Preliminary investigation on the effect of irradiation on tribocorrosion behavior of 316L stainless steel alloy
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ABSTRACT
The effect of irradiation on the tribocorrosion behavior of 316L stainless steel alloy was investigated in 0.02 M Na$_2$SO$_4$ solution, using a ball-on-flat configuration, which was connected with a three electrode-chemical cell. The rubbing and irradiation track morphology were investigated using Scanning Electron Microscopy and profilometric measurements after rubbing and irradiation tests. The rubbing tests, in the presence or absence of irradiation, were performed under 20 N normal force using an alumina ball as a counter body. The surfaces were characterized through electrochemical measurements, optical microscopy, and elemental analysis while the corrosion phenomenon was examined by electrochemical impedance spectroscopy (EIS) and polarization potentiodynamic measurements. The open-circuit potential measurements and EIS measurements were used to evaluate the electrochemical reactivity of the 316L stainless steel surface before, during and after sliding tests. The corrosion rate was determined using the Tafel extrapolation technique. It was found that when the sample subjected to both tribo-corrosion and irradiation, the corrosion potential shifted more toward the anodic region and affects the corrosion kinetics. It is found that the surface of 316L stainless steel has a reasonable corrosion-irradiation resistance.

1. Introduction
Stainless steel (SS) alloy is one of the most prevalent corrosion-resistant materials used in numerous applications not only owing to their superior corrosion resistance. The corrosion resistance is provided by the spontaneous creation of an oxide film on the metallic surface of a thickness ranging from 1 to 10 nm containing mainly Cr$_2$O$_3$ for stainless steel. Accordingly, SS is the most significant material of construction, generally utilized in both advanced gas-cooled reactor (AGR) nuclear fuel materials and in nuclear reactors construction. The 316 L SS is used as a structural nuclear material when higher temperature and special corrosive medium, such as sulfates or chlorides, are used. Generally, the corrosion are not particularly dependent on composition and microstructure of SS. The corrosion rates for the Cr/Mo SS are usually only a factor of 2 to 3 less than the others (Raja et al., 2013). This behavior reflects the dominance of the corrosion rate on corrosive medium, and the buildup of corrosion product deposits. In many cases, stainless steel surfaces are exposed to various corrosion actions owing to fluid impact, mechanical friction, and irradiation. These surfaces are subjected to scratching, abrasion, erosion, and other forms of wear damage in a corrosive-irradiative environment (Wood, 2007).

The resulting tribocorrosion phenomena comprise mechanical and chemical/electrochemical interactions between surfaces in relative motion in the existence of a corrosive environment. A corrosive environment increases the material loss rate by the aforementioned mechanisms; leading to the acceleration of the rate of wear. A tribocorrosion failure is often a serious problem for human health and safety (Pina, Neves, & Bandarra, 2011). Up to now, the tribocorrosion mechanisms are not yet completely understood. Previous studies were performed under potentiostatic condition where the passive film reconstruction is maintained active. However, under normal conditions of use, no potential are applied to materials and passivation is only related to the natural passive film growth. As the contacted surfaces under electrochemical control circumstances are affected by a variety of factors, for instance, the nature of the solution, the influence of gamma radiation fields, the material’s surface properties, the electrochemical parameters and the external mechanical conditions (Wang, Yan, Su, & Qiao, 2019). Most studies, interested in the tribocorrosion behavior of stainless steel, are conducted in neutral solutions (Sun & Rana, 2011; Zhang, Yin, & Yan, 2015; Zhang, Yin,
Yan, Wang, & Yan (2015). However, in practical applications, stainless steel is frequently used in an acidic medium, for instance, descaling, oil well acidizing, industrial pickling and certain nuclear power fields. Few researches study the tribocorrosion behavior of 316L stainless steel alloy in sulfuric acid. Hong et al. and Perret et al. (Hong & Pyun, 1991a, 1991b; Perret et al., 2010) found a change in the surface potential of stainless steel in sulfuric acid illustrated by various characterization means. Their results revealed that the degree of deformation of the subsurface at the applied potential was more noticeable than that of the cathodic one, owing to the passive film barrier effect. Stachowiak and Zwierzycki (2012) studied the tribocorrosion mechanism of stainless steel in both sulfuric acid and NaCl solution and showed that the formed surface passivation film helped in the reduction of surface deformation under low contact stress and weak corrosive medium circumstances. Subramanian et al. revealed that the exposure of steel to radiation may enhance tribocorrosion as it affects corrosion kinetics (Subramanian et al., 2004). Accordingly, the surface corrosion kinetics change resulted from irradiation cannot be ignored. Rubbing and gamma irradiation may destruct the formed passive film and accordingly increases the corrosion rate. Research concerning radiation effects addresses extensively neutrons, charged particles, or electromagnetic radiation on metals or alloys. Exposure to these radiations may lead to the electronic excitations, displaced atoms, or other defects that arise from the interactions; including the overall properties on performance and structural properties. However, the combination of tribocorrosion and simultaneous radiation damage constitutes a major challenge for metal structure (Gadow et al., 2017; Glass, Van Konynenburg, & Overture, 1985; Tachibana et al., 2012).

