Friction and wear characterization of graphite/Polytetrafluoroethylene composites against stainless steel: A comparative investigation under different environments

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Abstract. The friction and wear characteristics of Polytetrafluoroethylene composites filled with 15 wt.% and 25 wt.% graphite were investigated against stainless steel under dry sliding and in aqueous environments. A pin on disc tribometer was employed for experimentation at room temperature. The friction performance of 15 wt.% Graphite/Polytetrafluoroethylene proved better than 25 wt.% Graphite/Polytetrafluoroethylene under all conditions, however the wear performance was better for 25 wt.% Graphite/Polytetrafluoroethylene. Moreover, the tribological behaviour of all the composites enhanced in natural sea water environment. An average COF (0.02) and wear rate (1.27×10⁻⁵mm³/Nm) were attained for 15 wt.% Graphite/Polytetrafluoroethylene in sea water; and an average COF (0.0293) and wear rate (5.2×10⁻⁶mm³/Nm) were obtained for 25 wt.% Graphite/Polytetrafluoroethylene in sea water. From SEM analysis it was revealed that the better tribological performance of graphite/Polytetrafluoroethylene in sea water is due to the formation of lubricious films on the surfaces in sea water.

1. Introduction
Polytetrafluoroethylene composites are widely used as self-lubricating materials for dry running applications where the use of lubricating oil is avoided. Moreover, polytetrafluoroethylene composites are also suitable for use in aqueous environments like sea water due to low water absorption and good chemical resistance [1, 2]. Since its discovery by Dr. Plunkett at DuPont Laboratory USA in 1938, research has been extensively conducted on Polytetrafluoroethylene composites and it has been applied successfully in self-lubricating applications in bearings and seals [3-5].

The literature enlightening the tribo-performance of polytetrafluoroethylene composites with various reinforcements like glass fibers, carbon fibers, MoS₂, TiO₂, graphite, bronze etc. is sufficient with regard to dry sliding [6-27]. However, limited literature is available with regard to friction and wear behaviour in aqueous environments. Moreover, very limited amount of work has been reported on graphite/Polytetrafluoroethylene composites. Wang and Yan examined the tribological performance of 15 vol.% graphite/Polytetrafluoroethylene under dry sliding and observed that graphite/Polytetrafluoroethylenexhibited better wear resistance than virgin Polytetrafluoroethylene owing to strong adhering of the transfer film on the counter body [28]. Goyal
and Yadav investigated the tribological performance of graphite/Polytetrafluoroethylene composites with varying percentage of graphite (0-10 wt. %) in dry conditions and observed that development of a thin and firm transfer film of the Polytetrafluoroethylene composites on stainless steel counter bodies lead to better tribological performance of graphite/Polytetrafluoroethylene composites than virgin Polytetrafluoroethylene [8]. Yamada and Tanaka investigated the wear properties of 15 wt.% graphite/Polytetrafluoroethylene with stainless steel counter surface under dry conditions and boundary lubricated condition with water and observed that wear behaviour of 15 wt.% graphite/Polytetrafluoroethylene composite is better under dry sliding than under boundary lubricated condition with water [29]. Wang et al., studied the tribological performance of 20 vol.% Graphite/Polytetrafluoroethylene composites with GCr15 steel and Ni-Cr-WC alloy in sea water and observed that the significant factors impacting the friction and wear under sea water are lubricating influence and corrosiveness of sea water [30].

The friction and wear studies have not been carried out on 15 wt. % Graphite and 25 wt. % Graphite filled polytetrafluoroethylene composites in natural sea water against stainless steel. Therefore, the current research study comparatively investigated the tribological performance of the aforesaid Polytetrafluoroethylene composite grades in natural sea water, distilled water and ambient air (dry sliding). The results of this research will assist in design/selection of friction pairs for aqueous environments where graphite/Polytetrafluoroethylene composites are suitable materials.

2. Materials and experimental

2.1. Materials
The graphite/Polytetrafluoroethylene composites and counter surface stainless steel (AISI 420) were purchased from trustworthy sources within the country. 15 wt.% Graphite/Polytetrafluoroethylene and 25 wt.% Graphite/Polytetrafluoroethylene composites were obtained in the form of discs and were finished to dimensions of 30 mm diameter and 10 mm height, whereas counter surface stainless steel material (AISI 420) was obtained in the form of balls of 10 mm diameter. The chemical composition of as received balls is presented elsewhere in [31]. The natural sea water taken from Mumbai (GOI coast) was used in the study. The microstructure of graphite/Polytetrafluoroethylene composites is shown in Figure 1.

