Int. J. Nonlinear Anal. Appl. In Press, 1–9
ISSN: 2008-6822 (electronic)
http://dx.doi.org/10.22075/ijnaa.2024.35354.5263

Wear rate of PMMA and UHWPE reinforcement with SiO_2 nano fillers

Hoda Doostmohammadi, Nima Refahati*

Department of Mechanical Engineering, Damavand Branch, Islamic Azad University, Damavand, Iran

(Communicated by Majid Eshaghi Gordji)

Abstract

Improving the quality of biomaterials and increasing their durability has always been one of the significant concerns in biomechanical studies. The use of nano-polymers may enhance the properties of implants and biomaterials. The purpose of this paper is to evaluate the influences of adding a different percentage of Sio_2 nanoparticles on wear resistance refinement. To measure the impacts of SiO_2 nanoparticles on wear resistance, reinforced PMMA and UHWPE with Nano SiO_2 powders were produced. The effect of 0%,3%, and 5% Mass fraction of SiO_2 fillers on the wear rate of UHWPE as the artificial joint and 0%,3%, 5%, and 7% fraction of SiO_2 fillers on the wear rate of PMMA denture base, experimented by wear machine Tuber GT-7012-T according to ASTM 99g 2017. The experimental results demonstrate that at 5% mf of Nanoparticles, the wear rate reduces up to 40%. However, increasing the mf of Nanoparticles is improper and decreases the wear resistance. One-way ANOVA analysis was applied to determine significant differences between data.

Keywords: PMMA, UHWPE, nano fillers, wear test, denture
2020 MSC: 82D80, 70Q05

1 Introduction

Poly methyl methacrylate, PMMA, is standard in dentistry, especially in artificial teeth, dentures, and obturators. This widely use is because of low water absorption, bio capability, and simple manufacturing process [1]. One of the most important physical properties of PMMA base dentures is wear resistance, which significantly influences dentures' durability [3]. Due to denture wear, natural occlusion is lost, so the chewing process, jaw connections, and stability of dentures will be changed, increasing stresses on anterior teeth due to reducing denture ridge [5]. To improve the properties of PMMA, researchers have evaluated the effect of various factors, including fillers, matrices, as well as the interface between the matrix and the filler, but the results show that their properties have not changed significantly with changes in the matrix of composites. Therefore, studies have focused on fillers [24]. The properties of nanofiller-reinforced composites depend on the size, shape, type, and concentration of particles added. In recent years, several nanoparticles, such as ZrO_2, SiO_2, TiO_2, and diamond nanoparticles, have been used in an attempt to enhance the physical and mechanical properties of PMMA [23, 9, 8, 21, 22, 7, 2].

A review has been conducted on investigating numerous nano-filled materials into PMMA the incorporated materials have been demonstrated to have positive antimicrobial effects against Candida albicans, Staphylococcus aureus,

*Corresponding author
Email addresses: hoda.doostmohamadi@gmail.com (Hoda Doostmohammadi), refahati@damavandiau.ac.ir (Nima Refahati)

Received: June 2024 *Accepted:* October 2024

and Streptococcus mutans [4]. In recent years, silica nanoparticles (NPs) have attracted a lot of attention due to their regular structure, ease of surface modification, and affordable costs [17]. NPs are often used as fillers to improve the properties of dental resin, including their wear resistance, mechanical properties, and refractive index [12, 16]. The strength of the chemical bond between PMMA and NPs is very important because it enables the dental resin material to transfer external forces from the weak polymer base to the much stronger nanoparticle fillers. Also, the homogeneous and uniform distribution of nanoparticles in the polymer matrix reduces the formation of stress concentration areas and as a result, improves the mechanical properties and light transparency of the dental resin [10, 11].

Different researchers investigated mechanical properties, such as wear resistance, in dentures. Alhareba et al. studied the influence of $Al_2O_3/Y-TSZ$ filler on the PMMA denture base. The study shows that the radiopacity of the PMMA matrix increases due to adding fillers [1]. Hasanen et al. studied the effect of SiO_2 Nanoparticles on the PMMA denture base. The result shows that adding Nano filler refines PMMA surface hardness and strength [14]. Alqahtani. investigated the mechanical properties of self-cured PMMA-zirconia and boron nitrate Nanoparticles. The study demonstrated that adding Nano fillers improved bending strength, elastic properties, and hardness [3]. Preis et al. investigated eight groups of different dentures by in vitro wear test. The results were subjected to one-way ANOVA and showed significant differences [20].

