TRIBOLOGY AND CORROSION CHARACTERISTICS OF CARBON NANOTUBE AND POLYETHERETHERKETONE/CARBON NANOTUBE-COATED POROUS TITANIUM-TANTALUM SHAPE MEMORY ALLOYS FOR BIOMEDICAL APPLICATIONS

AHMED GHAZI HASSAN

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DEDICATION

ALHAMDULILLAH

All Praise for Allah, Creator of This Universe
Thanks for The Precious Iman & Islam You Blessed on Me
Thanks for All the Strength and Knowledge You Granted on Me
and, Peace Be Upon the Holy Prophet Muhammad SAW.
Thanks

I dedicated this work to,
Soul of my Father and my mother, who sacrificed, support, and encouragement during their life,
and
All my family, whose love and patience.
My wife;
My daughters; Zahraa and Shams

led to achieving my doctoral degree

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ABSTRACT

An intensive development of medical technologies and surgical procedures led to placed new and more stringent requirements on the biomaterials used. Among these materials are shape-memory alloys (SMAs) like Ti-Ta. Despite the excellent biocompatibility of Ti-Ta SMAs, certain issues like corrosion behaviour and poor tribological properties limit their widespread applications as biomedical implants which need to be resolved. Thus, this research aimed to investigate microstructures, corrosion, and tribological properties effect of coating materials on porous Ti-Ta SMA through electrophoretic deposition method (EPD). Based on this fact, some multi-walled carbon nanotubes (MWCNT) and polyetheretherketone, PEEK/MWCNT-coated porous Ti-30 at.%Ta SMAs were fabricated. These SMAs were prepared using mechanical alloying followed by microwave sintering. Electrophoretic deposition (EPD) at various applied voltages were performed to coat these SMAs using CNT (at concentration of 3 mg/mL) and MWCNT/+ PEEK (at ratio of 3 mg/mL of CNT to 3, 4.5, 6, and 7.5 mg/mL of PEEK). The microstructures of both uncoated and coated SMAs were characterized using scanning electron microscopy (SEM) equipped with energy dispersive X-ray (EDX), and X-ray diffractometry (XRD). The pull-off test was used to determine the adhesion of the coating, and water contact angles were measured to evaluate the surface wettability, the roughness and micro-hardness of the surfaces were also evaluated. Potentiodynamic polarization and immersion tests (in Kokubo simulated body fluid) were performed to determine the corrosion behavior of the uncoated and coated SMAs. A linear reciprocating wear test (ball on flat) was conducted to record the tribology behavior of the uncoated and coated SMAs. The EDX and XRD results showed the successful formation of MWCNT and MWCNT/PEEK coating on the surface of Ti-30 at.% Ta SMAs. The adhesion strength of the MWCNT layer (highest value of 7.27 MPa at 40 V) was weaker than that of the MWCNT/PEEK layer (maximum 31.29 MPa for 6P85V). The wettability of MWCNT coated surface was less than both MWCNT/PEEK coated and uncoated ones. The hardness of MWCNT/PEEK-coated samples was decreased with the increase of EPD voltages and PEEK contents. The best corrosion resistance for the MWCNT-coated samples was achieved at 40 V and for MWCNT/PEEK-coated specimens the best value was observed at higher voltage and PEEK concentration. The wear resistance of the coated samples was increased with the increase of EPD voltages and PEEK concentration, wherein the highest value was obtained for the specimen prepared at 85 V with 6 mg PEEK. Therefore, the present fabrication of SMAs, coating and comprehensive performance evaluation of the MWCNT/+PEEK-coated SMAs may constitute a basis for the development of potential biomaterials with enhanced biocompatibility desired for hard tissue engineering and implantations.

