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Review Article

Significance of Tribocorrosion in Biomedical Applications: Overview and Current Status

M. T. Mathew,[1] P. Srinivasa Pai,[2] R. Pourzal,[3] A. Fischer,[3] and M. A. Wimmer[1]

[1] *Section of Tribology, Department of Orthopaedic Surgery, Rush University Medical Center, Chicago, IL 60612, USA*
[2] *Department of Mechanical Engineering, NMAM Institute of Technology, Nitte 574 110, Karnataka, India*
[3] *Department of Materials Science and Engineering II, University of Duisburg-Essen, Lotharstr 1, 47057 Duisburg, Germany*

Correspondence should be addressed to M. T. Mathew, mathew_t_mathew@rush.edu

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Recently, "*tribocorrosion,*" a research area combining the science of tribology and corrosion, has drawn attention from scientists and engineers belonging to a wide spectrum of research domains. This is due to its practical impact on daily life and also the accompanying economical burdens. It encompasses numerous applications including the offshore, space, and biomedical industry, for instance, in the case of artificial joints (Total Hip Replacement, THR) in orthopedic surgery, where implant metals are constantly exposed to tribological events (joint articulations) in the presence of corrosive solutions, that is, body fluids. Keeping the importance of this upcoming area of research in biomedical applications in mind, it was thought to consolidate the work in this area with some fundamental aspects so that a comprehensive picture of the current state of knowledge can be depicted. Complexity of tribocorrosion processes has been highlighted, as it is influenced by several parameters (mechanical and corrosion) and also due to the lack of an integrated/efficient test system. Finally a review of the recent work in the area of biotribocorrosion is provided, by focusing on orthopedic surgery and dentistry.

1. Introduction

Tribocorrosion has evolved into a new and emerging area of research with many applications going beyond the conventional. It is basically an integration of two major areas of significance and application in mechanical systems namely *Tribology* and *Corrosion* [1, 2]. Tribology is the science of friction, wear, and lubrication, whereas corrosion relates to chemical aspects of the material degradation in mechanical systems [3–5].

Tribocorrosion can be defined as a degradation phenomenon of material surfaces (wear, cracking, corrosion, etc.) subjected to the combined action of mechanical loading (friction, abrasion, erosion, etc.) and corrosion attack caused by the environment (chemical and/or electrochemical interaction) [6, 7], as highlighted in Figure 1. The history of tribocorrosion (tribo-electrochemistry) dates back to 1875, when Edison observed a variation in friction coefficient at various applied potentials [8]. Recently, the field of tribocorrosion has grown and developed and is attracting the attention of researchers from various fields of science and engineering, mainly due to its practical importance and economic benefits. Some of the realistic applications are listed in Figure 2. Fundamentally, tribocorrosion studies deal with an irreversible transformation of materials or their function as a result of simultaneous mechanical and chemical/electrochemical interaction between surfaces in relative motion [6, 7, 9, 10].

Tribocorrosion can be characterized by its synergy resulting from the coupling of mechanical and environmental effects. This synergism results in degradation and, hence, loss of material that often is much larger than the one which would be expected by simply summing up the degradation due to individual process. This synergism can have positive or negative effects depending upon the specific reaction products formed on the surface of the materials, which can protect the surface as in the case of self-lubricating and/or self-healing layers or can aggravate the material degradation process causing more material removal [10–12].

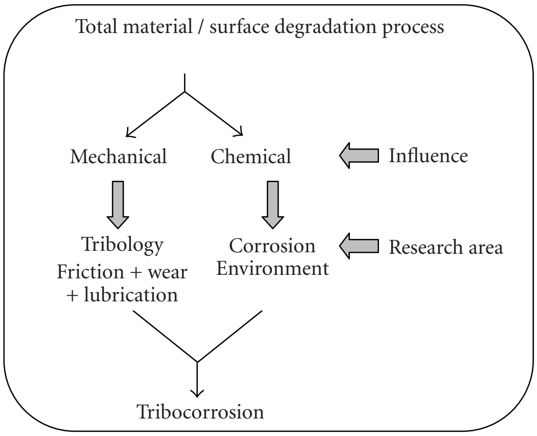


Figure 1: Basic concept and definition of tribocorrosion.

Tribocorrosion involves mechanical and chemical/electro chemical interaction between surfaces in relative motion in the presence of a corrosive environment. It is encountered in many areas where it can cause damage to installations, machines, and devices and there are other applications, where this phenomenon is put to good use, for example, electromechanical machining. However, the role of corrosion and electrochemical reactions are not very predominant, in such conditions. It is also noticed in living systems as in the case of metallic implants in the human body such as artificial joints, orthopedic plates and screws, and dental implants. Hence this whole field of tribocorrosion is being studied and researched under two categories—tribocorrosion in industrial systems and tribocorrosion in living systems [3, 4, 8–10]. In fact, the available wear-corrosion synergism ASTM standard is G119, which has been published in 1995 [13]. In 2001, an attempt was made by Mischler [6], to conduct interlaboratory studies among the tribocorrosion research labs, in Europe (Round-robin). Further, Tribocorr-net work was initiated by M.M. Stack at University of Strathclyde, UK, to provide new directions for research in the area of tribocorrosion (http://www.tricorrnet.strath.ac.uk/) [14–16].

This paper aims to present an introductory review of this fascinating and emerging field of engineering, with reference to the still limited literature that is available. The paper starts with a brief description of the phenomenon, the factors affecting tribocorrosion, the state of the art, and current status and culminates with the practical limitations and the challenges faced in the studies related to tribocorrosion. The technological importance of tribocorrosion duly supported by examples and case studies is also being discussed.

2. Tribocorrosion: Some Important Aspects

2.1. Multidisciplinary Approach in Tribocorrosion. Tribocorrosion is a general term encompassing all the mechanical (wear) and chemical (corrosion) interactions that provoke the degradation of materials in relative motion. Despite its widespread occurrence and industrial relevance, it is still poorly understood. The interaction of material surfaces causes reaction products, its removal, reformation, and so forth, leading to a cycle of positive and negative synergisms depending upon the mechanical interaction taking place. Hence, there is a need for a multidisciplinary approach to understand the system consisting of a material surface, an environment, and a mechanical contact. This study requires an integration of researchers from various disciplines, namely, material science, mechanical engineering, surface engineering, electrochemistry/chemistry, tribology, biology, and medicine. Interactions happening at the macroscopic level of material surfaces can be studied at the micro- and nano- levels, which should lead to a more holistic understanding of the subject [17, 18]. In fact, the principle of tribocorrosion is not a new subject. During last 15 years, very active and interesting investigations were reported (erosion-corrosion, sliding wear-corrosion, fretting wear-corrosion).

2.2. Some Practical Examples. Tribocorrosion phenomena are encountered in a wide variety of applications and lead to uneconomical material loss as well as durability, reliability, safety, performance, energy efficiency, pollution, health, or the optimization of manufacturing process and economic competitiveness, as shown in Figure 2. Some industries where tribocorrosion can occur include nuclear, process industry, chemical and petrochemical industry, marine industry, material handling, mining, aerospace industry, automotive industry, food, offshore, and biomedical [11, 12].

As already mentioned, tribocorrosion is also encountered in living systems—areas where it can cause damage to human joints, prosthesis and restorative dentistry, and so forth, thereby establishing their implications on human health and quality of life [6, 10].

2.3. Classifications of Tribocorrosion. Material degradation due to simultaneous chemical and mechanical effects may occur under a variety of conditions and contact modes as shown in Figures 3 and 4. Tribocorrosion includes the interaction of corrosion with the following:

(i) solid particle erosion,
(ii) abrasion,
(iii) cavitation erosion,
(iv) fretting,
(v) biological solutions,
(vi) sliding wear and tribo-oxidation.

Two body or three body contacts between sliding surfaces are a common cause of tribocorrosion. The relative motion of the surfaces can be unidirectional as in case of a pin-on-disk wear test apparatus or reciprocating. Fretting involving reciprocating motion of small magnitude is a special type of tribological contact. Rolling contact occurring in ball bearings also experiences tribocorrosion. Particle impingement happening in erosion corrosion, which is a combination of mechanical and chemical attack on materials, occurs in pumps and pipes carrying slurries.