Bragdon et al. introduced a new pin-on-disc test method to obtain the wear rate value. The tester for measuring wear rate shows that two-directional motions cause a considerable wear rate compared to one-directional movement [6]. Zietz et al. overviewed the articles that studied different in vivo and in vitro wear testing of Total Knee Replacements (TKR). It is obtained that a new method of wearing test which simulates real situations of individual cases is helpful to determining wear rate more accurately [25]. Kang studied wear factors resulting from multi-directional motion in both experimental and computing ways. The results show a 30% difference between the two groups [15]. Liu investigated the effect of adding graphitic plates to UWHPE at different linear speeds of the probe. The best result of adding nanoplates in 1.3 m/s and all probe velocities reinforcement improved the wear resistance [18]. McGloughlin reviewed articles that investigated impressive parameters in vitro wear test results. The study demonstrated that conditions such as lubricants and load tests considerably influence UHWPE wear test results [19].

This paper evaluates the influences of adding the different percentages of SiO_2 Nanoparticles on wear resistance refinement. First, the processes of producing Nanoparticles and specimens have been described. Then the wear test's conditions were applied to the specimens, and the results were extracted. Finally, conclusions and suggestions for future research are given.

2 Material and methods

2.1 Producing SiO_2 Nanoparticles

To synthesize SiO_2 nanoparticles, 3 ml of Tetraethyl orthosilicate ($Si(OC_2H_5)_4$) was added to 50 ml of Ethanol (C_2H_6O). The resulting solution was placed in a magnetic stirrer for 48 hours without any heating conditions. Then, the system was heated to evaporate the solvent and thicken the sample. The resulting concentrated solution was heated in a vacuum oven at 80° C for 2 hours and then at 150° C for 2 hours [13]. After drying in the oven, it is placed in the furnace at 500° for 2 hours. To analyze purity, the nanoparticles were subjected to an XRD test as pic 1 shows 100% purity of nanoparticles.

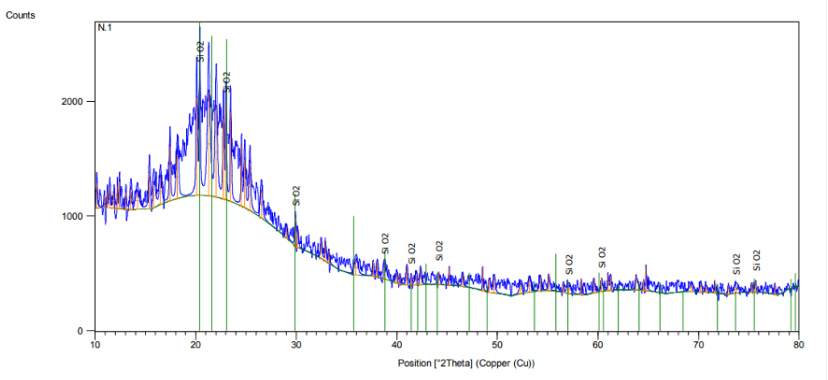


Figure 1: XRD test result for SiO_2 Nanoparticles

No. of Peak	Pos. [°2Th.] in Ref [6]	Pos. [°2Th.] in Test	d-spacing [$\dot{A}$] in Ref [6]	d-spacing $\dot{A}$ in Test
1	4.36	4.36	20.37	20.39
2	4.11	4.17	21.37	21.27
3	3.85	3.87	23.09	22.99
4	2.99	3.07	29.86	29.07
5	2.52	2.49	35.61	35.93

2.2 Construction of PMMA-Nano SiO2 specimens

White Heat cure acrylic base resin PMMA produced by Acrosun Company used for dental purposes was applied as base material. Mentioned SiO_2 nanoparticles in three mass fractions, 3%, 5%, and 7%, were added to PMMA powder. To blend the two powders properly, the mixture is placed in an ultra-sonic mixer for 2 hours.

To cure PMMA, it is combined with Benzoyl peroxide. When the material reaches the dough stage, it is inserted into the plaster mold held by a metal cast (Fig 1) with two portions. Eventually, two pieces are placed on top of each other and pressed under 20 bars for 5 minutes, and the clamped cast is placed in the water bath at 80 degrees for 45 minutes [20]. The size of the specimen. All samples were polished after taking out of the mold.

