

Synergistic wear-corrosion analysis and modelling of nanocomposite coatings

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ABSTRACT

This paper presents analysis and modelling of synergistic wear-corrosion performance of Nickel-Graphene (Ni/GPL) nanocomposite coating and compares it with un-coated steel 1020 under reciprocating-sliding contact. A novel synergistic wear-corrosion prediction model incorporating Archard description with nano-mechanics and electrochemistry was developed for Ni/GPL and steel 1020. The model is equally applicable to any kind of nanocomposite coating and bulk material like metals. For various nanocomposite coatings; their respective mechanical parameters should be used as inputs such as Poisson's ratio (ν), Elastic Modulus (E), Hardness (H), Coefficient of Thermal Elastic mismatch (CTE) and intrinsic grain size (D_0). The synergistic wear-corrosion effects were significantly prominent in steel compared to Ni/GPL especially under contaminated lubricating oil conditions. This behaviour of Ni/GPL attributes to compact, refined grain structure leading to minimal grain pull-out during wear cycles which was also assured by less severe micro-ploughing in Ni/GPL compared to severe micro-cutting in steel. The predictions and experimental results were in good-agreement. Modelling of synergistic effects of wear-corrosion applied to nano-composite coatings have never been presented prior to this research. The significance of this work in terms of precision based wear-corrosion synergistic analysis, modelling and predictive techniques is evident from various industrial applications. This work will bring impacts for both in-situ and remote sensor based condition monitoring techniques to automotive, locomotive, aerospace, precision manufacturing and wind turbine industries.

1. Introduction

A nanocomposite coating is a state-of-the-art method of producing highly durable and reliable novel materials at room temperature for current advanced technological applications, for example automotive, defence and aerospace [1,2]. A nanocomposite coating compared to other coating types provides excellent functional properties such as wear and corrosion resistance to the coated surface. The introduction of nano particles in metal matrix had found to be super strong in Tribological strength [3,4]. Various nickel matrix nanocomposite coatings comprising diverse range of inert nano particles such as Al_2O_3 , SiC, ZrO_2 , Graphene (GPL), TiO_2 and diamond, etc., have been electrodeposited by using distinct electrolytes having suspended nanoparticles [5–9].

Synergistic wear-corrosion can be defined as “a process, where the

removal of the material results from combined activities of mechanical and electrochemical mechanisms” [10]. Literature survey shows different numerical models for predicting wear mechanisms under the effects of mechanical and electrochemical parameters [11–19]. Initial wear-corrosion models only included the effects of either wear-on-corrosion or corrosion-on-wear but did not address the synergistic wear-corrosion process [11,12,14,15]. In the last two decades, some advanced synergistic wear-corrosion models were developed as shown in Table 1. A synergistic model developed by Garcia et al. [17] showed the relation of corrosion current density with worn area. Garcia's model was further modified by Goldberg [18] for corrosion currents generated as a result of scratching passive surfaces. Another advanced model was developed by Mischler et al. [19] for reciprocating contacts including the influences of material hardness and load on synergism. The

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Nomenclature

$a_{(i)}$	half width of the contact at the i th wear cycle (m)
$h_{(i)}(X)$	wear depth at the x position of the interface (2D contact) at the i th wear cycle (m)
K_V	Archard wear coefficient related to the wear volume analysis ($\text{mm}^3 (\text{N m})^{-1}$)
L	axial length of the cylinder/plane contact (mm)
P	normal force (N)
P_L	normal force per unit of axial length (2D contact) (N/mm)
V	wear volume (m^3)
$W_{(i)}$	Archard factor dissipated during the i th wear (N/m)
$W_H(0)$	Hertzian approximation of the Archard factor during the i th wear cycle (N m/m^2)
$\sum W$	(accumulated) Archard factor (Nm)
$\sum W(0)$	(accumulated) Archard factor density dissipated at the centre of the interface ($x = 0$, 2D contact) (N m/m^2)
P_S	surface porosity (%)
$\sigma_C(0)$	biaxial surface stress of the coating at $x = 0$ (GPa)
E_1, E_2, E_3	elastic moduli of coating, ball and substrate (GPa)
ΔT	change in temperature from fabrication temperature (K)

$h_C(0)$	thickness of coating at the centre of the wear scar (mm)
ζ_r	radius of curvature of coating-substrate system due to residual stress (mm^{-1})
D_o	grain size of coating at the time of deposition (nm)
V_W	volume loss due to wear (mm^3)
V_C	volume loss due to corrosion (mm^3)
ΔV_W	change in corrosion volume due to wear (mm^3)
ΔV_C	change in corrosion volume due to wear (mm^3)
K_V	wear rate (mm^3/Nm)
K_C	corrosion rate (mm/year)
K_{C-W-C}	synergistic effect of wear-corrosion on corrosion rate (mm/year)
$\bar{J}$	corrosion current density (A/mm^2)
j_o	equilibrium exchange current density (A/mm^2)
S	synergistic factor (mm^3)

Greek symbols

δ	displacement (m)
δg	sliding amplitude (m)
ρ	density of the nanocomposite coating material (g/mm^3)

Table 1

Some advanced synergistic wear-corrosion models.

