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Optimization Parameters for Ceramic Crown Crack Repair with Strength and Biocompatibility Testing

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In this study, we investigated the development of advanced testing methodologies for evaluating the mechanical properties of ceramic crown crack-repair systems, alongside the characterization of hydroxyapatite (HA) thin films deposited by vacuum coating technology for antibacterial and biocompatibility applications. These innovations are aimed at addressing common clinical challenges, including variability in technician-fabricated prostheses, crown surface cracking caused by mastication, and insufficient antibacterial performance. A nanomedical resin reinforced with inorganic nanopowders was developed, and the Taguchi quality engineering method using an $L_9(3^3)$ orthogonal array was employed to determine the optimal processing parameters. The optimal formulation consisted of 2 wt% SiO_2 nanopowder and a baking temperature of 100 °C, resulting in the highest compressive strength. In addition, HA thin films deposited by RF magnetron sputtering exhibited excellent adhesion performance corresponding to HF2–HF3 levels satisfying the VDI 3198 standard. Antibacterial evaluation demonstrated that the HA-coated crown specimens achieved 64.33–85.23% greater antibacterial effectiveness than uncoated specimens. Furthermore, biocompatibility testing using MG-63 cells revealed cell viability exceeding 90% after five days for coatings deposited at 100 or 150 W for 60 min, confirming their non-cytotoxic characteristics. These findings demonstrate that the combination of optimized nanomedical resin repair and HA surface functionalization significantly enhances the mechanical strength, antibacterial performance, and biocompatibility of ceramic crown restoration systems.

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1. Introduction

1.1 Research background and motivation

Teeth play a crucial role in daily human function, and tooth loss can significantly impact both mastication and the structural integrity of the oral cavity. Many elderly individuals and dental implant patients experience issues such as surface cracking of crowns and insufficient antibacterial efficacy, leading to considerable discomfort in their daily lives. In this study, we aim to develop a nanomedical resin by incorporating various proportions of inorganic Al_2O_3 and SiO_2 nanopowders into a medical-grade resin and applying it to ceramic crown cavities to optimize their mechanical properties. Through the integration of these inorganic materials, the structural integrity and load-bearing capacity of the dental medical resins are significantly reinforced. To ensure precision during compressive characterizations, the testing assembly relied on specialized internal sensors. Specifically, a high-precision electronic load cell was employed to monitor continuous force propagation, while an integrated axial extensometer dynamic sensor tracked real-time microstrain deformations within the localized gauge length of resin specimens. Furthermore, to enhance the mechanical performance of crown surfaces, we investigated the application of vacuum-deposited hydroxyapatite (HA), an inorganic calcium phosphate compound, as a thin-film coating to improve surface density, HA adhesion, and biocompatibility. The findings of this study are expected to contribute to the durability of crowns, making them more suitable for crown restoration and structural reinforcement.

Additionally, the characteristics of ceramic materials make them suitable for fabricating various sensor devices, such as optical fiber sensors, biosensors, piezoelectric force sensors, and acoustic emission sensors. Regardless of whether ceramic materials are employed for biomedical or sensor applications, it is important to improve their mechanical properties to expand their service lifetime. Thus, in this study, we have focused on the antibacterial properties of SLM-prepared ceramic materials.

1.2 Research objective

This research is structured into four primary phases, wherein the Taguchi method is utilized to maximize the structural compressive strength of the ceramic crown crack repair, which are subsequently HA-coated to impart antibacterial properties and cytocompatibility, bridging the gap between mechanical reinforcement and biomedical coating. The first phase is focused on formulating a high-strength, highly adhesive nanomedical resin optimized via inorganic nanopowder dispersion. In the second phase, Taguchi quality engineering is employed to systematically identify optimal processing parameters, including nanopowder composition, the weight percentage of nanopowder, and baking temperature, to maximize compressive strength. In the third phase, the optimal crack-repair performance of crown-based specimens is evaluated through a combination of compressive strength testing. Finally, the fourth phase entails the deposition of a HA monolayer coating via RF magnetron sputtering followed by comprehensive

surface evaluations to ensure outstanding antibacterial efficacy and cytocompatibility. Ultimately, the successful development of this nanomedical resin with superior adhesion properties provides a standardized evaluation method and a valuable reference for industrial applications. The complete experimental workflow is illustrated in Fig. 1. Crucially, the primary focus of this work centers on defining the specific optimization parameters governed by Taguchi quality engineering. By identifying and isolating these pivotal processing parameters, we established a systematic foundation for evaluating structural integrity and biological safety, directly addressing the underlying optimization framework required for reliable clinical restorations.

To enhance the surface mechanical properties of crowns, we formulated a nanomedical resin and applied it to repair cracks in ceramic crowns. Additionally, HA [$Ca_{10}(PO_4)_6(OH)_2$] thin films were deposited using vacuum coating HA technology to improve surface density. These processes serve both gap-filling and surface-coating functions, leading to enhanced mechanical strength, film adhesion, and antibacterial performance in dental crowns.

To mitigate the risk of crown cracks and crack formation, we employed nanomedical resin and nanopowders as base materials, utilizing dispersion technology to fabricate nanomedical resin specimens. The Taguchi method was then applied to identify the optimal manufacturing parameters that maximize compressive strength. This study encompasses ceramic crack

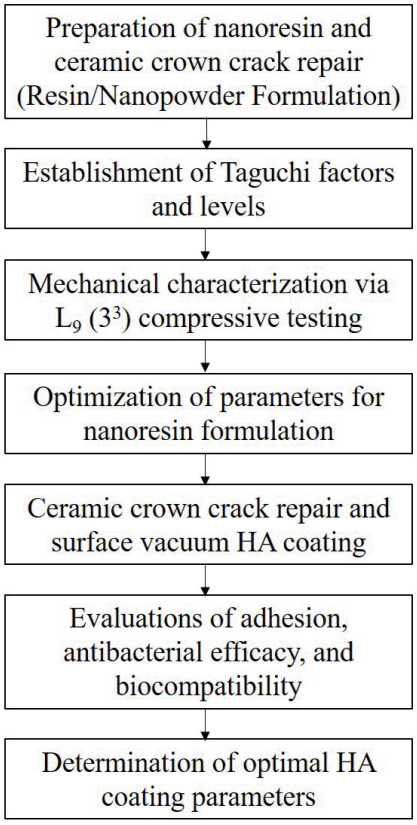

Fig. 1. Experimental procedure.

inspection, the formulation of optimized nanomedical resin, resin-based crack repair, and standardized evaluation methods for medical resin surfaces. The successfully developed nanomedical resin, which exhibits superior adhesion properties, provides a valuable reference for industrial applications.