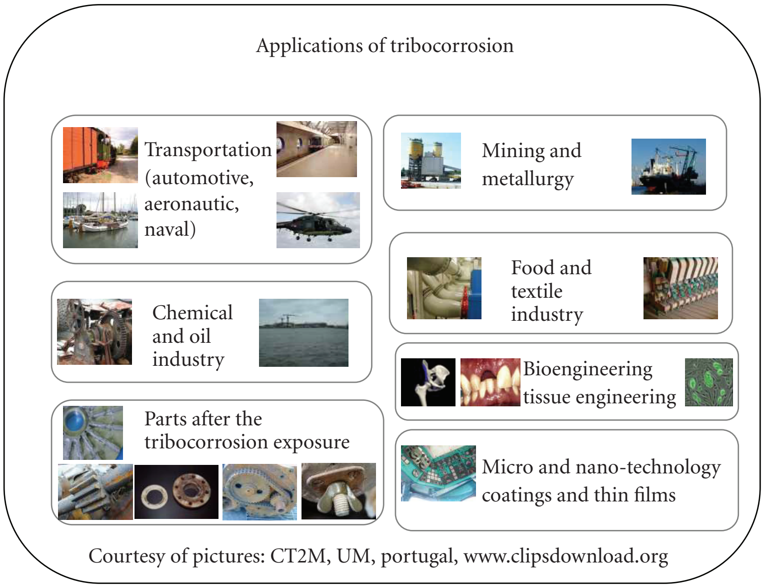


Figure 2: A spectrum of practical importance of tribocorrosion.

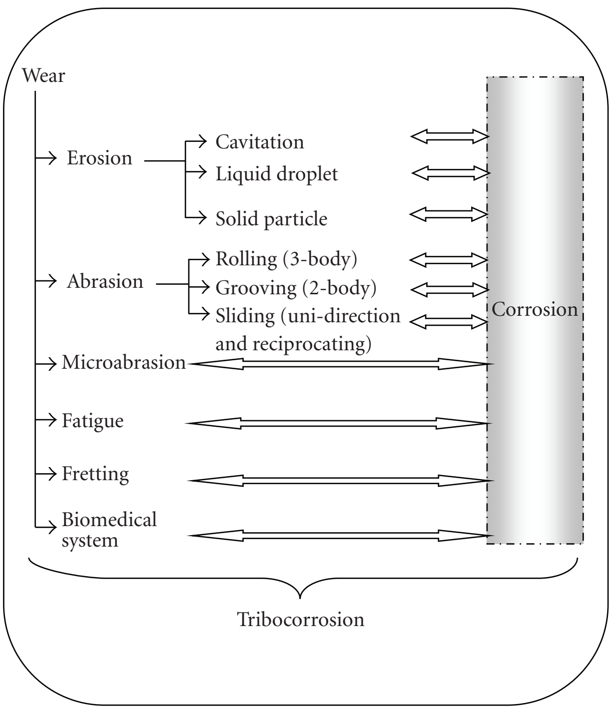


Figure 3: General types of tribocorrosion system.

Contact mode	Schematic
Sliding • Unidirectional • Reciprocating Corrosive wear Chemo-mechanical polishing	Two body; Three body
Fretting Dentistry Body joints (hip and knee)	Amplitude is less than 500 μm (approx.); Two body; Three body
Rolling Dentistry Body joints (hip and knee)	
Microabrasion Rolling Grooving	Slurry; Rotating ball
Impingement Erosion corrosion Impingement attack	

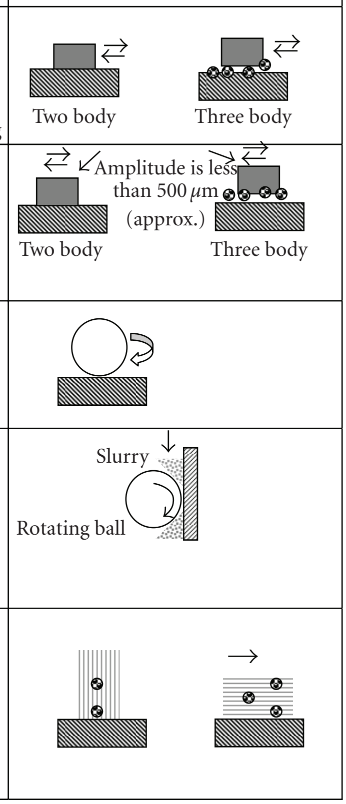


Figure 4: Contact modes in tribocorrosion.

From a physical point of view, tribocorrosion includes a variety of mechanical and chemical degradation phenomena, namely, corrosive wear, erosive wear, wear accelerated corrosion, erosion corrosion, oxidative wear, fretting corrosion, stress corrosion cracking, and corrosion fatigue [2, 7–12].

2.4. Factors Affecting Tribocorrosion Process and Mechanisms. Tribocorrosion behavior depends on (i) the properties of the contacting materials, (ii) the mechanics of the tribological contact, and (iii) the physicochemical properties of the environment. These aspects are strongly interrelated—either synergistic or antagonistic, which can have beneficial or

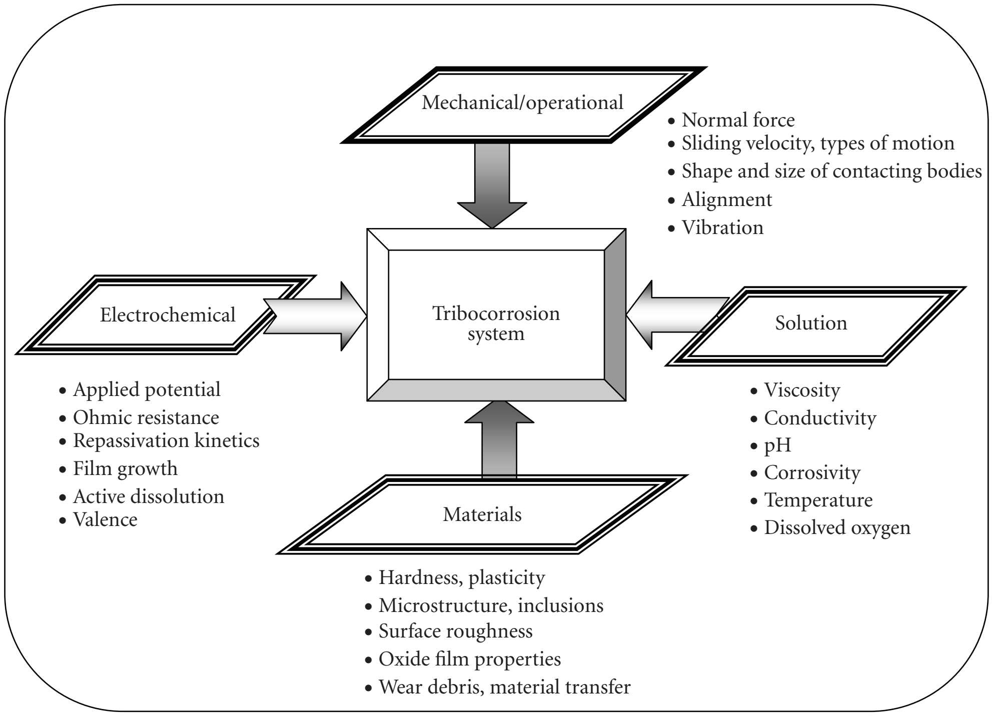


Figure 5: Factors influencing the tribocorrosion.

deleterious influence over the performance of the tribological system. Therefore, the need is to study tribocorrosion from a systems perspective as it involves an integration of several subsystems. Figure 5 shows the important parameters affecting the tribocorrosion behavior in case of a sliding contact under electrochemical control. The following paragraph enumerates some of the important factors affecting this phenomenon [5, 6, 11].