![Figure 1. Microstructure (a) 15 wt. % Graphite/Polytetrafluoroethylene; (b) 25 wt. % Graphite/Polytetrafluoroethylene.](image-url)

2.2. Tribological tests
The tribo-tests were executed on ball on disc tribo-tester in natural sea water, distilled water and ambient air (dry sliding) under reciprocating sliding conditions. The description of the ball on disc tribometer is shown elsewhere in [31]. The tribological experiments were executed at 10N normal load while maintaining the reciprocating frequency at 25Hz and reciprocating stroke at 2 mm. The test
duration was kept constant at 60 minutes. The COF was attained using a DAQ System through a computer coupled to the tribometer. The volume loss of material or wear volume was obtained by using the equations put forth in [32]. Further, the specific wear rate was calculated using equation (1).

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\text{Specific wear rate} = \frac{\text{Volumeloss}(\text{mm}^3)}{\text{Normal load (N)} \times \text{Sliding distance (m)}} \tag{1}
\]

Three samples were tested for each set of experiments as every tribological experiment was repeated three times and mean of obtained result values is presented.

3. Results and analysis

3.1. Friction analysis

Figure 2 (a) and Figure 2 (b) show the friction coefficient vs. sliding time for 15 wt.% graphite/Polytetrafluoroethylene and 25 wt.% graphite/Polytetrafluoroethylene composites respectively sliding against stainless steel under dry conditions and in aqueous environments. From Figure 2 (a) it can be observed that under dry sliding the friction coefficient of 15 wt.% graphite/Polytetrafluoroethylene upsurges with advancement in sliding time till 500 seconds and then nearly attains a stable state. The friction coefficient of 15 wt.% graphite/Polytetrafluoroethylene under distilled water is comparatively lesser than dry running and it upsurges with advancement in sliding time till 2400 seconds and then nearly attains a stable state. Further, the friction coefficient of 15 wt.% graphite/Polytetrafluoroethylene is lowest in sea water and it fluctuates with ups and downs till 2100 seconds advancement in sliding time and then obtains a stable state. Also, from Figure 2 (b) it can be seen that friction coefficient of 25 wt.% graphite/Polytetrafluoroethylene upsurges with advancement in sliding time in case of dry running. However, the friction coefficient of 25 wt.% graphite/Polytetrafluoroethylene under distilled water is comparatively lesser than dry conditions and it fluctuates till 900 seconds of sliding and then reduces with advancement in sliding time till 2700 seconds and then obtains a stable state. Moreover, the lowest friction coefficient is attained for 25 wt.% graphite/Polytetrafluoroethylene in sea water. The COF initially decreases with advancement in sliding time till 1500 seconds and then nearly obtains a stable state. The average friction coefficients for 15 wt. % graphite/Polytetrafluoroethylene and 25 wt. % graphite/Polytetrafluoroethylene for all test conditions are presented in Figure 3 (a). It is clear from Figure 3 (a) that for the 15 wt. % graphite/Polytetrafluoroethylene the lowest average COF of 0.02 is attained in sea water tailed by distilled water (0.033) and dry sliding (0.056). Also, for the 25 wt. % graphite/Polytetrafluoroethylene the lowest average COF of 0.029 is obtained in sea water tailed by distilled water (0.059) and dry sliding (0.075). It is evident from the results obtained that the friction performance of 15 wt.% graphite/Polytetrafluoroethylene is better than 25 wt.% graphite/Polytetrafluoroethylene in all sets of conditions. This is in conformity with results obtained in [8], wherein it is reported that COF increases with increase in graphite wt. %age in Polytetrafluoroethylene. However, in [8] the friction tests were conducted only in the dry state and the chosen wt. %ages of graphite were 2, 5 and 10. Also, in the present case, it is evident from the results that for both the graphite/Polytetrafluoroethylene composites lowest average friction coefficient is observed in sea water tailed by distilled water and dry running conditions. So, water environment offers better friction performance than dry conditions. This is in conformity with results attained in [33] and [34] wherein the authors reported that introducing water at the polymer/metal friction pair interface can decrease the COF.