2. Literature Review

2.1 Surface coating technology

We review surface coating technologies, focusing on their effects on mechanical and chemical properties. He *et al.*[1] demonstrated that the metal surfaces after nanomodification could promote cell proliferation and mechanical effects. In addition to biocompatibility, the coated effect is also of vital significance for the stability of porcelain-fused-to-metal (PFM) crowns. Carlo *et al.*[2] further reported that surface modification and coating technologies can improve the biological and functional properties of biomedical materials. Merker *et al.*[3] investigated thin-film deposition and discussed its effect on surface characteristics and material performance.

In this study, after the deposition of HA coatings on ceramic crown specimens, microscopic observation and mechanical property evaluations were conducted. After determining the suitable coating parameters, adhesion tests, antibacterial assessments, and biocompatibility evaluations were performed. All testing procedures were designed to comply with cytotoxicity safety requirements. Xu *et al.*[4] evaluated coating-related surface characteristics using hardness testing. Lu *et al.*[5] investigated zirconium-based surface treatment for dental materials and reported that a surface coating can improve the mechanical performance of the substrate.

Yang *et al.*[6] investigated the corrosion behavior and biological performance of metallic materials, whereas Fatani *et al.*[7] evaluated the antimicrobial properties of dental materials. Although the benefits of thin-film coatings, surface treatments, and biomedical material evaluations were demonstrated in these previous studies, they were mainly focused on individual aspects such as mechanical performance, corrosion resistance, and biocompatibility. However, the dual-functional challenge of simultaneous structural crack repair and biological protection for ceramic crowns has been addressed in few studies. Therefore, the present study bridges this gap by establishing an optimized framework that combines nanoresin crack repair with HA thin-film surface functionalization. This approach improves mechanical strength, enhances biofilm resistance, and maintains cell viability above 90%, thereby extending beyond conventional single-function coating applications.

2.2 Research procedures and methods

The experimental methodology of this study is outlined in the flowchart shown in Fig. 1. Prior to experimentation, research and discussions were conducted to address issues related to tooth cracks and cavities. To ensure clinical relevance, simulated dental application evaluations were performed by three dental specialists from the Department of Dentistry at Chi Mei

Hospital, Liouying, namely, a senior prosthodontic specialist, an attending prosthodontic and implantology specialist, and an attending digital dentistry and prosthodontics specialist. Their professional feedback was incorporated into the refinement and evaluation of the ceramic crown crack-repair procedures.

Subsequently, nanomedical resin specimens with various nanopowder compositions and resin-to-powder weight ratios were fabricated for compressive testing. Quality engineering techniques, specifically, the Taguchi method, were employed to determine optimal processing parameters. The nanomedical resin was then applied to the surface of tooth cracks, followed by the deposition of a surface coating layer. Comprehensive mechanical evaluations were conducted, including compressive strength testing and assessments of antibacterial performance and biocompatibility. If the experimental results meet the required standards, the findings can be used to establish optimal processing parameters.

2.3 Execution steps and methods

In this study, we primarily focused on the restoration of dental cracks and cavities, aiming to determine optimal processing parameters through comprehensive mechanical characterization. Initially, medical resin test specimens with various nanopowder compositions were fabricated, followed by compressive strength assessments of the cured specimens. The medical resin was subsequently used for cavity filling, and its mechanical performance was evaluated through compressive strength and adhesion strength testing.

2.4 Compressive testing of specimens and quality engineering

In this study, compressive strength testing was performed on medical resin and nanomedical resin specimens with various nanopowder compositions for the repair of ceramic dental crowns. The compression rate was set at 2 mm/min, with the objective of determining the optimal formulation and maximizing compressive strength. Figure 2 shows the experimental setup for the compressive strength evaluation of dental specimens.

To identify the optimal processing parameters for the nanomedical resin material, three primary control factors were established: the type of nanopowder incorporated, its weight percentage, and baking temperature; the term “level” refers to the specific experimental settings, operational conditions, or discrete numerical values assigned to each control factor to evaluate their individual and combined effects on the material properties. The Taguchi quality engineering method was employed to systematically input these factors and their respective levels into an $L_9(3^3)$ orthogonal array, with the objective of maximizing compressive strength. Therefore, a total of nine distinct experimental specimen formulations (designated as Specimen Nos. 1–9) were systematically prepared and evaluated, each representing a unique combination of the three control factors across their three designated levels as specified by the orthogonal matrix.

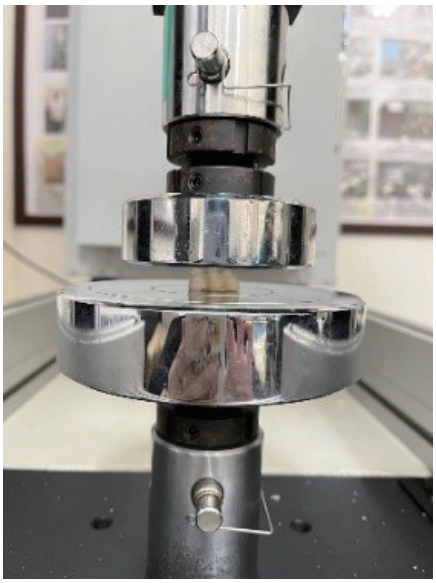

Fig. 2. (Color online) Compressive testing of ceramic crown.

Experimental data were collected from all nine specimen groups and subsequently analyzed to evaluate the effects of each factor and level on the material's mechanical strength and hydrolysis resistance. Utilizing Taguchi's analytical approach, we determined the optimal processing parameters, as summarized in Table 1, which details the $L_9(3^3)$ orthogonal array configuration. To identify the optimal processing parameters for the nanomedical resin material, three primary control factors were established: the type of nanopowder incorporated, its weight percentage, and curing temperature. The Taguchi quality engineering method was employed to systematically input these factors and their respective levels into the $L_9(3^3)$ orthogonal array. In this quality engineering context, the term "level" designates the specific discrete values or operational settings assigned to each experimental control factor. As systematized in Table 1, three distinct levels were established for each of the three control factors to map their performance variations: for Factor A (nanopowder added), Levels 1, 2, and 3 correspond to None, Al_2O_3 and SiO_2, respectively; for Factor B (weight percentage of the nanopowder), the levels are set at 2, 3, and 4%; and for Factor C (baking temperature), the levels are defined as 90, 100, and 110 ℃.

