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Future Needs for Tribo-Corrosion Research and Testing

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Future Needs and Challenges in Tribo-Corrosion Research and Testing

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Abstract

Tribo-corrosion is an emerging interdisciplinary subject that spans from basic research on the behavior of surfaces in mechanical contact in chemically active surroundings to the test methods needed to quantify its effects, and from the selection of materials for bio-implants to the minimization of surface degradation and wastage in advanced energy conversion systems. Such a diverse field brings with it many challenges in understanding, testing, standardization, and application to engineering practice. This paper summarizes a panel discussion and participant survey held at the Third International Symposium on Tribo-Corrosion in Atlanta, Georgia, USA, in April 2012. It reflects a sense of agreement on many of the key scientific challenges in the field and the fact that tribo-corrosion is still in its infancy in terms of broad industry recognition, education, and the ability of those who conduct tribo-corrosion research to connect their laboratory results and theories to applications. Some sub-fields, notably the bio-tribo-corrosion of medical implants, have witnessed active international research efforts, but the engineering community in many other important areas of technology may not yet be aware of the field despite numerous tribo-corrosion problems that may exist within their purview.

1.0 Introduction

Research in tribo-corrosion is based on the growing recognition that wear in chemically-active surroundings can be quite different from that which occurs from mechanical wear alone. Likewise, it has been recognized that corrosion rates under static, free-surface conditions can be quite different than when those exposed surfaces are also rubbed or abraded. A moment's reflection reveals the widespread occurrence of such situations in machinery and the need to formalize both their study and approaches to their mitigation. The field of tribo-corrosion, therefore, is an emerging, interdisciplinary subject that spans broadly from basic research on the nano-scale behavior of surfaces in mechanical contact in chemically active environments to the test methods and standards needed to quantify its effects, and from the selection of materials for bio-implants to the minimization of surface degradation and wastage in advanced energy conversion systems like off-shore wind turbines and deep sea oil drilling rigs.

Various workshops, working groups in technical societies, symposia, and informal collaborations have been addressing aspects of tribo-corrosion for more than two decades. Similarly, technical sessions within larger conferences on bio-materials, tribology, or mechanical engineering have dealt with the subject. The 3rd International Symposium on Tribo-Corrosion (Tribo-Corrosion 2012), whose content is reflected in this volume, is another in that on-going series.

The concluding session of Tribo-Corrosion 2012 comprised a discussion among several keynote speakers and the general attendees in order to address future needs and challenges in tribo-corrosion research and testing. Some of the topics discussed resulted from a written survey of symposium attendees and others evolved during the discussion. This paper summarizes the issues that emerged during that discussion. It is not meant to be an all inclusive assessment of the state-of-the-art of tribo-corrosion related research and development, but rather a snapshot of issues that the attendees felt offered the potential to advance the field through improved understanding of mechanisms, methods for testing, and the translation of laboratory results into engineering practice in different fields of application.

During the discussion and frequently occurring in questionnaires was the term bio-tribo-corrosion. A working definition for the term, which is herein proposed for consideration of subcommittee ASTM G02.91 on Terminology Relating to Wear and Erosion, and for eventual incorporation within ASTM G40 [1] is as follows:

> ***bio-tribocorrosion***, n. – a form of tribocorrosion in which living organisms are present in the contact region of the tribo-elements and which affect the interfacial chemistry and contact conditions . Note: Use of this term includes applications such as medical or dental implants in human or animal bodies, but it can also encompass liquids containing bacterial matter and the interactions of degradation products (wear debris) with living organisms.

Note that the foregoing definition adds no hyphen between tribo and corrosion to be consistent with the term "tribocorrosion" that currently exists in ASTM G40-10b. Both hyphenated and non-hyphenated forms of that term can be found in the tribology literature, but in this paper the hyphenated form will be used.

Finally, this paper sought to capture fairly and without prejudice, the frank and open discussions which took place during Tribo-Corrosion 2012. The field of tribo-corrosion, like any other progressive human endeavor, thrives on the presentation and debate of new ideas, examining and questioning what has gone before, while at the same time harboring uncertainties about what lies ahead. Therefore, the information reported here does not necessarily represent the personal views of the co-authors, nor does it reflect the positions of ASTM International, or a consensus view of those who attended the event. Instead, the intent is to stimulate new ideas. research, improvements in methodology, and standardization in the field of tribo-corrosion.

