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Influence of Counterface Materials on the Tribological Behavior of Dental Polymethyl Methacrylate Reinforced by Single-Walled Carbon Nanotubes (SWCNT)

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Abstract: The objective of this research is to study counterface materials effect on the tribological behavior of dental polymethyl methacrylate reinforced by single-walled carbon nanotubes (SWCNT) of 0.1 wt. % content. PMMA denture base material is prepared in hot acrylic resins. The counterface materials effect on the tribological behavior of PMMA and SWCNT/PMMA composite was observed using a list of counterface materials that used in the oral cavity are used in both of dry and wet conditions. The lubrication liquid that used in the wet condition was artificial saliva. The counterface materials that used in the study were polymethyl methacrylate (PMMA), stainless steel, porcelain, amalgam and buffalo teeth. Friction coefficient and wear are measured by testing the specimens on a reciprocating device at room temperature. It can be noticed that the counterface materials had a distinct effect on the coefficient of friction, wear and \ surface roughness of the PMMA composites. According to the results, it was found that the buffalo tooth and porcelain counterface lead to higher wear resistance, while the amalgam material showed minimal wear resistance under dry and wet conditions. The amalgam material had the highest coefficient of friction value in the dry and wet test, the PMMA material showed the highest value of the coefficient of friction. The surface roughness of stainless steel showed the highest value while the other counter-face materials can have the same value in the dry state while in the wet state the surface roughness of the buffalo teeth showed the minimum value, while other counterface materials may have the same value.

Keywords: PMMA, SWCNTs, wear, friction coefficient, Counterface material.

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1. Introduction

Removable dentures are widely used for replacing missing teeth in dental applications, [1]. Polymethyl methacrylate (PMMA) is the material commonly used to fabricate denture bases using the heat-curing technique since the 1940s [2]. It has the advantage of low cost, a simple fabrication process, light weight, satisfactory aesthetics, color matching ability, and easy to do finishing and polishing processes, [1]. However, some disadvantages remain, such as insufficient surface hardness; weak and brittle, [3–5]. Denture fracture is a common clinical problem that usually occurs due to large occlusal forces or accidental damage. Most denture fractures are produced by a grouping of fatigue and impact failure, while for mandibular prostheses 80% of fractures are produced by impact and involve very high repair costs worldwide [6]. In 1997, over a million dentures were required to be repaired in the United Kingdom alone because of the impact strength and the poor fracture of the used material. Therefore, dental technicians need an accurate considerate of the reasons and mechanisms of fracture, in addition to the improvement of enhanced materials [7]. In addition, prosthesis fracture is also recurrently related to defective design, manufacture, and choice of material [8]. One of the important requirements for a good performance of the prosthesis-based resin is its adequate impact resistance and fracture toughness [9]. Another crucial property is surface hardness, which helps to facilitate finishing/polishing and provides good scratch resistance during denture cleaning [10, 13]. The main disadvantage of the PMMA denture base is the low fracture toughness [3].