2.5 Surface vacuum coating of ceramic dental specimens

We utilized a physical vapor deposition vacuum coating system (Model: COMBO-300, manufactured by Shih Hsin Technology Co., Ltd.) to sputter HA onto the surfaces of the specimens to enhance surface coating quality and adhesion. HA vacuum coating is applied to the specimen surfaces by setting specific coating manufacturing parameters, followed by characterization assessments to evaluate the surface properties and identify the optimal coating parameters.

Figure 3 shows the SEM image of a HA-coated crown, revealing a cross-sectional structure composed of two layers, namely, a ceramic layer and a HA-coated layer, as shown in Fig. 3. To

Table 1
$L_9(3^3)$ orthogonal array.

Factor	Level		
	1	2	3
A: Added nanopowder	none	Al_2O_3	SiO_2
B: Weight percentage of the nanopowder	2%	3%	4%
C: Baking temperature	90 ℃	100 ℃	110 ℃

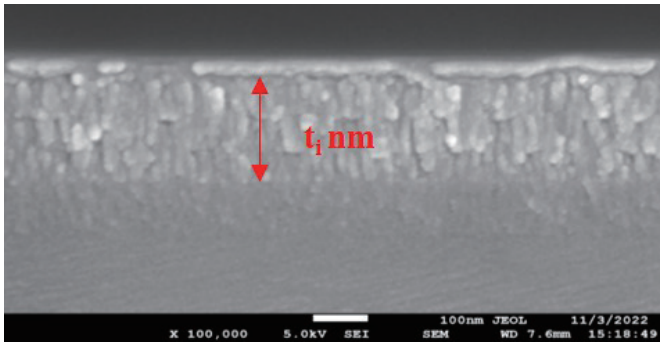

Fig. 3. (Color online) SEM image of cross-sectional structure of HA-coated crown.

ensure precise HA film interpretation, explicit graphical boundary markers are mapped directly onto the SEM image to clearly define the thickness of HA-coated films. These visual markers explicitly demarcate the transitions between the bulk ceramic substrate, the applied resin repair layer, and the outermost vacuum-sputtered HA coating layer, the thickness of which measures approximately t_i nm.

2.6 Adhesion test

The adhesion between the coating and the substrate was evaluated referring to the adhesion testing standard VDI 3198 (Germany). A Rockwell hardness tester (Future-Tech FR-1AN, shown in Fig. 4) equipped with a diamond indenter was used to apply a load, creating an indentation on the coating surface. Subsequently, the indentation was observed using an optical microscope (OM, Olympus BX-53M, shown in Fig. 5).

The adhesion quality is classified into the levels HF1 to HF6 (as shown in Fig. 6). HF1 to HF4, which showed minor cracks around the indentation, represent excellent adhesion. Conversely, HF5 and HF6, which exhibit significant delamination around the indentation, represent the poorest adhesion.

2.7 Assessment of antibacterial properties of HA monolayer films on ceramic crowns and test specimens

The antibacterial assessment in this study was conducted using an experimental method involving bacterial strains in liquid culture for the activation of *Streptococcus mutans* (ATCC 25175), biofilm staining assay, and liquid culture assay, which quantified the analysis via the

Fig. 4. (Color online) Rockwell hardness tester.

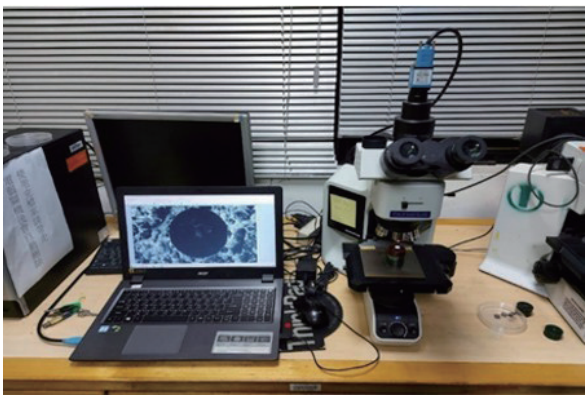

Fig. 5. (Color online) OM test.

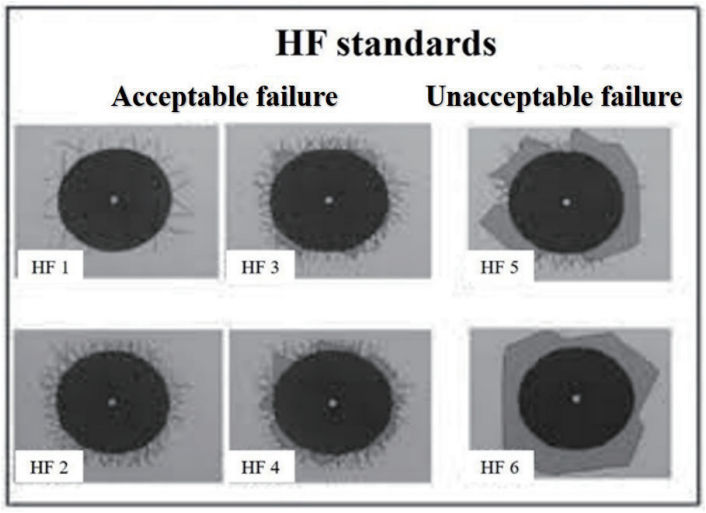

Fig. 6. Adhesion testing standard VDI 3198 (Germany).

spectrophotometric analysis of bacterial strains to evaluate the antibacterial efficacy of the HA monolayer coating on artificial crowns or test specimens. The experimental setup reflects the experimental procedure, including the activation of ATCC 25175 strains, biofilm staining assay for crystal violet (CV) staining, and subsequent optical density (OD) measurements for the quantitative assessment of antibacterial performance.