2.0 Responses to Attendee Questionnaires

Attendees to Tribo-Corrosion 2012 were provided questionnaires that asked to provide written opinions on the following questions:

1) Which basic research areas in tribo-corrosion are least understood or require more study?
2) Which areas of tribo-corrosion testing need development?

3) Are the current standards for tribo-corrosion testing adequate? If not, what new tests are needed?
4) Which important areas of applications-related tribo-corrosion research need more attention?

Of the more than 55 registrants, 17 questionnaires were returned prior to the concluding session. The comments contained in those questionnaires are summarized in Tables 1 – 4, organized by the respective survey questions. Not all responses were produced verbatim. In some cases, the use of abbreviations, grammar, and sentence order were revised for clarity yet with due care to retain the essence of the responder's remarks. Responses are not listed below in any particular order of priority, but similar responses from different participants were consolidated into individual entries, and the number of similar responses is indicated in parentheses. In some cases, indicated by [ ], the authors have inserted words to reflect the intent of somewhat cryptic handwriting styles. References to specific ASTM standards are provided as footnotes in the tables in which they are mentioned.

The comments listed in Tables 1-4 obviously represent the opinions of a relative small sample of researchers and applications-oriented engineers, many of which are focused on the bio-implants area; however, there are number of common themes, all of which point to the need for better education of technologists on the broad impact and practical implications of tribo-corrosion. Some of the comments may reflect increased awareness of certain issues following exposure to the presentations made during the symposium.

In addition to the aforementioned comments, there was other written comments specifically related to the need for events such as the current symposium. For example, one individual suggested that international symposia on tribo-corrosion be held every two years rather than every three years, as has been done historically. Furthermore, they suggested that the event be focused on tribo-corrosion for industrial applications in order to attract more individuals from industry.

3.0 Issues Addressed During the Open Discussion

The concluding session of the symposium was attended by thirty-five delegates, ranging from fundamental researchers to practicing consultants in failure analysis and medical device design. By and large, the discussion centered on the survey questions presented earlier, although not necessarily in the order presented. That is because the various survey questions are interrelated. For example, it was expressed that one cannot effectively design tribo-corrosion tests unless the basic mechanisms of the phenomenon were sufficiently well understood to know how and what must be controlled and measured. An attempt was made to organize the discussion issues by topic in the following paragraphs, even though the order of discussion was not necessarily chronological.

3.1 *Research Needs in General Tribo-corrosion.*

Little seems to be known about aqueous tribo-corrosion at low open circuit potentials. Experiments are sometimes designed to apply more aggressive conditions, yet tribo-corrosion can occur at lower potentials as well. These are more difficult to observe and to study.

Recent work is correlating the microstructure and properties of near surface layers in metals with imposed tribo-corrosion conditions. This work is leading to new insights on the formation of wear particles in the deformed layers, especially in the presence of electrical currents. It should be expanded.

Research on tribo-corrosion would be benefited by the development of more in situ probes for sensing changes in the local conditions of the contact in response to different rubbing conditions, temperature, and electrolyte chemistry. Examples included FTIR and micro-Raman techniques. Not only electrochemical potential, but impedance measurements would benefit our understanding of tribo-corrosion experiments.

Tribo-corrosion models should integrate phenomena occurring at various size scales, from nano to macro.

3.2 *Research Needs Specific to Bio-tribo-corrosion*. The field of bio-tribo-corrosion is an important subfield of tribo-corrosion and involves considerations that are unique to situations in which wear occurs in biological environments. The following comments made during the discussion referred specifically to this subfield:

3.2.1 Role of proteins. Additional research was said to be needed on the influence of proteins on tribo-corrosion of implants because protein concentration has been shown to produce changes in the rate of corrosion and wear in joints.