ABSTRAK

Perkembangan intensif teknologi perubatan dan prosedur pembedahan telah meletakkan keperluan baru dan lebih ketat pada biobahan yang digunakan. Antara bahan ini ialah aloi memori bentuk (SMAs) seperti Ti-Ta. Walaupun biokeserasian SMA Ti-Ta yang sangat baik, isu-isu tertentu seperti tingkah laku kakisan dan sifat tribologi yang lemah telah menghadkan aplikasinya yang meluas sebagai implan bioperubatan yang mana perlu diselesaikan. Oleh itu, tujuan penyelidikan ini adalah untuk menyiasat kesan mikrostruktur, kakisan dan sifat-sifat tribologi bahan salutan pada aloi memori bentuk (SMA) berliang melalui kaedah pemendapan elekroforetik (EPD). Berdasarkan fakta ini, beberapa nanotiub karbon berbilang dinding (MWCNT) dan polietereterketon, PEEK/MWCNT disalut pada Ti-30 at.%Ta SMA. SMA ini disediakan menggunakan pengaloian mekanikal diikuti dengan pensinteran gelombang mikro. Kaedah pemendapan elektroforetik (EPD) telah digunakan pada pelbagai voltan untuk menyalut SMA ini menggunakan CNT (pada kepekatan 3 mg/mL) dan MWCNT/+ PEEK (pada nisbah 3 mg/mL CNT kepada 3, 4.5, 6, dan 7.5 mg/mL PEEK). Mikrostruktur kedua-dua SMA yang tidak bersalut dan bersalut dicirikan menggunakan mikroskop imbasan elektron (SEM) yang dilengkapkan dengan serakan tenaga sinar-x (EDX) dan pembelauan sinar-X (XRD). Ujian tarik-keluar digunakan untuk menentukan lekatan salutan, dan sudut sentuhan air diukur untuk menilai kebolehbasahan permukaan, kekasaran dan kekerasan mikro permukaan juga dinilai. Ujian polarisasi dan rendaman potensiodinamik (dalam cecair badan simulasi Kokubo) telah dilakukan untuk menentukan kelakuan kakisan SMA yang tidak bersalut dan bersalut. Ujian haus salingan linear (bola di atas rata) telah dijalankan untuk merekodkan tingkah laku tribologi SMA yang tidak bersalut dan bersalut. Keputusan EDX dan XRD menunjukkan kejayaan pembentukan salutan MWCNT dan MWCNT/PEEK pada permukaan Ti-30 pada.% Ta SMA. Kekuatan lekatan lapisan MWCNT (nilai tertinggi 7.27 MPa pada 40 V) adalah lebih lemah daripada lapisan MWCNT/PEEK (maksimum 31.29 MPa untuk 6P85V). Kebolehbasahan permukaan bersalut MWCNT adalah kurang daripada kedua-dua MWCNT/PEEK bersalut dan tidak bersalut. Kekerasan sampel bersalut MWCNT/PEEK telah berkurangan dengan peningkatan voltan EPD dan kandungan PEEK. Rintangan kakisan terbaik untuk sampel bersalut MWCNT dicapai pada 40 V dan untuk spesimen bersalut MWCNT/PEEK, nilai terbaik diperhatikan pada voltan dan kepekatan PEEK yang lebih tinggi. Rintangan haus sampel bersalut meningkat dengan peningkatan voltan EPD dan kepekatan PEEK, yang mana nilai tertinggi diperoleh untuk spesimen yang disediakan pada 85 V dengan 6 mg PEEK. Oleh itu, fabrikasi SMA sekarang, salutan dan penilaian prestasi komprehensif SMA bersalut MWCNT/+PEEK mungkin menjadi asas untuk pembangunan biobahan berpotensi dengan biokeserasian dipertingkat yang dikehendaki untuk kejuruteraan tisu keras dan implantasi.