In the experimental method of ATCC 25175 strains, the experimental procedure begins with the preparation of the liquid culture medium, which is sterilized using an autoclave for subsequent use. To activate the biological activity of the ATCC 25175 strains, the lyophilized bacteria were revived from frozen stock and initially inoculated into sterile brain heart infusion (BHI) broth or tryptic soy broth (TSB). The culture tubes were subsequently incubated under anaerobic conditions (supplemented with 5% CO_2) at 37 ℃ for 24 h to undergo log-phase replication. Following this initial activation, a subculture was performed by transferring a loopful of the bacterial suspension into fresh culture medium, which was incubated under identical conditions for an additional 24 to 48 h. This step ensured that the bacterial strains reached a stable OD of approximately 0.5, corresponding to a standard bacterial concentration and achieving a highly stable and consistent level of biological activity prior to being pipetted into the centrifuge tubes containing the experimental test specimens.

Figure 7 also shows the testing processes, that is, four different specimens (noncoated one-piece crown, noncoated two-piece crown, HA-coated one-piece crown, and HA-coated two-piece crown) were immersed in a CV solution for 15 min at room temperature. After rinsing the stained specimens five times with double-distilled water (ddH_2O), their surfaces were observed to evaluate the amount of residual CV dye, where less residue indicates superior antibacterial efficacy. For the antibacterial evaluation, a spectrophotometer (Metertech SP-830 Plus) was utilized in the liquid culture assay to measure the OD values, which indicate the concentration of the bacterial suspension, as shown in Fig. 8. Antibacterial efficacy and cytotoxicity assessments were performed using a spectrophotometer at an OD of 595 nm. This equipment detects the relative concentration of *S. mutans* under room temperature conditions. Before the test, the four different specimens were placed in an *S. mutans* culture for 24 or 48 h.

3. Results and Discussion

In this research, we focused on crack repair techniques for ceramic crowns, primarily utilizing the Taguchi method to determine the optimal nanopowder type, additive percentage, and curing temperature. Additionally, we included observations of cross-sectional images and adhesion tests for the HA-coated ceramic crowns, along with the results pertaining to antimicrobial efficacy and biocompatibility. In the following sections, we present the results and discussion of this research.

3.1 Quality engineering

In this research, the compressive testing of the nanomedical resin specimens was conducted at a rate of 3 mm/min. Specimen No. 8 demonstrated the highest average ultimate compressive

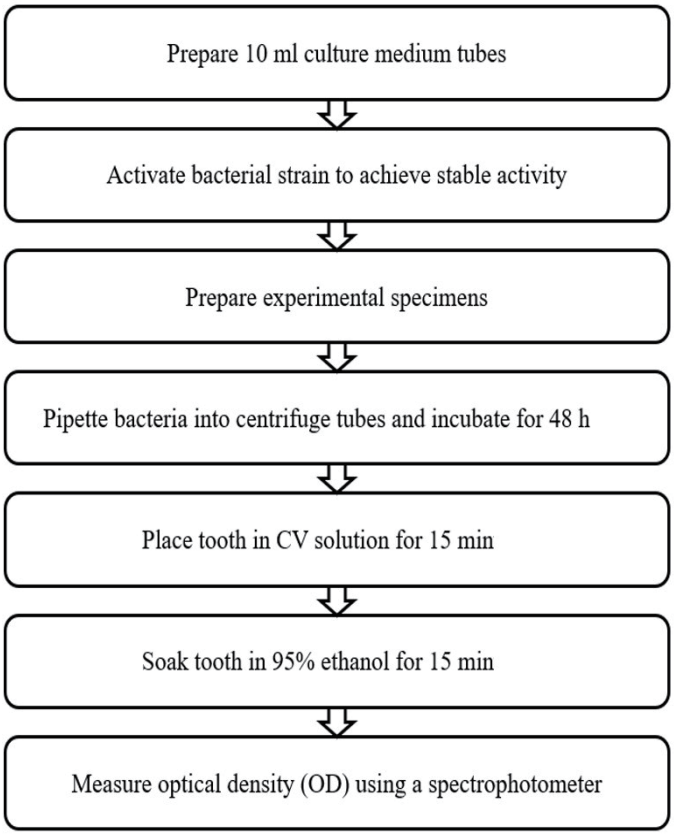

Fig. 7. Flowchart of testing processes with liquid culture for antibacterial evaluation.

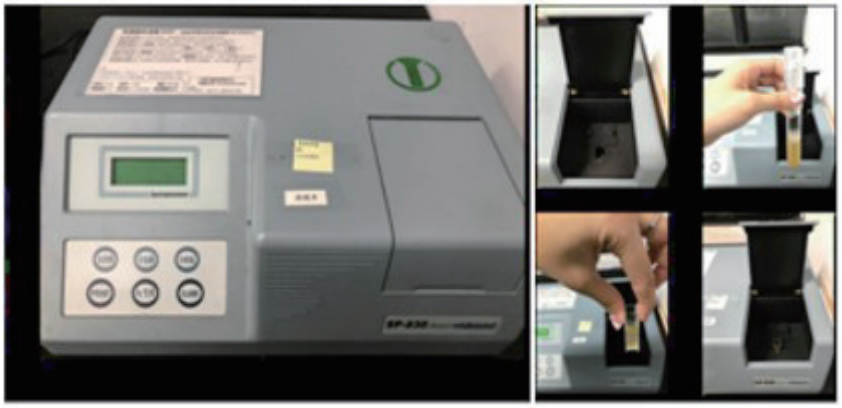

Fig. 8. (Color online) Testing process with spectrophotometer.

strength, measured at 16.1 MPa, as outlined in Table 2. Factors A, B, and C represent the primary control parameters selected for the Taguchi orthogonal array design. The parameters for Specimen No. 8 included the incorporation of SiO_2 nanopowder at a weight percentage of 3% and a baking temperature of 100 °C. The response data are presented in Table 3, with the corresponding graphical representation shown in Fig. 9. In this study, the response data, derived

Table 2
Integrated Taguchi methods.

A	B	C	A	B	C	Ultimate compressive strength (MPa)	SN ratio of ultimate compressive strength
1	1	1	None	2%	90 ℃	7.61	17.628
1	2	2	None	3%	100 ℃	8.01	18.073
1	3	3	None	4%	110 ℃	8.11	18.180
2	1	2	Al_2O_3	2%	100 ℃	15.72	23.929
2	2	3	Al_2O_3	3%	110 ℃	12.72	22.090
2	3	1	Al_2O_3	4%	90 ℃	12.08	21.641
3	1	3	SiO_2	2%	110 ℃	15.80	23.972
3	2	2	SiO_2	3%	100 ℃	16.10	24.137
3	3	1	SiO_2	4%	90 ℃	15.67	23.901

Table 3
Response data.