Thus, the present work aims to study the effect of irradiation and tribocorrosion in the 316L stainless steel surfaces, and to evaluate the kinetic of passivation and repassivation processes against an alumina pin in open-circuit condition. This is of particular interest in the nuclear industry due to ionizing radiation creates oxidizing radiolysis products and alters the redox potential of a corroding solution. A detailed surface characterization of the 316L stainless steel sample was carried out. A series of experiments have been conducted to evaluate the effect of irradiation and rubbing action on the tribocorrosion. The mechanism of electrochemical reactions and the dielectric properties of stainless steel were investigated by Electrochemical Impedance Spectra (EIS).

2. Experimental work

2.1. Materials and characterization

The tribocorrosion test system was divided into two main parts, namely, electrochemical control and friction control as illustrated in Figure 1. The samples were immersed in the cleaning solution at room temperature for 90 min and then they were cut into pieces for further experiments. All the electrochemical corrosion tests and electrochemical impedance spectroscopy (EIS) results were obtained using a computer-controlled potentiostat with a conventional flat three-electrode test cell outfitted with an EC-lab ultra-low current SP-300 electrochemical system. The system included an aluminum ball that causes the wear corrosion (essentially inert in chemical environments, ∅8.00 mm), a graphite rod as counter electrode (CE), a sample to be tested as working electrode (WE) and...
a standard calomel electrode (SCE) was used as a reference electrode (RE). To maintain consistent test conditions, the electrodes were always positioned in the same locations inside the cell. All tests were executed in 0.02 M Na$_2$SO$_4$ solution at room temperature. The samples were corroded first freely for about 30 min to attain a quasi-stationary value of the open-circuit potential (OCP). The potentiodynamic polarization curves were acquired in the range from $-0.5$ V with respect to OCP to 0.5 V (vs. SCE) at a scan rate of 1 mV/s. The EIS tests were assessed in a similar three-electrode configuration as used in the tribo-corrosion tests and at the OCP with 10 mV sinusoidal potential amplitude, running from 100 kHz to 0.02 Hz. Specimens with dimensions of 5 mm x 5 mm x 2.5 mm were irradiated at room temperature using a 60Co gamma-ray under a dose rate of ~ 0.9 kGy/h for different dose period (Gamma Cell model MG 20 in Cyclotron building, Nuclear Research Center, Atomic Energy Authority of Egypt). The results are representative of the average of at least three measurements. Wear tracks profiles were measured using a high-resolution optical microscope, Leica DVM 2500 model, which had Leica Application Suite software for the analysis of 3D models.