Many studies have been made to develop denture base materials properties through adding appropriate fillers into the PMMA denture base. Synthetic rubbers (styrene butadiene copolymer, SBR) act as an impact modifier that absorbs (absorbing) energy during the application of fracture load. However, to date there are no reports on the use of nitrile butadiene rubber (NBR) to reinforce the PMMA denture base. The adding of NBR particles in the PMMA compound could be beneficial to absorb part of the fracture or impact force and go from a brittle to a ductile character and, moreover, it does not have an allergic reaction on contact with the oral tissue of the prostheses(non-toxic), [14]. Therefore, the remaining problems on the impact resistance and fracture toughness of the PMMA denture base can be more enhanced by adding of NBR particles. The adjustment of the properties of hardness, toughness and possibly radiopacity can be modified by incorporation of ceramic fillers (Al2O3 and YSZ). The Al_2O_3 particles are more brittle and rigid than the matrix of resin and so develop the dental composite hardness [15]. Adding YSZ reinforcement can increase the composite strength, [16]. Both YSZ and Al2O3 are very popular as structural bioceramics because of their inert properties in higher fracture toughness and physiological media, [17]. The adding particles of NBR that mixed with different contents of two types of ceramic fillers (treated with a silane coupling agent) was explored in order to develop the fracture toughness and the impact resistance of the base material of the prosthesis, PMMA [18]. The results recommend that the fracture toughness and impact resistance of the heat cured PMMA denture resin was improved after filling by treated ceramic fillers and NBR particles, while the VH was not significantly enhanced. These improvements have been achieved through the use of a silane coupling agent which offers the possibility of further improving the properties. This research revealed that the optimum content of fillers in this composite is 7.5% NBR with 2.5% Al_2O_3/2.5% YSZ. Consequently, when high KIC and IS are required, reinforcement of PMMA denture base with NBR and ceramic fillers is the best choice for removable dentures. The researchers now days went to use nanotechnology in dentistry. It has also been observed that loading the resin with small amounts of Al_2O_3 nanoparticles plays a prominent role in prosperity their properties [19]. The nanofillers effect on the friction and wear of polymeric composites was investigated. It can be noticed that the hardness, friction coefficient and wear resistance of polymeric composites affected by concentration of nanofillers and normal load, [20- 23]. Carbon nanotubes are especially presented into polymer matrices like epoxy to produce polymer matrix nanocomposites which presents a new production of composite materials, [24 - 28]. Increase in strength and Young's modulus of fabricated double-walled carbon nanotubes/epoxy nanocomposites was reported at nanotubes content of 0.1 wt. %, [24] the resulting nanocomposites. The influence of dispersed multi-walled carbon nanotube (MWCNT) on the improvement of tribological behavior of PMMA was investigated, [29-31]. The wear, friction and hardness were affected by adding different contents of MWCNTs. The enhancement of strength and Young's modulus of phenolic composites reinforced by single-walled carbon nanotubes was stated, [26].The tribological behavior of the polymeric composites and the influence of counterface materials on the wear and friction coefficient of dental composite resin was investigated, [32-35]. In the current work, the effect of counterface materials on the tribological behavior of dental polymethyl methacrylate reinforced by single-walled carbon nanotubes (SWCNTs) is studied.

2. Experimental

2.1 Materials

The composite matrix used in the present study is polymethyl methacrylate (PMMA) which filled with fiber of single-walled carbon nanotubes (SWCNT). Practically, PMMA is found in two forms as cold and heat cured acrylic resins. Table 1 shows the properties of PMMA as acrylic resin which was purchased from (Acrostone Dental & Medical Supplies Company), Cairo, Egypt. Table 2 shows properties for SWCNT which was purchased from Nanostructured &Amorphous materials, Inc., texas, USA.

2.2 Preparation of Test Specimen

Test specimens have been made of a PMMA matrix. The SWCNT were added in a content of 0.1 wt. %. specimens have been fabricated from PMMA with 0%wt.of the filler (as received) and the rest specimens have been fabricated by adding a content of 0.1 wt. % SWCNTs to the PMMA powder in a glass beaker, then mixed for 20 second and added to the mold of specimens of cylindrical shape as shown in **Figures 1** and **2**. The molds of the hot cured specimens were put in a water bath at 100°C for 30 Minutes and then ejected and left for cooling at room temperature. Test specimens were cut at both ends to flatten the two bases and finished by emery paper of 1000 grain size. **Figures 3** and **4** show photographs for specimens of pure PMMA and composite of PMMA with SWCNTs filler respectively.