Level	Factor		
	A: Added nanopowder	B: Weight percentage of nanopowder	C: Baking temperature
1	17.96025	21.87625	21.0568
2	22.55338	21.43297	22.04607
3	23.03663	21.24105	21.84139
Difference value	5.07638	0.63520	1.898685

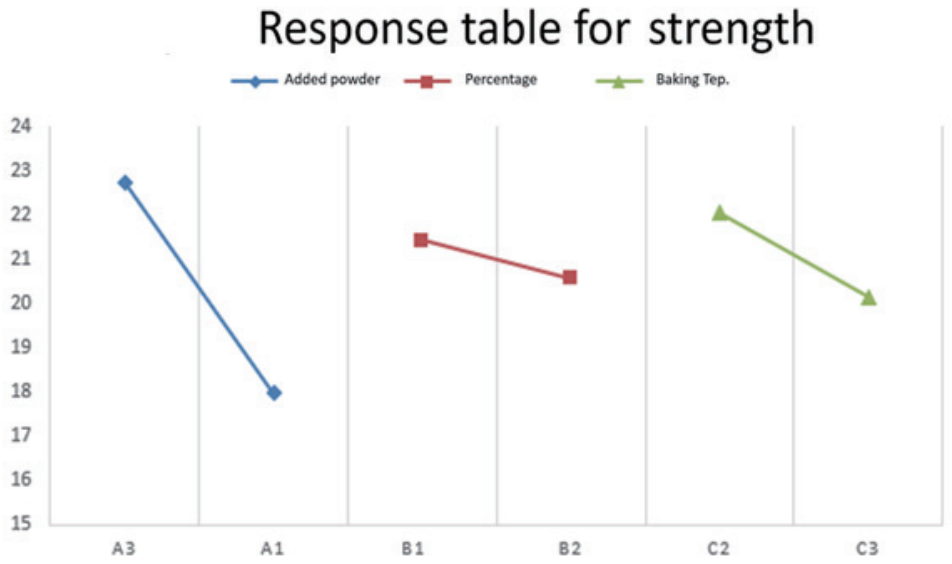

Fig. 9. (Color online) Taguchi response graphs for ultimate compressive strength showing main effects of three control factors across different experimental levels.

from the average signal-to-noise (S/N) ratios of each specific factor-level combination in Table 3, were analyzed to evaluate the effects of individual control factors on the ultimate compressive strength. Specifically, the response values represent the average S/N ratios calculated from the ultimate compressive strength results and were used to evaluate the effects of the control factors and determine the optimal processing parameters. In Table 3, the 'Difference value' represents the degree of variation for each factor across its different levels. A larger difference value indicates that the factor has a more significant effect on the compressive strength of the crown repair. This demonstrates that the type of added nanopowder (Factor A) is the most critical determinant of the repair compressive strength.

The maximum load for the compressive strength test of ceramic specimens with 2% SiO_2 and a baking temperature of 100 ℃ was 17.15 MPa, whereas that for ceramic specimens with 3% SiO_2 and a baking temperature of 100 ℃ was 16.10 MPa. This indicates that ceramic specimens with 2% SiO_2 exhibit superior compressive strength compared with those with 3% SiO_2. Furthermore, when comparing the two materials, Al_2O_3 and SiO_2, the addition of 2% SiO_2 nanoparticles resulted in enhanced mechanical properties.

3.2 Surface vacuum deposition and surface characterization

In this research, we utilized a vacuum coating system for the sputtering of HA films on ceramic crowns, with parameters set at a temperature of 500 ℃ and a sputtering duration of 1 h. The cross-sectional images of the HA-coated ceramic crowns were obtained by scanning electron microscopy (SEM) (Model: Jeol JSM-7401F). This analysis was used to determine the thickness of the HA monolayer film and subsequently calculate the deposition rates.

The HA thin films were deposited using different sputtering powers (100 and 150 W) and various deposition times (30, 60, and 180 min), and their thicknesses were observed by SEM.

At a deposition power of 100 W, the resulting coating thicknesses after 30, 60, and 180 min were 48, 96.56, and 225 nm, corresponding to deposition rates of 1.60, 1.61, and 1.25 nm/min for the single-layer HA thin films, respectively. On the other hand, at a deposition power of 150 W, the coating thicknesses after 30, 60, and 180 min were 57.5, 114 and 285 nm, corresponding to deposition rates of 1.92, 1.90, and 1.58 nm/min, respectively. Figures 10(a) to 10(f) show the thickness variations of the HA thin films deposited on sapphire substrates as observed by SEM at a magnification of 80000×. To ensure a precise HA film interpretation, explicit graphical boundary markers were mapped directly onto the SEM image to clearly define the thickness of HA-coated films.

3.3 Adhesion testing of coated HA films

Figures 11(a) to 11(f) show the OM images of the surrounding indentations on the ceramic crack-repair specimens coated with a single-layer HA thin film after adhesion testing for Rockwell hardness. No significant delamination of the single-layer HA thin film was observed on the crack-repair substrate, and its adhesion quality was graded between HF2 and HF3.