### 2.2. Electrochemical tests

The tribocorrosion tests were executed in Na$_2$SO$_4$ (0.02 M) solution at (pH 6), using a ball-on-flat tribometer (UMT-2, Bruker instrument) which was connected with a three electrode-chemical cell (Figure 1). All rubbing tests, in the existence or the absence of irradiation, were executed under 20 N normal force, considering a stroke length of 2.5 mm, a rubbing velocity of 10 mm/s with a relative wear distance of 100 m. Electrochemical measurements, namely, open-circuit potential and electrochemical impedance measurements were executed before, during rubbing, and through irradiation tests. A quasi-steady-state is achieved when OCP is smaller than 1 mV/min. For electrochemical impedance spectroscopy, measurements performed before, during rubbing, and through irradiation tests, a sinusoidal potential perturbation of 5 mV amplitude was applied at frequencies ranging from 0.02 Hz to 100 kHz. Two different tribocorrosion tests were executed, OCP and potentiodynamic tests; Tribocorrosion tests at OCP consist in recording the potential versus time. First, the OCP was measured for 300 s without motion for stabilization and then the rubbing started while the OCP was maintained. The variations of OCP were plotted before, during, and after the rubbing, either this rubbing was with or without irradiation.

Potentiodynamic polarization test was executed to provide significant useful information regarding the susceptibility of the utilized 316L SS to corrosion in the exposed environment under the effect of rubbing and radiation.

### 3. Results and discussion

#### 3.1. Characterization

The EDS analysis of the sample is provided in Figure 2. It is clear from this Figure that the sample under study contains chromium that increases the corrosion resistance, nickel that improves its mechanical and fabricating properties, and molybdenum that increases pitting resistance. The Pitting Resistance Equivalent Number (PREN) that gives a good indication of the pitting resistance of 316L SS can be calculated as: $\text{PREN} = \text{Cr} + 3.3 \times \text{Mo} + 16 \times \text{N}$. (Papavinasam, 2014)

As seen from this formula, Cr, Mo, and N act as important factors which improve pitting resistance, and, further, Po, Si, Mn, and Ni are known to be the elements which improve pitting resistance. The value of PREN was found to be about 29 which is considered as a low value indicating the probability of the used 316L SS for pitting corrosion. Figure 3 shows a typical three-dimensional view of the rubbing track produced.
During tribocorrosion under 20 N load and at 1 Hz frequency, together with the measured surface profile across the rubbing track. The wear tracks were measured to obtain the worn depth area (track height average) in all samples. The depth damage caused by the tribocorrosion and irradiation tests on the sample was observed; that is related to the high change suffered by the surface which is attributed to the synergy between wear, irradiation, and corrosion. It is observed from Figure 4 that the surface of the wear track of this particular sample predominantly failed because of the cohesive fracture and surface delamination.

3.2. Electrochemical measurements

3.2.1. Open-circuit potential (OCP)
The OCP or the free potential is a qualitative indicator of the state of corrosion of a metal substrate in an electrolytic medium and it also helps to determine the immersion time required for reaching the steady state. OCP examines preliminary information on the nature of the processes that take place at the metal surface/electrolyte interfaces. Before the start of rubbing, the sample was immersed for 4 h in Na$_2$SO$_4$ solution. The electrochemical reactivity of the studied sample surface was monitored by the evolution of OCP throughout this immersion period. At the beginning of immersion, the OCP was primarily around $-0.55$ V/SCE. Then, throughout the immersion period, a continuous increase in the open-circuit potential values were observed. This behavior proposes that the sample was in a passive state, and that the protective oxide layer formed on its surface has been reinforced over time (Figure 5(a)). After 4 h of immersion in Na$_2$SO$_4$ solution, the OCP reaches a steady state value of –
0.414 V/SCE. Figure 5(b) presents the evolution of the potential during rubbing and irradiation tests executed at three different conditions (under the effect of tribocorrosion, tribocorrosion then irradiation and irradiation then tribocorrosion). A passive film was formed on the sample model after 4 h of immersion in Na₂SO₄ (0.02 M) solution at room temperature, before starting the rubbing and irradiation tests. At the start of rubbing, a deterioration of the passive film was produced for all the used conditions. This passive film degradation was reflected by the sharp drop of the potential when the rubbing and irradiation tests started. The OCP drop indicates depassivation of the metal in the rubbing and irradiation track on areas in contact with the pin and irradiation source and the existence of a dissolution process, inside the track areas (Papavinasam, 2014). The OCP throughout the rubbing outcomes from the galvanic coupling targeted the depassivated wear track (anode) and the passive-undamaged area (cathode) (Martin, Azzi, Salishchev, & Szpunar, 2010). The potential shows a minor variation of about 0.05 V owing to the formation of a dynamic equilibrium that targeted repassivation and depassivation mechanisms. This is a result of the periodic growth and elimination of the passive film in the rubbing process. At the end of the rubbing, the potential exhibits an anodic shift, signifying the repassivation occurrence of the active area of the damaged zone resulting from the straining generated by rubbing.