Table 1 Typical properties of acrylic PMMA

PROPERTY		VALUE
Physical	*Density (kg/m³)*	1188
	Water Absorption, 24 hrs. (%)	0.3
Mechanical	*Tensile Strength (MPa)*	50-70
	Tensile Modulus (Mpa)	2410-3440
	Tensile Elongation at Break (%)	2
	Fracture Strength (Mpa)	80-115
	Fracture Modulus (Mpa)	2410.16-3440.37
	Compressive Strength (Mpa)	75-130
	Compressive Modulus (Gpa)	2.70-3.30
	Hardness, Rockwell Scale M	M80-M100
	IZOD Notched Impact (KJ/m^2)	1.5

Table 2 Properties of the filler SWCNTs

Diameter, (nm)	Length, (μm)	Surface area, (m^2/g)	Purity, %
6	10-25	95-340	97

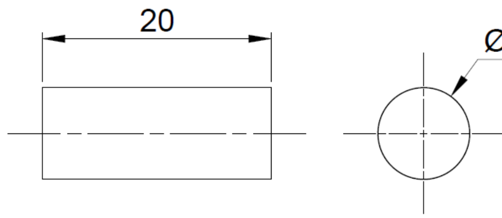

Fig. 1 Wear test specimen

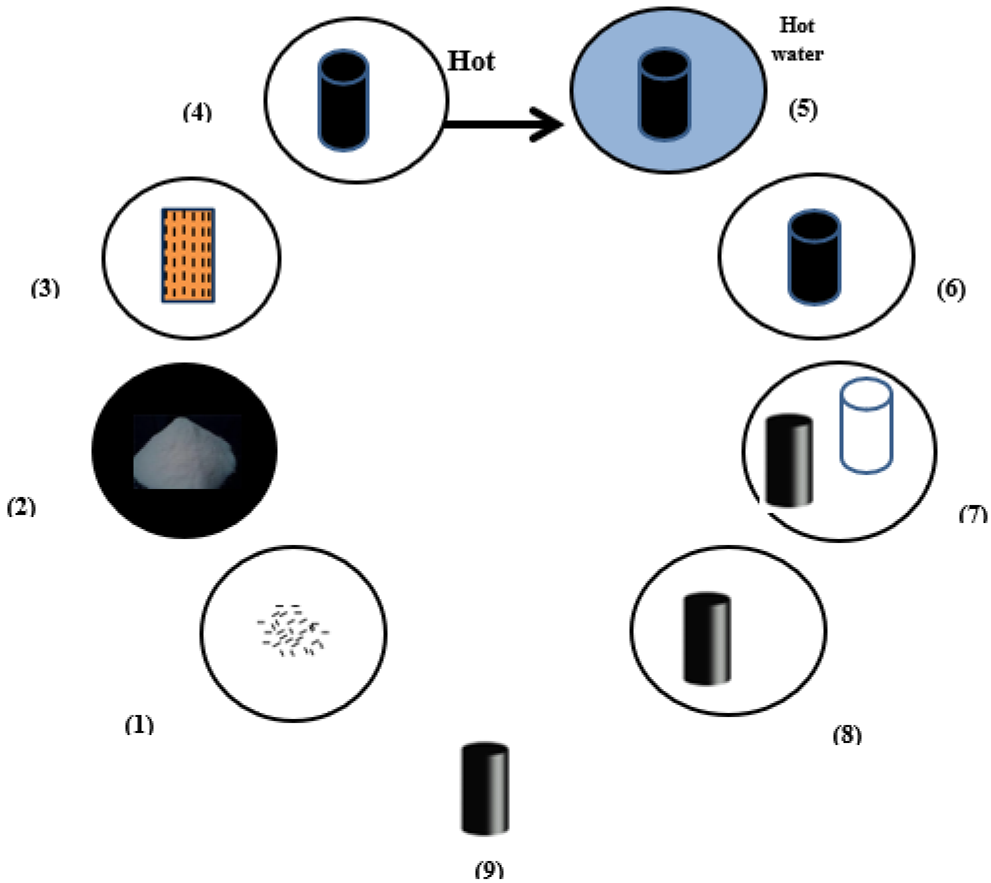

Fig. 2 Preparation steps of test specimens 1. SWCNTs, 2. PMMA, 3. Mixing, 4. Packing, 5. Curing, 6. Bench Cooling, 7. Removing, 8. Grinding, 9. Final Specimen.