3.2.2 Metal on metal couples. One discusser was concerned that recent problems with failed metal/metal body implants might in effect decimate research programs in that area. Some persons have suggested that inadequate methods for tribo-corrosion testing of such implants before certification may have been a contributing factor to the reported problems, but this assertion remains speculative and subject to verification. However, it was also suggested that rather than terminate metal/metal implants research, that work should be further supported to determine whether such issues could be avoided in the future by improved test methods for material selection and design. Knowledge of basic bio-tribo-corrosion mechanisms of these systems at the nano- and micro-scales is essential.

3.2.3 Third-bodies. Wear particle formation and the role of third-bodies in tribo-corrosion of bio-implants should be more systematically investigated, including such aspects as particle detachment mechanisms and how such particles leave the interface. The particles may also agglomerate or otherwise form new third-body species. Their characterization would be beneficial in understanding post-detachment processes. The interactions of third body particles with cells and interaction with the immune system should also be investigated in more detail.

3.3 *Needs for Improved Standardization in Tribo-corrosion*. Standardization can take many forms including specimen preparation procedures, standard test methods, standard ways of analyzing and reporting data, definitions of terms, and guides to conducting experiments in specific situations. The following comments were made regarding the usefulness or improvement of current standards for tribo-corrosion testing as well as needs for additional standardization.

3.3.1 Terminology. Some of the terminology in the field of tribo-corrosion is not consistently used, and this can lead to misunderstandings. Standard definitions for certain terms in this specialized field should be developed to improve the accuracy of written and oral communications. It was suggested that the experts in tribo-corrosion identify key terms, and draft definitions for consideration by ASTM Committee G02.91 on Standard Terminology

Relating to Wear and Erosion. One participant went so far as to suggest that a conference of experts and practitioners be convened to reach consensus on certain key terms in the field.

3.3.2 Enhancement of existing standards. Several of the existing ASTM wear testing standards, like ASTM G75 [3] and G105 [4], are basically tribo-corrosion influenced tests, but they do not monitor the electrochemical conditions at all, reducing their usefulness for tribo-corrosion studies. The G2 committee should look into what would be necessary to increasing such usefulness of existing standards. In terms of correlating data with industrial applications, perhaps new versions of some existing standards could be developed to enable the imposition of electrical currents to better simulate the environments of specific applications.

3.3.3 Resistance to changing test methods. It was suggested that it might be difficult for certain industries to adopt new tribo-corrosion test methods, even if improved, because organizations have so heavily invested in testing and data collection using prior methods, that they are hesitant to lose that investment by adopting new approaches to product screening.

3.3.4 ASTM G119. The current G119 standard for wear-corrosion synergism [5] should be improved by including a discussion of latency time. In fact, it was discussed among participants that work should begin on an Appendix to the current standard to provide additional guidance in such matters. One discusser questioned the usefulness or meaning of the term 'synergy', asserting that identifying the basic mechanisms was more critical than struggling to determine a numerical synergy parameter. The cumulative errors or uncertainty associated with synergistic or antagonistic values should be quoted as these can be very high. Repeatability of wear and corrosion tests should be assessed and standards should reflect those differences. Do we know how well we control experiments (particularly electrochemical ones)? Faradaic conversions of current into mass loss often assume a certain reaction(s) (number of electrons transferred) without actual proof what reactions are occurring, particularly on alloys or cermets.

3.3.5 Elevated temperature tests for automotive applications. The automotive industry needs a useful test for screening candidate engine valve materials at high temperature. One company uses a modification of ASTM G133 [6]; however, the test was really designed for ambient temperature testing and they found it necessary to significantly modify the test conditions (decrease the load and stroke length, but increase the temperature) in order to produce screening data for valve seat materials. This would require incorporation of a new procedure (Procedure "C") or a completely new standard based on G133.

3.3.6 Standard guide for analyzing tribo-corrosion. It was suggested by a participant from a major specialty steel company that a standard guide be developed by ASTM G2 to help systematically analyze tribo-corrosion problems in industrial applications. That comment also relates to the discussion in Section 3.4.

3.4 *Applications-Oriented Challenges in Tribo-corrosion*. Tribo-corrosion is prevalent in many industrial environments, and the selection of materials for durable service touches on concerns in understanding, testing, standards, and data analysis.

