RESEARCH ARTICLE

Nanoreinforced PEKK: Enhancing Dental Implant Performance with SiO_2 Nanoparticles

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ABSTRACT

Objective(s): Despite a global increase in dental implant procedures -now exceeding one million annually-there remains significant potential for advancement in implant materials. In order to create a better substitute for the materials used in dental implants today, this study examines how reinforcement with silicon dioxide (SiO_2) nanoparticles can improve the mechanical and physical properties of polyetherketoneketone (PEKK).

Methods: Biomedical composites were prepared by incorporating SiO_2 nanoparticles into a PEKK matrix at weight percentages of 0%, 2%, 3%, and 4% (n=5 per group). The nanoparticle and polymer powders were homogenized in ethanol, dried at 120°C, and compression-molded at 310°C under 15 MPa for 20 minutes. The resulting specimens were evaluated for their mechanical (flexural strength), physical (surface roughness, wettability), and morphological (SEM, AFM) properties.

Results: The incorporation of SiO_2 nanoparticles, particularly at 3 wt%, led to significant improvements in both mechanical and physical characteristics of the PEKK composite. The 3% SiO_2/PEKK group demonstrated the maximum flexural strength and improved surface hydrophilicity and roughness, which was verified with the help of SEM and AFM analysis.

Conclusions: The results indicate that PEKK/3%SiO_2 nanocomposites possess enhanced biomechanical and biological behavior over the neat PEKK. The PEKK/3%SiO_2 nanocomposites hold the potential to be used as biocompatible substitutes of titanium in the field of dental implants.

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INTRODUCTION

Nowadays, dental implants are a popular method of replacing lost teeth, giving patients a functional and cosmetic repair. Global demand for dental implants is on an inclining trend, thanks to improved life expectancy and an enhanced focus on quality of life and oral health [1]. Although titanium-based implants have become universally used, considerable interest still exists in the development of newer materials that may counteract specific limitations of metals, namely hypersensitivity reactions, aesthetic issues, and radiopacity [2,3].

Polyaryletherketone (PAEK) polymers, particularly polyetherketoneketone (PEKK), have emerged as promising candidates for dental and orthopedic applications due to their excellent mechanical strength, chemical resistance, radiolucency, and biocompatibility[3]. The mechanical properties of PEKK closely resemble those of natural bone, which can help minimize stress shielding and promote favorable load transfer at the bone-implant interface. However, a

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major drawback of PEKK and related polymers is their bioinert nature; they lack intrinsic bioactivity and osteogenic potential, which can limit their integration with surrounding bone tissue [4-8].

To cope with this challenge, various recent studies have concentrated on the surface or chemical structure modification of PEKK to advance its biological performance. One viable route is the introduction of bioactive ceramic nanofillers, like silicon dioxide (SiO_2), into the polymer matrix. The incorporation of SiO_2 nanofillers is capable not only of developing the mechanical features of the composite but, more importantly, of enlarging its surface roughness and hydrophilicity, which is helpful in terms of cellular adhesion and osseointegration. Additionally, the homogenous nanofillers dispersion in the polymer matrix is capable of inducing heterogeneous crystallization, and this is able to favor the structural and functional features of the composite further. Considering the latter, the PEKK-based nanocomposites reinforced with SiO_2 nanofillers represent an attractive route in the production of the new-generation dental implant materials. Nonetheless, the optimal nanofillers concentration and their influence on the features of the composite still need detailed research[3,9-13].

The objective of the current work is to assess the influence of different concentrations of SiO_2 nanoparticles on the mechanical, physical, and morphological behavior of PEKK composites. It is hypothesized that the introduction of the SiO_2 nanoparticles will considerably improve the biomechanical and biological features of PEKK and provide an acceptable alternative option compared to the conventional titanium implants.

MATERIALS AND METHODS

Materials

The materials used in this study included SiO_2 powder obtained from Riedel-de Haën (Germany), 95% ethanol supplied by Scarlab SL (Spain), and PEKK powder provided by Zibo Zichuan Yaodong Chemical Co., Ltd. (China).

Method

Preparation of SiO_2/PEKK Composites

The PEKK/SiO_2 composites were synthesized via the compression molding process. Initially, the SiO2 powder (average size 0.9 μm) was ultrasonically mixed with 95 % ethanol with varying SiO2:ethanol weight ratios to offer adequate wetting between the powder grains. Subsequently, the PEKK powder (average size 33 μm) was added to the suspension to fill the final composite mixture. For ten more minutes, the resultant mixture was co-dispersed ultrasonically to create a uniform powder blend.