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LIST OF ABBREVIATIONS

Co-Cr - Cobalt Chromium
Cp-Ti - Commercial Pure Titanium
Ti-Ni - Titanium Nickel
Ti-Nb - Titanium Niobium
Ti-Ta - Titanium Tantalum
SMAs - Shape Memory Alloys
SME - Shape Memory Effect
SE - Superelasticity
PEEK - Polyetheretherketone
CNT - Carbon Nanotube
OM - Optical Microscope
SEM - Scanning Electron Microscope
FE-SEM - Field Emission Scanning Electron Microscopy
XRD - X-Ray Diffraction Microscopy
EDX - Energy Dispersive X-Ray Spectroscopy
RAMAN - Raman Spectroscopy
AFM - Atomic Force Microscope
TEM - Transmission Electron Microscopy
SBF - Simulated Body Fluid
ASTM - American Society For Testing And Materials
ISO - International Organization For Standardization
EDM - Electro-Discharged Machining
SPS - Spark Plasma Sintering
EPD - Electrophoretic Deposition
UHMWPE - Ultra-High Molecular Weight Polyethylene
PU - Polyurethane
BCC - Body Centered Cubic
FCC - Face Centered Cubic
HCP - Hexagonal Close Packing
PM - Powder Metallurgy

MWS - Microwave Sintering
PEO - Polyethylene Oxide
CVD - Chemical Vapor Deposition
PVD - Physical Vapor Deposition
MWCNTs - Multi-Walled Carbon Nanotubes
SWCNTs - Single-Walled Carbon Nanotubes
HA - Hydroxyapatite
SR - Surface Roughness
Ra - Roughness Average
WCA - Water Contact Angle
R_p - Polarization Resistance
Rct - Charge-Transfer Resistance
DIW - Deionized Water
GO - Graphene Oxide
IEP - Isoelectric Point
HVOF - High Velocity Oxygen Fuel
APS - Atmospheric Plasma Spraying
PTFE - Polytetrafluoroethylene
PEEK - Polyetheretherketone
PE - Polyethylene
EAW - Ethanol, Acetone and Water
R_{corr} - The Rate of Corrosion
E_{corr} - Corrosion Potential
EIS - Electrochemical Impedance Spectroscopy
I_{corr} - Corrosion Current Density
COF - The Coefficient of Friction
W_V - The Specific Wear Rate of The Specimen
SCF - Short Carbon Fibers

LIST OF SYMBOLS

ζ - Zeta Potential
μm - Micrometre
E - Young’s Modulus
α, β - Lattice angles
wt.% - Weight percentage
at. % - Atomic percentage
ρ - Density
βa - Anodic tafel slope
βc - Cathodic tafel slope
°C - Degree Celsius
Θ - Theta
Ω - Ohm
μ - Micro
cm^{-1} - Per centimeter
V - Volt
eV - Electronvolt
kN - Kilonewton
L - Liter
mg - Milligrams
mL - Milliliter
MPa - Megapascal
min^{-1} - Per minute
rpm - Rotation per minute
Hz - Hertz
mV - Millivolt

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CHAPTER 1

INTRODUCTION

1.1 Research Background

At present times, with the rapid advancement of technology, socio-economic conditions, and the modernized lifestyle of people worldwide, high-performance biomedical devices became demanding for personalized applications, especially for the elderly with ever-increasing failure of bones and teeth tissues. Generally, the hard tissues in the human body are more susceptible to failure, causing permanent paralyzing and bedridden. The joints of elderly people are subjected to fast deterioration due to aging-related physiological conditions, biological processes, accidents, and degenerative diseases. The patient with such ailments may become impaired throughout their life, leading to unbearable pain and or even loss in the function of certain organs unless inhibited. To overcome these problems, scientists and engineers have constantly been putting effort into getting high-performance implants. Researchers put considerable effort into achieving a proper biomedical solution to replace the damaged tissues caused by various degenerative diseases like arthritis and accidents. Through repeated studies over the years, it has been realized that various biomedical implants can be the potential solution to the tissue breakdown-related problems in different parts of the human body, wherein surgical implantation of biomedical implants of customized shapes can help to revive the tasks of the defective structures with functional compromise [1, 2].

