

# Advancements in Modelling the Tribocorrosion Current

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Tribocorrosion in passive metals involves a complex and interactive mechanism between mechanical and electrochemical actions at a rubbing contact in a corrosive environment. The mechanical wear mechanism disrupts the passive film on the metal surface; and instantly, the metal repassivates and dissolves in the corrosive environment. This surface damage failure can occur in various components such as marine structures and medical implants which can force significant downtime and repair costs. In this article, historical advance-

ment in the well-known theories and models which have been developed for passivation and tribocorrosion current (as a measure for wear-accelerated corrosion) is presented and discussed. The strengths and limitations associated with the models are reviewed to generate an overall picture of the progress in the field. The links between different models are also discussed and finally, some possible directions for future research are suggested.

## 1. Introduction

As a multi-disciplinary area, tribocorrosion deals with the surface damage of a passive metal under a wear mechanism within a corrosive environment,<sup>[1–3]</sup> as schematically shown in Figure 1. Various methodologies such as the mechanistic and synergistic approaches (each with its own advantages) are employed for analysing tribocorrosion.<sup>[1,4–7]</sup> One important parameter in the mechanistic approach is to capture the tribocorrosion current emitted from the passive metal.<sup>[3,8–10]</sup> The current originates from passivation and dissolution processes.<sup>[11–14]</sup> Passivation is a spontaneous reaction from the metal to the aqueous/gaseous environment to protect the underlying metal from further chemical degradation. Throughout this reaction, a very thin oxide film initiates and builds up over the exposed surface which ultimately acts as a corrosion barrier.<sup>[15,16]</sup> This process has been considered as one driving force for the metals-based civilisation<sup>[16]</sup> as it occurs in various fields.<sup>[17–20]</sup> The passive film greatly affects the tribocorrosion behaviour of an interface;<sup>[8,21,22]</sup> therefore, its growth mechanism is crucial to be better understood since this enriches the tribocorrosion-related knowledge; and subsequently, improves designs for rubbing surfaces.

The tribocorrosion current is affected by both mechanical and electrochemical parameters such as the acting normal and friction forces, rubbing stroke and its frequency, temperature, solution type and its pH, and the metal type. Great advancements in the modelling phase of this phenomenon have been

made in recent decades,<sup>[1,4,23–25]</sup> however, there are still shortcomings associated with the developed models. Given the multi-factorial nature of the tribocorrosion current, and taking into account the inherited complexities of a real application (e.g. variations in loading, contact region, and working environment), the mechanical and electrochemical parameters require to be carefully measured and reported, and the developed models need to be equipped with their own specific constants. This is more pronounced when one works with metal-on-metal (MoM) contacts which happen in real situations. Most models have been proposed for ceramic-on-metal (CoM) contacts where ceramic is postulated as an inert counterpart.<sup>[4,8,24,25]</sup> This concept review aims to provide an overview of some of the well-known formulations for passivation and tribocorrosion current. It also aims to discuss the models with their advantages and shortcomings to ultimately generate an overall picture of the recent advancements in this area.

## 2. Passivation Theories

The literature shows various physically and/or chemically oriented conjectures for formulating and describing how and why a passive film is established and thickened.<sup>[11–14,16,26–29]</sup> The following subsections briefly review three well-known conjectures for passivation.

### 2.1. High-field Model (HFM)

One of the earliest pioneering models was envisaged by Cabrera and Mott in 1947.<sup>[14]</sup> This model was premised on metal cations as the main migrating species for the growth of oxide film. These species are liberated from the metal-oxide interface and transported across the oxide thickness (via a high field with constant strength) to the oxide-solution interface where they finally react with the adsorbed atomic oxygen. Hence, the rate-limiting reaction for this hypothesis was the escape of metal cations from metal-oxide interface. Depending on temperature,

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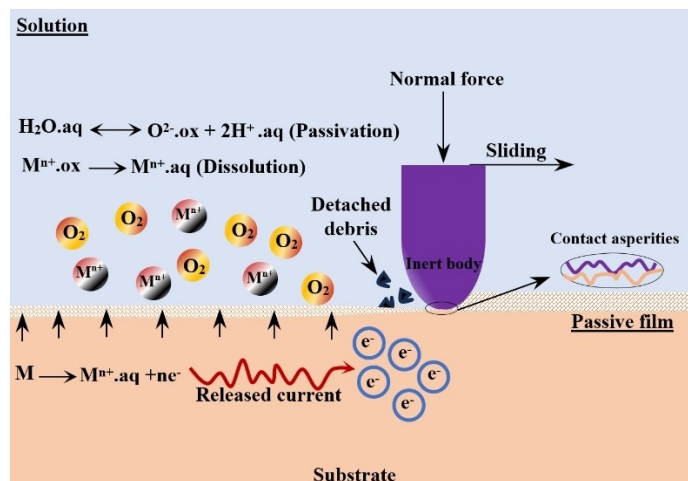