3.2.2. Electrochemical characterization during rubbing and irradiation

The potentiodynamic polarization (Tafel polarization curve) was executed in the presence and absence of both irradiation and tribocorrosion to explore the electrochemical behavior of the tested sample. As illustrated in the presented potentiodynamic polarization curves (Figure 6), the sample that has not been exposed to neither irradiation nor tribocorrosion passivate with a current density in the order of 0.00631 A/cm². The non exposed sample relatively has corrosion resistance in contradiction of the exposed sample to tribocorrosion that are more susceptible to corrosion in SO₄⁻-containing solutions. The Tafel polarization indicates that besides numerous electrochemical polarization parameters comprising cathodic and anodic Tafel slopes (βc and βa), corrosion current density (icorr), corrosion potential (Ecorr), and their corresponding inhibition efficacy percentage are shown in Table 1. It is clear from Figure 6 that at the beginning of rubbing, current increases owing to the stirring effect of the counterpart that improves the mass transport and the mechanical elimination of the passive film that is known to hinder the cathodic reaction. The existence of sulfate anions would collapse the passive film of the studied sample at the defects sites, for instance, secondary phase, particles grain boundaries and

![Figure 5](image1.png)

**Figure 5.** (a) Evolution of the open-circuit potential of the sample at ambient temperature without any external effect, (b) Evolution of the open-circuit potential of the sample at ambient temperature, before, during and after continuous unidirectional sliding tests performed at 600 cycles at 20 N of normal force.

![Figure 6](image2.png)

**Figure 6.** Determination of polarization parameters by Tafel extrapolation method.
At high potentials, the corrosion resistance of the sample decreases to 0.000407 µA cm\(^{-2}\). This active corrosion potential shift was owing to the passive nature of the sample. Equation (1) was employed for assessment of the inhibition efficiency (η%) at several exposure sample conditions. From the η% values calculated from Equation (1) as given in Table 1, it is expectable that the sample exposed to rubbing only heads for better inhibition efficiency (93.54%) compared to bare sample. From the literatures, it is recognized that the change in the surface corrosion potential consequential from irradiation increased, this may be owing to the relatively low corrosion resistance of the used 316L SS, which is affected by sulfate ions in Na\(_2\)SO\(_4\). In the electrolyte with the sulfate concentration, it can be found that the addition of sodium sulfate inhibits pitting corrosion and has a better inhibitor effect in SS (Calderón-Hernández, Hincapie-Ladino, Magnabosco, & Alonso-Falleiros, 2019; Vazquez-Arenas & Pritzker, 2010). In the steels used in the present investigation, there is not expected a considerable occurrence of MnS due to low S content. Its low corrosion resistance toward different external effects may be owing to the passive layer's rupture by sulfate ions that is when exposed to chemical or mechanical damage, the protective film will be reformed rapidly, but when the damage rate is larger than the repair rate, the progressive active corrosion may occur. Also, the anodic passive current density has significantly increased in the existence of radiation (Vazquez-Arenas & Pritzker, 2010).