Figure 2: Plaster mold and metal cast used to cure PMMA

2.3 Construction of UHMPE-Nano SiO_2 specimens

To add Nanoparticles to polyethylene, PE granules and SiO_2 powder were placed in the internal mixer, and the rotational speed of the rotors was set to 190° C and 150 rpm, respectively. The process continued until all granules melted, then the Nanopowder was added to the melting robber in 0%, 3%, and 5% mass fractions (mf) and appropriately mixed with the rubber. The specimens were removed from the mixture and cooled down slowly in a room environment for 48 houses. Fig 3 shows the internal mixer components used in this study.

Figure 3: The internal mixer component

The resulting rubber mixture was fragmented into one-size granules by using the granulator. By multiplying the internal volume of the mold by 110% estimated density of the compound, the sufficient mass of granules for each mold was calculated. The molds ($25mm \times 15mm$ internal dimensions) were placed in a heat press machine, and the system was preheated up to 180° C. Then the mold was subjected to 100 bar pressure for 3 minutes. Then, the hydraulic cooling system, set to 15° C/min, started to cool the molds. Fig 4 shows the heat press machine and its settings.

Figure 4: Heat press machine

After polishing the surface to the wear test machine, four polished specimens were subjected to a wear test. Test performed according to ASTM 99g 2017 for pin-on-disk wear testing with 150 cr6 steel pin ASI 52100. The testing machine load, the linear probe velocity, and the temperature were set to 70 N 1 m/min and 35° C, respectively. At each 60 m mileage of probe, the specimen was removed, weight loss was measured, and reloaded again. The test continued until the 300 m mileage of the probe.

2.4 Wear test

After preparing to wear the test machine, four polished PMMA-NanoSiO_2 specimens were subjected to a wear test. The test was performed according to ASTM 99g 2017 for pin-on-disk wear testing with 150 cr6 steel pin ASI 52100 on Arya Modern Sanat wear tester. The testing machine load, the linear probe velocity, and temperature were set to 40 N 1 m/min and 35° C, respectively, to be close to the molar teeth' actual boundary condition [13].

At each 200 m mileage of probe, the specimen was removed, mass loss measured and reloaded again. At 600 m, the specimen was removed and coated with gold, and SEM (scanning electron microscope) micro photo grammetry was applied.

UHMPE-Nano SiO_2 specimens were also polished and placed at the same wear tester. The testing machine load, the linear probe velocity, and the temperature were set to 70 N 1 m/min and 35° C, respectively. At each 60 m mileage of probe, the specimen was removed, weight loss was measured, and reloaded again. The test continued until the 300 m mileage of the probe.

3 Results

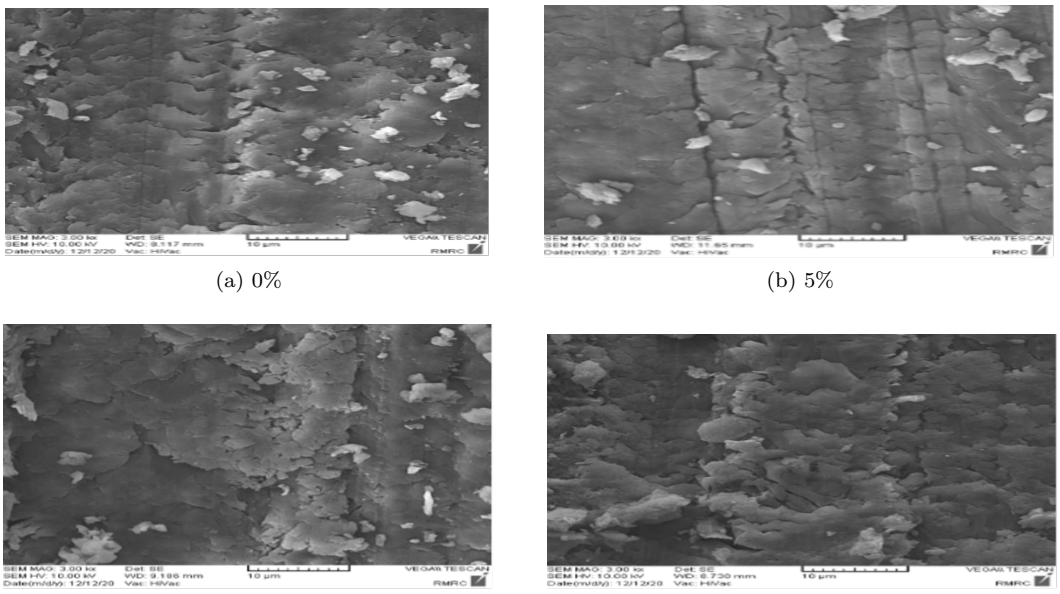
Table 1 shows the mass loss of PMMA-Nano SiO_2 specimens. It presented that a 5% mass fraction caused the lowest mass loss among other specimens, 31%, compared with PMMA.