Fig. 3 Sample of PMMA. material

Fig. 4 Sample of PMMA material reinforced with SWCNT.

2.3 Measuring Parameters

2.3.1 Wear Measurement

The test specimens wear resistance with 8 mm diameter and 20 mm length has been examined. Each specimen was held in the test specimen holder of the test rig and examined under normal load of 14 N as the maximum available load for a running time of 2, 4 and 6 minutes against a list of counterface materials that use in the oral cavity. The counterface materials that used in the study were polymethyl methacrylate (PMMA), stainless steel, porcelain, amalgam, and buffalo teeth and were used in both of wet and dry conditions. Artificial saliva was used as a lubricating fluid in wet condition. Each counterface material was adhered to the table of linear bearing. The table moved reciprocally at velocity of 60 stroke/min. Each specimen was abraded for a running distance of six meter against the counterface. The specimens were weighted before and after wear test using a digital balance of accuracy ± 0.0001g, then wear was determined by the weight loss. **Figure 5** shows the details of the reciprocating test rig. The counter face materials that used are shown in Table 3. The artificial saliva composition is shown in Table 4.

Table 3: The counter face materials used in the wear test

No.	Counter Face
1	Stainless steel
2	Porcelain
3	PMMA
4	Amalgam
5	Buffalo

Table 4: The composition of artificial saliva

Compound	Concentration
Na_2HPO_4	0.4 g
$NaHCO_3$	1.7 g
$CaCl_2$	0.15 g
H_2O	800 ml
HCL-1M	2.5 ml

2.3.2 Coefficient of Friction Measurement

Friction force is determined through subjecting each specimen against a list of counterface materials that use in the oral cavity under. The specimens were held in the test specimen holder of the test rig and examined to friction test using the reciprocating sliding apparatus. It is important to notice that the tests have been carried out at velocity of 60 stroke/min. and normal load of 14 N for a running time of 2, 4 and 6 minutes. The friction coefficient is determined using the relationship:

$$\mu = F / N$$

2.3.3 Surface Roughness Measurement

The surface roughness of counter faces has been detected before and after the wear tests using surface roughness measuring tester (SJ-210). Here, the peak to valley height (R_Z) was considered as a roughness parameter. The