Figure 1. Schematic representation of the tribocorrosion damage process on the surface of a passive metal.

film thickness, and metal type, various functions such as parabolic, cubic, and inverse logarithmic were proposed to express the film growth kinetics based on elapsed time. Having the exponential relationship between the field strength and the diffusional rate of the migrating species for very thin oxide films, the model relates the oxidation rate to the denominator of the oxide thickness as in Eq. (1):

$$\frac{dh}{dt} = i_{hf}^0 \cdot e^{\frac{B(U-E_0+h_0)}{h}} \quad (1)$$

where  $h$  is the thickness of the oxide film,  $t$  is the time elapsed for oxide film growth,  $i_{hf}^0$  is the long-term corrosion current,  $E_0$  is the electric field inside the film,  $B$  is a constant,  $U$  is the governing potential, and  $h_0$  is the initial thickness of oxide film. With integrating Eq. (1) and neglecting higher terms, a reverse logarithmic function was resulted for very thin oxide films.



Dr. Mohsen Feyzi is a postdoctoral researcher at Flinders University, Australia. His PhD focused on tribocorrosion at metal-on-metal interfaces using analytical and experimental approaches. In his PhD, Dr Feyzi developed a new analytical framework for modelling the tribocorrosion current in contacts with various material combinations. His overall research direction is to explore tribology in materials and determine failures, fatigue fracture, and continuum damage mechanics in components to enhance their mechanical durability and efficiency.



Dr Reza Hashemi is a Senior Lecturer in Mechanical Engineering and Research Leader in the College of Science and Engineering at Flinders University, Australia. He leads the tribocorrosion research lab and supervises several students working on various projects in the field. One key focus of his work is on biomaterials, from their tribocorrosion and mechanical failures to the design and development of new alloys. His research has resulted in over 65 journal articles. He has guest edited several special issues, and is on the editorial board for a number of journals.



Professor Margaret Mary Stack is an Irish graduate Engineer from University of Galway and originally from County Kerry. She has published over 150 journal papers in the areas of Tribo-Corrosion. She moved to University of Strathclyde in Glasgow in 2001 where she started a Tribology group in the Department of Mechanical Engineering as Professor of Mechanical Engineering. Her group founded the first journal in Tribo-Corrosion, Journal of Bio- and Tribo-Corrosion (Springer, New York) in 2014 which published 119 papers in 2022 (CiteScore of 5.8 for 2022, and Q1 in Mechanical Engineering). She sits on several editorial boards including Tribology International.

## 2.2. Interface Model (IFM)

In HFM hypothesis, it was assumed that dissolution remains constant throughout the passivation course.<sup>[26]</sup> This was later questioned by Vetter and Gorn.<sup>[11]</sup> Through some experiments, Vetter and Gorn<sup>[11,12]</sup> found that both the dissolution and film formation rates depend on the potential at the oxide-solution interface. Both these rates were represented by their associated current densities as a function of this potential. The rate of oxide film formation was expressed as:

$$\frac{dh}{dt} = i_{if}^0 \bullet e^{g^+ \bullet \varepsilon_{2,3}} \quad (2)$$

where  $i_{if}^0$  is the long-term corrosion current,  $g^+$  is a constant, and  $\varepsilon_{2,3}$  is overpotential at oxide-solution interface. As the potential difference at the oxide-solution interface was not measurable, they related the dissolution and formation currents by cancelling out this potential from the equations. This model realised a physical meaning for the growth of an oxide film with zero thickness (initiation phase), which was not the case in HFM. This is originated from the base of HFM which assumes that the first monolayer pre-exists on the surface and HFM aims to formulate the growth phase.<sup>[14]</sup>

These two models (i.e., HFM and IFM) were later merged into a new model by Kirchheim.<sup>[26]</sup> Kirchheim's model used Sato's and Cohen's formulation<sup>[27]</sup> and included the potential reduction at both the oxide-solution interface and across the film. The model partly covered the shortcomings associated with HFM and IFM and was indicated to better agree with experimental measurements. HFM and IFM conjectures were shown to be special cases of this general model.<sup>[26]</sup>

