid lubrication	$\approx 10^{-6}$
No lubrication (severe wear)	10^{-4}- 10^{-2}

It is evident that sliding wear under hydrodynamic lubrication conditions is the most desirable state and in the design, all measures must be taken to promote it under operating conditions. The most important factor that determines the lubrication regime is the minimum thickness of the lubricating layer compared to the surface roughness, which can be calculated by specialized nomograms, taking into account another factor λ, integrating all the influencing parameters (Stolarski, 1990).

Selection of Materials and Surfaces in Engineering

The selection of appropriate materials for the manufacture of components for friction pairs is often limited to factors that have little to do with Tribology, such as their cost, for example. Weight is a factor that can be important and also resistance to corrosion. Mechanical properties, stiffness and toughness are of great importance, too, in engineering applications. Although these factors can 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 the use of selection maps, such as Ashby (2011), is convenient.

However, most of the listed properties, except perhaps corrosion resistance, are material volume properties and this provides the possibility to focus on varying surface properties, of major 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 in the sublayer, belonging to the volume of the material, leads to the so-called surface engineering. The various possible processes to apply

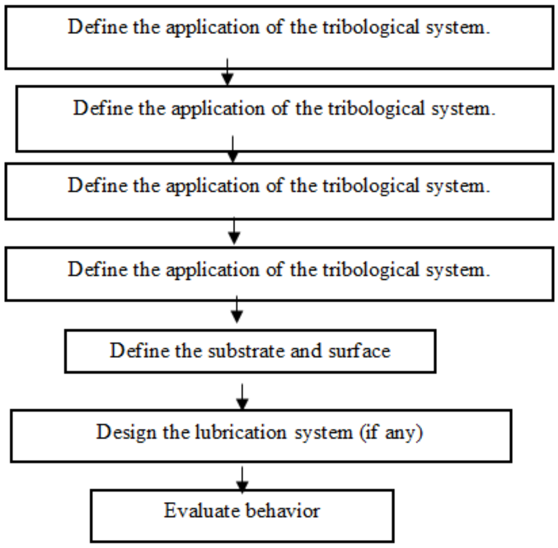

FIGURE 2. Algorithm that offers the system of steps to follow in the design of a tribological system.

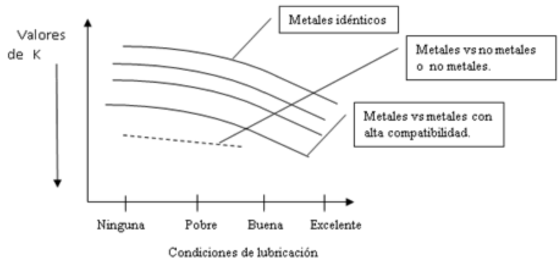

FIGURE 3. Comparative values of wear coefficients K of different materials in sliding pairs under different lubrication conditions.

must be considered as an essential part in the design of tribological systems (Martínez, 2009). In Fig. 2 an algorithm is shown that shows the sequence of steps to be followed in the design of a tribological system.

The selection of materials and the methods of obtaining the engineered surfaces, for tribological applications, depends to a large extent, on the mechanism and particular type of predominant wear.

In Fig. 4, a comparative scheme of typical values of wear coefficients K of different materials in sliding conditions under different forms of lubrication, is shown.

Hard coatings or diffusion deposited layers, which are also of very limited ductility, have 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. On the contrary, polished surfaces have a higher probability of damage.

The wide diversity of existing engineering surface materials allows the designer to select them, at least to

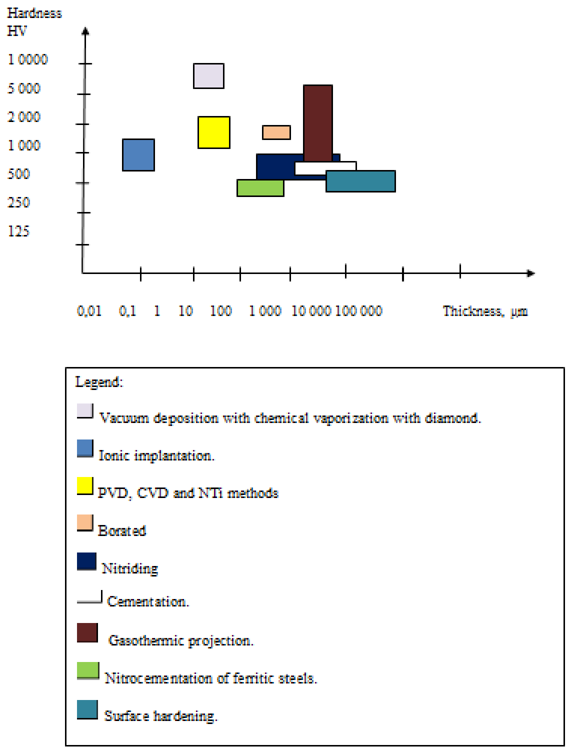

FIGURE 4. Typical depth and hardness of different forms of coatings and surface hardenings.

a certain extent, instead of using materials volumetrically equal to that of their surface.

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

From Figure 4, it can be concluded that different methods offer different possibilities for combining depths and hardness of the surface layer. It is noteworthy that, some methods such as chemical nickel, nickel plating, chrome plating, phosphating and others are missing.

CONCLUSIONS

It is clear, from all that has been stated, that the engineer responsible for the design must take into account the aspects of the Tribodesign, be it that of bearings or other motion transmission systems and must be able to analyze the situation that he confronts and take into account the important aspects indicated, for their solution. Furthermore, it is obvious that an adequate appreciation of the tribological situation requires a high degree of scientific sophistication, while having, at the same time, the most modern aspects of engineering and knowledge of the materials to be used. Today, within the scientific aspects, it is necessary to consider those related to Surface Engineering.

The present study has provided the necessary elements to acquire the main knowledge concerning the Tribodesign, the application of the Tribodesign to several of the most important machine elements has been analyzed. The concept of a protective layer has been the object of deep analysis, differentiating between those cases in which it is desired to concentrate the stresses on the protective layer, without penetrating the structural material of the element, from those in which the applied stresses are divided between the protective layer and the structure of the base material.

In both cases, it is extremely important to properly combine the strength of the protective layer and its depth. For this, the possible materials to be used for the formation of the layer and several of the different technologies that can be applied have been analyzed.

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