Generally, biomedical implants are made of metallic, ceramic, and polymeric biomaterials. Biomaterials are particular kinds of biocompatible and bioactive materials that can be used and adapted customized for diverse need-based medical applications. The biomedical implants made of metallic materials are estimated to be approximately 70 to 80%, and the market consequence rate stays at around 20 to 25%. Certainly, these materials are exceptionally valuable for reconstructing failed hard tissues in humans [3, 4]. Numerous factors can affect the metallic materials' suitability for bone replacement or fixation components such as screws, pins, and plates. First, the biomaterial must have excellent osteointegration ability with the bone cell, playing a significant role in the fixation or strength of the bonding between the implant and the bone. Second, releasing dangerous metallic ions towards the body system that may lead to allergic and carcinogenic influences must be minimized. Third, the difference or mismatch of the strength between bone and metallic or alloy component used as implant should be minimal, wherein such mismatch may encourage the effect of stress-shielding, subsequently the degradation of bones [5].

The metallic biomaterials such as Co-Cr, stainless steel, commercially available pure titanium (CP Ti), and its alloys have emerged as potential implants due to their superior mechanical characteristics. Essentially, the toughness and strength of these biomaterials are indispensable safety issues under various load-bearing conditions, determining their long-term durability and performance. The evolution must be achieved based on metallurgy, thus resulting in alloys with a serviceable equilibrium between the corrosion resistance and mechanical attributes. In this regard, titanium and its alloys are superior because titanium and its alloys meet the materials implantation requirements compared to other materials competing. Therefore, Ti-based alloys are preferred for most biomedical applications [6, 7]. Yet, the mechanical traits of CP Ti cannot meet the biomaterials requirements in some situations where high strength is required, like replacement of hard tissue or below intense wear uses [8]. To surmount this limitation, the CP Ti was replaced with Ti-based alloys ($\alpha + \beta$-type) called Ti-6Al-4V alloy [9].

Despite its many interesting mechanical attributes, the Ti-6Al-4V alloy made from cytotoxic elements like V and Al suffers from some issues when implanted within the human body, where the vanadium has an a toxicity on gastrointestinal, reproductive and urinary system, and its effect on fertility and the malformations of foetuses [10]. To overcome the toxicity effects of V on humans, the shape memory alloys (SMAs) of Ti-Nb and Ti-Ta based have been introduced [5]. Both alloys show outstanding metallurgical and mechanical characteristics comparable to those of Ti-6Al-4V alloys. The Ti-Nb [11, 12] and Ti-Ta-based alloys [13] with certain β-Ti alloys display both shape memory effect (SME) and superelasticity (SE) [14]. Furthermore, the critical stress of Ti-Nb alloys is very low for a slip, leading to difficulty obtaining a favorable SME [12].

Conversely, the Ti–Ta alloys owing to their excellent SME, low modulus of elasticity, and high corrosion resistance, are preferred for various biomedical applications [13, 15-18]. For load-bearing orthopedic applications, the element Tantalum (Ta) is confirmed to be bioactive and thus recommended as a promising metal for various novel studies (for example, in vivo, in vitro, and clinical applications) [19]. Tantalum is hard, ductile, and possesses good apposition to human bones with strong resistance against chemical attacks or corrosion. It can directly form a layer of passive oxide with excellent adherence for metal, simplifying the bone in-growth below in vivo conditions through the development of bone-like apatite and thus encouraging soft- and hard -tissues adhesion [20, 21].

In recent years, numerous studies have been conducted to accurately determine the young's modulus of human bone, indicating its much lower value than some α + β-type and α-type Ti-based alloys [4, 5, 7]. This observation may lead to stress shielding effects [5] desirable for an effective biomedical implant. Meanwhile, diverse porous materials have been synthesized to lower the young modulus of Ti-based alloys further. The main reason for highlighting the porous materials research is that the quantity of raw matter required to produce the same cross-section as that of bulk materials is much lower, often leading to superior traits to their bulk counterparts. In addition, the stiffness is weaker for porous materials, and deformation is higher under increasing stress levels. The main concept behind the porous alloys-based implants is to reduce the stiffness considerably, thus encouraging the bone tissue in-growth into the pores of the implants. Definitely, the porous materials can provide exceptional biological fixation, enabling homogeneous stress transfer among the implants and bone tissues [8, 9, 22].