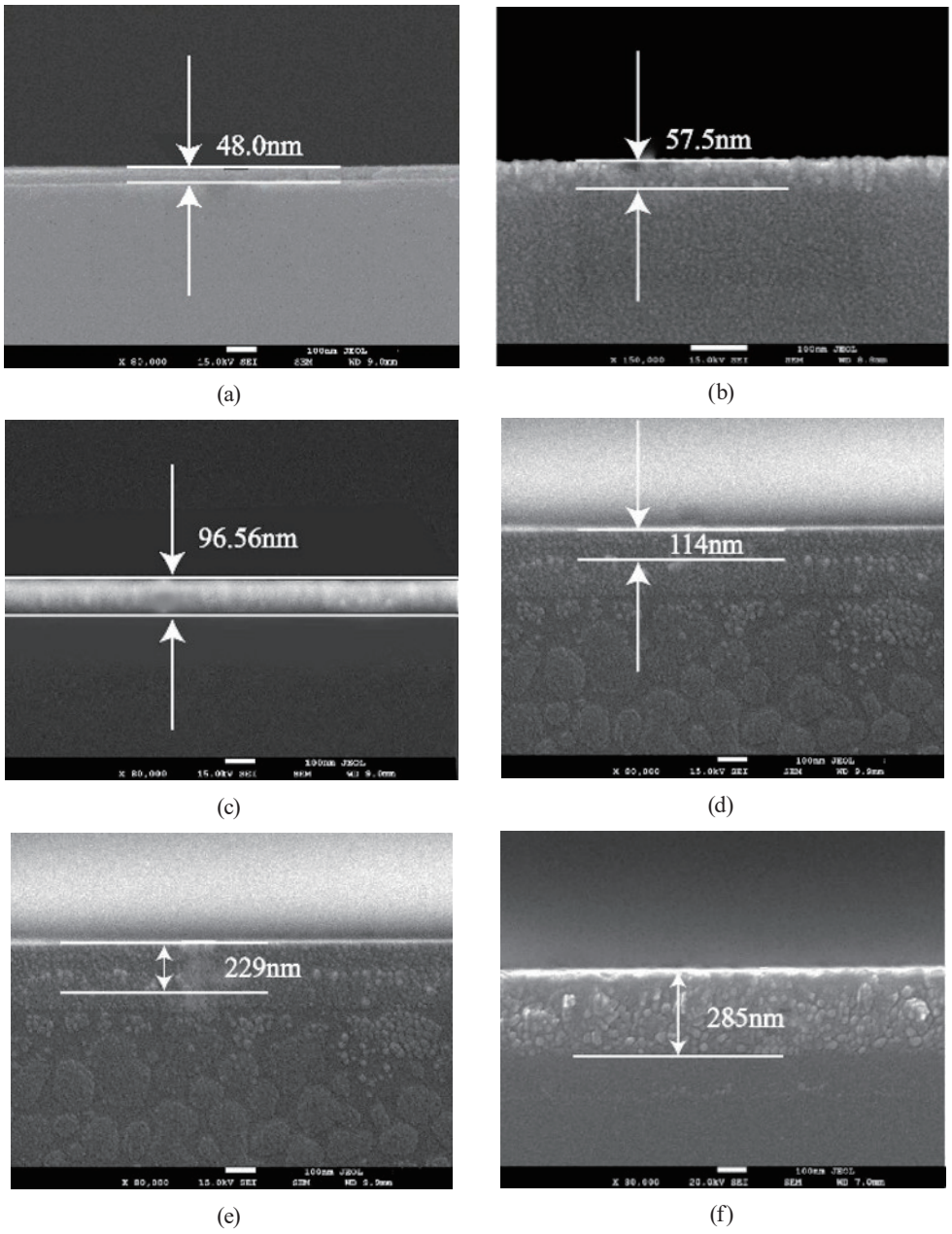

Fig. 10. SEM images of deposited HA thin films: (a) 100 W 30 min, (b) 150 W 30 min, (c) 100 W 60 min, (d) 150 W 60 min, (e) 100 W 180 min, and (f) 150 W 180 min.

3.4 Antimicrobial testing

The antibacterial assessment in this study was conducted by liquid culture assay and biofilm staining assay. Figure 12 shows the initial appearance of the HA-coated ceramic crowns during the evaluation by biofilm staining assay. The newly deposited thin films are optically transparent, making visual differentiation difficult by the naked eye; the functional variance

