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DRY WEAR STUDIES ON REDUCED GRAPHENE OXIDE FILLED UHMWPE COMPOSITES

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Abstract: *Reduced graphene oxide filled ultra-high molecular weight polyethylene matrix composites were produced by a method of liquid phase ultrasonic mixing and then hot press molding. The wear and friction behavior of UHMWPE composites containing up to 3.0 wt. % RGO filler were investigated in sliding against an Al_2O_3 counterface by a constant loading (5 N) and sliding speed (1.7 cm s^{-1}) experiments carried out in a reciprocating friction testing machine under dry conditions at room temperature. The results showed that, when the content of RGO was up to 1.0 wt. %, wear resistances of the composites were improved significantly. To analyze wear mechanisms, wear surfaces were examined by field emission scanning electron microscopy (FE-SEM) and it was found that, as RGO was added into the UHMWPE matrix the tribological behavior of the UHMWPE composites transformed from fatigue wear to adhesive wear associated with the increase of interaction between RGO and UHMWPE matrix and lubricant and binder properties of RGO.*

Keywords: *Reduced graphene oxide, UHMWPE, Composite, Friction, Dry wear.*

1. INTRODUCTION

Ultrahigh molecular weight polyethylene (UHMWPE), with molar weights exceeding one million, has been extensively used as a bearing material for arthroplasty applications especially in knee and hip artificial implant due to its unique characteristics, such as high impact strength, good biocompatibility and low friction coefficient [1-3]. However, UHMWPE has several disadvantages such as the low surface hardness and Young's modulus, and anti-fatigue capacity [4-5]. Moreover, UHMWPE produces wear debris during application and these debris limits to the life time of UHMWPE joints [2]. Therefore, remedial approaches have been developed to enhance the mechanical and tribological properties of the UHMWPE. The use of graphene and graphene derivatives is one of the research efforts exploited to achieve this goal. The reduced graphene oxide (RGO) is chemical type of graphene, inexpensive and a new antibacterial filler material for bio based polymer composites [6-7]. There are several studies conducted to improve mechanical and wear properties of UHMWPE composites with graphene derivatives [1, 6, 8-9].

However, to the best of our knowledge, there are no previous studies reported in the literature about synthesis and wear properties of UHMWPE composites with RGO fillers that was synthesized by vitamin C. The objective of this work is to investigation of dry wear properties of UHMWPE composites with the use of RGO. A series of UHMWPE composites with RGO fillers were prepared to study the dry wear properties, such as the wear rate and friction coefficient, and compared with unfilled UHMWPE. Therefore, we concluded that RGO plays a pivotal role in enhancing the tribological properties because of the good interactions and excellent incorporation of RGO fillers into the UHMWPE matrix.

2. EXPERIMENTAL METHODS

GO was prepared according to a modified Hummers' method [10]. To prepare RGO, 1 g of GO was dispersed in 500 mL of DI water. pH of the GO suspension was adjusted to ~10 by using ammonia solution. Then 1 g of vitamin C was added to the mixture and heated at 95°C for 12 h. After that the mixture was filtered, washed with DI water several times and dried at 65°C for 12 h to obtain the RGO sample as a black powder.

A series of the composites were prepared with the mass ratios (RGO:UHMWPE) of 0.1, 0.3, 1.0, 2.0 and 3.0 wt%. The codes of unfilled UHMWPE and these five composites were UHMWPE, RGO-0.1/UHMWPE, RGO-0.3/UHMWPE, RGO-1.0/UHMWPE, RGO-2.0/UHMWPE, and RGO-3.0/UHMWPE. The prepared RGO powders were dispersed by ultrasonic treatment (30 min) in ethyl alcohol to form a well-dispersed suspension. After that, the suspensions were added into the UHMWPE powders and the mixture was stirred for 30 min and then ultrasonicated for 1h. Then the ethyl alcohol was removed at 60-70°C in an oil bath and the composite powders were completely dried in an oven at 60 °C. Finally, the unfilled UHMWPE and composite powders were molded by hot-pressing at 180°C under a 10 MPa pressure and holding at this pressure for 30 min. The synthesis process of UHMWPE composites was illustrated in Figure 1. Tribological properties of obtained composites were investigating using a reciprocating wear tester under dry sliding conditions. The ambient temperature was approximately 25 °C and the relative humidity was nearly 30 ± 5 %. The wear tests on all samples were performed under a constant load of 5 N using a 10 mm diameter Al_2O_3 ball at a sliding velocity of 1.7 cm s^{-1} , while sliding distance was 50 m. The wear was calculated by analysing width and depth of wear scars developing on composite surfaces with the help of a contact stylus profilometer (SJ400). Worn surface morphologies of composites were observed by using a Carl Zeiss AG, SUPRA 40 model field emission Scanning Electron Microscope (FE-SEM). Following the wear tests, the Al_2O_3 counterface surfaces were examined under an Optical Microscope (OM) in order to investigate the wear mechanisms.