3.4.1 Application specific tests. The development of tribo-corrosion test methods to simulate practical applications was said to be a worthy goal, but to do that it will be necessary to better understand the application's electrochemical characteristics so that the laboratory tests can be properly designed to simulate not only mechanical contact characteristics but corrosion-related characteristics as well.

3.4.2 Education and awareness of tribo-corrosion. Some industries, like that involving dental restoratives, are only slowly being made aware of the existence of the field of tribo-corrosion. Plant engineers and product designers may not follow the tribology or corrosion literature where tribo-corrosion studies are published. A significant exception concerns the bio-tribology community which is very focused on the role of body environment on the wear performance and debris generation characteristics of implants like femoral heads, knee joints, artificial heart valves, and even stents in which a second stent may fret against a previously inserted one.

3.4.3 Condition monitoring. It was suggested that instrumenting practical tribo-systems with electrochemical potential or current sensors could make use of the tribo-corrosion processes for condition monitoring. That approach would depend on the practically of installing such sensors to obtain unambiguous readings and the ability of the those who monitor the sensor output to understand the meaning of the data.

3.4.4 Industry commitments to tribo-corrosion research. A question arose during the discussion as to whether industrial firms were really interested in the research aspects of tribo-corrosion or whether they simply wanted to know a rate of wear and/or wear mechanism for various materials, irrespective of how that process mechanistically takes place. This suggestion evoked a strong reaction from some in the audience who asserted that industry had invested heavily in application-oriented tribo-corrosion research. Notably, at least one company concerned with tribo-corrosion of oil sand handling equipment had established a university chair to elucidate the science behind the processes that were degrading their equipment. Therefore, it is not possible to generalize about the degree to which a given company or an industrial sector is willing to invest in the science underlying a materials problem, even one that can so strongly affect its productivity. If industry were to become more aware of the field of tribo-corrosion, what it concerns, and how its insights could solve costly practical problems, private sector research on applied tribo-corrosion might greatly expand.

4.0 Conclusions

The conclusions summarized here are based on a relatively small sample of individuals (about 54); however, some participants are leaders in the field of tribo-corrosion research or have had direct experience with the phenomenon in practical applications, including litigation and failure analysis.

4.1 Diversity of applications. Clearly, there are numerous instances in mechanical and bio-systems in which wear and corrosion interact. These include industrial sectors like material processing; transportation by ground, air, and sea; energy conversion; oil and gas exploration; tar sands harvesting; medical and dental implants; agriculture; surgical devices; military equipment; and many more.

4.2 Maturity of the field. While the impacts of tribo-corrosion processes in machines and the human body are broad, experimental tribo-corrosion research is in an infant stage compared to other aspects of tribology.

4.3 Laboratory testing in basic research. Testing geometries for fundamental studies are largely dominated by simple pin-on-disk or reciprocating pin-on-flat configurations, and while they produce some useful insights, they do not reflect the wide diversity of contact situations in machine components or in the human body in which tribo-corrosion occurs. Experimenters sometimes impose larger potentials to produce the most easily measurable effects; yet there are some situations in which the potential difference in tribo-contacts is relatively small, producing subtle changes in rates of wear and surface recession that may only be detectable after long observation times. Experimentally, the contact area that is being affected by tribo-corrosion may be only a tiny fraction of the total area exposed to the corrosive medium; thus, it may be difficult to ascribe changes in the signals from remotely-positioned electrodes to those areas in which tribo-corrosion is occurring. In bio-tribo-corrosion, multi-station hip joint (walking) simulators are in widespread use for product development, but they tend not to be sufficiently instrumented for tribo-corrosion studies.

4.4 Modeling. Modeling at an early stage of development of this field embodies a set of simplifying assumptions to select dominant wear and corrosion processes, and affect the selection of synergy (interaction) parameters. Some models are based on thermodynamic or thermochemical equilibria that do not include the role of kinetics. *Ab initio* models based on the actual mechanisms (once indentified and understood) should be developed.