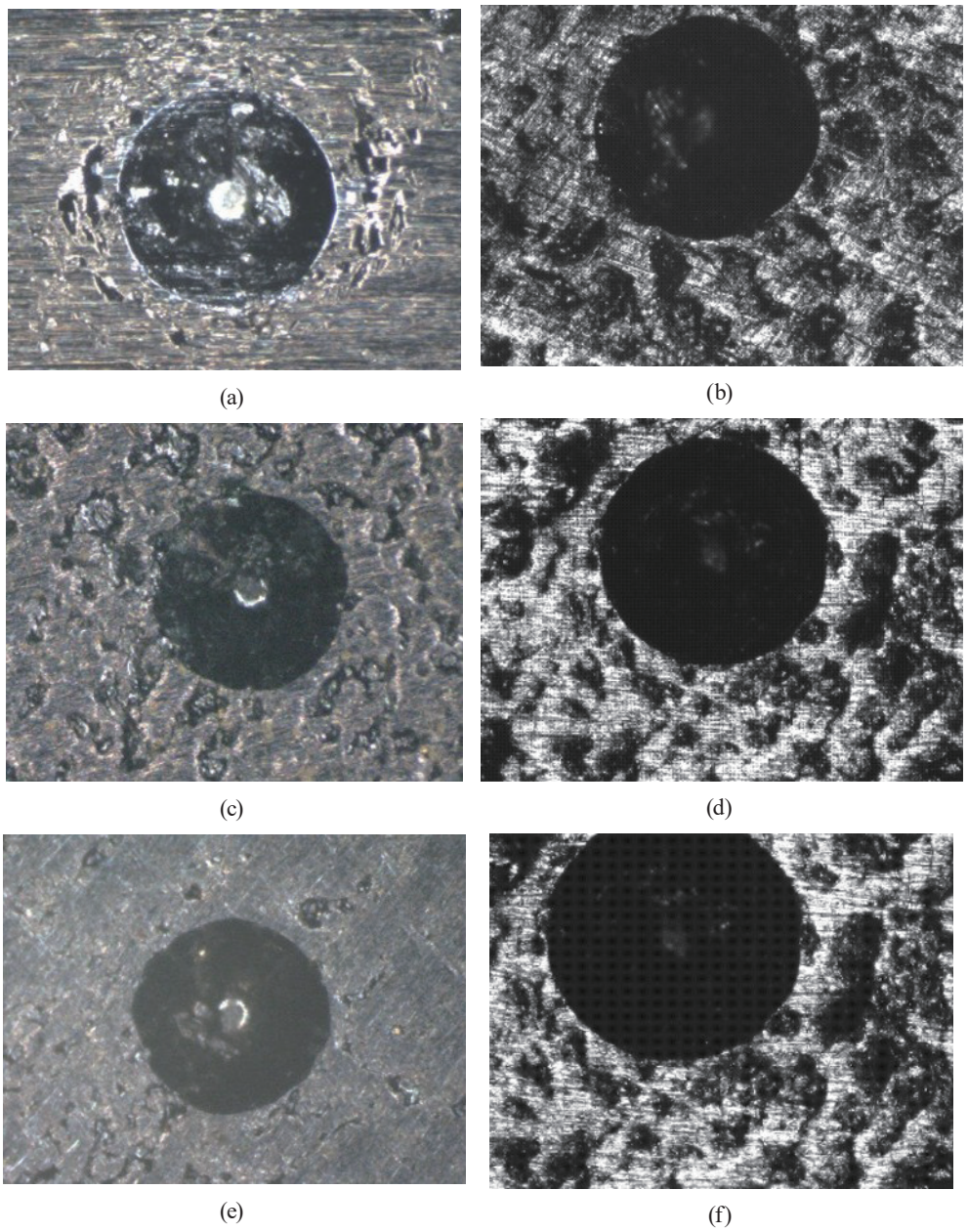

Fig. 11. OM mages of the surrounding indentations (20×) on the ceramic crack-repair specimens coated with a single-layer HA thin film: (a) 100 W 30 min (HF3), (b) 150 W 30 min (HF2), (c) 100 W 60 min (HF2), (d) 150 W 60 min (HF2), (e) 100 W 180 min (HF2), and (f) 150 W 180 min (HF2).

becomes highly pronounced following the biofilm staining assay. Figure 13 also shows the two types of crown soaked in CV solution for 15 min at room temperature to stain the accumulated *S. mutans* biofilms. The check mark (√) indicates the experimental group featuring the vacuum-sputtered HA monolayer coating, whereas the cross mark (×) indicates the control group consisting of the unmodified and uncoated HA specimens. Figure 14 shows the appearance of the crowns after being rinsed five times with ddH_2O following dye application. In these

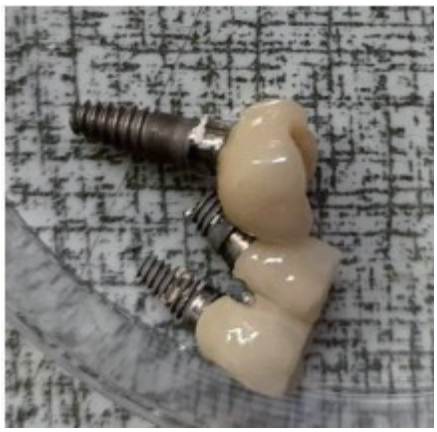

Fig. 12. (Color online) Initial appearance of the HA-coated ceramic crown.

Fig. 13. (Color online) Visual representation of ceramic dental crowns specimens immersed in CV liquid solution for 15 min at room temperature. The cross mark (\times) indicates uncoated HA specimens and the check mark (\sqrt) indicates coated HA specimens.

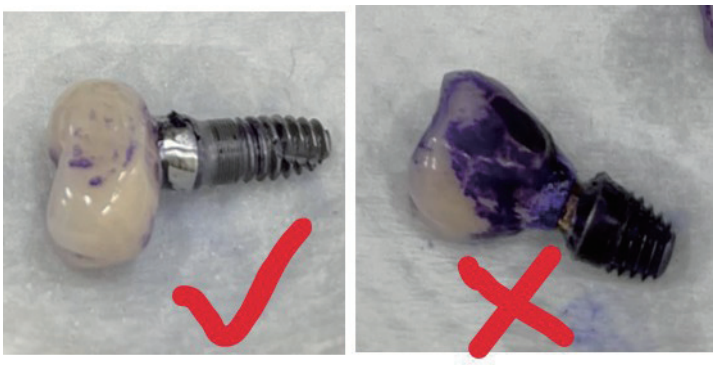

Fig. 14. (Color online) Phenotypic appearance of dental specimens after being subjected to five consecutive rinses with ddH_2O to remove nonadherent dye.

photographs, it is evident that while the surfaces of the HA-coated specimens (indicated by the marks) retain significantly less residual purple dye, the amount of residual CV adsorbed onto the uncoated control specimens (indicated by the √ marks) is notably greater. The check mark (√) indicates the HA-coated specimens showing minimal purple biofilm retention, whereas the cross mark (×) indicates the uncoated control specimens exhibiting heavy, multilayered CV residue accumulation. This distinct phenotypic variance demonstrates that the HA-coated surface provides superior protection against bacterial residue accumulation, visually validating the effective biofilm resistance of the sputtered inorganic monolayer.

Additionally, a liquid culture assay was conducted to rigorously quantify the antimicrobial efficacy of the specimens, with the stained biomass analyzed spectrophotometrically. Because the OD is directly proportional to the bacterial concentration within a specific range, the

measured OD values provide a reliable quantitative assessment of the microbial quantity. Test specimens of crown were prepared and sequentially wet-abraded in the liquid culture bacteriostatic test. The four test specimen categories are detailed in Table 4. The four specimens include (1) uncoated one-piece crown control group, (2) uncoated two-piece crown control group, (3) one-piece crown experimental group functionalized with a HA thin film sputtered at 100 W for 60 min, and (4) two-piece crown experimental group functionalized under the same HA sputtering parameters (100 W, 60 min). The specimens extracted from the control group (uncoated one-piece and two-piece crown specimens) and experimental group (HA-coating one-piece and two-piece crown specimens) were placed in test tubes containing bacterial suspensions for 24 and 48 h, respectively, after which the OD values of the control and experimental group crowns were measured. We used Eq. (1) to obtain the inhibition rate (%) of the specimens.

$$Inhibition\ rate(\%) = \frac{\left(OD\ value\ of\ control\ group - OD\ value\ of\ \exp erimental\ group\right) \times 100\%}{OD\ value\ of\ control\ group} \quad (1)$$

Following preparation, the OD values of these four specimens were measured using a calibrated spectrophotometer. According to the quantitative data compiled in Table 4, the specimens extracted from the noncoated one-piece and two-piece crowns had average OD values of 0.448±0.015 and 0.854±0.016 (24 h), respectively. The OD of the control group (noncoated two-piece crowns) is 0.854 ± 0.016. Conversely, the specimens derived from the HA-coated one-piece and two-piece crowns (100 W, 60 min) had average OD values of 0.260 ± 0.012 and 0.132 ± 0.013 (24 h) and inhibition rates (antibacterial effects) of 69.55 and 84.54% (24 h), respectively. Thus, the HA-coated two-piece crown (100 W, 60 min) with the optimal inhibition rate of 84.54% (24 h) demonstrated the greatest antimicrobial efficacy. After 48 h, as shown in Table 5, the average OD of the control group (noncoated two-piece crowns) was 0.859±0.015 (48 h), and the specimens extracted from HA-coated one-piece and two-piece crowns (100 W, 60 min) had average OD values of 0.272 ± 0.015 and 0.139 ± 0.016 (48 h) and antibacterial effects of 68.33 (48 h) and 83.82 (48 h), respectively. In Tables 4 and 5, the HA-coated two-piece crowns (100 W, 60 min) showed the best antibacterial efficacy. The noncoated two-piece crowns had the highest OD values (worst group) and lowest antibacterial efficacy.