Table 1: Mass loss of PMMA-Nano SiO_2specimens due to wear test

Percentage of Nanoparticles	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Band	Upper Band		
0.00	3	.1149	0.05635	0.03254	-0.0251	0.2549	0.06	0.17
3.00	3	.0820	0.05006	0.02890	-0.0423	0.2064	0.03	0.13
5.00	3	.0789	0.05157	0.02977	-0.0492	0.2070	0.03	0.13
7.00	3	.0926	0.05250	0.03031	-0.0379	0.2230	0.04	0.15

SEM results at a magnification of 10 μm shown in Fig 1. The grooves caused by probe movement on specimens decrease due to adding Nanoparticles to PMMA; however, in specimens with a mass fraction more than 5% of SiO_2

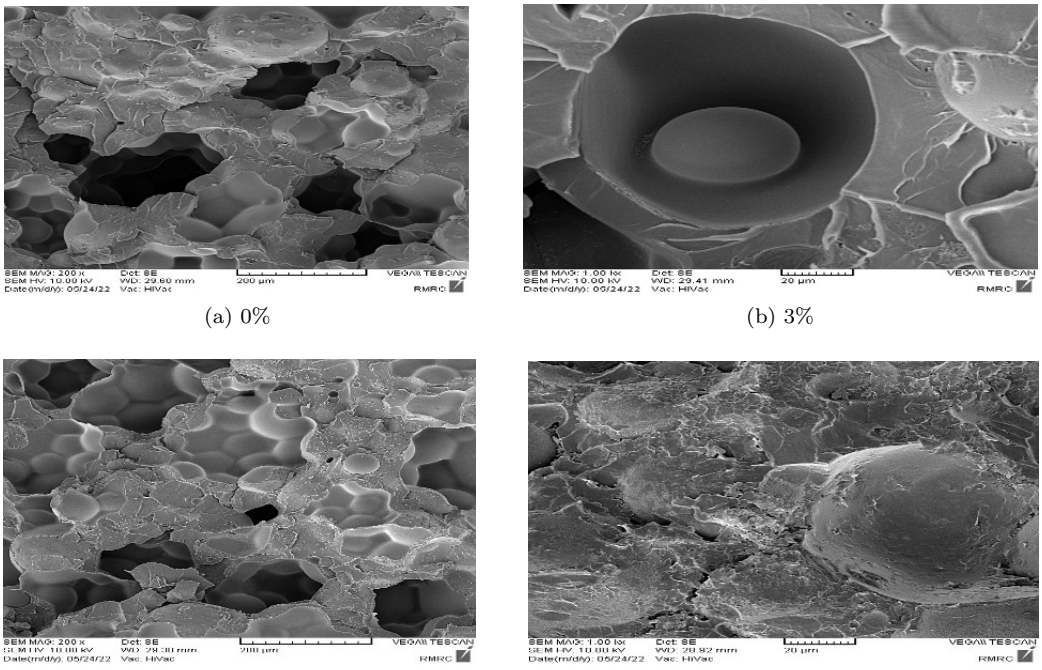
Nanoparticles, improving wear resistance reduces because of the increasing chance of agglomeration. Table 2 shows



(a) 0% (b) 5%

(c) 7% (d) 10%

Figure 5: SEM for PMMA reinforced with nanosilicaa



(a) 0% (b) 3%

(c) 5% (d) 10%

Figure 6: UHWPE reinforced with nanosilica

the mass loss of UHMPE-Nano SiO_2 specimens. It presented that a 5% mass fraction caused the lowest mass loss among other specimens, 51%, compared with UHMPE.