2.4.1. Materials. The properties of all the materials involved in the tribological contact including those of the reaction products formed on the rubbing surface are of importance. In the absence of corrosion, wear resistance of a material depends on properties such as hardness, rigidity, ductility, and yield strength. The relationship between these properties on tribocorrosion rate is not very clear. Published research has tried to study the synergistic effects between wear and corrosion processes which result in accelerated material loss and in some cases actually decelerate material loss.

A wide range of corrosion resistant materials rely on a relatively thin surface oxide film to provide a barrier to charge transfer between the relatively active bulk material and the corrosive environment. This film renders the surface passive, but within the tribological contacts, the passive film can be removed by mechanical wear or impingement processes. Wherever the film is mechanically damaged and removed, the charge transfer can take place at the interface without any resistance from the barrier film. This interaction between tribological and electrochemical corrosive effects increases loss of materials significantly. It will be much higher than the summation of material loss under pure corrosion (without tribological movements) and pure wear conditions (preventing corrosion under cathodic conditions) [11, 12].

The microstructure of the materials and the presence of defects, like phase distribution, grain size and orientation, nonmetallic inclusions, segregations, dislocation density, and so forth, are critical for the mechanical behavior of the materials. The topography and the chemical composition of the contacting surfaces also play a crucial role in tribocorrosion. This includes the initial surface roughness, its evolution over time, formation of plastically deformed surface layers due to rubbing or impacts, the growth and the mechanical properties of oxide films formed, and the formation of reaction product layer and its adsorption. In case of metals exposed to high temperatures, the mechanical and chemical properties of the thick oxide layers formed determine the tribocorrosion rate.

2.4.2. Mechanical/Operational Parameters. The rate of tribocorrosion for a given metal-environment combination depends on the applied forces and the type of contact—sliding, fretting, rolling, or impact. The other factors include sliding velocity, type of motion, shape and size of contacting bodies, alignment, vibration, and so forth. For example, in the case of fretting corrosion, there are small amplitude oscillations occurring in a corrosive environment. Contact geometry involving shape and size of contacting surfaces is another important parameter in tribocorrosion, as it determines the size of the contact zone and the alignment of the rubbing surfaces. Different mechanical processes have different parameters affecting the process, like in case

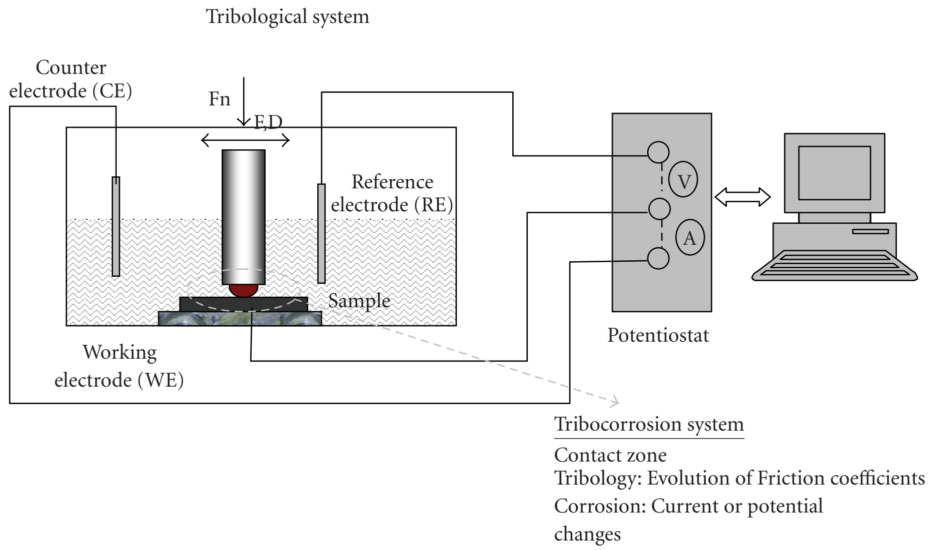


Figure 6: Basic methodology in a tribocorrosion study.

of erosion, the energy and the angle of incidence of the impacting particles and their shape are critical variables.

2.4.3. Solution/Environment. For a given contact conditions (metal pair or nonmetal pair), environmental effects/variables play a major role in tribocorrosion. Its influence is in the form of the medium at the interface, that is, solid, liquid, or gaseous and its corresponding properties like viscosity, conductivity, pH, corrosivity, temperature, and so forth. For example, when the metals are exposed to air, the relative humidity will determine whether a thin liquid electrolyte film may form at the surface changing the corrosion mechanism.

In case of aqueous systems, concentration of oxygen, pH and concentration of certain anions like chloride ions influences corrosivity. In case of high-temperature applications, the physical nature of the scales formed is critical. Certain corrosion products containing sulfur have a relatively low melting point, which can lead to the formation of highly corrosive molten salts on the surface.

2.4.4. Electrochemical Parameters. In tribocorrosion, electrochemical aspects are very important, as the corrosion monitoring is being done by using basic electrochemistry. Basic parameters are applied potential, ohmic resistance, passive film growth, active dissolution, and so forth, as shown in Figure 5. The electrochemical aspect is considered mainly because tribocorrosion phenomena have been studied for many years by electrochemists and tribologists. Electrochemists have concentrated their attention on the study of the kinetics of repassivation of metal surfaces activated by scratching, whereas tribologists have been interested as to how surface oxidation during rubbing affects the rate of mechanical wear. More recently, the mutual dependence of mechanical and electrochemical mechanisms has been formulated [2, 6–9].

3. Tribocorrosion: Test System and Methodology

3.1. Basic Methodology. As mentioned earlier, in order to study the tribocorrosion behaviour, mechanical and corrosion responses from the tribocorrosion test system are required to be collected and monitored. Generally, tribometer has facility to measure the evolution of frictional forces and electrochemical technique is used to monitor the corrosion response from the test system. A schematic diagram of the basic methodology of a tribocorrosion test system is shown in Figure 6. Electrochemical interfacing consists of a potentiostat and three electrode attachments, such as reference electrode (RE, either SCE (standard calomel electrode) or SHE (standard hydrogen electrode)) and counter electrode (CE, platinum wire or graphite rod). The sample is acting as the working electrode (WE).

Basic/general steps in a tribocorrosion tests are explained in a schematic diagram in Figure 7. The selection of parameters depends on the application and research interest. For example, in case of an orthopedic application, the influence of load or cycles might be the parameter of interest. In dental application, the pH of the solution could play a role and might be investigated. The technique to be used varies with the nature of the test system. Generally, open circuit potential (OCP) measurements provide the evolution of potential and potential changes in the system with respect to standard electrodes (e.g., standard calomel electrode, SCE). Further, the corrosion current evolution can be studied at a constant potential from the system. Likewise electrochemical impedance spectroscopy (EIS) can be used to understand the properties or characteristics of films formed at the contact zone. Usually such measurements are taken before and after the sliding or tribotest.

The online measurements of friction coefficient and corrosion parameter (either current or potential) can be very useful in analysis. An example from a previous

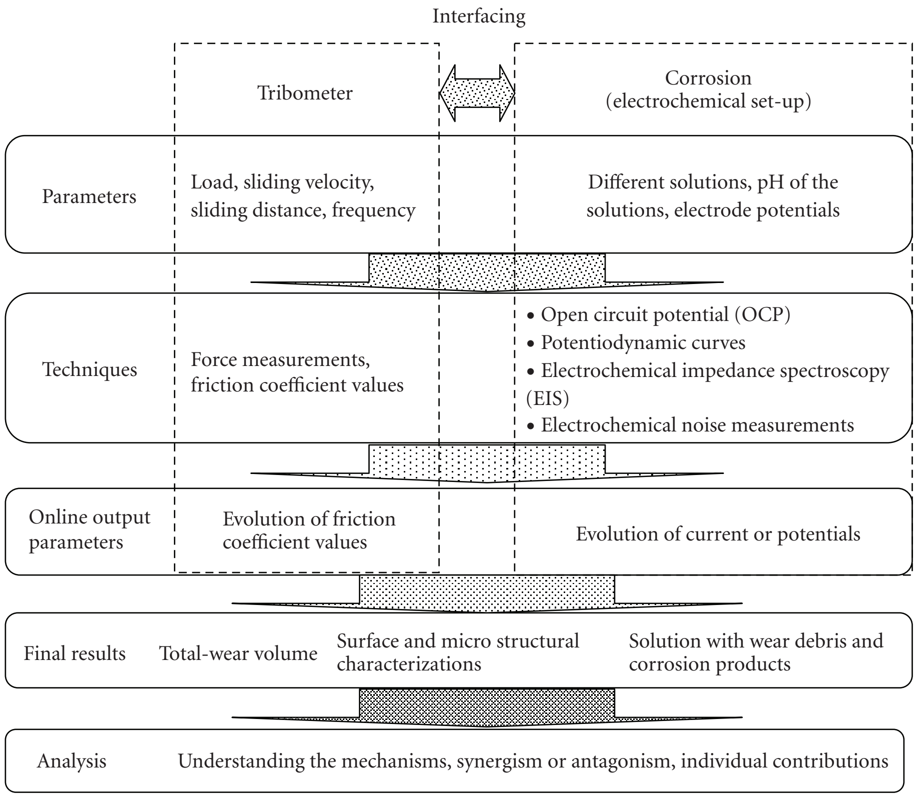


FIGURE 7: Basic steps in a typical tribocorrosion study.