Table 4
Antibacterial evaluation results for 24 h.

Value	Specimen			
	One piece, no coating	Two piece, no coating (a)	HA-coated one-piece (100 W, 60 min) (b)	HA-coated two-piece (100 W, 60 min) (b)
OD (*Mean* ± *SD*)	0.448 ± 0.015	0.854 ± 0.016 (worst)	0.260 ± 0.012	0.132 ± 0.013 (best)
Inhibition rate $(a - b) \times 100\%/a$	—	—	69.55%	84.54%

Table 5
Results of antibacterial tests in liquid culture for 48 h.

Value	Specimen			
	One piece, no coating	Two piece, no coating (a)	HA-coated one-piece (100 W, 60 min) (b)	HA-coated two-piece (100 W, 60 min) (b)
OD values (*Mean* ± *SD*)	0.457 ± 0.016	0.859 ± 0.015 (worst)	0.272 ± 0.015	0.139 ± 0.016 (best)
Inhibition rate $(a - b) \times 100\%/a$	—	—	68.33%	83.82%

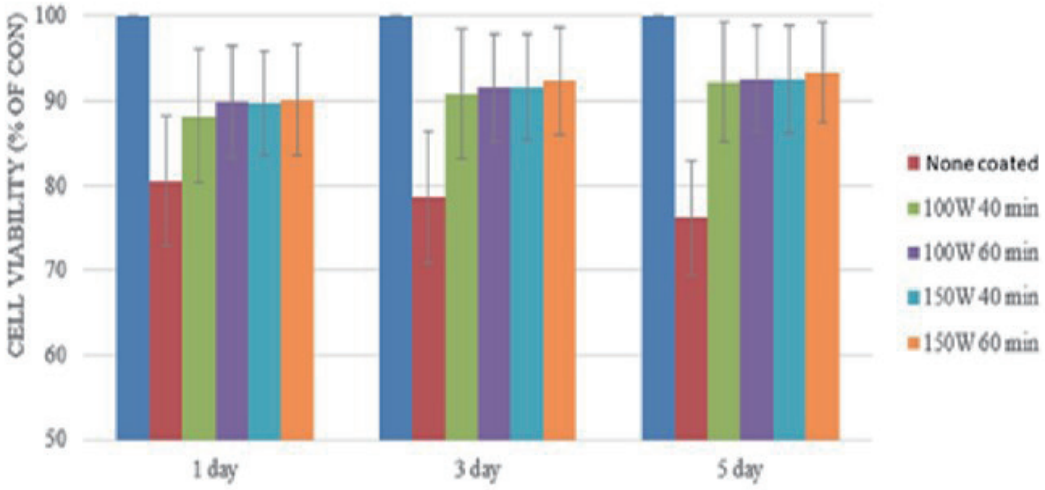

Fig. 15. (Color online) Cell survival rate.

3.5 Biocompatibility testing

The MG-63 cells used in this study are a well-established osteoblast-like model. They are of the adherent cell type, obtained from the Food Research Institute in Hsinchu City, Taiwan. MG-63 cells were used to evaluate the cell viability results of HA-coated ceramic crown crack-repair specimens. The cell viability results from the MG-63 cell cultures can provide an indication of the potential biocompatibility and cytotoxicity of HA-coated and noncoated ceramic crown crack-repair specimens.

In this research, we investigated the impact of crack-repaired and HA-monolayer-film-coated crowns (with various coating parameters) on the viability of MG-63 cells, using a control group set at 100% for comparative analysis. The results were fully compiled and presented in the cell survival rate graph shown in Fig. 15, which indicates that the cell viability on day 5 following HA coating ranges from 92.2 to 93.2%. According to the standard ISO 10993-5, our cell viability results for the HA-coated repaired crowns are all above 85%, demonstrating the absence of cytotoxicity. As shown in Fig. 15, the cell viability results obtained from the MG-63 cultures provide an indication of the potential biological safety and tissue compatibility of the HA-coated ceramic crown repair system.

4. Conclusions

We began this research by preparing nanomedical resins in varying proportions, which were subsequently fabricated into nanoresin specimens. The crown crack-repair specimens were then subjected to compressive strength, adhesion, antimicrobial, and biocompatibility tests. On the basis of the results of various mechanical property assessments, the following conclusions have been drawn.

(1) We successfully applied the Taguchi quality engineering method to identify the optimal factors and levels during compressive testing, that is, 2% SiO_2 and a baking temperature of 100 °C were determined to be the optimal manufacturing parameters.
(2) In adhesion testing, the results fell within the HF2–HF3 range of the testing standard VDI 3198, indicating that the coated HA thin films had the best adhesion on the specimens. This confirmed the success of the HA-coating technique of the ceramic crown surface.
(3) In the antimicrobial testing of ceramic crowns, the HA-coated two-piece crowns (100 W, 60 min) demonstrated the most effective antibacterial performance.
(4) The vacuum-coated HA on ceramic crowns achieved a cell viability rate exceeding 90% on day 5, indicating that the coated ceramic specimens are non-cytotoxic.
(5) Looking forward, while traditional spectrophotometric and culturing methodologies provided robust quantitative data in this study, there is a profound potential for integrating advanced biosensors in future iterations. Implementing real-time electrochemical or optical biosensors during antimicrobial and biocompatibility assessments can enable the nondestructive, continuous monitoring of bacterial metabolic kinetics and dynamic cell-substrate attachment profiles, thereby significantly advancing the screening efficiency of nanomedical dental materials.

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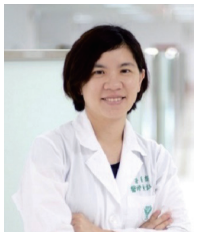

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