[14]. The powder combination was dried for ten hours at 120°C to eliminate any remaining moisture. After drying, the powder was put into a mold that had already been made [15].

Prior to compression, the mold was preheated to 150°C. A pressure of 15 MPa was used to compress the powder. The composite was kept in situ between heated platens at a maximum temperature of 310°C for 10 minutes in order to guarantee complete mixing of SiO2 particles within the molten PEKK matrix. Following this heating phase, the heaters were shut off while keeping the pressure at 15 MPa until the cooling process was finished.

Sample Preparation and Characterization

The hardened compression-molded sheets were machined into disk-shaped samples with a diameter of 15 mm and a thickness of 2 mm using a turning lathe. Prior to machining, each sheet was measured six times with a vernier caliper to confirm dimensional consistency.

Flexural Strength Test

Rectangular specimens measuring 65 mm in length, 10 mm in width, and 3 mm in thickness were prepared, with two samples tested per condition. Flexural strength testing was performed at room temperature using an Instron universal testing machine, operating at a crosshead speed of 2 mm/min, in accordance with ASTM D790-03 standards. The flexural strength (S) was calculated using the following formula:

$$S = \frac{3PL}{2bd^2}$$

where:

S = flexural strength (MPa), P = load at a specific point on the load-deflection curve (N), L = support span length (mm), b = specimen width (mm), d = specimen thickness (mm).

Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX)

The microstructure of the samples was examined using a scanning electron microscope (LEO, model 1455VP, UK) operated at an accelerating voltage

of 10–20 kV. Elemental composition analysis was conducted simultaneously via energy dispersive X-ray spectroscopy (EDX). EDX relies on the principle that each element emits a characteristic electromagnetic spectrum due to its unique atomic structure. The interaction between the sample and the X-ray excitation source generates elemental-specific emission peaks, enabling qualitative and quantitative elemental analysis.

Atomic force microscopy (AFM)

Atomic force microscopy was employed to obtain roughness. The technique involves scanning a sharp tip attached to a cantilever across the sample surface using piezoelectric scanners. Deflections of the cantilever caused by tip-sample interactions were detected via optical or capacitive tunneling sensors. To minimize surface deformation, measurements were performed under zero standard pressure conditions.

Contact angle measurement (wettability test)

Surface wettability was evaluated by measuring the contact angle using a goniometer equipped with a charge-coupled device (CCD) camera. Images of sessile droplets were captured and analyzed using LabVIEW software to determine the contact angle values.

Statistical Analysis

All quantitative data were analyzed using SPSS software version 24. Descriptive statistics, including mean and standard deviation, were calculated for each test group. Inferential statistical comparisons were performed using paired sample t-tests and analysis of variance (ANOVA), with significance levels set appropriately.

RESULTS AND DISCUSSION

PEKK is an appealing biomaterial with prospective applications in dental, orthopedic, and cranial implants. However, its clinical significance is diminished based on the lack of osteogenic and bioactive features, intrinsic hydrophobicity, inadequate integration with bone tissue, and limited cellular adhesion[16]. To overcome these limitations, bioactive ceramics can be incorporated into the PEKK matrix to enhance its functionality [6]. Nanocomposites, which consist of at least one nanoscale filler uniformly dispersed within a continuous polymer matrix [17], offer a novel approach to improving material properties. This study focuses on reinforcing high-performance thermoplastic PEKK with nanofillers to enhance bioactivity and potentially promote osteogenic differentiation [18].

The result of measuring of the flexural strength for the samples was described in Table 1. The highest mean value obtained for PEKK/ 3% SiO_2 (128.6) while the lowest value obtained for PEKK/ 4% SiO_2 (116.5).

The flexural strengths of PEKK and SiO_2/PEKK composite materials were evaluated in the present work according to the ISO 178:2010 standard test method. From the results, it was determined that the flexural strength of PEKK enhanced notably with the incorporation of 3% nano-SiO_2. Consistent with the results of Rikitoku et al [19], the introduction of 3% SiO_2 into PEKK is the best way of boosting its mechanical performance, yielding significant flexural strength with respect to neat PEKK. This is attributed to the large surface area of the nanometric SiO_2, giving rise to the formation of an appreciable interphase and broad interfacial contact between the polymer matrix and the filler, thereby promoting mechanical reinforcement. The SEM photos also confirmed the uniform dispersion of the SiO_2 particles into the PEKK matrix, with very minimal particle agglomeration being observed. Pure PEKK and the SiO_2/PEKK composite were subjected to SEM examination to investigate the effects of implant texture on cell culture and other physiological responses of PEKK with and without SiO_2. There were visible SiO_2 particles on the SiO_2/PEKK surface (Figure 1). There was a noticeable difference in the surface morphology between the rough and smooth sample surfaces that were prepared for the bioactivity analysis.

