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Evaluation and optimization of biopolymer composite fabricated by 3D printing process for denture applications

A Thesis Submitted to Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for Master’s Degree in Materials Engineering Science.

by

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Abstract

The introduction of 3D printing technology has revolutionized the dental industry, providing a fast, reliable, and affordable method for producing a variety of dental instruments, including denture bases. Unlike conventional denture base materials, 3D-printed denture base materials typically have poor mechanical properties. Furthermore, the properties of the printed resin can be affected by 3D printing parameters, including exposure time and layer thickness. This issue has been addressed by incorporating nanoparticles into denture base materials to produce a novel nanocomposite material with improved mechanical properties. This study investigates the development of a novel nanocomposite material for denture bases by injecting varying concentrations(0,0.5,1,2)%wt of titanium dioxide rutile (TiO_2) nanoparticles and zirconium dioxide (ZrO_2) nanoparticles into 3D-printed denture base photopolymer resin. The effect of this incorporation on its mechanical (flexural strength, impact strength, hardness) characteristics and surface quality in terms of surface roughness was studied. Using 3D printing with digital light processing (DLP), composite materials were fabricated and analyzed using a design of experiment (DOE) based on the Taguchi L_{16} method optimized using ANOVA based grey relational analysis. Initially, different levels of 3D printing parameters with concentrations of metal (TiO_2) and ceramic (ZrO_2) of nanoparticles were determined. The mechanical properties and surface quality were compared with unmodified 3D-printed resin. The results showed that the optimal mechanical properties and surface quality were achieved with (0.5)%wt TiO_2, a (0.02) mm layer thickness, and an 8-second exposure time. Compared to the composite without metal dioxide nanoparticles, the percentage improvement in flexural strength was (22%), impact strength was (33%), hardness was (11%), and surface roughness was (26%). While

using (0.5)%wt of ZrO_2, (0.02) mm of layer thickness, and of (4)second exposure time, the highest percentage improvement was in flexural strength (31%), impact strength was (20%), hardness (16%), and surface roughness was (15%). The lowest values in mechanical properties at a concentration of (0.5)%wt, of (TiO_2)(ZrO_2) a layer thickness of (0.11) mm, and an exposure time of (6) seconds. Statistical analysis confirmed that nanoparticle concentration was the most influential factor, followed by the printing layer thickness, while the effect of exposure time was negligible. In addition, loading of (0.5)%wt (TiO_2) or ZrO_2 favors the surface morphology of denture and decrease in porosity, making the denture materials strong and durable. Overall, nanoparticle reinforcement of denture resin using DLP 3D printing represents a promising path to improve the performance of denture materials specifically.

CHAPTER ONE

INTRODUCTION

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Introduction

1.1 Introduction

Additive manufacturing, or 3D printing, is a printing technology that replicates computer-aided design (CAD) models by building objects layer by layer. With its superior precision, high drug-loading, and complex structure production capabilities, this technology can effectively address the drawbacks of traditional dosage forms and produce efficient customized medications and medical devices [1, 2] The vast field of additive manufacturing, is divided into several categories by the ISO (International Organization for Standardization) /ASTM (American Society for Testing and Materials), including material extrusion, vat photo polymerization, powder bed fusion, material jetting, binder jetting, direct energy deposition, and sheet lamination. The additive manufacturing (AM) technique offers many benefits to humanity, but its industrial application is limited by its slow manufacturing speed in comparison to traditional manufacturing processes. The scarcity of pharmaceutically approved printing materials, and its inefficiency when producing large quantities [3, 4]. 3D printing, which involves various methods, materials, and equipment, has evolved over the years and can transform manufacturing and logistics processes. In denture manufacturing, 3D printing replaced traditional methods by enabling the fabrication of customized dentures with greater precision and efficiency. The integration of 3D printing in dentistry offers the potential for improved fit, comfort, and aesthetics in denture design, marking a significant advancement in the field of prosthodontics [5]. Another benefit of 3D printers is that they do away with the need for lengthy steps and multiple laboratory molding processes for traditional heat-cured acrylic resin prostheses [6]. Additive Manufacturing (AM) technology, often known as three-dimensional (3D) printing, is a cutting-edge instrument with a wide range of potential uses in numerous industries. With the current explosion of 3D printing, a significant revolution in medical care is anticipated, particularly in the manufacturing processes that will lead to individualized medicine [2]. It is a type of digital manufacturing technology that constructs physical elements from an engineering model through the addition of materials. It is a rapidly expanding field as 3D printing has become common practice around the world and mass customization and open source manufacturing of designs have become increasingly common in the agricultural, healthcare, automotive, and locomotive industries [7]. When comparing two different production processes conventional and 3D printing, the latter provides better flexibility for researching the entire denture base. Thus, the 3D printing method offers a viable alteration for the denture foundation [8]. The most popular material for dental restorations made with 3D printing is polymers. Unlike metals and ceramics, polymers possess physical and chemical properties such as elasticity and tensile strength that could provide the high performance and durability required for tooth restorative materials [9]. Polymers improved mechanical and biological qualities, simplicity of processing, affordability, and adaptability have led to an increase in their application in dentistry. Diverse dental structures can be fabricated thanks to the large range of polymeric materials supported by various 3D printing processes. The portion of the denture that rests on the soft tissues of the oral cavity and supports fake teeth is called the denture base. For DBMs to work in the complex and dynamic oral environment, they should ideally have mechanical, physical, chemical, and biological properties. Additionally, they must to be highly aesthetically pleasing, adhere well to artificial teeth, be economical, precise, and dimensionally stable, as well as have high insolubility, low sorption in oral fluids, acceptable thermal properties, chemical stability, and biocompatible [10].