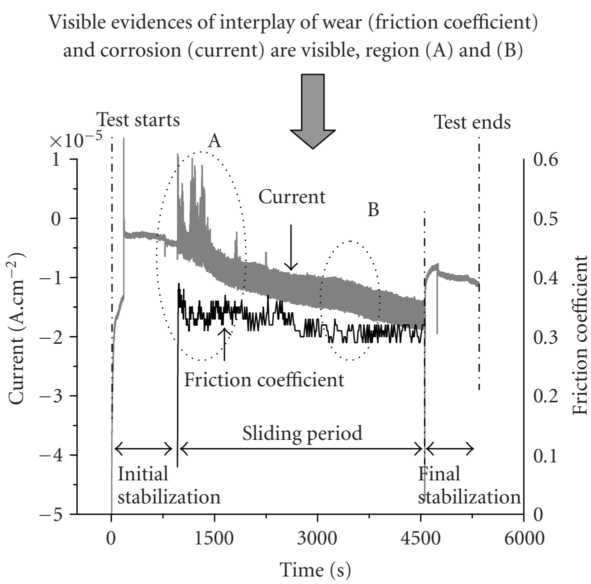


FIGURE 8: An example of tribocorrosion study evolution of friction coefficient, and current, as a function of sliding time [19].

tribocorrosion study of TiC_xO_y film (Titanium carboxide film for decorative applications, Electrolyte: artificial sweat solution) is shown in Figure 8 [19, 20]. In fact, the worn surface analysis using SEM or AFM provides valuable information on the driving wear and corrosion mechanisms. Further, the analysis of wear debris and corrosion products can also hint valuable clues about the tribocorrosion process.

The most important step in tribocorrosion analysis of a system is to understand the combined as well as individual effect of tribology and corrosion along with their interaction which can either be beneficial or detrimental. Figure 9 illustrates the basic concept about the tribocorrosion analysis. Different terms and analysis techniques are explained else [6, 14–16]. Although various approaches were used by researchers, all the methods are targeted towards a better understanding on the mechanisms of tribocorrosion process. Because of the complexity of the phenomenon, the mapping approach [14–16] used by some of the investigators may also indicate the acting/driving mechanisms in association with material loss as a function of the selected parameters.

3.2. Practical Limitations and Challenges in the Tribocorrosion Studies

3.2.1. Test Apparatus. One of the major difficulties in tribocorrosion studies is the interlaboratory comparability of the results and finding because of lack of a standard test apparatus. As it is a recent area, several investigators and research laboratories are trying to modify existing/classical tribometers, which are commercially available or home made to incorporate the electrochemical test set-up. One of such modified systems, a pin-on disk tribometer used for tribocorrosion studies of thin films [19, 20], is shown in Figure 10. In fact, such test systems have an advantage of

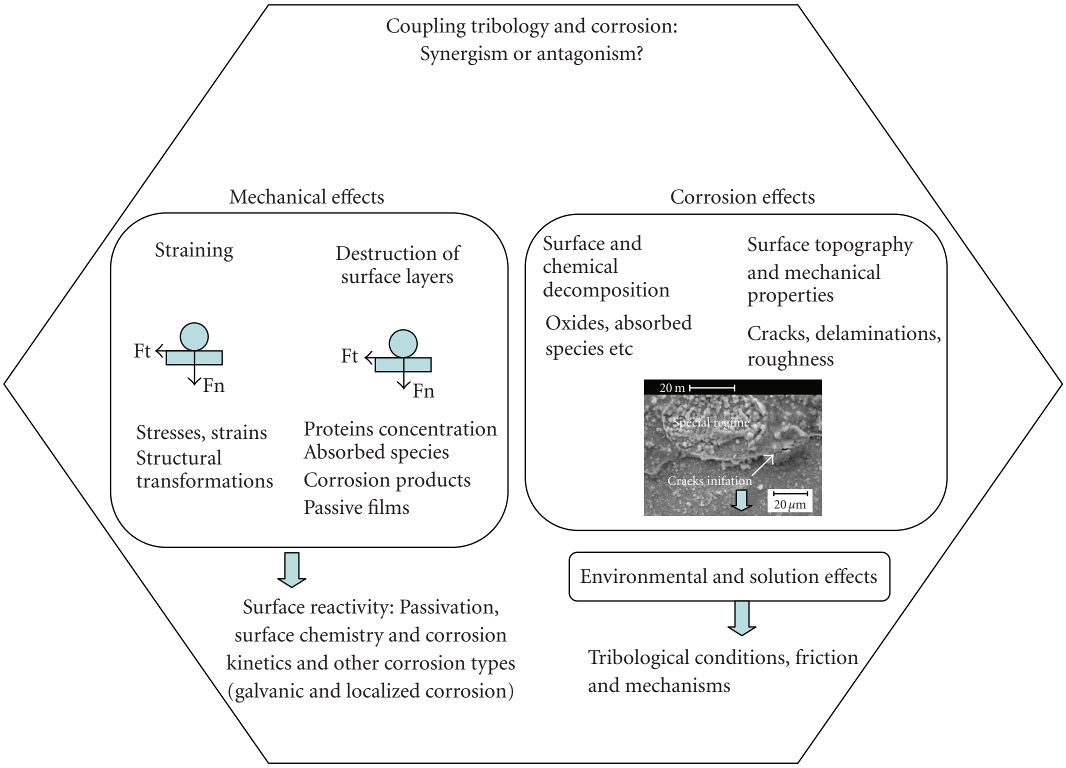


Figure 9: Basic concept of linking tribological events and corrosion process in tribocorrosion process in understanding the synergism.

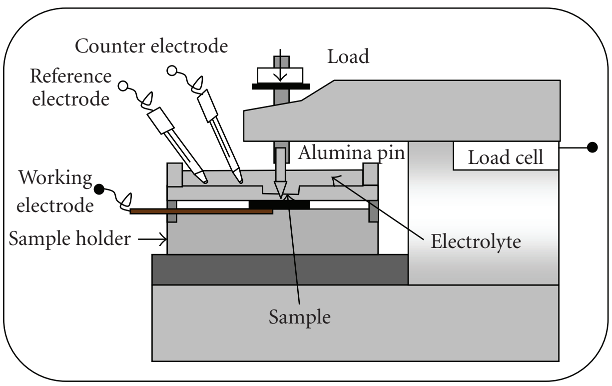


Figure 10: Example of modified tribocorrosion experimental set-up with a reciprocating sliding tester (Courtesy to Research centre, CT2M, University of Minho, Portugal) [19, 20].

distinct methods in collecting and processing the tribological responses. However, several practical and technical problems may arise in employing such systems for carrying out the experimental studies on tribocorrosion and analysis of the results. Some of the limitations of a modified system can be listed as follow; (i) geometry and construction of a corrosion cell (appropriate for the tribometer), (ii) proper/consistent locations of electrode (iii) possible leakage of the solution/electrolyte, and (iv) collection and synchronization of the data from the tribometer and potentiostat. Therefore, recently, attempts have been undertaken by many research laboratories to design and develop tribocorrosion test systems with the specific purpose of tribocorrosion studies (selection of the contact configurations as per the required applications, e.g., ball-on-plate). Certainly, unique tribocorrosion test system will be able to yield more accurate and reliable results.