## 2.3. Point defect Model (PDM)

In 1981, Chao et al.<sup>[13]</sup> presented a novel conjecture that turned the attention to oxygen vacancies, as the migrating species for the film growth. Oxygen vacancies are diffused from the metal-oxide interface and are annihilated at the oxide-solution interface which results in the film growth. The diffusion of metal vacancies from the oxide-solution interface and their annihilation at the metal-oxide interface are accounted for the dissolution. Hence, the rate-limiting reaction for the film growth is how fast oxygen vacancies are generated and diffused across the passive film. This model was finally written as:

$$e^{2 \bullet K \bullet h} - 2 \bullet K \bullet h - 1 = 2 \bullet C \bullet t \quad (3)$$

where  $K$  and  $C$  are the constants of the point defect model. By expanding Eq. (3) and neglecting higher order terms for very thin oxide films, a parabolic function (not inverse logarithmic as in HFM<sup>[14]</sup>) was obtained.

This model was extended to its second, third, and fourth generations to address the shortcomings of its first form.<sup>[16]</sup> As a major shortcoming, it is observed from the first generation that the film thickness tends to be infinite if one increases the

elapsed time to infinity (in clear contradiction with reality). Furthermore, this model does not address the dissolution of the built-up film.

In addition to the three reviewed conjectures, the literature confirms various models with their own specific limitations such as those proposed by Sato and Cohen,<sup>[27]</sup> Sato and Notoya,<sup>[28]</sup> Dignam et al.,<sup>[30-32]</sup> and Fehlner and Mott.<sup>[29]</sup> For instance, Sato and Cohen<sup>[27]</sup> used a "place-exchange" concept through which oxygen is adsorbed on the metal surface and exchanges its place with a metal atom, possibly with a rotation motion. All the models for passivation are employed to calculate the emitted current density from a metal which can ideate how fast the film builds up over the metal surface. Some of these models have been incorporated through tribocorrosion current formulations which will be reviewed in the next section.

## 3. Tribocorrosion Current

In tribocorrosion, mechanical abrasion disrupts the established oxide film; and thereby, the electrochemical equilibrium of the metal-oxide-solution system is disturbed.<sup>[33,34]</sup> In return, oxide film starts to re-establish quickly for restoring initial equilibrium.<sup>[1,10,24,25,35,36]</sup> Therefore, models for capturing the tribocorrosion current require to incorporate mechanical abrasion, electrochemical parameters, and the passivation kinetics of the base metal. This current is used in the mechanistic approach to quantify the wear-accelerated corrosion.<sup>[1,5]</sup> There are various models for tribocorrosion current in the literature with their own limitations and degrees of flexibility. Some well-known models are discussed in this section.

One model for the fretting corrosion current can be derived by differentiating the earliest formulation that was developed by Uhlig.<sup>[37]</sup> Uhlig believed that the mechanical abrasion disrupts the oxide film at the contacting asperities. Through sliding, some areas of bare metal are exposed and repassivate. Therefore, the emitted current from those areas equals the exposed area times the current density released from the area. Assuming a logarithmic relationship and a homogeneous distribution for the current density, the current after a single rubbing stroke can be derived as a rational function of elapsed time as follows:

$$I(t) = \alpha \bullet n \bullet R \bullet \delta \bullet \frac{\beta}{1 + \beta \bullet t} \quad (4)$$

where  $\alpha$  and  $\beta$  are constants reflecting the distance of contacting asperities and the rubbing velocity, respectively.  $R$  is the average radius of the asperities,  $\delta$  is the rubbing stroke,  $n$  is the number of asperities, and  $t$  is the time for repassivation after completing one stroke. Eq. (4) shows that the current starts from a peak and reduces to very small magnitudes over time.