3. RESULTS AND DISCUSSION

Wear rate and friction coefficient are the most two important representative values to characterize the tribological properties [11]. Fig. 2 showed the impact of loading content of RGO on the wear rate of the UHMWPE composites. As presented in Fig. 2, the wear rate of the UHMWPE composites was decreased by the high RGO content (up 1.0 wt. %).

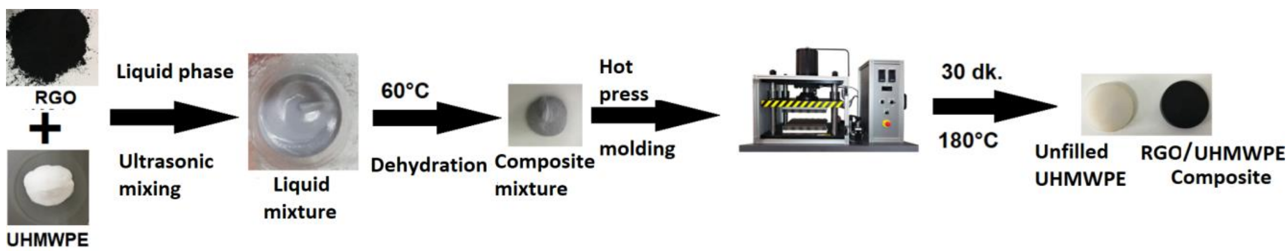


Figure 1. Illustration for the preparation of UHMWPE composites

The RGO filler improved the wear resistance of polymer matrix at a relatively high loading. The UHMWPE composite with 3.0 wt% RGO content showed the lowest wear rate under dry test conditions. The similar results have been found by Tai et al. [1]. RGO network transfered good load because ıt has ideal mechanical properties and high specific surface area [6]. Table 1 showed that the friction coefficient values of unfilled UHMWPE and UHMWPE composites. As can be seen in Table 1, the all composites with RGO fillers exhibited a continuously decreasing trend except for the composite with 1.0 wt% of RGO. For RGO-0.1/UHMWPE, RGO-0.3/UHMWPE, RGO-2.0/UHMWPE and RGO-3.0/UHMWPE composites, RGO displayed lubricant properties because of a decrease in the friction coefficient, when RGO was added into UHMWPE matrix. However friction coefficient increased, lubricating effect of graphene decreased in the composite with 1.0 wt% of RGO. This can be attributed to the encounter of lateral force with RGO-UHMWPE bond or RGO-RGO interlayer van der Waals bonds during wear process [8, 12].