3.2.2. Other Challenges. There are several issues to be considered while performing a tribocorrosion test, such as the proper insulation against corrosion current and the choice of the appropriate counter body.

(1) Proper Insulations. In a tribocorrosion test system, the sample is subjected to an electric current; therefore, it is very important to take care of any leakage of the current through the contact or part of the circuit of the conducting materials in the system. Generally, the tribocorrosion cell is made of an insulating material, employed to prevent any contact with the tribometer or any other conducting materials.

(2) Counter Body. The selection of the appropriate counter body is very important in tribocorrosion studies. If the two contacting surfaces are conductive, the collection of responses related to corrosion. Hence, generally, one of the contacting bodies is kept as an insulator and the conductive body is studied for its tribocorrosion resistance. However, in practice, there are such conditions existing that two conductive bodies are in contact, for example, MOM hip joint. There are not many studies on metal-on-metal

couplings compared with metal-on-nonmetal pairings [6]. Additional research is required to solve such limitations and establish a standard method and procedure.

(3) Dynamic Tribocorrosion Test System and Understanding the Synergism. It is also important to note that corrosion test favors a stabilized system and indicates the changes in the surface chemistry under the influence of solution or environments. It is also important to note that corrosion testing systems favor a stabilized system and monitor the changes in the surface chemistry under the influence of environmental factors. However, it is impossible to have a tribological system (where the contacting bodies are in motion), under stable conditions. Hence, it is a challenge in understanding and/or interpreting the corrosion results from the tribological/dynamic conditions. At the same time, this is the novelty of the tribocorrosion studies. Better knowledge about the interaction of both tribology and corrosion will help in understanding the impact on the system. For example, in the tribocorrosion studies in a reciprocating sliding tribometer (Figure 10), the current evolution is associated with sliding movement and velocity evolutions. Such effects are visible in the evolution of current and friction coefficient values as a function of time. For example, the marked regions "A and B" in Figure 8 demonstrate that the sudden variation in the evolution of current is linked with changes in the friction coefficient, indicating the interplay of tribology and corrosion in the tribocorrosion process [14, 15, 19, 20].

4. Tribocorrosion: Current Status

The area of tribocorrosion has been a subject of intense research, since last several years. Though the research in the field started as early as 1980s, many Universities, research organizations, and industries got actively engaged in research on this area only more recently. The in-depth study of the mechanisms behind tribocorrosion was recently initiated in different fields to clarify the insitu durability of interacting material surfaces. There has been a multidisciplinary approach of the systems, making it an attractive area of research, involving researchers from different fields.

As corrosion is important component of a tribocorrosion system, there is a need to simulate the corrosive testing environment, which requires a potential that can be determined by both its electrochemical properties and the concentration of the oxidizing agents present in the environment. To simulate the effect of an oxidizing agent one can impose a corresponding corrosion potential on the metal by means of an external current source. Electrochemical techniques are also available, which allow variation in corrosion conditions over a wide range by varying the applied potential. Hence, a large volume of research is concentrated in this area. In the following paragraphs, the authors attempted to include some review work in this area and highlighted the significance of tribocorrosion in the biomedical applications by presenting some recent works (known as bio-tribocorrosion).

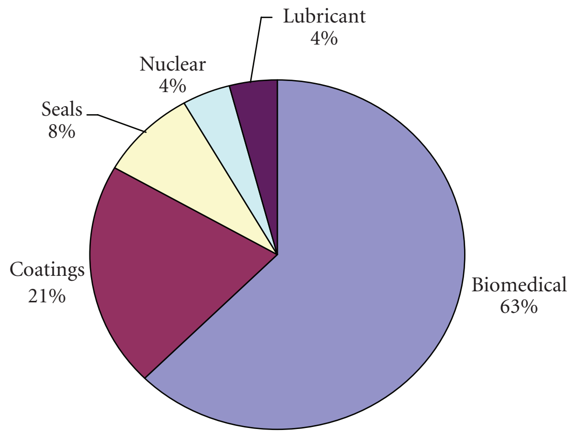


Figure 11: Reported studies (1996–2006) in the area of tribocorrosion based on the review of Mischler, in 2008 [6]. This shows the importance tribocorrosion in biomedical applications.

4.1. Reported Review Works. In 2001, Landolt et al. [10] have discussed the application of electrochemical methods to the study of tribocorrosion phenomenon. The importance of controlling the mechanical parameters and the contact geometry has been stressed and it has been shown that these parameters can significantly affect the electrochemical response of a tribocorrosion system. These methods offer distinct advantages for the study of tribocorrosion systems in that they permit to simulate the oxidation characteristics of a corrosive environment by applying a known electrode potential.

In a related study [2], the same author discussed about the electrochemical and material aspects of tribocorrosion systems. Electrochemical methods have been used to yield information about synergistic and antagonistic mechanisms, for which they must be applied insitu under strictly controlled mechanical conditions, using materials with well-characterized surface properties. Ponthiaux et al. [12] highlighted electrochemical techniques for studying the combined corrosion-wear degradation of materials in sliding contacts immersed in electrically conductive solutions. The techniques discussed are open circuit potential measurements, the potentiodynamic polarization measurements, and the electrochemical impedance measurements. The capabilities and limitations of these techniques were discussed based on a tribocorrosion study of AISI 316 stainless steel and an iron-nickel alloy immersed in aerated 0.5 M sulfuric acid and sliding against a corundum counterpart.

The role of coatings/thin films and its performance under combined wear and corrosion conditions is another area of research in tribocorrosion. It is essential to understand how coatings perform under different tribocorrosion conditions, in order to predict the service life of the equipment and to explore ways to enhance it.

Wood [11] comprehensively reviewed the tribocorrosion performance of coatings deposited by a variety of techniques and the main mechanisms associated with their degradation under combined wear and corrosion. Coating

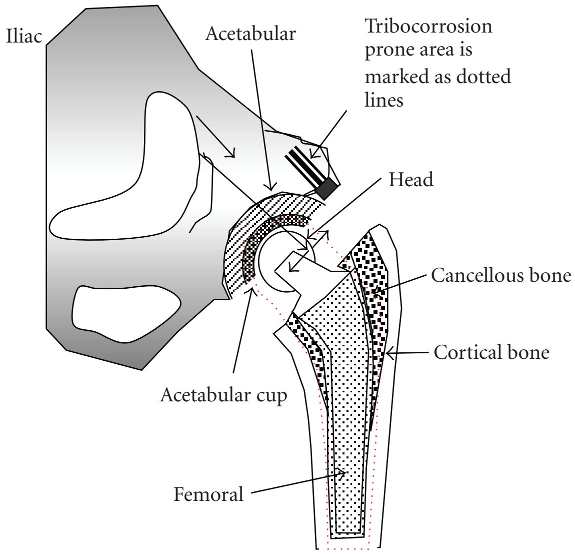


Figure 12: Possible tribocorrosion affected areas (red dotted line) in an artificial hip joint (metal-on-metal).