In another tribocorrosion current model, Mischler et al.<sup>[8]</sup> proposed a novel method to incorporate the influence of both the normal force and electrochemical potential, to address the shortcomings associated with the models developed in<sup>[38]</sup>

and.<sup>[39]</sup> The average current was modelled by multiplying the depassivated area by the mean of current density over one rubbing stroke. The depassivated area was then related to the normal force, hardness of the softer body in contact, and the characteristics of the asperities.<sup>[8]</sup> The average current was finally formulated as follows:

$$I_r = C \cdot \delta \cdot f \cdot \left(\frac{W}{H}\right)^{0.5} \cdot \int_0^{1/f} i \cdot dt \quad (5)$$

where  $I_r$  is the average current,  $\delta$  is the rubbing stroke,  $f$  is two times the frequency of oscillation,  $W$  is the normal force,  $H$  is the hardness of the softer body, and  $i$  is the current density.  $C$  is a constant reflecting the number of asperities and the average of their radius, the possibility of their overlap, and their active areas for repassivation.<sup>[8]</sup> From Eq. (5), it is observed that the power of normal force is expressed as 0.5. One interesting study by Landolt et al.<sup>[4]</sup> represented this power as a dependent parameter on the relative hardness and roughness of the contacting bodies. If the two counterbodies have a comparable hardness, this power is then 0.5. If one body is quite harder compared to the other, the power could be either 0.5 (if the harder body is of high roughness) or 1 (if the hard body is smooth).<sup>[4]</sup> Therefore, it is expected that, depending on the real situation of a contact, this power would have a value between 0.5 and 1. It should be noted that the number of asperities is affected by the normal force which should probably increase these values. Jiang et al.<sup>[7]</sup> proposed a mathematical model to unravel the synergistic interactions between pure wear and pure corrosion which exacerbate the material loss. Using Mischler's model<sup>[8]</sup> and a time-dependent formulation for the current density, Jiang et al.<sup>[7]</sup> separately modelled and quantified the pure corrosive wear and wear-accelerated corrosion. This model described some observed phenomena and provided a basis for constructing the tribocorrosion maps.

As stated previously, an average rate of depassivated area generation is included in both the models by Mischler et al.<sup>[8]</sup> and Landolt et al.,<sup>[4]</sup> and the main focus is somehow on the real contact area. If one increases the rubbing stroke, and the passive metal enrolls as a disk in a ball/pin-on-disk configuration, it is expected that the depassivated area left behind the pin/ball contributes to the overall current. Therefore, it is desirable to somehow incorporate this influence into the current formulation. To address this, Jemmely et al.<sup>[40]</sup> developed a model through which the whole wear track length was segmented to a number of cross-width elements. The current density from each of these elements was postulated to be based on HFM and the time available for the repassivation of the element.<sup>[40]</sup> The current density from each elemental area was multiplied by its area to yield the elemental current. The current of the wear track was finally captured by integrating all the elemental currents.<sup>[40]</sup> Since the HFM theory is not analytically integrable for the film thickness, the numerical integration was conducted. Therefore, other passivation theories may be preferred for a full analytical current model. This trend is observed in the literature too. Olsson and Stemp<sup>[25]</sup> employed

the IFM theory into their formulations and obtained a logarithmic relationship for the oxide film thickness as follows:

$$\xi(t) = \frac{1}{g^+ \cdot E_0} \cdot \ln(1 + g^+ \cdot E_0 \cdot k_f \cdot i_0 \cdot e^{g^+ U} \cdot t) \quad (6)$$

where  $g^+ \cong 18 - 20$  (1/V) is the generalised charge transfer coefficient,  $E_0 \cong 5e8$  (V/m) is the electric field inside the oxide layer,  $k_f$  is the film coefficient,  $i_0 \cong 1e - 4$  (A/m<sup>2</sup>) is the long-term growth current density, and  $U$  is the applied anodic potential. Current density (dependent on the derivative of Eq. (6)) was then integrated alongside the wear track to yield the current as follows:

$$I(t) = \frac{2 \cdot R \cdot v}{k_f} \cdot \xi(t) \quad (7)$$

where  $R$  is the contact radius and  $v$  is the rubbing velocity. Key differences for the ceramic-on-metal with metal-on-ceramic (MoC) configurations were observed which could even affect the mathematics for the current function.<sup>[25]</sup> This model has been improved in<sup>[24]</sup> to incorporate the Ohmic resistance of tribosystem, too.

Based on a different view, Swaminathan and Gilbert<sup>[23]</sup> obtained another formulation for the current peak in fretting corrosion as follows:

$$I_{peak} = \frac{2 \cdot R \cdot \delta \cdot v}{\Delta \cdot k_f} \cdot h = \frac{2 \cdot R \cdot p \cdot v}{k_f} \cdot h \quad (8)$$

where  $h$  is the stabilised thickness for the oxide film and equals  $h = m \cdot U$  ( $m$  is the anodisation constant),  $\Delta$  is the inter-asperity distance, and  $p$  is the number of inter-asperity distances in the fretting direction.