### Table 1. The Tafel polarization parameters.

| Test conditions                        | \( E_{corr}, V \) | \( R_p, \Omega \) | \( i_{corr}, \mu A cm^{-2}\) | \( \beta_c \) | \( \beta_a \) | \( \eta, \% \) |
|----------------------------------------|------------------|-----------------|-----------------------------|--------------|-------------|-------------|
| Sample without radiation nor friction  | −0.58            | 742.25          | 16.22                       | 0.00631      | −13.31      | −56.5       |
| Sample exposed to friction only        | −0.36            | 761.89          | 1.04                        | 0.000407     | −0.72       | −75.59      |
| Sample exposed to radiation and friction | −0.55          | 4572.56         | 3.62                        | 0.00141      | −35.97      | −25.23      |

### Active zone
In this zone, the metal directly dissolves in contact with the corrosive solution (Na\(_2\)SO\(_4\)). This zone stands for the actual corrosion rate of the test electrodes that may relate quantitively to the Stern-Geary equation (Papavinasam, 2014):

\[
i_{corr} = \frac{\beta_c \beta_a}{2.3R_p(\beta_c + \beta_a)} \quad (1)
\]

where \( i_{corr} \) is the corrosion current density of the test sample, \( \beta_c \) and \( \beta_a \) are the cathodic and anodic Tafel slopes and \( R_p \) is the polarization resistance. The values of parameters are illustrated in Table 1.

### Passive zone
Within this zone, a protective passive film begins to grow up on the surface that helps in defending the bare material from dissolution resulted from the aggressive test electrolyte nature. It is also observed that the onset of friction (−0.555) takes place very close to its corrosion potential (−0.584). Moreover, the onset of the sample exposed to both irradiation and friction takes place at significantly higher anodic potential (−0.328V).

### Transpassive zone
At high potentials, the passive layer film breaks down and the current severely increases with potential that pass through the layer, and as a result the oxygen begins to evolve and the dissolution occurs. Irradiation in solution showed approximately 100 mV potential shift in the active direction. The potential shift could be attributed to the polarization of 316L SS by reducing radiolysis products.

When the tested sample was subjected to the corrosion owing to the immersion in the electrolyte corrosive solution media, the corrosion potential was about −0.58 V, corrosion current density is 0.00631 µA cm\(^{-2}\) as illustrated in Figure 6. When the tested bar is subjected to tribocorrosion, the potential shifted from −0.58 V to −0.36 V toward anodic region, and corrosion current density decreased to 0.000407 µA cm\(^{-2}\). This decrease in corrosion current density may be a sign for relatively high corrosion resistance of the tested material. Simultaneously when the sample was subjected to both tribocorrosion and radiation, the corrosion potential shifted more toward anodic region yielding a density of 0.00141 µA cm\(^{-2}\). This active corrosion potential shift was owing to the passive nature of the sample. Equation (1) was employed for assessment of the inhibition efficiency (η%) at several exposure sample conditions. From the η% values calculated from Equation (1) as given in Table 1, it is expectable that the sample exposed to rubbing only heads for better inhibition efficiency (93.54%) compared to bare sample. From the literatures, it is recognized that the change in the surface corrosion potential consequential from irradiation increased, this may be owing to the relatively low corrosion resistance of the used 316L SS, which is affected by sulfate ions in Na\(_2\)SO\(_4\). In the electrolyte with the sulfate concentration, it can be found that the addition of sodium sulfate inhibits pitting corrosion and has a better inhibitor effect in SS (Calderón-Hernández, Hincapie-Ladino, Magnabosco, & Alonso-Falleiros, 2019; Vazquez-Arenas & Pritzker, 2010). In the steels used in the present investigation, there is not expected a considerable occurrence of MnS due to low S content. Its low corrosion resistance toward different external effects may be owing to the passive layer’s rupture by sulfate ions that is when exposed to chemical or mechanical damage, the protective film will be reformed rapidly, but when the damage rate is larger than the repair rate, the progressive active corrosion may occur. Also, the anodic passive current density has significantly increased in the existence of radiation (Vazquez-Arenas & Pritzker, 2010).