Table 2: Mass loss of UHMPE-Nano SiO_2 specimens due to wear test

Percentage of Nanoparticles	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Band	Upper Band		
0.00	5	0.2073	0.10752	0.04808	0.0738	0.3408	0.07	0.34
3.00	5	0.1414	0.07354	0.03289	0.0501	0.2327	0.04	0.23
5.00	5	0.1065	0.05377	0.02405	0.0397	0.1732	0.04	0.17

3.1 Wear rate

To measure wear resistance, the wear rate is calculated by eq. (3.1) [13], in which $\omega(mm_3N_{-1}m_{-1})$ wear rate, $\Delta m(g)$, $F(N)$, and $l(m)$ represent wear rate, weight loss, wear machine load and mileage of probe, respectively.

$$\omega = \frac{\Delta m}{l \times F \times \rho} \tag{3.1}$$

The results corresponded with data obtained in the previous section. Table 3 and table 4 show the wear rate of specimens.

Table 3: wear rate $(mm_3N_{-1}m_{-1}e_6)$ of PMMA-Nano SiO_2 specimens

Percentage of Nanoparticles	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Band	Upper Band		
.00	5	.2073	.10752	.04808	.0738	.3408	.07	.34
3.00	5	.1414	.07354	.03289	.0501	.2327	.04	.23
5.00	5	.1065	.05377	.02405	.0397	.1732	.04	.17

Table 4: wear rate $(mm_3N_{-1}m_{-1}e_6)$ of UHMPE-Nano SiO_2 specimen

Percentage of Nanoparticles	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Band	Upper Band		
0.00	3	0.0588	0.00104	0.00060	0.0562	0.0614	0.06	0.06
3.00	3	0.0382	0.00654	0.00378	0.0219	0.0544	0.03	0.04
5.00	3	0.0357	0.00734	0.00424	0.0174	0.0539	0.03	0.04
7.00	3	0.0427	0.00395	0.00228	0.0328	0.0525	0.04	0.05

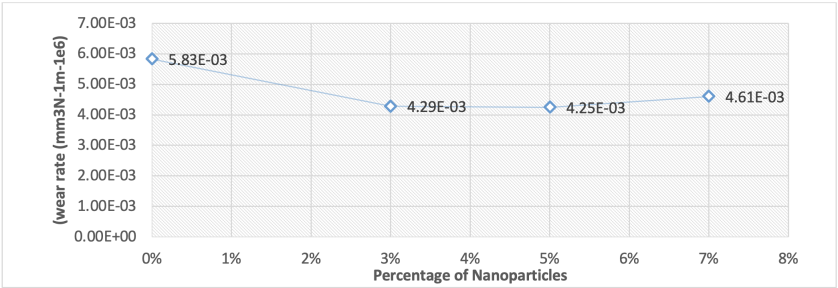


Figure 7: wear rate of 4 PMMA-Nano SiO_2 specimens at 600 m of mileage

One-way ANOVA compares the means of two or more groups and determines if they have significant differences. It is commonly used in hypothesis testing to evaluate whether the variation between group means is more significant than within the groups. Table 5 shows one-way ANOVA calculated with IBM SPSS Statics 23 software. It presents that the P-factor is less than 0.05 (equal to .03); therefore, there is a significant difference between the 4 data groups of PMMA-Nano SiO_2.

Table 6 shows one-way ANOVA for UHMPE-Nano SiO_2 calculated with IBM SPSS Statics 23 software. It presents that the P-factor is less than 0.05 (equal to .000), and therefore there is a significant difference between 3 data groups.

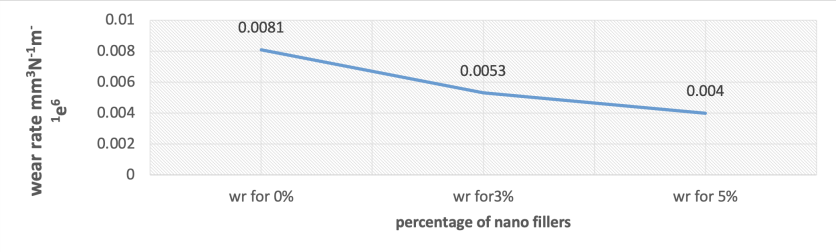


Figure 8: wear rate of 4 PMMA-Nano SiO_2 specimens at 600 m of mileagee

Table 5: One-way ANOVA of wear rate results for PMMA-Nano SiO_2

One way-ANOVA					
	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	.001	3	.000	11.427	.003
Within Groups	.000	8	.000		
Total	.001	11			