Eq. (7) is re-written as follows:

$$I(t) = \frac{2 \cdot R \cdot v}{k_f} \cdot \xi\left(\frac{\delta}{v}\right) = \frac{2 \cdot R \cdot v}{k_f} \cdot \xi\left(\frac{1}{2 \cdot f}\right) \quad (9)$$

If one reduces the frequency to very small magnitudes,  $\xi(\infty)$  equals the stabilised film thickness and Eq. (7) would be somehow similar to Eq. (8) if the contact is assumed as one sliding asperity (i.e.,  $\delta = \Delta$ ). The similarity might be backed up by the assumption made in<sup>[23]</sup> where repassivation was taken as a quick reaction. On the other hand, if frequency increases to very large values,  $\xi(0)$  is approximated using the Maclaurin's series; hence, Eq. (9) takes the following form:

$$I(t) = \frac{2 \cdot R \cdot v}{k_f} \cdot \xi\left(\frac{\delta}{v}\right) \cong \frac{2 \cdot R \cdot v}{k_f} \cdot g^+ \cdot E_0 \cdot k_f \cdot i_0 \cdot e^{g^+ U} \cdot \frac{1}{2 \cdot f} \cong R \cdot \delta \cdot g^+ \cdot E_0 \cdot i_0 \cdot e^{g^+ U} \quad (10)$$

If time approaches very small magnitudes, Eqs. (4 and 10) seem to be somewhat similar. This is consistent with the findings in the literature where Uhlig's model<sup>[37]</sup> was successful under high-frequency regime; however, it failed under low

frequencies for which the logarithmic function of oxidation was suggested as the main underlying reason. For low-frequency applications, Eq. (7) yields lower currents compared with that from Eq. (8). The level of difference depends on the passivation kinetics of the alloy, solution type and its pH, and also the electrochemical potential.

Eq. (7) is written as follows:

$$I = \frac{2 \cdot R \cdot v}{k_f} \cdot \frac{1}{g^+ \cdot E_0} \cdot \ln(1 + g^+ \cdot E_0 \cdot k_f \cdot i^0 \cdot e^{g^+ U} \cdot t) \quad (11)$$

For a passive metal alloy, the mathematical term in parenthesis depends on both the potential and elapsed time (or rubbing frequency). For conditions where this term is quite larger than 1 (i.e., high potentials and low frequencies), Eq. (11) takes the following form:

$$I \cong \frac{2 \cdot R \cdot v}{k_f} \cdot \frac{1}{g^+ \cdot E_0} \cdot \ln(g^+ \cdot E_0 \cdot k_f \cdot i^0 \cdot e^{g^+ U} \cdot t) \cong \frac{2 \cdot R \cdot v}{k_f} \cdot \frac{1}{g^+ \cdot E_0} [\ln(g^+ \cdot E_0 \cdot k_f \cdot i^0 \cdot t) + g^+ \cdot U] \quad (12)$$

The parameter  $E_0$  might be replaced by  $\frac{1}{m}$ ; hence, the second term predicts the current as similar to Eq. (8). For enough elapsed time (small frequency), the first term should be negligible in most tribocorrosion circumstances compared to the second term. Overall, the current linearly depends on the potential, rubbing velocity, and rubbing stroke.

For values where the mathematical term in parenthesis of Eq. (11) is quite smaller than 1 (low potentials and high frequencies), Eq. (11) is re-written as follows:

$$I \cong 2 \cdot R \cdot i^0 \cdot e^{g^+ U} \cdot \delta \cong 2 \cdot R \cdot i^0 \cdot \delta \cdot (1 + g^+ U) \quad (13)$$

which predicts a linear relationship between the current, and potential and rubbing stroke not the rubbing velocity if the effective radius is assumed as independent from the velocity. It