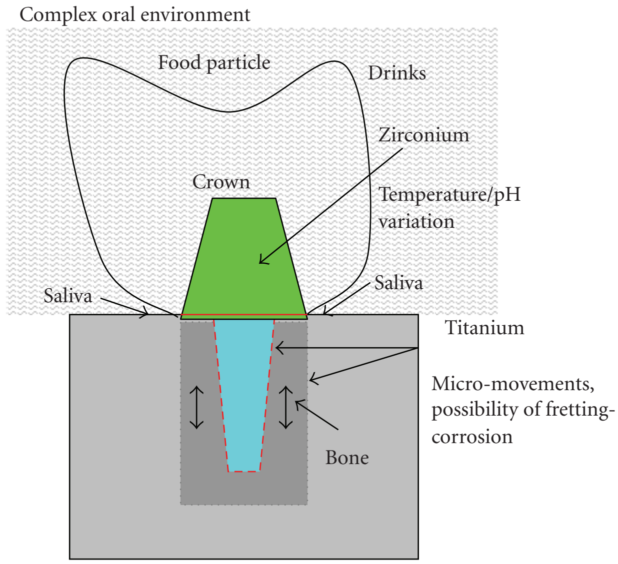


Figure 13: Possible tribocorrosion affected areas (red dotted line) in a dental implant.

composition, microstructure, defect level, adhesion, cohesion, and substrate properties are reported as some of the critical elements in coating performance when subjected to tribocorrosion contacts. The importance of postcoating deposition treatments such as laser resurfacing and sealing is also being discussed. Some models and mapping techniques evolved to provide information regarding coating selection and performance prediction are presented. The review also highlights the need for a more concentrated approach toward tribocorrosion testing and the way in which the results could be analyzed and presented.

In a recent review, Mischler [6] reported the importance of electrochemical techniques and evaluation methods used in tribocorrosion studies, during the last 10 years. The identified studies were focused on the practical applications, such as, coatings, biomedical, seals, nuclear, and lubricants. It is interesting to note that, among the 42 studies reported, the biomedical area stands first and is drawing increased attention of researchers, as shown in Figure 11. Hence, the next section of the paper deals with some of the aspects of tribocorrosion in biomedical applications.

4.2. Some of the Reported Tribocorrosion Case Studies in Biomedical Applications. In the biomedical area, the application of tribocorrosion can be studied under two major areas, namely, orthopedic surgery/science and dentistry. Some of the reported studies are explained below.

4.2.1. Orthopedic Science. Tribological aspects of the body joints, especially hip and knee joints are explored by many researchers, to improve the life span of such joints, helping the patients to avoid the revision surgery. However, as the tribological event in such joints are influenced by the body fluids at the interface (Periprosthetic fluid), tribocorrosion comes into picture. The possible tribocorrosion areas in a hip joint are shown in Figure 12. Some of the recent studies are as given below.

Contu et al. [21] studied the stability of the passive film on commercially pure titanium, Ti6Al4V, Ti6Al7Nb, and CoCrMo implant alloys in bovine serum as well as the repassivation rate after mechanical disruption of the passive film through fretting corrosion, considered as the principle cause of implant failure. The authors highlighted the need and importance of a better understanding of the electrochemical behavior of metallic implants after mechanical disruption of both the passive film and the stability of the protecting oxide film when exposed to physiological solutions.

Mischler et al. [22, 23] studied the possible degradation phenomena (wear, corrosion, changes in surface composition) arising from friction between bone and Ti6Al4V alloy, a widely used material in implants. It has been observed that bone-implant interfaces are subject to friction, which can cause fretting corrosion with inflammatory tissue reaction. After a set of preliminary studies, they stressed on the need to study the tribological behavior at the interface as the phenomena occurring are complex in nature. Further, Dahm and Dearnley [24] studied the wear (abrasion response) of coated biomedical steel in a corrosive environment.

Recently, Yan et al. [25, 26] also reported a very interesting work on the tribocorrosion behavior of CoCrMo alloy for the hip joint applications in a special experimental set-up. Further, Brown et al. [27] at Case Western Reserve University, USA, and Hallab et al. [28] at Rush University Medical Centre, USA, also specifically studied the fretting-corrosion behaviors of the implant materials by simulating the contact condition of the body joint articulations. Other reported studies on fretting-corrosion behaviour of orthopedic implants are Kraft et al. [29], Geringer et al. [30], Hendry and Pilliar [31], and Duisabeau et al. [32]. Moreover,

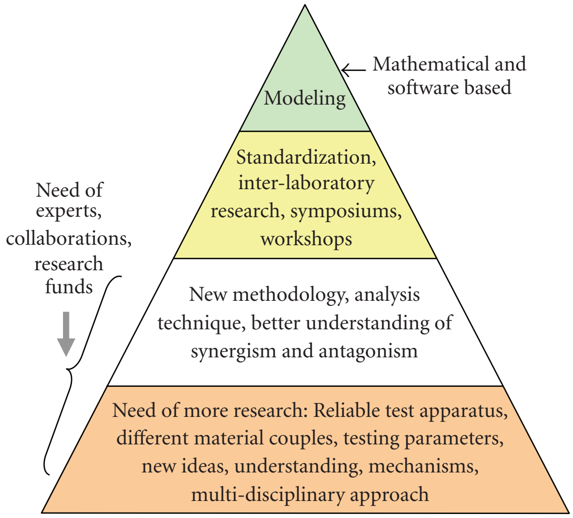


Figure 14: Future perspective in tribocorrosion research for the next 10 years.

Azzi and Szpunar [33] highlighted the importance of tribo-electrochemical technique to study tribocorrosion behaviour of biomaterials.

Stack et al. [16] studied microabrasion-corrosion behaviour of a steel/polymer couple in carbonate/bicarbonate solution by simulating the hip joint contact conditions. The effect of two variables, applied load and potential, has been investigated on the wear rate, enabling quantification of the corrosion and wear contributions. In addition, microabrasion-corrosion maps were constructed showing the transitions between the microabrasion-corrosion regimes as a function of load and applied potential. Wood et al. [34, 35] also studied the microabrasion-corrosion characteristic of more implant couples, for example, CoCrMo alloy and polymers.

There are many other studies reported on the tribocorrosion behavior of the implant metals, based on the specific applications. However, explaining all of them is beyond the scope of this paper.

4.2.2. Dentistry. Dentistry is another biomedical area, where tribocorrosion has a direct application. In fact, our each mastication/chewing process is a tribocorrosion cycle, as the rubbing occurs between tooth and food particle in the presence of chemical liquid, namely, saliva. The possible tribocorrosion areas in a dental implants are shown in Figure 13. Some of the reported studies are given below.

Rocha et al. [36] investigated the tribocorrosion behavior of commercially pure titanium in contact with artificial saliva solutions. Tests were conducted in a reciprocating sliding geometry with movement amplitudes ranging from 200 μm (fretting) to 6 mm (sliding wear) and normal loads between 2 and 10 N. The electrochemical noise technique was used by the authors, in order to follow the evolution of both the corrosion current and the open circuit potential of the system during the wear tests. The pH of the artificial saliva solution was varied between 4 and 7. The results showed that materials behaviour is strongly influenced by the pH of the solution and the acidification of the solution improves the electrochemical response of the material.

As a continuation of the above study, Vieira et al. [37] studied the repassivation evolution of commercially pure titanium in artificial saliva solutions by conducting tests in different kinds of artificial saliva solutions (artificial saliva (AS), AS + citric acid, AS + anodic, cathodic or organic inhibitor). The results showed that, in some solutions, the OCP, after repassivation, was nobler than that measured before sliding. Also, the repassivation evolution appeared to be strongly affected by the electrolyte nature. The AS + citric acid solution provided a better repassivation evolution with time [12].

Ribeiro et al. [38] investigated the tribocorrosion behavior of titanium grade 2 in reciprocating sliding conditions in contact with artificial saliva solutions. To reproduce the oral environment around the dental implant, some additives (citric acid, anodic, cathodic, and organic inhibitors) were added to simple artificial saliva constituted mainly by NaCl and KCl and with a pH between 5 and 7. It was found that titanium in artificial saliva solution with citric acid had the highest weight loss. Recently, there are many other research groups investigating the tribocorrosion behaviour of dental materials.

5. Future Perspective

A number of studies on tribocorrosion have been carried out and are still being pursued at various academic and research laboratories all over the world to explore the underlying mechanisms of this complex but interesting phenomenon. One of the major areas of research where tribocorrosion has a significant role to play is in understanding the performance of implants and mechanisms.

Despite the continued research in the field since 1990, the development of a standard test apparatus is still a major concern. Further, in using a technique/method to understand synergism and antagonism, there are many disparities in interpretation of the results and postulating findings. Authors believe that this is the most important area to be addressed, by taking a step of conducting more inter-laboratory analysis (e.g., Round robin in Europe, Biotribology workshop at University of Minho) or by the efforts of other international standard bodies [15].