### Electrochemical impedance spectroscopy (EIS) study
The impedance plot (Nyquist diagram) obtained for the sample in different exposure times at different exposure conditions are depicted in Figure 7. The charge transfer resistance (reaction resistance) of the corrosion reaction increased as a result of increasing the diameter of the semicircle which increases with increasing the exposure time. The impedance plots that have not appeared as a semicircle at different times for the samples that have not been exposed to irradiation may be assigned for the frequency dispersion in addition to the inhomogeneity of the surface (Calderón-Hernández et al., 2019).

Randle equivalent circuit was used for impedance spectra interpretation. The Nyquist plot for the samples exposed to irradiation at different times illustrated the semicircle shape having the capacitive loop at a lesser frequency range that represents the intact
passive film formation (Ionscu, Abrudeau, Ponthiaux, Wengerb, & Rize, 2011; Tachibana et al., 2012). The capacitance is proportional inversely to film thickness \( L \) as given by Equation (2)

\[
L = \varepsilon\varepsilon_0 A/C
\]

where, \( C \) is the passive film capacitance, \( \varepsilon \) is the oxide film dielectric constant, \( \varepsilon_0 \) is the space permittivity and \( A \) is the electrode area. It was clear from the Figure 7 that a lesser depressed semi-circle was obtained from the sample that has not been exposed to irradiation as compared to others. The \( R_p \) of the sample that has not been exposed to neither irradiation nor tribocorrosion was found to be the least and increases as the exposed conditions increase. Thus, the sample that has not been exposed to irradiation reflects the better passivation behavior as compared to the other samples.

### 4. Conclusions

The effect of irradiation on the tribocorrosion behavior of 316L stainless steel was investigated by continuous sliding tests against an aluminum pin in 0.02M \( \text{Na}_2\text{SO}_4 \) solutions at room temperature. It is appeared that when the sliding started with and without irradiation, a degradation of the passive film was executed under 20 N normal force and irradiated at room temperature with 16 MeV This deterioration of the passive film and the resulting electrochemical wear component were qualitatively evaluated. The total wear increases with both the effect of irradiation and irradiation period and thus it must be taken into account. It is concluded that the studied 316L stainless steel has a reasonable corrosive resistance but coating the studied 316L stainless steel are recommended for enhancing the tribocorrosion protection.

### Disclosure statement

No potential conflict of interest was reported by the authors.

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### References

Calderón-Hernández, J. W., Hincapie-Ladino, D., Magnabosco, R., & Alonso-Falleiros, N. (2019). Effect of sulfate on the pitting potential of austenitic stainless steels 18Cr8Ni and 17Cr6Mn5Ni in chloride media. REM - International Engineering Journal, 72, 97–103.

Epelboin, I., Joussellin, M., & Wiart, R. (1981). Impedance measurements for nickel deposition in sulfate and chloride electrolytes. Journal of Electroanalytical Chemistry and Interfacial Electrochemistry, 119, 61–71.

Gadow, H. S., Motawea, M. M., & Elabbasy, H. M. (2017). Investigation of myrrh extract as a new corrosion inhibitor for a-brass in 3.5% NaCl solution polluted by 16 ppm sulfide. RSC Advances, 7, 29883–29898.

Glass, R. S., Van Konyenburg, R. A., & Overturf, G. E. (1985). Corrosion processes of austenitic stainless steels and copper-based materials in gamma-irradiated aqueous environments Lawrence Livermore National Laboratory Report. UCRL-92941.

Hong, M. H., & Pyun, S. I. (1991a). Applied potential dependence of corrosive wear behaviour of 304-L stainless steel in sulphuric acid solution. Journal of Materials Science, 10, 716–719.

Hong, M. H., & Pyun, S. I. (1991b). Corrosive wear behaviour of 304-L stainless steel in 1 N H2SO4 solution part 2. Effect of chloride ion concentration. Wear, 147, 69–78.

Ionscu, C., Abrudeau, M., Ponthiaux, P., Wengerb, F., & Rize, V. (2011). Effect of normal force on Tribo-corrosion behavior of Ni – 30 Cr model alloy in LiOH– H3BO3 solution. Revue Roumaine De Chimie, 56, 907–915.