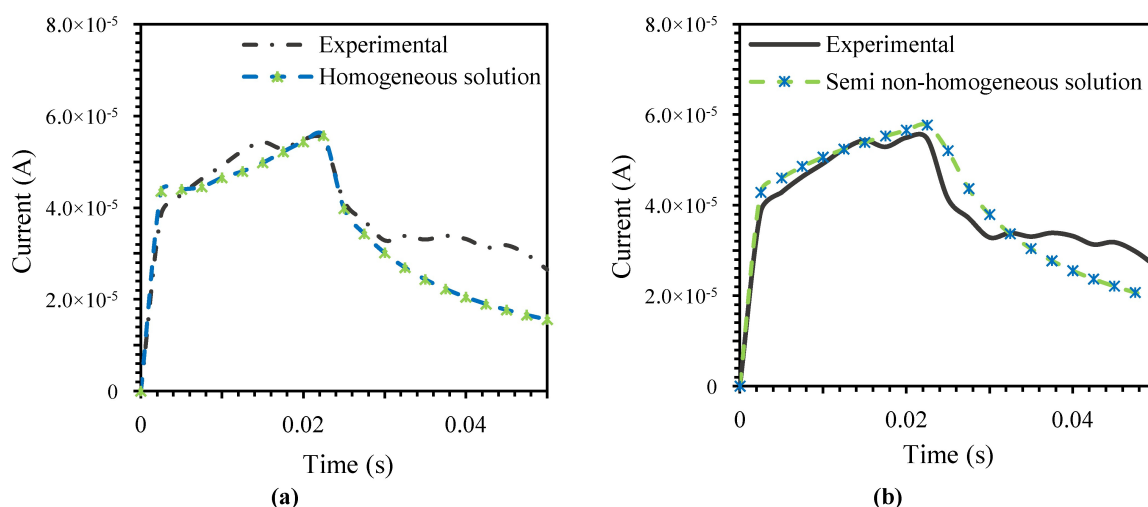
should be noted that the contact radius might be affected by the sliding velocity.<sup>[10]</sup> Overall, one can see that the current models are closely linked together and under specific situations, one could be derived from the other.

The models discussed above formulate the current under potentiostatic conditions. If one passive metal alloy experiences an open circuit potential (OCP) condition, a galvanic cell is formed between the rubbed (anode) and un-rubbed (cathode) areas, and a driving force for the repassivation of the rubbed area is generated.<sup>[11]</sup> The current from anodic and cathodic sides of the cell are equal resulting in a net zero current. These provide key differences between OCP and potentiostatic conditions, and new models are required for OCP. The literature indicates an attempt by **Vieira et al.**<sup>[41]</sup> to quantify the released current as follows:

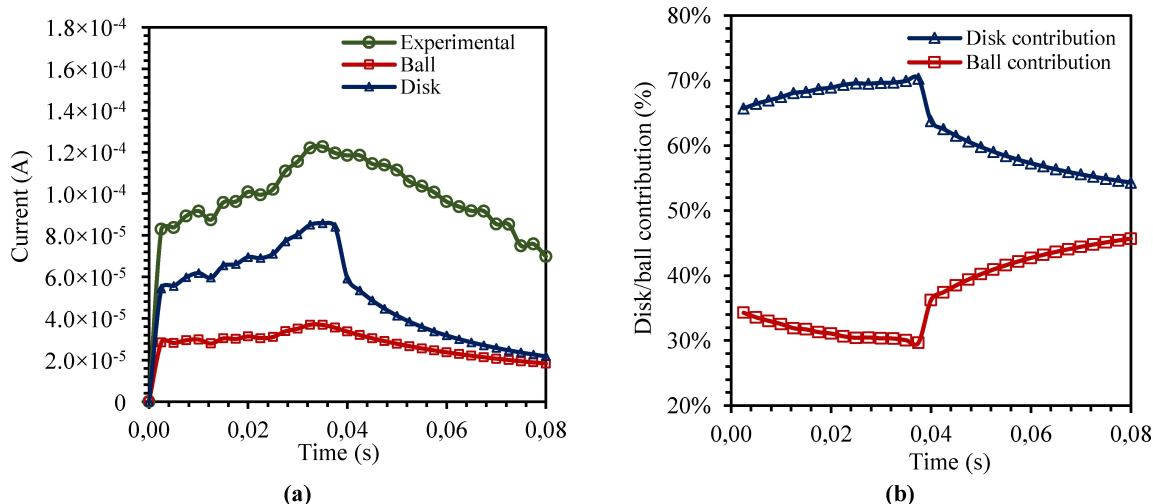
$$\log I_a = \frac{1}{b_c} [E_{corr} - E_c + a_c + b_c \cdot \log(A_c)] \quad (14)$$

where  $E_{corr}$  and  $E_c$  refer to the corrosion potential and cathodic potential attained before the cessation of rubbing, respectively. The parameters of  $a_c$  and  $b_c$  represent the constants for a fitted line on the cathodic branch of a polarisation curve.  $A_a$  and  $A_c$  refer to the rubbed and un-rubbed areas, respectively. Since wear tracks tend to expand by experiencing the tribocorrosion cycles, this might then affect both the anodic and cathodic areas. In a study by **Espallargas et al.**,<sup>[42]</sup> an experimental method (so-called "zero-resistance ammetry (ZRA)") was proposed to better control these areas. The results of the galvanic model were found to be in good agreement with the experiments.<sup>[42]</sup>