4.5 On the importance of basic mechanistic understanding for test development. There was general agreement that the development of appropriate tests for tribo-corrosion, whether standardized or not, cannot be done without a better understanding of the basic mechanisms of tribo-corrosion. The same argument can be extended to bridging the gap between laboratory results and practical applications for the purpose of material selection. The tribo-corrosion processes that occur in a given application should be correctly matched with test methods that simulate those particular influences, albeit in a well-controlled and monitored manner.

4.6 Need for more frequent symposia. Some of the industry representatives in attendance suggested more frequent symposia on tribo-corrosion, especially those focused on investigating and solving diverse practical problems. This suggestion supports the observation that there is a general lack of awareness on the part of some companies that are experiencing costly wear-corrosion failures that the field of tribo-corrosion research even exists. Some companies, notably a few in Europe, have invested considerable funding to investigate the fundamental causes for tribo-corrosive failures in equipment, but that seems to be a notable exception to the common practice of treating wear and corrosion problems separately.

4.7 Need for better education and awareness of tribo-corrosion. Due to the prevalence of tribo-corrosion problems in engineering and medicine, more awareness of the field and specialized education for both practicing engineers and students is needed. The easiest start would be for universities or research institutes to offer regular short courses on the subject, but academicians are urged to consider adding tribo-corrosion content to university-level courses in mechanical engineering, materials engineering, bio-engineering, and of course, tribology.

5.0 References

[1] ASTM G40, Standard Terminology Relating to Wear and Erosion, ASTM Annual Book of Standards, Vol. 03.02, ASTM International, West Conshohocken, PA.

[2] R. M. Voitic (1993), Realizing Bench Test Solutions to Field Tribology Problems Utilizing tribological Aspect Numbers, in Wear Test Selection for Design and Application, ed. A. W. Ruff and R. G. Bayer, STP 1199, ASTM, West Conshohocken, PA, pp. 45-59.

[3] ASTM G75, Standard Test Method for Determination of Slurry Abrasivity (Miller Number] and Slurry Abrasion Response of Materials (SAR Number), ASTM Annual Book of Standards, Vol. 03.02, ASTM International, West Conshohocken, PA.

[4] ASTM G105, Standard Test Method for Conducting Wet Sand/Rubber Wheel Abrasion Tests, ASTM Annual Book of Standards, Vol. 03.02, ASTM International, West Conshohocken, PA.

[5] ASTM G133, Standard Test Method for Linearly-Reciprocating Ball-on-Flat Sliding Wear, ASTM Annual Book of Standards, Vol. 03.02, ASTM International, West Conshohocken, PA.

6.0 Acknowledgements

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Table 1.

Consolidated Responses to the Question: "Which basic research areas in tribo-corrosion are least understood or require more study?"

1) One important aspect to be addressed is in the incorporation of kinetics of corrosion in all aspects of tribocorrosion.

2) [Establish a] link between measurable quantities such as [potential] E, [current] I, the [synergistic wear rate] SWR, and friction coefficient with mechanisms actually occurring at the interface.

3) Develop new materials [that are specially formulated to be] resistant to tribo-corrosion.

4) Bio-tribo-corrosion of implant materials, including other than metal/metal combinations (3).

5) [Additional research on the] role of proteins in bio-tribo-corrosion.

5) Models for tribology couples with and without corrosion (2).

6) [Tribo-corrosion] interactions and wear at the nano-scale (2).

7) [More emphasis on] the role of small particles (not nano-scale, because they are too small to affect wear, and not macro particles which get fractured to make fresh sharp-edged particles). [Rather consider those in the proper size range relative to the interfacial processes] that should be characterized, modeled, and researched. (2)

8) [Tribo-corrosion research and bench testing results] need to be better linked to industrial applications.

9) Surface chemistry (adsorption, wettability).

10) Effects of debris on the passivation behavior during tribo-corrosion.

11) [More research is needed in areas] in addition to bio-tribo-corrosion.

12) Role of the environment on fretting corrosion.

Table 2.

Consolidated Responses to the Question: "Which areas of tribo-corrosion testing need development?"

1) Development of high temperature tribo-corrosion tests.

2) In situ potential and current measurements. [Some tests conducted in environments known to produce tribo-corrosion are not adequately instrumented to probe its effects.]