1.2. The gaps and limitations in the existing research

1. 3D printing processes of dentures hold aptitude as an alternative to traditional processes. In addition, the evaluation of polymer materials utilized in 3D printing for dentures highlights the notable progress and possible obstacles in the industry. Collaborative research endeavors can help address gaps and limitations, leading to the creation of denture solutions that are safe, long-lasting, and tailored to patients' needs. This, in turn, can enhance the quality of dental treatment and improve treatment results. Therefore, further in-depth research is required the use of 3D-printing technology in dental applications.
2. Most research focuses on established materials like PMMA, PEEK, and ABS, while novel polymer combinations or advanced composites receive less attention. The reinforcement by nanoparticles is an approach to modify the denture 3D-printed resin properties to overcome its limitations . However further investigations in this field are needed.
3. Although acrylate is widely used in denture fabrication due to its aesthetic properties, biocompatibility, affordability, and ease of manipulation. Acrylate has limitations such as insufficient mechanical properties, and vulnerability to bacterial and fungal growth. So, the potential of acrylic composites reinforced with nanomaterials (e.g., TiO_2, carbon nanotubes ZrO_2, graphene) remains underexplored and may lead to the development of new materials that could address current shortcomings, such as improving the fracture resistance, hardness, surface quality of dentures.

1.3. Research Objectives

The objectives of this research include the following :

1. Enhancing the mechanical properties in terms of impact strength, bending strength and hardness of 3D printed denture base resin by adding metal and ceramic nanoparticles.

2. Improving and selecting the best surface quality of 3D printed denture in terms of surface roughness.

3. Studying the effect of printing parameters on the mechanical properties and surface quality of biomedical polymer composite.

4. Investigating the morphology characteristics of fabricated 3D printed denture material.

5. Using design of experiment DOE and gray rational analysis methods GRA to develop the 3D printing process for polymer denture composite biomedical applications and enable manufacturers to make skilled decisions based on the results

1.4. Outlines of the thesis

This thesis comprises five chapters:

1- Chapter one: gives an introduction to Additive Manufacturing (AM) technology (3D Printing Technology) especially Vat Polymerization Processes, and regarding digital Light processing (DLP) and its Parameters, as well as denture materials.

2- Chapter two: includes literature review, research, and works on the subject of the thesis, such as research on the 3D printing of polymers in dental applications , as well as denture based polymer composites and the gaps and limitations in the existing research and objectives .

3- Chapter three: presents the experimental procedures involving the 3D printing of denture samples and the incorporation of reinforcing nanoparticles. It also details the post-printing processing steps, the application of the Taguchi design method, logical gray analysis, and the evaluation of mechanical properties and surface morphology.

4- Chapter four: deals with presenting the experimental findings from mechanical testing of 3D-printed dentures, including analysis of variance (ANOVA) for signal-to-noise ratio, regression analysis of mechanical properties, multi-parameter optimization of 3D printing settings, ANOVA of relative grayscale values, and validation through confirmation tests and microscopic examination.

5- Chapter five: affords a summary of the findings and limitations of the study . It also includes the thesis and suggestions for future work.