As reviewed, there have been great advancements in the modelling of tribocorrosion current over the last few decades. For studying the current, researchers typically study a passive body by rubbing it against an inert counterbody. This helps reduce the complexities of the contact and allow for studying the metal in isolation; however, it does not reproduce what



**Figure 2.** A comparison between the predicted tribocorrosion current of ceramic-on-CoCr contacts tested at 10 Hz: (a) Homogeneous solution, and (b) Semi non-homogeneous solution [35]. Reused from reference [35], with permission from publisher.



**Figure 3.** (a) The decomposition of the experimental current to the partial roles of the disk and ball in a Ti-on-CoCr contact tested at 5 Hz, and (b) The percentile current contributions from the disk and ball components [10]. Reused from reference [10], with permission from publisher.

Model	Formulation	Developed based on IFM/HFM	Developed for CoM/MoC/MoM
Uhlig <sup>[37]</sup>	$\alpha \cdot n \cdot R \cdot \delta \cdot \frac{\beta}{1+\beta \cdot t}$	×	CoM
Mischler et al. <sup>[8]</sup>	$C \cdot \delta \cdot f \cdot \left(\frac{W}{H}\right)^{0.5} \cdot \int_0^{1/f} i \cdot dt$	×	CoM
Landolt et al. <sup>[4]</sup>	$C \cdot \delta \cdot f \cdot \left(\frac{W}{H}\right)^b \cdot \int_0^{1/f} i \cdot dt;$ $0 < b < 1$	×	CoM
Jemely et al. <sup>[40]</sup>	$\frac{A}{N} \cdot \sum_{k=1}^N i(t - t_k);$ A: Wear track area, N: The number of areal segments	HFM	CoM
Olsson and Stemp [25]	$\frac{2 \cdot R \cdot v}{k_f} \cdot \xi$	IFM	CoM
Swaminathan and Gilbert [23]	$\frac{2 \cdot R \cdot \delta \cdot v}{\Delta \cdot k_f} \cdot h$	×	MoM
Vieira et al. [41]	$10^{\frac{1}{2} \cdot E_{corr} - E_c + a_c + b_c \cdot \log(A_c)}$	×	CoM
Feyzi and Hashemi [35]	$A \cdot R_{eff}^2 + B \cdot R_{eff}$	IFM	CoM, MoC, and MoM

happens in many real situations wherein two either similar or dissimilar metals come into contact. The complexities in this type of contact (MoM) highlights the significance of geometry (whether the metal enrolls as ball or disk) and the passivation kinetics of both metals. To address this significant gap, **Feyzi and Hashemi**<sup>[35]</sup> recently developed a novel framework for the tribocorrosion current at MoM contacts. This framework was constructed by unifying new IFM-based current models for the disk and ball components. Two special cases namely as “semi non-homogeneous” and “homogeneous” solutions were extracted from this general framework. The “homogeneous” solution ultimately resulted in the following equation:

$$\begin{aligned}
 I_{tot, MoM} &= [I]_{disk} + [I]_{ball} = A \cdot R_{eff}^2 + B \cdot R_{eff} \\
 ; A &= \pi \cdot \left[ \left[ \frac{1}{k_f} \cdot \frac{dh}{dt}(0) \right]_{disk} \right. \\
 &+ \left. \left[ \frac{1}{k_f} \cdot \frac{dh}{dt}(0) \right]_{ball} \right] \text{ and } B = \left[ 2 \cdot \frac{1}{k_f} \cdot v \right]_{disk} \cdot \\
 &\left[ \left( h \left( \frac{x_1}{v} \right) - h_b \right) + \left( h \left( \frac{2\delta}{v} + t_{dwell} \right) - h \left( \frac{\delta + x_1}{v} + t_{dwell} \right) \right) \right]_{disk}
 \end{aligned} \quad (15)$$

where  $R_{eff}$  is the effective contacting radius,  $t_{dwell}$  is the dwelling time at the end of a rubbing stroke,  $x_1$  is the location of the ball alongside the rubbing stroke,  $h$  is the film thickness,  $\frac{dh}{dt}(0)$  is the instantaneous rate of repassivation, and  $h_b$  is the “balanced film thickness” (obtained from a physical counterbalance between the mechanical abrasion and repassivation).<sup>[35]</sup> Other parameters have the same definitions as detailed in the previous equations. The results of the two solutions were validated in ceramic-on-CoCr contacts and showed good agreements with the experiments tested under different sliding frequencies from 1–