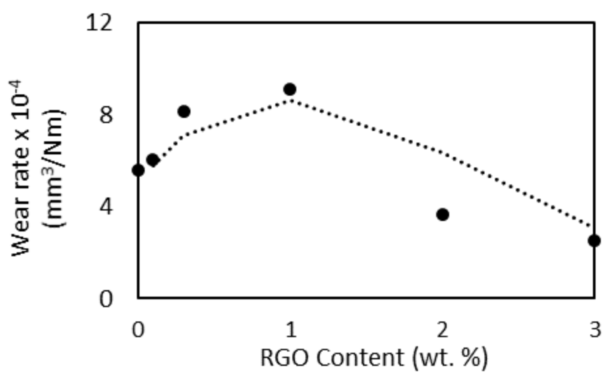


Figure 2. Wear rate of UHMWPE filled with various contents of RGO

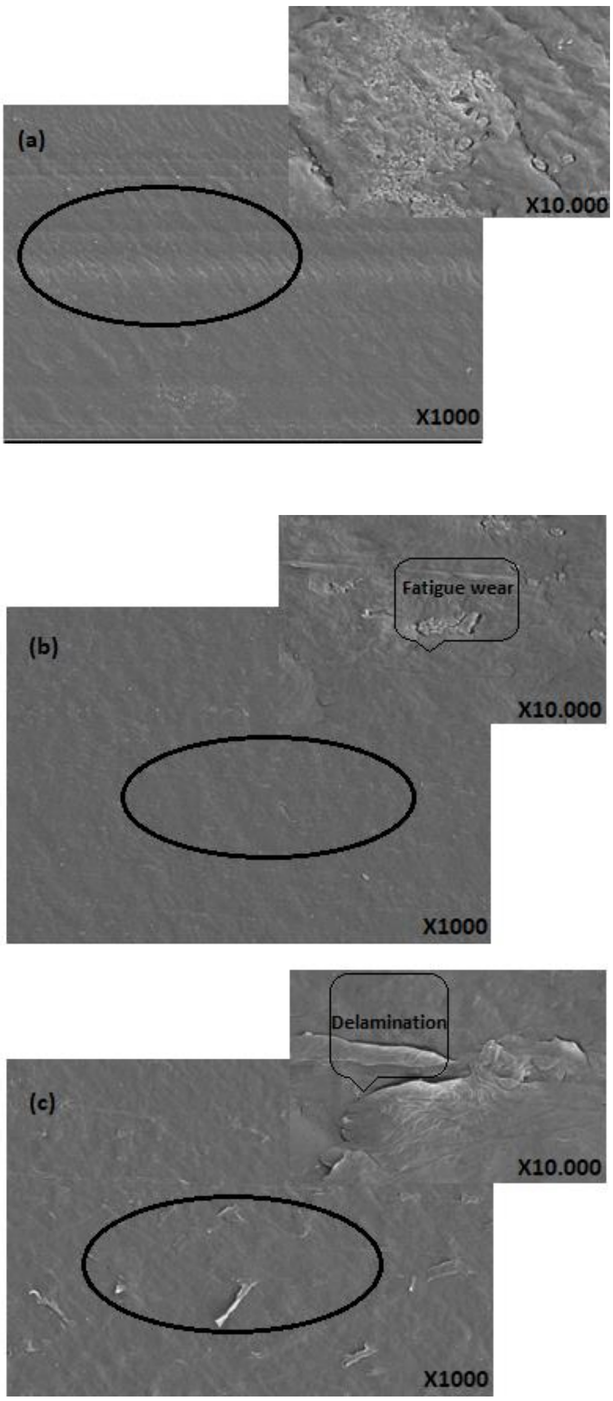
In the present study, the worn surfaces of the UHMWPE composites were characterized using FE-SEM observation to understand the influence of the RGO loading content on its dry wear mechanism (Fig. 3a-f). Plastic deformation could be found on unfilled UHMWPE worn surface in the low magnified image (Fig.3a), which are the typical characteristics of adhesive wear [13]. The fatigue wear was found dominant where the surface layer of the unfilled UHMWPE were stripped large pieces of material in the high magnified image (Fig.3a) [6].

Table 1. Friction coefficient values of UHMWPE filled with various contents of RGO

Samples	*Friction coefficient*
UHMWPE	0,098
RGO-0.1/UHMWPE	0,068
RGO-0.3/UHMWPE	0,056
RGO-1.0/UHMWPE	0,062
RGO-2.0/UHMWPE	0,046
RGO-3.0/UHMWPE	0,036

The wear tracks of RGO-0.1/UHMWPE composites shown in Fig. 3b depicted smaller pieces of material as compared to the unfilled UHMWPE and adhesive wear tracks decreased on a large scale. From the image shown in Fig. 3(c), it can be seen that there were large flakes of wear debris, which indicated that delamination. Surface delamination in Fig. 3(c) is sign of fatigue wear [14]. For the RGO-1/UHMWPE composite, the debris obtained from the worn surface after the sliding wear test acted as a second body in between the contact surfaces which corresponded well with the previous analysis of the friction coefficient (Table 1). From the low magnified image shown in Fig. 3(d), it is clear that adhesive wear tracks increased on surface of composite. The obvious tear layers were observed on the surface of RGO-1/UHMWPE as shown in high magnified image (Fig. 3d), which indicated the shedding of composite material. The RGO-2/UHMWPE and the RGO-3/UHMWPE composites exhibited a smooth wearing surface after the test, although it had a small amount of debris. Thus, resulted in better tribological performance because of a lubrication mechanism by bonding the RGO and UHMWPE along the interlayer surface.

In order to explain the mechanisms involved in the wear process, the Al_2O_3 ball counterfaces were analyzed by OM. All wear tracks showed formation of a transfer layer on the Al_2O_3 ball surface. The worn surface morphology of Al_2O_3 ball against unfilled UHMWPE as shown in Fig. 4 are similar to that of RGO-0.1/UHMWPE and RGO-2/UHMWPE composites and they have a thin and uniform transfer film on the Al_2O_3 ball but the transferred debris increased on the surface of RGO-0.3/UHMWPE, RGO-1/UHMWPE and RGO-3/UHMWPE composites. At the same time, many particule-like wear debris was seen throughout over the Al_2O_3 ball surface of the rapidly wearing RGO-1/UHMWPE composite (Fig. 4). This image of counterface was consistent with the results obtained from wear rate and friction coefficient (Fig.2 and Table 1).