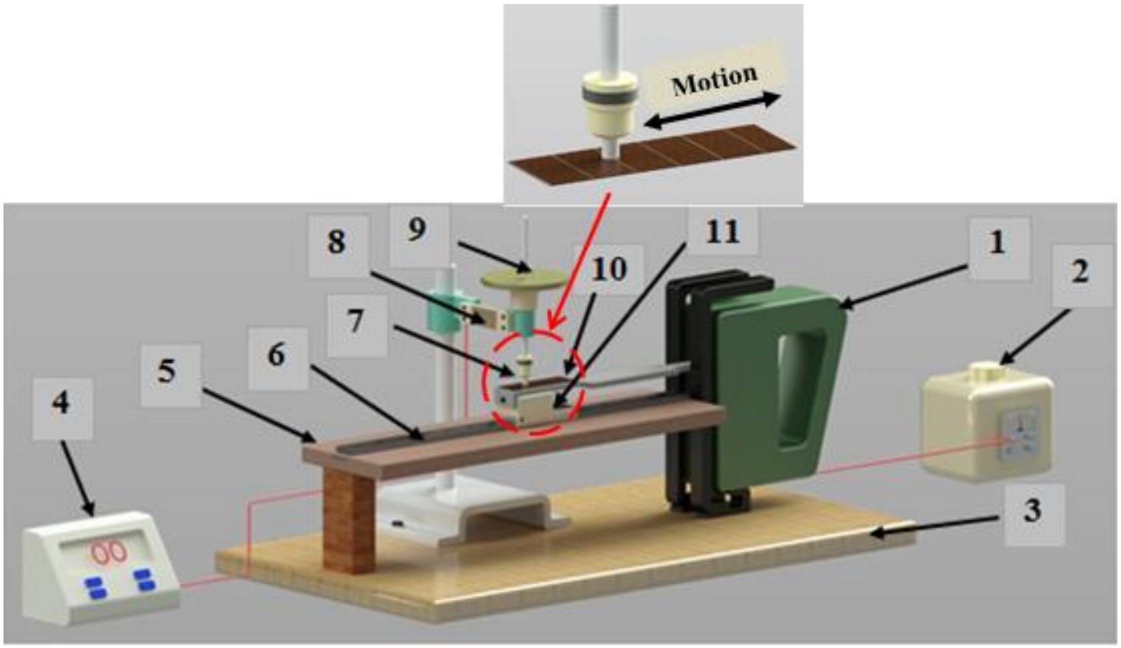

Fig. 5 Reciprocating test rig 1. Motor, 2. Voltage regulator, 3. Base, 4. Friction force screen, 5. Plate, 6. Linear Bearing, 7. Sample, 8. Load cell, 9. Normal Load, 10. Emery Paper, 11. Table

Fig. 6 The surface roughness measuring tester (SJ-210).

3. Results and Discussion

3.1 Effect of Counterface Material on the Tribological behavior of PMMA under wet and dry conditions

To study the effect of contact surface materials on the coefficient of friction and wear exhibited by SWCNT/PMMA composites, a series of contact surface materials used in the oral environment were tested under sliding conditions in both wet and dry. These counterface materials were stainless steel, polymethylmethacrylate (PMMA), porcelain, buffalo teeth, and amalgam.

Figure 7 shows the variation in wear of counterface materials used in this work in both wet and dry conditions. The results obtained revealed that the counterface material showed a pronounced effect on wear. It is observed that in the dry state the amalgam counterface has the highest wear value (7.8 mg), after that the stainless-steel material (5.9 mg), after that the PMMA material (2.9 mg), then buffalo teeth (2.3 mg) and then porcelain material (1.9 mg). In the wet state, the amalgam counterface material also has the highest wear value (1.9 mg), after that the stainless-steel material (1.4 mg), then the PMMA (1.2 mg), then the buffalo tooth material (0.9 mg), then porcelain materials (0.5 mg). It can be seen that the porcelain counterface material had the highest wear resistance in wet and dry conditions.

Figures 8, 9 investigate the relationship between wear and test time for PMMA under wet and dry conditions. It is evident in **Figs. 8, 9** that wear increased with increasing test time till to 6 minutes. When comparing the wear in line with the counterface materials, it was observed that the porcelain counterface material has a higher wear resistance, while the amalgam material showed a minimum wear resistance in both wet and dry conditions.

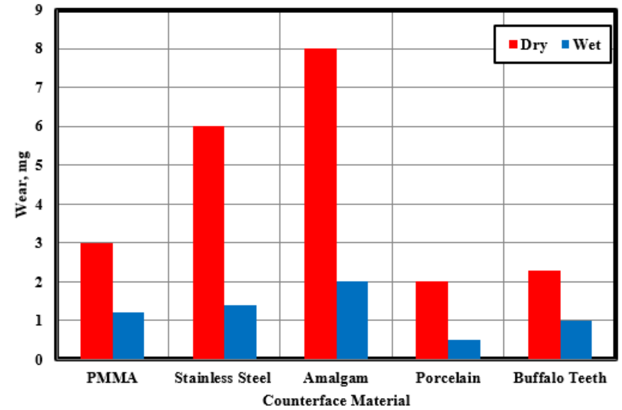

Fig. 7 The Counterface materials effect on the wear of PMMA in the wet and dry conditions

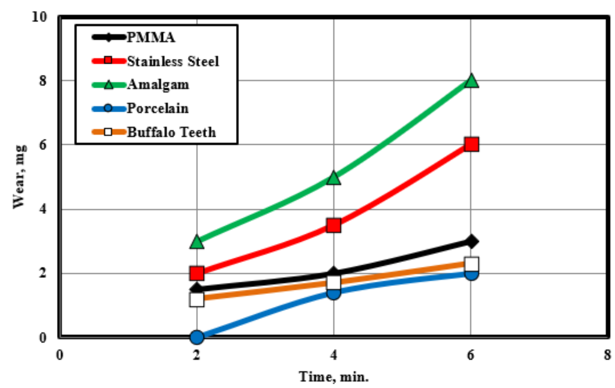

Fig. 8 Test time effect on the wear of PMMA acrylic resin when sliding against different counterface materials in the dry condition.