Table 1. Descriptive Statistics and ANOVA test for flexural strength data of pure PEKK and SiO_2/PEKK nanocomposites

Group	N	Minimum (MPa)	Maximum (MPa)	Mean (MPa)	Std. Dev.
PEKK	8	119.50	125.40	123.10	1.70
PEKK/ 2% SiO_2	8	125.20	127.40	126.30	0.64
PEKK/ 3% SiO_2	8	127.30	129.60	128.60	0.72
PEKK/ 4% SiO_2	8	109.20	124.20	116.50	4.48

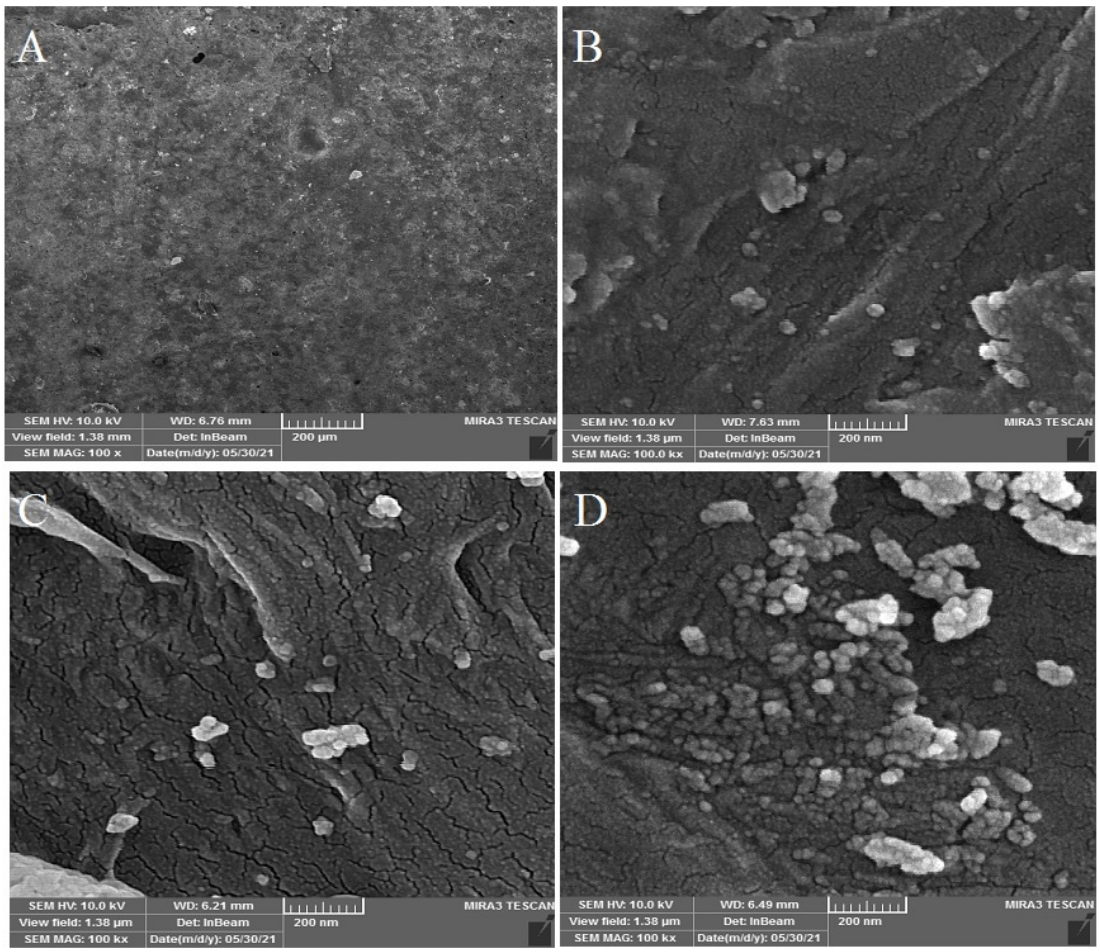

Fig. 1. SEM images of PEKK and SiO_2/PEKK composites; (A) Pure PEKK, (B) PEKK with 2% SiO_2, (C) PEKK with 3% SiO_2, (D) PEKK with 4% SiO_2.