Table 6: One-way ANOVA of wear rate result for UHMPE-Nano SiO_2

One way-ANOVA					
	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	.000	2	.000	463.702	.000
Within Groups	.000	12	.000		
Total	.000	14			

4 Conclusion

The impact of nanoparticles on composites used as biomaterials is the subjected in this experimental research. In particular, it examines the effect of SiO_2 Nanofillers with mass fractions of 3%, 5%, and 7% on the wear rate of PMMA denture base. The wear tests were conducted using a wear machine following the ASTM 99g 2017 standard. After specimens were subjected to wear test, these findings were extruded:

1. At a mass fraction of 5% of Nanoparticles, the wear rate of the PMMA denture base decreases by a significant 40%. This shows that the The combination of Nanoparticles with the base material can effectively enhance the wear resistance of this biomaterial. However, more mass fraction does not result less wear rate. The findings show that nanoparticles beyond 5% does not yield further improvements in wear resistance.

2. In a related investigation, the influence of 3%, 5%, and mass fraction SiO_2 nanofillers on the wear rate of UHMPE was examined using the same wear machine and ASTM 99g 2017 standard. Surprisingly, the results demonstrate a different trend compared to the PMMA denture base study. At a mass fraction of 5% of nanoparticles, the wear rate of the UHMPE denture base decreases by a substantial 50%. This suggests that higher mass fractions of nanoparticles lead to enhanced wear resistance in UHMPE composites, in contrast to the findings observed in the PMMA denture base experiments.

5 Suggestions for future research

1. While these findings suggest the potential benefits of adding nanoparticles as reinforcement in PMMA denture base, additional studies are necessary to determine the optimal percentage of Nanoparticles mass fraction. These future investigations should delve into a wider range of mass fractions to identify the ideal concentration that maximizes wear resistance without compromising other mechanical properties.

2. In the case of the dental material, due to the importance of preservation of sub gingival cortical bone tissue the cortical bone inspecialy in the elderly group of patients, the life test of the these specimens is recommended as a supplement to the results of this research.

References

[1] O. Alhareba, H. Akilb, and Z. Ahmadc, *Influence of Al2O3/Y-TSZ mixture as filler loading on the radiopacity of PMMA denture base composites*, Procedia Chem. **19** (2016), no. 4, 646–650.

[2] A. Alhotan, J. Yates, S. Zidan, J. Haider, and N. Silikas, *Flexural strength and hardness of filler-reinforced PMMA targeted for denture base application*, Materials **14** (2021), no. 10, 2659.

[3] Alqahtani, *Mechanical properties enhancement of self-cured PMMA reinforced with zirconia and boron nitride nanopowders for high-performance dental materials*, J. Mech. Behav. Biomed. Mater. **110** (2020), no. 2, 103937.

[4] S. An, J.L. Evans, S. Hamlet, and R.M. Love, *Overview of incorporation of inorganic antimicrobial materials in denture base resin: A scoping review*, J. Prosth. Dent. **130** (2023), no. 2, 202–211.

[5] H. Azlina, J. Hasnidawani, H. Norita, and S. Surip, *Synthesis of SiO_2 nanostructures using Sol-Gel method*, Acta Phys. Polonica A **129** (2016), no. 4, 842–844.

[6] Ch.R. Bragdon, D.O. O'Connor, J.D. Lowenstein, M. Jasty, S.A. Biggs, and W.H. Harris, *A New Pin-on-Disk Wear Testing Method for Simulating Wear of Polyethylene on Cobalt-Chrome Alloy in Total Hip*, J. Arthropl.**16** (2001), no. 5, 658–666.

[7] A. Cahyanto, M.V. Martins, O. Bianchi, D.P. Sudhakaran, N. Silillkas, S.G. Echeverrigaray, and V. Rosa, *Graphene oxide increases PMMA's resistance to fatigue and strength degradation*, Dental Mater. **39** (2023), no. 9, 763–769.

[8] N.W. Elshereksi, A. Muchtar, and C.H. Azhari, *Effects of nanobarium titanate on physical and mechanical properties of poly (methylmethacrylate) denture base nanocomposites*. Polym. Polym. Compos. **29** (2021), no. 4, 484–496.