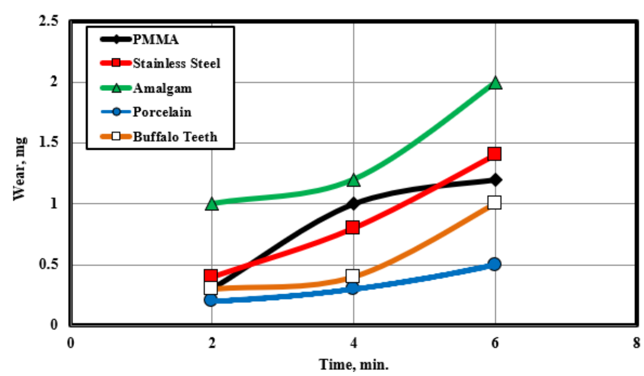

Fig. 9 Test time effect on the wear of PMMA acrylic resin when sliding against different counterface materials in the wet condition.

The surface roughness of the different counterface materials after the test in both dry and wet conditions is shown in **Fig. 10**. By comparing the roughness of surface of the different counterface materials in the dry test, it was found that the surface roughness of stainless steel showed the highest value while the other counter face materials may be showed the same value. In wet condition the surface roughness of buffalo teeth showed the minimum value, while the rest of counterface materials may be had the same value.

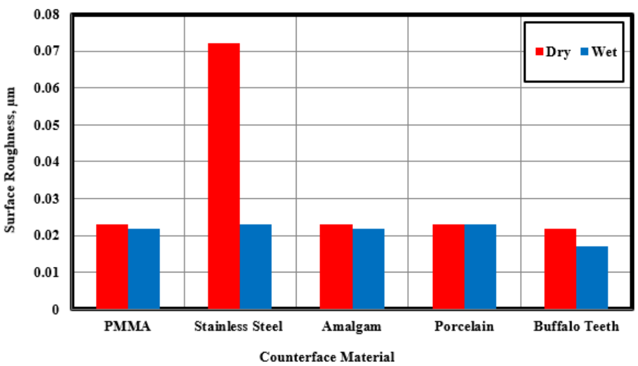

Fig. 10 Surface roughness of the different counterface materials after the test of wear in the wet and dry conditions when sliding against of PMMA acrylic resin.

Figure 11 shows the relation of the coefficient of friction against the contact surface materials used in this work under wet and dry conditions. The obtained results presented in **Figure 11** revealed that contact surface materials exhibited distinct effects on the coefficient of friction in all contact surface materials used. From **Fig. 11**, it is shown that in the dry test, the amalgam material had the highest coefficient of friction value; followed by PMMA, buffalo tooth material, then stainless steel, then porcelain material showed the lowest value of the coefficient of friction. In the wet state, the PMMA material had the highest coefficient of friction value, followed by buffalo teeth, amalgam, stainless steel, and finally, the porcelain material showed the lowest value.

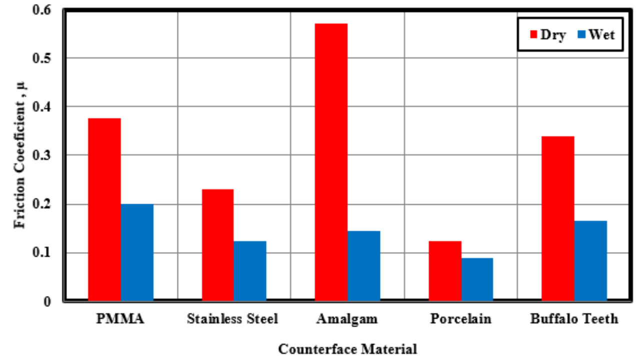

Fig. 11 Friction coefficient of the different counterface materials in the wet and dry conditions when sliding against of PMMA acrylic resin.