SEM images revealed that samples exhibiting smoother fracture surfaces corresponded to higher interfacial adhesion between the composite components. The fractured surfaces of the composites indicated effective fusion. At low filler concentrations, the nanoparticles are able to overcome physical repulsive forces and disperse uniformly throughout the polymer matrix. As the interparticle distance decreases, these repulsive forces diminish, leading to particle agglomeration. This clustering of filler particles can interfere with the fusion of PEKK particles, adversely affecting the composite's microstructure. Consequently, such filler aggregation results in altered composite properties, often increasing brittleness[20].

The results of the water surface roughness and contact angle measurements for the samples are presented in Table 2.

PEKK is an appealing biomaterial with the potential application in dental, orthopedic, and cranial implants. However, its clinical efficacy might be affected because of the lack of osteogenic and bioactive functionalities, intrinsic hydrophobicity, poor integration with the bone tissue, and poor cellular adhesion.[16]. To overcome these limitations, bioactive ceramics can be incorporated into the PEKK matrix to enhance its functionality [6]. Nanocomposites, which consist of at least one nanoscale filler uniformly dispersed within a continuous polymer matrix [17], offer a novel approach to improving material properties. This study focuses on reinforcing high-performance thermoplastic PEKK with nanofillers to enhance bioactivity and potentially promote osteogenic differentiation [18]. The surface roughness (Ra) of the unmodified PEKK discs was quantified,

Table 2. Mean Values and Standard Deviations of Surface Roughness and Contact Angle for Pure PEKK and SiO_2/PEKK Nanocomposites

	Surface roughness (nm)		contact angle (°)	
groups	mean	Std.	mean	Std.
PEKK	0.69	0.01	90	5.34
SiO2/ PEKK	1.45	0.01	78.49	2.88
Sig (2-tailed)	P < 0.001		P < 0.001	

and the introduction of SiO_2 nanoparticles was observed to enhance surface roughness compared with the control. This enhancement is likely due to the introduction of nanofillers in the polymer matrix, which is also responsible for enhanced interfacial adhesion between the composite components [14]. Smoother surfaces are generally less conducive to microbial adhesion and proliferation [16]. Although the addition of SiO_2 raised the surface roughness compared to pure PEKK, the overall roughness remained lower than that of some other materials currently in use. Surface hydrophilicity is an important factor in the physiological performance of dental implants due to its improved interaction with the implant materials and the tissue that is in its vicinity[10]. The water contact angle of the composites and the unmodified PEKK was investigated to determine the level of hydrophilicity and hydrophobicity. The maximum contact angle of the pure PEKK was seen to be about 90°, which shows its level of being hydrophobic. When 3% SiO_2nanofiller was added to the PEKK matrix, the contact angle dropped considerably, to 78.49°, which implies that there is an increase in the level of hydrophilicity, because SiO_2 is inherently hydrophilic[21]. Variations in contact angle measurements between pure PEKK and SiO_2/PEKK nanocomposites were observed, which can be attributed to changes in surface topography induced by the incorporation of nanofillers. Although SiO_2 nanoparticles are hydrophilic, the addition of 3% hydrophobic nano-SiO_2 to the PEKK matrix resulted in modifications to surface roughness. The decrease in surface roughness may be explained by the small particle size of the nanoparticles (20–30 nm) and their uniform dispersion within the PEKK matrix and on the composite surface[22].

CONCLUSION

This study demonstrates that reinforcing PEKK with nanoscale SiO_2 significantly enhances its mechanical and surface properties, addressing some of the inherent limitations of pure PEKK as a biomaterial for dental, orthopedic, and cranial implants. The incorporation of 3% SiO_2 nanofiller yielded the highest flexural strength, indicating optimal mechanical reinforcement likely due to the large surface area and uniform dispersion of nanosized particles within the polymer matrix. SEM analysis confirmed the effective integration and minimal agglomeration of SiO_2 particles, which contributed to improved interfacial adhesion and composite integrity. Furthermore, the addition of SiO_2 nanoparticles increased surface roughness and enhanced hydrophilicity, as evidenced by a significant reduction in water contact angle compared to pure PEKK. These surface modifications are expected to promote better cellular interactions and bioactivity, which are critical for implant integration and osteogenic differentiation. Although higher filler concentrations (4% SiO_2) led to particle agglomeration and reduced mechanical performance, the results highlight the importance of optimizing nanofiller content to balance mechanical strength and surface characteristics.

Overall, SiO_2/PEKK nanocomposites, particularly those with 3% SiO_2, show great promise as advanced biomaterials with improved bioactivity and mechanical properties suitable for implant applications. Future work should focus on in vitro and in vivo biological evaluations to further validate their clinical potential.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to this work.

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