[9] G. Ergun, Z. Sahin, and A.S. Ataol, *The effects of adding various ratios of zirconium oxide nanoparticles to poly (methyl methacrylate) on physical and mechanical properties*, J. Oral Sci. **60** (2018), no. 8, 304–315.

[10] A.A. Fatalla, M.S. Tukmachi, and G.H. Jani, *Assessment of some mechanical properties of PMMA/silica/zirconia nanocomposite as a denture base material*, IOP Conf. Ser.: Mater. Sci. Engin.: IOP Pub. **987** (2020), no. 1, 12031.

[11] M.A. Golshokouh, N. Refahati, and P.R. Saffari, *Effect of silicon nanoparticles on moisture absorption and fracture toughness of polymethyl methacrylate matrix nanocomposites*, J. Compos. Sci. **8** (2024), no. 2, 69-80.

[12] K. Gonga, B. Luo, B. Di Feng, and L. Changhai, *Wear of Ni3Al-based materials and its chromium-carbide reinforced composites*, Wear **265** (2008), no. 11, 1751–1755.

[13] N.A. Hassan, J.N. Hasnidawani, N. Hassan, and S.N. Surip, *Synthesis of SiO_2 nanostructures using sol-gel method*, Acta Phys. Polonica **129** (2016), no. 4, 842–844.

[14] A. Hasanen and M. Mudhaffer, *The effect of Silicon di oxide Nano-Fillers reinforcement on some properties of heat cure polymethyl methacrylate*, J. Bagh College Dent. **26** (2014), no. 10, 32-36.

[15] L. Kang, A.L. Galvin, T.D. Brown, J. Fisher, and Z.M. Jin, *Wear simulation of ultra-high molecular weight polyethylene hip implants by incorporating the effects of cross-shear and contact pressure*, J. Engin. Med. **222** (2007), no. 8, 1049–1065.

[16] Sh.H. Kenneth, M. Warren, W. Corrine, and H. Hacker, *In vitro wear of resin denture teeth*, J. Prosth. Dent. **79** (1998), no. 2, 152–158.

[17] D.W. Lee and B.R. Yoo, *Advanced silica/polymer composites: Materials and applications*, J. Ind. Engin. Chem.**38** (2016), no. 11, 1–12.

[18] T. Liu, B. Li, B. Lively, A. Eyler, and W.H. Zhong, *Enhanced wear resistance of high-density polyethylene composites reinforced by organosilane-graphitic nanoplatelets*, Wear **309** (2009), no. 1, 43–51.

[19] T.K. McGloughlin and A.G. Kavanagh, *Wear of ultra-high molecular weight polyethylene (UHMWPE) in total knee prostheses: a review of key influences*, Proc. Instn. Mech. Engrs. **214** (2000), no. 4, 349–359.

[20] V. Preis, S. Hahnel, M. Behr, and M. Rosentritt, *Contact wear of artificial denture teeth*, J. Prosthod. Res. **62** (2017), no. 2.

[21] J. Slane, J. Vivanco, J. Meyer, H.L. Ploeg, and M. Squire, *Modification of acrylic bone cement with mesoporous silica nanoparticles: Effects on mechanical, fatigue and absorption properties*, J. Mech. Behav. Biomed. Mater.

29 (2014), no. 1, 451–461.

[22] F.J. Tommasini, L.D. Ferreira, L.G. Tienne, V.D. Aguiar, M.H. Silva, L.F. Rocha, and M.D. Marques, *Poly (methyl methacrylate)-SiCnanocomposites prepared through in situ polymerization*, Mater. Res **21** (2018), no. 6, e20180086.

[23] D. Tzetzis, K. Tsongas, and G. Mansour, *Determination of the mechanical properties of epoxy silica nano composites throughFEA-supported evaluation of ball indentation test results*, Mater. Res. **20** (2017), no. 10, 1571–1578.

[24] M.S. Zafar, *Prosthodontic applications of polymethyl methacrylate (PMMA): An update*, Polymers **12** (2020), no. 10, 2299.

[25] C. Zietz, J. Reinders, J. Schwiesau, A. Paulus, J. Ph. Kretzer, T. Grupp, S. Utzschneider, and R. Bader, *Experimental testing of total knee replacements with UHMW-PE inserts: Impact of severe wear test conditions*, Clinic. Appl. Biomater. **26** (2015), no. 3, 133–146.