Conversely, the existence of porous spaces on the surface of Ti-based alloys may increase the surface roughness [23], indicating the availability of a large surface area effective for the contact of an implant, thereby increasing the corrosion rate and reducing the wear resistance [24, 25]. Additionally, some systematic studies [1, 26, 27] revealed that a weak resistance to plastic shearing of the Ti alloys and low protection against more oxidation exerted by a thin surface oxide layer could lead to their poor tribological properties. Hence, implementing Ti alloys as biomedical implants possessing wear and friction (in the case of acetabulum and head of hip endoprostheses) can lead to significant clinical issues unless inhibited.

It is established that Ti alloys enable close apposition to the bone tissues under suitable conditions with surface treatments wherein the following attributes are essential [28]:

(a) High mechanical strength, strong corrosion resistance, and low elastic modulus, wherein high wear resistance are required to avoid mechanical failures.

(b) To avoid the biological failures, it must have better biocompatibility without allergic reactions, carcinogenicity, and cytotoxicity.

(c) For improved and faster osteointegration, more bioactive surfaces are required.

(d) To lower the infection-related failures, the antimicrobial properties of the implants must be improved.

Based on the abovementioned limitations regarding the existing biomedical implants and the ever-growing demand for efficient implants, this study intended to develop some new types of multi wall carbon nanotube (CNT) and Polyetheretherketone (PEEK Plastic, a polymer)/MWCNT-coated porous Ti-Ta shape memory alloys (Ti-30 at. % Ta SMA) beneficial for diverse biomedical applications. The as-prepared alloys (without and with coating) were characterized using various techniques to determine their microstructures, corrosion, and tribological properties. The surface properties of the alloys were enhanced via the surface coating, wherein the electrophoretic deposition (EPD) method was employed to deposit the biocompatible layers like MWCNT/+PEEK. The impact of various coating parameters, including EPD voltages and suspension concentration, on the adhesion strength, corrosion resistance, wettability, microstructural, mechanical, and tribological properties of the proposed SMAs were evaluated. The obtained results were analyzed, interpreted, discussed, and compared with other state-of-the-art findings to accomplish the proposed research objectives, thus making a major contribution to the field of novel biomedical implant developments for upcoming applications.

1.2 Problem Statement

As aforementioned, titanium and its alloys are highly compatible materials for biomedical applications because of their excellent traits that fulfill the main requirements of implants in hard tissue engineering. In this view, more systematic research is needed to improve the properties of titanium and its alloys, making them advantageous for high-performance biomedical implants. Nevertheless, several studies have recently been conducted to reduce the elastic modulus of Ti-based alloys, which is much higher than that of human bone, thus leading to the stress shielding effect. To overcome this drawback, dedicated efforts must be made to lower the elastic modulus and stiffness of Ti-based alloys, initiating active research on porous Ti-based alloys. The porous Ti-based alloys not only require a lower amount of raw materials than their bulk counterparts but also attains superior biological stability by promoting the growth of bone tissues through the pores of the implants. This, in turn, enables the transfer of homogeneous stress between implants and bones, promoting faster osseointegration and healing of the damaged tissues.

The presence of excess porosity on the surface of various Ti-based alloys can lead to increased surface roughness, imparting a larger contact surface area of an implant. Consequently, it increases the corrosion rate and reduces wear resistance, which is detrimental for the injured bone tissue recovery unless reversed. In addition, the load-bearing capacity of the orthopedic implants (especially for the acetabulum and head of hip endoprostheses) must provide a bearing surface with low friction and wear, thus coordinating the distribution of the loads between the parts in an implanted joint. Therefore, the poor tribological properties associated with the existing Ti-based alloys that cause a significant clinical problem and result in the reduction of the plastic shearing resistance and low protection against additional oxidation exerted by a thin surface oxide layer must be addressed. For these considerations, The surface finish is a necessary aspect to be considered to maximize both the corrosion and wear resistance of the implant while insuring its biocompatibility. This can be achieved through the surface coating of the Ti-based alloys with appropriate biocompatible and bioactive materials. Therefore, a HA, polymer, CNT, PEEK, etc., is considered a good choice In this aspect, However, It was clearly highlighted that the main drawback in HA coatings is their poor adhesion to the implants. Moreover, wear of the polymeric component constitutes a major obstacle limiting the longevity of the implants, where it is flexible and weak to meet the mechanical demands.