3.2 Effect of Counterface Material on the tribological Behavior of SWCNT/PMMA Composites under wet and dry conditions

Figure 12 shows the variation of wear against counterface materials in dry and wet conditions. Counterface materials showed a pronounced effect on wear for all counterface materials used. From **Fig. 12,** it is shown that in the dry state, the amalgam material has the highest wear value (5.4 mg), after that the stainless steel material (4.6 mg), buffalo teeth (1.9 mg), PMMA material (1.7 mg), while the porcelain material had the lowest value (0.8 mg). Under wet sliding conditions, the wear of the contact surface materials showed the same trend with relatively lower values than those observed for dry sliding. **Figures 13, 14** illustrate the relationship between wear and test time for SWCNT/PMMA composites under wet and dry conditions. It is observed in **Figs. 13, 14** that wear increased with increasing test time till to 6 minutes. Comparing the wear in line with counterface materials, it was investigated that the porcelain counterface material has a higher wear resistance, while the amalgam material showed a minimum wear resistance in both wet and dry conditions.

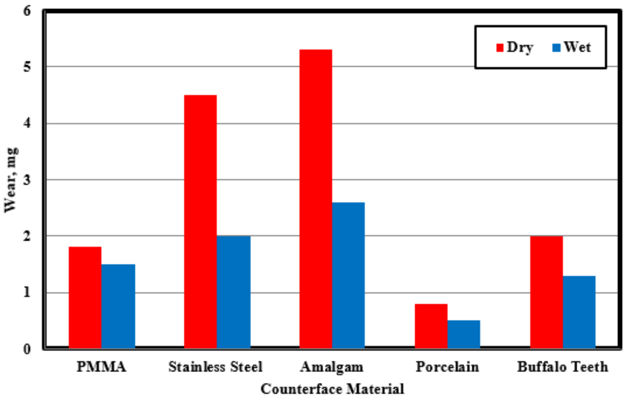

Fig. 12 Counterface materials effect on the wear of SWCNTs/PMMA composites in both wet and dry conditions

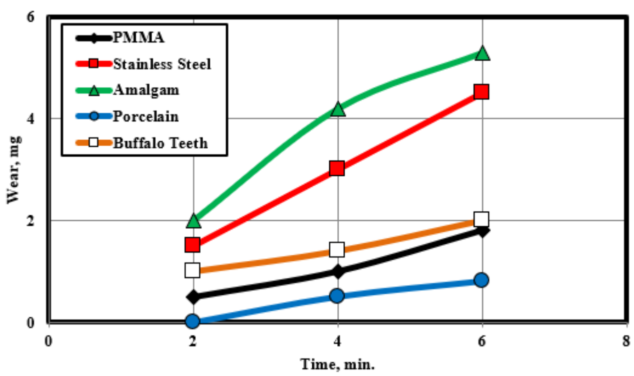

Fig. 13 Test time effect on the wear of SWCNT/PMMA when sliding against different counterface materials in the dry condition

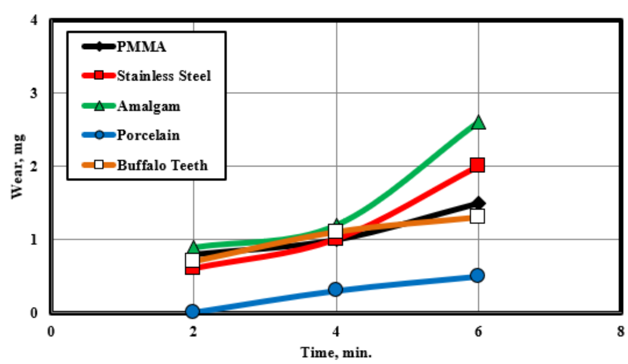

Fig. 14 Test time effect on the wear of MWCNTs/PMMA when sliding against different counterface materials in the wet condition.