In the present work, the highest friction coefficient of graphite/Polytetrafluoroethylene composites under dry sliding is ascribed to creation of non-tenacious and discontinuous transfer films on counter surfaces (Figure 5 (a) and Figure 7 (a)). The authors of [8] argued that graphite in the Polytetrafluoroethylene matrix hampers the transfer film formation as graphite particles tend to form aggregates and thus prevent the development of thin and firm transfer film. In case of sliding in
distilled water the average friction coefficient is less than that under dry conditions for both the graphite/Polytetrafluoroethylene composites. This is due to lubricating influence of distilled water. However, in natural sea water better friction results were obtained for both the graphite/Polytetrafluoroethylene composites in comparison to other testing conditions. Scanning electron microscopic analysis of the weartracks of the graphite/Polytetrafluoroethylene composites after tribo-tests in natural sea water showed the development of films on worn surfaces (Figure 4 (c) and Figure 6 (c)). Figure 4 (c) and Figure 6 (c) show the tribo-films formed on the surfaces of 15 wt.% graphite/Polytetrafluoroethylene and 25 wt.% graphite/Polytetrafluoroethylene in natural sea water respectively. Therefore, the low friction of graphite/Polytetrafluoroethylene composites is accredited to development of lubricious films on the worn surfaces of composites on sliding in sea water.

![Graph of Coefficient of friction vs. sliding time of graphite/Polytetrafluoroethylene composites](image)

**Figure 2.** Coefficient of friction vs. sliding time of graphite/Polytetrafluoroethylene composites (a) 15 wt. % Graphite/Polytetrafluoroethylene; (b) 25 wt. % Graphite/Polytetrafluoroethylene.

![Graph of Average COF and Specific wear rate](image)

**Figure 3.** Friction and wear outcomes of graphite/Polytetrafluoroethylene composites under different testing conditions (a) Average COF; (b) Specific wear rate.
Figure 4. SEM micrographs of wear surfaces of 15 wt.% Graphite/Polytetrafluoroethylene (a) Dry sliding; (b) Distilled water; (c) Natural sea water.

Figure 5. SEM micrographs of wear surfaces of stainless steel balls against 15 wt.% Graphite/Polytetrafluoroethylene (a) Dry sliding; (b) Distilled water; (c) Natural sea water.
3.2. Wear analysis

Figure 3 (b) represents the wear rate of 15 wt. % graphite/Polytetrafluoroethylene and 25 wt. % graphite/Polytetrafluoroethylene sliding against stainless steel under dry conditions and in aqueous environments. From Figure 3 (b) it is clear that 25 wt. % graphite/Polytetrafluoroethylene displays better wear performance than 15 wt. % graphite/Polytetrafluoroethylene in all sets of testing conditions. Similar results were attained in [8] wherein it is reported that wear resistance improves with increase in graphite content. However, as already mentioned in the preceding section, in [8] the tribo-tests were carried out only under dry sliding and the chosen wt. %ages of graphite were 2, 5 and 10. In the present case, in case of 15 wt. % graphite/Polytetrafluoroethylene the minimum specific wear rate of 12.7×10^{-6} mm^3/Nm is achieved under natural sea water environment tailed by distilled water environment (26.8×10^{-6} mm^3/Nm) and dry sliding (47.1×10^{-6} mm^3/Nm). In case of 25 wt. % graphite/Polytetrafluoroethylene the minimum wear rate of (5.2×10^{-6} mm^3/Nm) is achieved under...
natural sea water environment trailed by distilled water environment (9.9×10^{-6} \text{mm}^2/\text{Nm}) and dry sliding (11.2×10^{-6} \text{mm}^2/\text{Nm}).