Martin, E., Azzi, M., Salischchev, G. A., & Szpunar, J. (2010). Influence of micro structure and texture on the corrosion and tribocorrosion behavior of Ti–6Al–4V. Tribology International, 43, 918–924.
Muñoz, A., & Julián, L. (2010). Influence of electrochemical potential on the tribocorrosion behaviour of high carbon CoCrMo biomedical alloy in simulated body fluids by electrochemical impedance spectroscopy. *Electrochimica Acta*, 55, 5428–5439.

Papavinasam, S. (2014). *Corrosion control in the oil and gas industry* (pp. 79–247). Gulf Professional Publishing. Retrieved from https://www.elsevier.com/books/corrosion-control-in-the-oil-and-gas-industry/papavinasam/978-0-12-397022-0

Perret, J., Courjault, E. B., Canton, M., Mischler, S., Beaudouin, A., Chitty, W., & Vernot, J. P. (2010). EBSD, SEM and FIB characterisation of subsurface deformation during tribocorrosion of stainless steel in sulphuric acid. *Wear*, 269, 383–393.

Pina, C., Neves, A., & Bandarra, B. (2011). Corrosion-wear evaluation of a UHMWPE/Co–Cr couple in rubbing contact under relatively low contact stress in physiological saline solution. *Wear*, 271, 665–670.

Priya, R., Mallika, C., & Mudali, U. K. (2014). Wear and tribo-corrosion behaviour of 304L SS, Zr-702, Zircaloy-4 and Ti-grade2. *Wear*, 310, 90–100.

Raja, B., Kamachi Mudalib, U., Vijayarajakshmi, M., Mathewd, M. D., Bhadurie, A. K., Venugopalg, S., … Venkataramanj, B. (2013). Development of stainless steels in nuclear industry: With emphasis on sodium cooled fast spectrum reactors: History, technology and foresight. *Advanced Materials Research*, 794, 3–25.

Stachowiak, A., & Zwierzyczki, W. (2012). Analysis of the tribocorrosion mechanisms in a pin-on-plate combination on the example of AISI 304 steel. *Wear*, 294, 277–285.

Subramanian, V., Chandramoha, P., Srinivasan, M. P., Sukumar, A. A., Raju, B. V. S., Velmurugan, S., & Narasimhan, S. V. (2004). The effect of conditioning by permanganate on the dissolution behavior of stellite particles in organic complexing acid medium. *Journal of Nuclear Materials*, 334, 169–179.

Sun, Y., & Rana, V. (2011). Tribocorrosion behaviour of AISI 304 stainless steel in 0.5 M NaCl solution. *Materials Chemistry and Physics*, 129, 138–147.

Tachibana, M., Ishida, K., Wada, Y., Shimizu, R., Ota, N., & Hara, N. (2012). Determining factors for anodic polarization curves of typical structural materials of boiling water reactors in high temperature – High purity water. *Journal of Nuclear Science and Technology*, 49, 253–262.

Vazquez-Arenas, J., & Pritzker, M. (2010). EIS study of nickel deposition in borate–Sulfate solutions. *Journal of the Electrochemical Society*, 157, 283–D294.

Wang, Z., Yan, Y., Su, Y., & Qiao, L. (2019). Effects of stirring action during friction on electrode processes of AISI 304 stainless steel in sulphuric acid. *Electrochimica Acta*, 298, 756–769.

Wood, J. K. (2007). Tribo-corrosion of coatings: A review. *Journal of Physics D: Applied Physics*, 40, 5502–5521.

Zhang, Y., Yin, X. Y., & Yan, F. Y. (2015). Effects of halide concentration on tribocorrosion behaviour of 304SS in artificial seawater. *Corrosion Science*, 99, 272–280.

Zhang, Y., Yin, X. Y., Yan, Y. F., Wang, J. Z., & Yan, F. Y. (2015). Tribocorrosion behaviors of 304SS: Effect of solution pH. *RSC Advances*, 5, 17676–17682.