Many researchers have tried to develop mathematical or software-based models to understand the tribocorrosion process [6, 39]. However, these have limited applicability because of the number of influencing parameters that make the phenomenon more complex. Some of the studies have also reported the mapping approach [14–16]; however such techniques are limited to certain experimental conditions, and their extension and generalization to real conditions is often questionable. Hence, there are many issues which still need to be addressed by the tribocorrosion research in future.

In bio-tribocorrosion, another challenge to be addressed is the way to translate the research finding to the clinical applications. In fact, many studies are reported on the influence of metal ions and wear debris (from the implant metals) on the health of patients, but still there is a call for effective research in this area [40].

Recently, there has been a significant progress in the interactions and collaborations between the researchers around the world, in the area of tribocorrosion. As a step in this direction, in December 2006, tribocorrosion net work (initiated by M.M. Stack, University of Strathclyde, Glasgow, UK) organized the first International Symposium on Tribocorrosion in Hyderabad, India. The second one has been held in Austria, in March 2009. The future perspectives of tribocorrosion research in the next 10 years are shown as a schematic diagram, in Figure 14. As it is a multidisciplinary research area, there is a need of interactions among the skilled/expert researchers from different areas and ultimately translating the findings to a clinical practice is a main challenge in bio-tribocorrosion research. However, the authors believe that within next few years, tribocorrosion will emerge as a major research area in biotribology, by attracting tribologists, corrosion experts, bioengineers, biochemists, medical practitioners, and materials scientists, and will be applied to practical research questions.

6. Conclusions

The authors have attempted to present a broad picture of the current state of knowledge in the field of tribocorrosion, with a specific focus on biotribocorrosion. The present overview is focused to draw the attention of research and academic society towards the fundamentals of tribocorrosion and the recent developments in the area by providing a review on the important reported work. In general, following conclusions can be drawn.

(i) Tribocorrosion is an emerging area and it is relevant not only to material science and mechanical engineering but also to biomedical and biochemical engineering.

(ii) There are many challenges in the tribocorrosion research, such as developing a standard test apparatus, standardization of the analyzing techniques, and testing methodologies.

(iii) The current status of the tribocorrosion research has been analyzed and its practical importance in the area of biomedical applications, particularly in the area of orthopedics and dentistry, has been highlighted.

(iv) Finally, some of the future perspectives have been provided based on the author's point of view.

References

[1] J.-P. Celis and P. Ponthiaux, "Tribocorrosion," *Wear*, vol. 261, no. 9, pp. 937–938, 2006.

[2] D. Landolt, "Electrochemical and materials aspects of tribocorrosion systems," *Journal of Physics D*, vol. 39, no. 15, pp. 3121–3127, 2006.

[3] D. Drees, J. P. Celis, E. Dekempeneer, and J. Meneve, "The electrochemical and wear behaviour of amorphous diamond-like carbon coatings and multilayered coatings in aqueous environments," *Surface & Coatings Technology*, vol. 86-87, part 2, pp. 575–580, 1996.

[4] S. Mischler, S. Debaud, and D. Landolt, "Wear-accelerated corrosion of passive metals in tribocorrosion systems," *Journal of the Electrochemical Society*, vol. 145, no. 3, pp. 750–758, 1998.

[5] J.-P. Celis, P. Ponthiaux, and F. Wenger, "Tribo-corrosion of materials: interplay between chemical, electrochemical, and mechanical reactivity of surfaces," *Wear*, vol. 261, no. 9, pp. 939–946, 2006.

[6] S. Mischler, "Triboelectrochemical techniques and interpretation methods in tribocorrosion: a comparative evaluation," *Tribology International*, vol. 41, no. 7, pp. 573–583, 2008.

[7] S. Mischler and P. Ponthiaux, "A round robin on combined electrochemical and friction tests on alumina/stainless steel contacts in sulphuric acid," *Wear*, vol. 248, no. 1-2, pp. 211–225, 2001.

[8] Y. Y. Zhu, G. H. Kelsall, and H. A. Spikes, "Influence of electrochemical potentials on the friction and wear of iron and iron oxides in aqueous systems," *Tribology Transactions*, vol. 37, no. 4, pp. 811–819, 1994.

[9] A. K. Basak, P. Matteazzi, M. Vardavoulias, and J.-P. Celis, "Corrosion-wear behaviour of thermal sprayed nanostructured FeCu/WC-Co coatings," *Wear*, vol. 261, no. 9, pp. 1042–1050, 2006.

[10] D. Landolt, S. Mischler, and M. Stemp, "Electrochemical methods in tribocorrosion: a critical appraisal," *Electrochimica Acta*, vol. 46, no. 24-25, pp. 3913–3929, 2001.

[11] R. J. K. Wood, "Tribo-corrosion of coatings: a review," *Journal of Physics D*, vol. 40, no. 18, pp. 5502–5521, 2007.

[12] P. Ponthiaux, F. Wenger, D. Drees, and J. P. Celis, "Electrochemical techniques for studying tribocorrosion processes," *Wear*, vol. 256, no. 5, pp. 459–468, 2004.

[13] ASTM standard G119, "Standard guide for determining amount of synergism between wear and corrosion," in *Annual Book of ASTM Standards. Volume 03.02: Wear and Erosion, Metal Corrosion*, ASTM, West Conshocken, Pa, USA, 2001.

[14] M. M. Stack and K. Chi, "Mapping sliding wear of steels in aqueous conditions," *Wear*, vol. 255, no. 1–6, pp. 456–465, 2003.

[15] M. M. Stack, "Bridging the gap between tribology and corrosion: from wear maps to Pourbaix diagrams," *International Materials Reviews*, vol. 50, no. 1, pp. 1–17, 2005.

[16] M. M. Stack, H. Jawan, and M. T. Mathew, "On the construction of micro-abrasion maps for a steel/polymer couple in corrosive environments," *Tribology International*, vol. 38, no. 9, pp. 848–856, 2005.

[17] T. Yamamoto, K. Fushimi, M. Seo, S. Tsuri, T. Adachi, and H. Habazaki, "Current transients during repeated micro-indentation test of passive iron surface in pH 8.4 borate buffer solution," *Electrochemistry Communications*, vol. 9, no. 7, pp. 1672–1676, 2007.

[18] L. Benea, V. Iordache, F. Wenger, and P. Ponthiaux, "Nanostructured SiC-Ni composite coatings obtained by electrodeposition a tribocorrosion study," *The Annals of "Dunarea De Jos" University of Galati, Fascicle IX Metallurgy and Materials Science*, vol. 1, pp. 1453–1457, 2005.

[19] M. T. Mathew, E. Ariza, L. A. Rocha, A. C. Fernandes, and F. Vaz, "TiCxOy thin films for decorative applications: tribocorrosion mechanisms and synergism," *Tribology International*, vol. 41, no. 7, pp. 603–615, 2008.

[20] S. C. Ferreira, E. Ariza, L. A. Rocha, et al., “Tribocorrosion behaviour of ZrOxNy thin films for decorative applications,” *Surface & Coatings Technology*, vol. 200, no. 22-23, pp. 6634–6639, 2006.

[21] F. Contu, B. Elsener, and H. Bohni, “Stability and repassivation of metallic implants in serum bovine,” *European Cells and Materials*, vol. 1, no. 1, pp. 14–15, 2001.

[22] S. Mischler and G. Pax, “Tribological behaviour of titanium sliding against bone,” *European Cells and Materials*, vol. 3, no. 1, pp. 28–29, 2002.

[23] S. Barril, S. Mischler, and D. Landolt, “Influence of fretting regimes on the tribocorrosion behaviour of Ti6Al4V in 0.9 wt.% sodium chloride solution,” *Wear*, vol. 256, no. 9-10, pp. 963–972, 2004.

[24] K. L. Dahm and P. A. Dearnley, “Abrasion response and abrasion-corrosion interactions for a coated biomedical stainless steel,” *Wear*, vol. 259, no. 7–12, pp. 933–942, 2005.