Synergistic wear-corrosion models	Developer	Ref.
$\bar{J} = i \frac{R}{3} V_W \int_0^t j_o(t) dt + i \frac{R}{3} (V - V_W) \int_0^t j_o(t) dt$	Garcia et al.	[17]
$\bar{J} = \frac{R j_o}{3} V_W e^{\left[\frac{P}{H} \right]} + \frac{R}{3} \frac{\rho Z F V_W}{V_m}$	Goldberg	[18]
$\bar{J} = K_L i \frac{R}{3} \left(\frac{P}{H} \right)^{\frac{1}{2}} \int_0^t j_o dt$	Mischler et al.	[19]
$\bar{J} = \frac{F \rho}{K_A i} (V - (K_V \sum W) - S)$	Khan-Nazir II	Reported here

$\bar{J}$ = corrosion current density; i = wear cycles; j_o = equilibrium exchange current density; R = radius of ball; b_a = Tafel slope; n_i = scratch over potential; ρ = coating density; F = Faraday's constant; Z = number of transferred electrons; V = wear-corrosion volume loss; V_W = volume loss owing to wear; V_m = coating molar mass; H = hardness; P = normal loading; K_V = wear rate, K = electrochemical equivalent of specimen material, W = Archard factor density, A_s = area of the specimen, S = synergistic factor.

prediction of synergistic wear-corrosion response of steel 1020 from all the models listed in Table 1 under lubricating oil condition contaminated with sea salt (Medium-II [Table 2]) were compared with the experiment as shown in Fig. 1. Our developed model showed more accurate prediction compared with the conventional models.

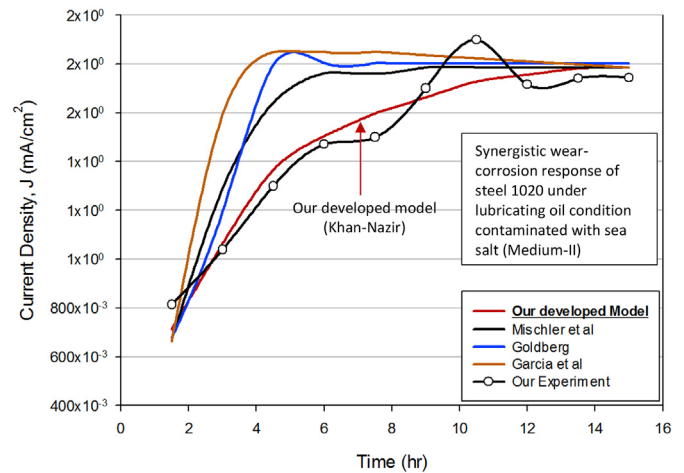
The existing synergistic wear-corrosion models [11–19] can predict the synergistic wear-corrosion in only bulk materials (metals) and alloys however predicting the synergistic wear-corrosion performance of nanocomposite coatings is still a grey area in wear modelling. Predicting the effects of intrinsic nano-mechanics parameters, such as the eigentresses, porosity, deposited grainsize and thermal mismatch of nanocomposites on their synergistic wear-corrosion has always been a challenge.

To address the above problem, a novel 2-D synergistic wear-corrosion

Table 2

Three types of lubricating oil conditions used during synergistic wear-corrosion experiments.

Oil Medium	Contaminate induced	Oil Contents
Medium-I	–	oil (uncontaminated)
Medium-II	5%(wt%) sea salt	oil Contaminated with sea salt
Medium-III	5%(wt%) sea salt and 10%(wt%) water	oil Contaminated with sea salt and water

**Fig. 1.** The comparison of predictions of synergistic wear-corrosion response of steel 1020 from all the models listed in Table 1 under lubricating oil condition contaminated with sea salt.

model for nanocomposite coatings has been formulated by combining the popular Archard equation with the nano-mechanics and the electro-chemical equations. The analysis uses gross slip conditions with wear corrosion, focusing on metal interfaces. In this paper the synergistic wear-corrosion performance of nanocomposite coating Ni/GPL was analysed and compared with the performance of un-coated steel 1020. The developed synergistic model can however be equally used for any kind of nanocomposite coating and bulk material. Similar studies in our group on coatings failures have been performed [20–34].

Water and other non-conventional lubrication have been studied in other projects within NCEM, for example [31–34] and is not within the scope of this research. The complexity of rotating electrolyte, inter-electrode spacing and relation to EIS (electro-chemical impedance spectroscopy) with varying constituents as salts, its molality and concentrations by weight percentage are challenging aspects in terms of in-situ corrosion condition monitoring. Previous and existing research projects within NCEM have been investigating marine applications where conventional lubricants are polluted. This includes

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