The surface roughness of the different counterface materials after the test of wear in the wet and dry conditions is shown in **Fig. 15**. By comparing the surface roughness results at the different counterface materials, it was revealed that the surface roughness of stainless steel in the dry test was the highest value, followed by amalgam, PMMA, after that buffalo teeth and porcelain had nearly the same surface roughness. In the wet test, it was revealed that stainless steel nearly had the highest value, then PMMA, while amalgam and porcelain had the same value, and buffalo teeth material had the lowest roughness value. Buffalo tooth surface roughness showed lowest surface roughness especially in the wet state.

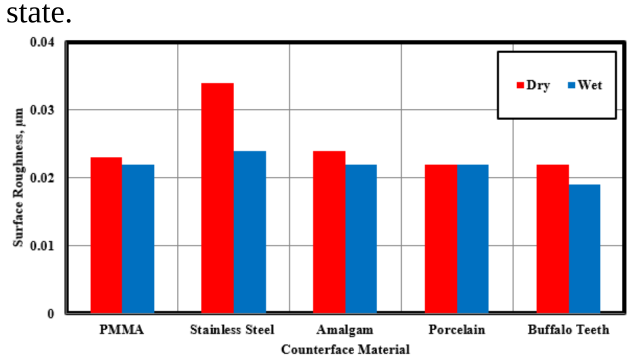

Fig. 15 Surface roughness of the different counterface materials after the test of wear in both dry and wet conditions when sliding against of SWCNT/PMMA composites

Figure 16 shows the relation of the coefficient of friction with the counterface materials used in this work in wet and dry conditions. The results obtained, as shown in **Fig. 16**, revealed that the contact surface materials showed distinct effects on the coefficient of friction in all the contact surface materials used. From **Fig. 16**, it was clear that in the dry test, the PMMA material as counter face had the highest value of coefficient of friction, after that amalgam, then buffalo tooth material, then stainless steel, then the porcelain material showed lowest value of the coefficient of friction. PMMA material in the wet state showed the highest coefficient of friction value, then buffalo teeth, then amalgam, then stainless steel, and then the porcelain material showed the lowest value.

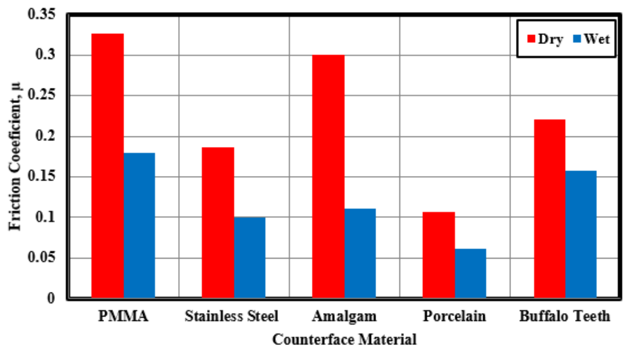

Fig. 16 Friction coefficient of the different counterface materials in both wet and dry conditions when sliding against of SWCNT/PMMA composites

4 Conclusions

From this study the followings can be concluded:

4.1 PMMA against the counterface materials

- In the dry and wet state the amalgam material as counter face has the lowest wear resistance while, porcelain counterface material had the highest wear resistance in dry and wet conditions.
- In the dry test, the surface roughness of stainless steel showed the highest value where, the surface roughness of buffalo teeth showed the minimum value
- In the dry test, the amalgam counterface had the highest coefficient of friction value while, in the wet state, the PMMA material showed the highest coefficient of friction value

4.2 SWCNT/ PMMA composite against the counterface materials

- The porcelain counterface material has the highest wear resistance, while the amalgam material showed a minimum wear resistance under both wet and dry conditions.
- The surface roughness of stainless steel in the dry test was the highest value where, in the wet test, it was found that stainless steel nearly had the highest value
- In the wet and dry test, PMMA material as counter face had the highest value of coefficient of friction

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