3) In situ tribo-corrosion measurements for walking simulators for hip implants.

4) More in vivo testing.

5) Use of more in situ sensors like micro-Raman and FTIR.

6) Impedance testing and interpretation [of its results].

7) [Tribo-corrosion testing for] nuclear energy environments involving fretting contact.

8) [Tribo-corrosion testing for] bio-implant environments involving fretting contact. [for example, bone cement/implant stems]

9) [Researchers] need an alternative corrosion 'barometer' than using Pour Baix cell measurements.

10) [Tribo-corrosion tests for] coatings and composite materials

11) Dedicated experimental and quantitative methods to determine wear, corrosion, and tribo-corrosion in specific areas of a surface.

12) Fretting in fluids, particularly moving fluids (2).

13) Need a liquid impingement test (without a potentiostat).

Table 3.

Consolidated Responses to the Question: "Are the current standards for tribo-corrosion testing adequate? If not, what new tests are needed?"

1) Add a new procedure based on ASTM G133[1] to be used as a screening test for selecting materials for internal combustion engine valvetrain wear. This would help the auto industry compare wear/corrosion interactions of valve insert materials in a standard manner.

2) Development and standardization of high temperature tribological testing, especially when and how to accept multi-specimen and single specimen test techniques. [Presumably this comment refers to when single test results of difficult-to-perform high-temperature tests can be accepted as valid to describe the material response.]

3) The current standard [ASTM G119[2]] places tribo-corrosion synergism into certain categories, but these may need to be qualified on expanded upon in a new Appendix for the standard that addresses time dependence and multi-component tribological phenomena.

4) G119[2] is just a good start, but need more procedures, guides, and standards.

5) The requirement of G119[2] to test 'linear polarization' is rather difficult to perform. It might be easier for the [industrial engineering community] to perform tests involving open circuit, potentio-dynamic, or potentio-static tests instead.

6) [Any such activities] have to be developed with synergistic approaches.

7) Current standards are probably not sufficient, but there may be some agreed upon standards in Europe.

8) Standardization in [tribo-corrosion] terminology and error analysis (particularly when calculating synergy/antagonism terms).

9) Expansion of test methods of bio-materials that promotes collaborations between ASTM committees such as G2 and F4 [Medical and Surgical Materials and Devices].

10) No. [What is needed is] a structured approach to integrate difficult aspects (tribological, electrochemical, and materials).

11) Need a standard for wear testing using a potentiostat.

Notes:
1. ASTM G133, Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear, ASTM Annual Book of Standards, Vol. 03.02
2. ASTM G119, Standard Guide for Determining Synergism Between Wear and Corrosion, ASTM Annual Book of Standards, Vol. 03.02

Table 4.

Consolidated Responses to the Question: "Which important areas of applications-related tribo-corrosion research need more attention?"

1) Air cleaning plants associated with iron and steel industry

2) Cryotribology [testing at temperatures well below room temperature]

3) Bio-tribo-corrosion of implants (4), in particular, studies that adapt techniques that have been developed for other aspects of tribo-corrosion into bio-tribo-corrosion.

4) Liquid metal erosion

5) Erosion-corrosion in oil and gas pipelines

6) Drilling

7) [Ocean] wave energy systems

8) [Tribo-corrosion in] ionic liquid lubricant environments

9) [Tribo-corrosion] mapping of applications in a multi-parameter space

10) Relative importance [of tribo-corrosion] specific to surgical and implanted devices (2).

11) Electrical devices

12) Mechanical devices

13) Automotive (2) and truck engines

14) Nuclear industry (3)

15) Need new methods to modify surfaces to improve material properties. Can include coatings and treatments like laser and plasma-assisted treatments.

16) Steam boilers.

17) Suggest implementing a Tribological Aspect Number (TAN) approach, perhaps adding a fifth digit to the TAN code to account for corrosive factors [Note: The four-digit 'TAN' code was developed by R. Voitic of Falex Corporation, as a convenient means to characterize macro-geometry, lubricant entrainment characteristics and other aspects of tribo-contacts. See ASTM STP 1199 [2].]