20 Hz.<sup>[35]</sup> As an example, Figure 2 shows the results of these two solutions at a frequency of 10 Hz for the ceramic-on-CoCr contact. The framework was then used in a singly-alloy MoM contact of CoCr to distinguish the partial current roles from the disk and ball components.<sup>[35]</sup> The “homogeneous” solution was proved to be capable of providing reliable estimates of the current roles; hence, in a later study,<sup>[10]</sup> it was employed in different MoM contacts involving Ti and CoCr alloys. Figure 3 illustrates the decomposition of the experimental current during a rubbing stroke (green line) to the partial roles emitted from the disk (blue line) and ball (red line) in a Ti-on-CoCr contact tested at 5 Hz.<sup>[10]</sup> This figure demonstrates that the partial role of the disk is much more significant compared with that from the ball. These partial roles and the associated current dominance were shown to be strongly dependent on the contacting materials and sliding frequency.<sup>[10]</sup> Although being useful and informative, this model was shown to have a number of limitations, as detailed in.<sup>[10,35]</sup> For instance, all the passivation kinetics and mechanical properties of the oxide film are time dependent. This dynamic nature requires to be somehow incorporated in a tribocorrosion current model. This may in turn necessitate the embodiment of analytical models in computational frameworks. Table 1 lists the well-known models developed for the tribocorrosion current.

#### 4. Conclusions and Future Implications

This paper provided a general outlook of the modelling advancements in tribocorrosion by reviewing some well-known models for the passivation and tribocorrosion current. The advantages and shortcomings of each model and the existing links between different models were discussed. Although the tribocorrosion knowledge has advanced over the past decades, there are still many aspects which need a better understanding through further research. Most of the models involve experimental constants which are related to the contacting asperities. Some other constants are not directly measured, and they are obtained in an ad-hoc fashion. Some of the constants are captured by conducting a few experiments and fitting the models on results.<sup>[3,33,41,43,44]</sup> These constants do not include the dynamic time-dependent nature of the contact such as its roughness, hardness, and the size of wear particles. This may necessitate the use of computational simulations such as those in<sup>[45-49]</sup> to better understand how and why the contact situation varies over the time of rubbing with/without the entrapped third-body particles and captivated fluid film. These models should be enriched with other influential parameters such as the local pH influence, local electrochemical potential, different states of the oxide film, material elements contributing to passivation,<sup>[50]</sup> Ohmic resistance at the contact, surface cracks, and the localised plasticity. The pH of the entrapped solution at the contact could be much different from the nominal pH<sup>[51]</sup> and the cracks can influence both the mechanical abrasion and passivation processes.<sup>[35]</sup> These could be conducted using multi-scale computational models which can then result in a thorough understanding of tribocorrosion. Furthermore, this

process could be extended to complex geometries and configurations.

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#### Conflict of Interests

The authors declare no conflict of interest.

#### Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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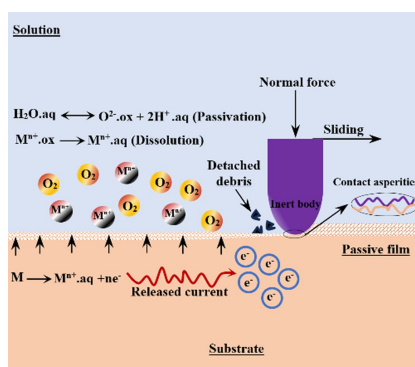
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## CONCEPT

In this article, advancements in modelling the passivation phenomenon in metals, and tribocorrosion current are reviewed and discussed. A number of well-known models together with their strengths and limitations are presented. Under various tribocorrosion circumstances, the models are juxtaposed to highlight their links and similarities from both physical and mathematical standpoints. Future research directions in this area are also suggested.



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### Advancements in Modelling the Tribocorrosion Current