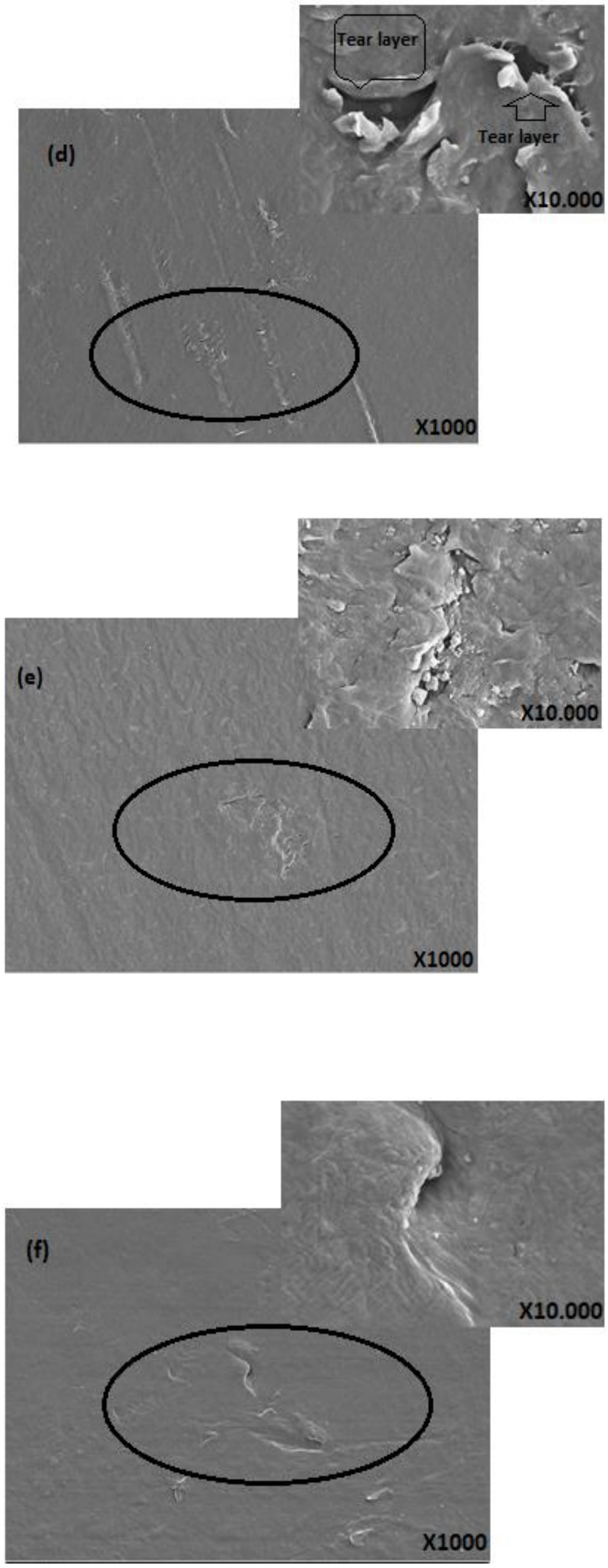


Figure 3. Low and high magnification SEM micrographs of wear tracks generated on the (a)UHMWPE, (b)RGO-0.1/UHMWPE, (c)RGO-0.3/UHMWPE, (d)RGO-1/UHMWPE, (e)RGO-2/UHMWPE and (f)RGO-3/UHMWPE composites

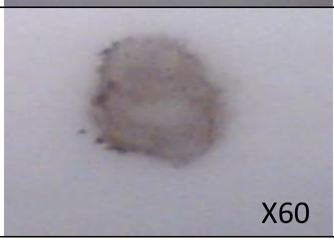
Samples	OM Images
Unfilled UHMWPE	 X60
RGO-0.1/UHMWPE	 X60
RGO-0.3/UHMWPE	 X60
RGO-1/UHMWPE	 X60
RGO-2/UHMWPE	 X60
RGO-3/UHMWPE	 X60

Figure 4. OM images of the Al_2O_3 balls sliding against the UHMWPE, RGO-0.1/UHMWPE, RGO-0.3/UHMWPE, RGO-1/UHMWPE, RGO-2/UHMWPE and RGO-3/UHMWPE composites.

4. CONCLUSIONS

The high aspect ratio and large surface area of RGO fillers provided a positive influence on the friction coefficient and in the wear rate. Also enhance the interaction between the polymer and the filler, resulting in an efficient load transfer from the matrix to the filler. At the high RGO percentages (2 and 3 wt%), the wear mechanism seems to be adhesive wear, while at the low RGO percentages (0.1, 0,3 and 1) fatigue wear predominates. The incorporation of RGO into UHMWPE in amounts around 2 and 3 wt. % can reduce the frictional coefficient and the wear rate. Under sliding contact, lubrication capability of graphene have a significantly effect.

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