Figures 4 (a), 4 (b) and 4 (c) present the scanning electron micrographs of wear surfaces of 15 wt. % graphite/Polytetrafluoroethylene under dry sliding, distilled water environment and natural sea water environment respectively. Also, Figures 6 (a), 6 (b) and 6 (c) present the scanning electron micrographs of wear surfaces of 25 wt. % graphite/Polytetrafluoroethylene under dry sliding, distilled water environment and natural sea water environment respectively. Figure 4 (a) indicates that under dry sliding for the 15 wt. % graphite/Polytetrafluoroethylene the wear mechanism is a combination of plastic deformation, severe delamination and adhesive wear. The formation of grooves accompanied with delamination wear is also observed. Also, Figure 6 (a) reveals that plastic deformation is the dominant wear mode accompanied with minor delamination and minor abrasion for the 25 wt. % graphite/Polytetrafluoroethylene dry sliding. No grooves are present on wear track of 25 wt. % graphite/Polytetrafluoroethylene under dry conditions. Comparing the two SEM micrographs (Figure 4 (a) and Figure 6 (a)), it is clearly observed that 25 wt. % graphite/Polytetrafluoroethylene has better wear resistance than 15 wt. % graphite/Polytetrafluoroethylene under dry conditions. Moreover, the corresponding Scanning electron micrographs of stainless steel balls under dry sliding show discontinuous and loose transfer films on the surfaces of stainless steel balls (Figure 5 (a) and Figure 7 (a)). This indicates the high wear of the graphite/Polytetrafluoroethylene composites under dry sliding compared to other testing conditions. However, in case of distilled water environment the scanning electron micrographs of wear surfaces of 15 wt. % graphite/Polytetrafluoroethylene and 25 wt. % graphite/Polytetrafluoroethylene show only plastic deformation as the dominant wear mechanism (Figure 4 (b) and Figure 6 (b)). No formation of grooves is observed. Moreover, the corresponding scanning electron micrographs of stainless steel balls under distilled water (Figure 5 (b) and Figure 7 (b)) show no transfer film formation on the surfaces. However, polishing of the balls is observed from the SEM micrographs. This implies that the contact pressure falls while sliding which indicates lower wear of the graphite/Polytetrafluoroethylene composites under distilled water environment compared to dry running conditions. Moreover, it is clear from Figure 5 (b) and Figure 7 (b) that greater polishing effect on the stainless steel ball is observed on sliding against 25 wt. % graphite/Polytetrafluoroethylene than 15 wt. % graphite/Polytetrafluoroethylene. This indicates that 25 wt. % graphite/Polytetrafluoroethylene has better wear resistance than 15 wt. % graphite/Polytetrafluoroethylene under distilled water. In natural sea water environment, the scanning electron micrographs of wear surfaces of 15 wt. % graphite/Polytetrafluoroethylene (Figure 4 (c)) and 25 wt. % graphite/Polytetrafluoroethylene (Figure 6 (c)) show the formation of continuous and tenacious films on the surfaces. Moreover, the corresponding SEM micrographs of the stainless steel balls in natural sea water (Figure 5 (c) and Figure 7 (c)) also show the similar films. Therefore, it is clear that the improved wear resistance of graphite/Polytetrafluoroethylene composites in natural sea water is because of the development of lubricious films on surfaces of graphite/Polytetrafluoroethylene and counter surface stainless steel on sliding under sea water environment. These films are formed due to corrosiveness of sea water. These films contain corrosion products of iron and chromium as oxides. This has been reported elsewhere in [28].

4. Conclusions
The conclusions of this study are summarized below:

1. The 15 wt.% graphite/Polytetrafluoroethylene composite possesses better friction performance than 25 wt.% graphite/Polytetrafluoroethylene composite under all sets of conditions. However, the 25 wt.% graphite/Polytetrafluoroethylene composite possesses better wear performance than 15 wt.% graphite/Polytetrafluoroethylene composite under all sets of conditions.

2. Both the graphite/Polytetrafluoroethylene composites show higher COF and specific wear rate under dry sliding conditions in comparison to sliding in distilled water and sea water. This is ascribed to the formation of non-tenacious and discontinuous transfer films on the counter surface stainless steel under dry sliding.
3. The polishing effect on counter surface balls is observed under distilled water environment due to which the contact pressure falls while sliding which results in lower wear of graphite/Polytetrafluoroethylene composites under distilled water environment in comparison to dry sliding.

4. The graphite/Polytetrafluoroethylene composites show better tribological behavior in natural sea water in comparison to distilled water and dry running which is credited to development of lubricious films on wear tracks of graphite/Polytetrafluoroethylene composites on sliding in sea water.

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