[25] Y. Yan, A. Neville, and D. Dowson, “Biotribocorrosion of CoCrMo orthopaedic implant materials—assessing the formation and effect of the biofilm,” *Tribology International*, vol. 40, no. 10–12, pp. 1492–1499, 2007.

[26] Y. Yan, A. Neville, D. Dowson, and S. Williams, “Tribocorrosion in implants-assessing high carbon and low carbon Co-Cr-Mo alloys by in situ electrochemical measurements,” *Tribology International*, vol. 39, no. 12, pp. 1509–1517, 2006.

[27] S. A. Brown, P. J. Hughes, and K. Merritt, “In vitro studies of fretting corrosion of orthopaedic materials,” *Journal of Orthopaedic Research*, vol. 6, no. 4, pp. 572–579, 1988.

[28] N. J. Hallab, C. Messina, A. Skipor, and J. J. Jacobs, “Differences in the fretting corrosion of metal-metal and ceramic-metal modular junctions of total hip replacements,” *Journal of Orthopaedic Research*, vol. 22, no. 2, pp. 250–259, 2004.

[29] C. N. Kraft, B. Burian, O. Diedrich, and M. A. Wimmer, “Implications of orthopedic fretting corrosion particles on skeletal muscle microcirculation,” *Journal of Materials Science: Materials in Medicine*, vol. 12, no. 10–12, pp. 1057–1062, 2001.

[30] J. Geringer, B. Forest, and P. Combrade, “Fretting-corrosion of materials used as orthopaedic implants,” *Wear*, vol. 259, no. 7–12, pp. 943–951, 2005.

[31] J. A. Hendry and R. M. Pilliar, “The fretting corrosion resistance of PVD surface-modified orthopedic implant alloys,” *Journal of Biomedical Materials Research Part B*, vol. 58, no. 2, pp. 156–166, 2001.

[32] L. Duisabeau, P. Combrade, and B. Forest, “Environmental effect on fretting of metallic materials for orthopaedic implants,” *Wear*, vol. 256, no. 7-8, pp. 805–816, 2004.

[33] M. Azzi and J. A. Szpunar, “Tribo-electrochemical technique for studying tribocorrosion behavior of biomaterials,” *Biomolecular Engineering*, vol. 24, no. 5, pp. 443–446, 2007.

[34] P. E. Sinnett-Jones, J. A. Wharton, and R. J. K. Wood, “Micro-abrasion-corrosion of a CoCrMo alloy in simulated artificial hip joint environments,” *Wear*, vol. 259, no. 7–12, pp. 898–909, 2005.

[35] D. Sun, J. A. Wharton, R. J. K. Wood, L. Ma, and W. M. Rainforth, “Microabrasion-corrosion of cast CoCrMo alloy in simulated body fluids,” *Tribology International*, vol. 42, no. 1, pp. 99–110, 2009.

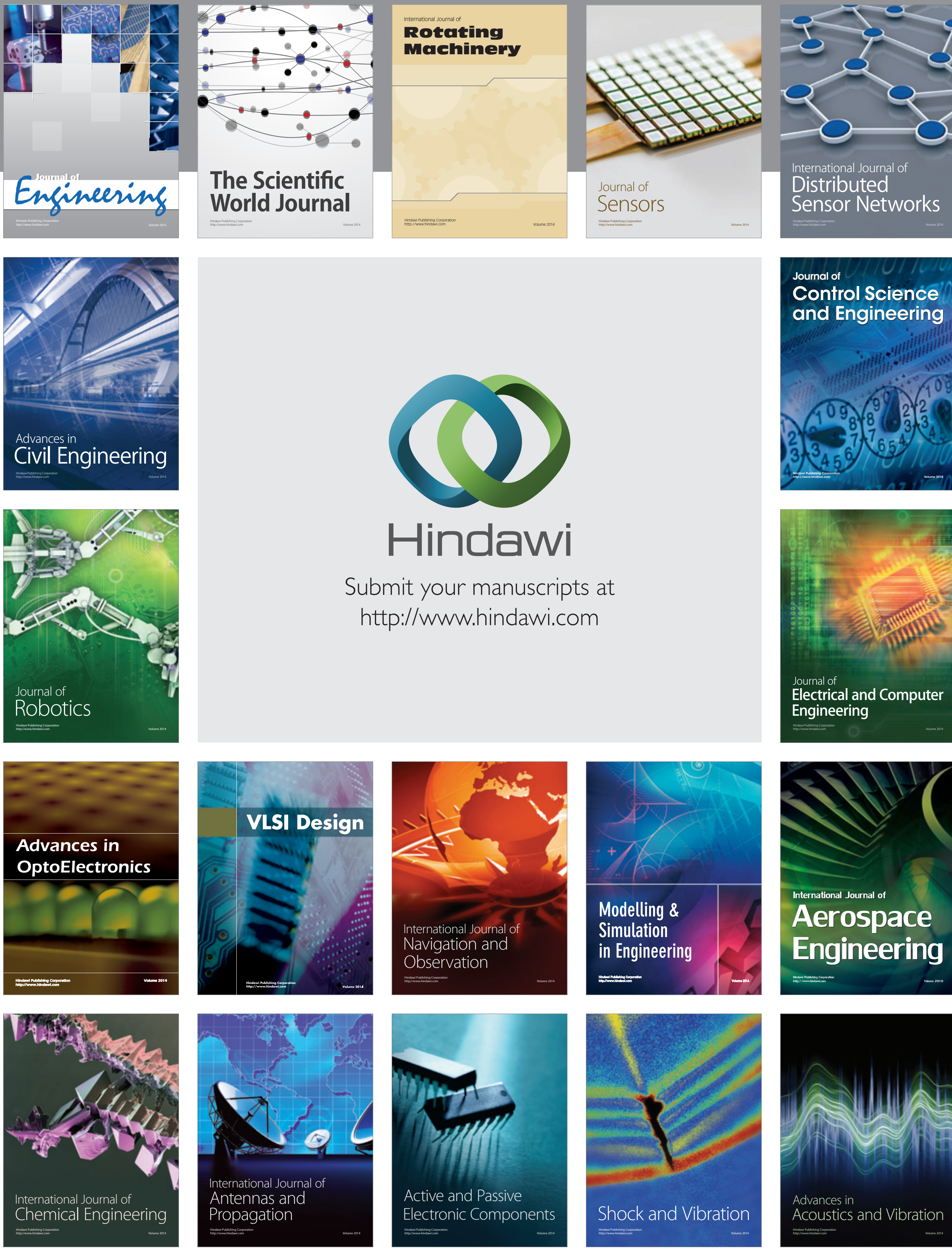
[36] L. A. Rocha, A. R. Ribeiro, A. C. Vieira, E. Ariza, J. R. Gomes, and J.-P. Celis, “Tribocorrosion studies on commercially pure titanium for dental applications,” in *Proceedings of the European Corrosion Congress (EUROCORR ’05)*, Lisbon, Portugal, September 2005.

[37] A. C. Vieira, L. A. Rocha, E. Ariza, J. R. Gomes, and J.-P. Celis, “Repassivation of commercially pure Ti in different saliva solutions under tribocorrosion condition,” in *Proceedings of the European Corrosion Congress (EUROCORR ’05)*, pp. 1–10, Lisbon, Portugal, September 2005.

[38] A. R. L. Ribeiro, L. A. Rocha, E. Ariza, J. R. Gomes, and J.-P. Celis, “Tribocorrosion behaviour of titanium grade 2 in alternative linear regime of sliding in artificial saliva solutions,” in *Proceedings of the European Corrosion Congress (EUROCORR ’05)*, pp. 1–10, Lisbon, Portugal, September 2005.

[39] P. Srinivasa Pai, M. T. Mathew, M. M. Stack, and L. A. Rocha, “Some thoughts on neural network modelling of microabrasion-corrosion processes,” *Tribology International*, vol. 41, no. 7, pp. 672–681, 2008.

[40] J. J. Jacobs, N. J. Hallab, R. M. Urban, and M. A. Wimmer, “Wear particles,” *Journal of Bone and Joint Surgery. American*, vol. 88, supplement 2, pp. 99–102, 2006.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