Considering the fundamental and applied significance of MWCNT and PEEK /MWCNT-coated porous Ti-Ta SMAa (Ti-30 at.% Ta) as high-performance biomedical implants, it became vital to prepare such alloys without and with coating and then characterize them systematically using various analytical techniques. Because the efficiency and functionality of these alloys depend on their corrosion resistance, wettability, microstructures, and mechanical and tribological characteristics, these properties must be improved before successful applications as biomedical implants. In addition, the surface finish is a crucial aspect that must be considered to optimize the implant's corrosion and wear resistance while ensuring its biocompatibility. On top, it is essential that the biomaterials’ coatings must have excellent mechanical and metallurgical bonding with the metal substrates. Eventually, the interfacial strength often poses a significant problem that must be addressed to achieve high-performance biomedical implants. Based on these existing research gaps, the following questions are posed with specific goals to attain.

1.3 Research Questions

1. Is it possible to achieve homogenous MWCNT/+PEEK coating on the surface of Ti-Ta SMA substrate for improved properties needed for biomedical implantation?

2. How can different coating compositions of MWCNT/+PEEK and the applied voltage of EPD influence the microstructure, corrosion and tribological characteristics (wear and friction behaviour), of the Ti-Ta SMA?

3. Can the MWCNT and MWCNT/+PEEK layer adhere well to the metal substrate?

4. How tribological behavior of the MWCNT/+PEEK-coated porous SMAs will be with the other properties corresponding to coating parameters.

1.4 Objectives of the Study

Based on the abovementioned research questions, the following objectives are set:

1. To produce a homogeneous coating of MWCNT/+PEEK on the Ti-Ta SMA substrate using the EPD technique at different EPD applied voltages (30-85V) and PEEK contents (3-7.5 mg).

2. To determine the microstructural, corrosion, and tribological attributes of the coated and uncoated Ti-Ta SMA through various characterizations.

3. To evaluate and establish better adhesion properties of the MWCNT/+PEEK coatings using varied EPD applied voltages and PEEK contents.

4. To evaluate in vitro the relationship between the tribological behavior with the other properties of the MWCNT/+PEEK-coated porous SMAs corresponding to coating parameters.

1.5 Hypothesis of the Study

1. The MWCNT/+PEEK coating layer is expected to deposit homogeneously on the surface of porous Ti-Ta SMA substrate.
2. The proposed coating can improve the microstructural, corrosion, and tribological properties of the porous Ti-30 at. % Ta SMA and it is advantageous for high-performance biomedical implant applications.
3. The obtained adhesion strength between the coating and titanium alloy substrate may be sufficient for the biomedical implant applications requirements.
4. The addition of PEEK to MWCNT coating together with different deposition parameters (varied EPD applied voltages (30-85V) and PEEK contents (3-7.5 mg)) can further enhance the adhesion strength of the modified coating, beneficial for biomedical implants in hard tissue engineering.

1.6 Scope of the Study

To fulfill the proposed research objectives and attain the set goals, this study covered the following aspects called the scope of the research:

1. Preparation of the samples by a powder metallurgy technique from commercially available high purity powders of Ti (99.99%) and Ta (99.99%) followed using the microwave furnace for the sintering process.

2. The optimized coating on the proposed Ti-Ta SMA was achieved using the standard EPD method with different voltages and concentrations of MWCNT and PEEK on the powdered sintered samples made of porous Ti-30 at.% Ta (as substrate materials).

3. The microstructural analysis of the coated and uncoated samples of Ti-30 at.% Ta SMA was performed using optical microscopy (OM), scanning electron microscopy (SEM), atomic force microscopy (AFM), transmission electron microscopy (TEM), X-Ray diffraction (XRD) measurement, and Raman spectroscopy.

4. The adhesion tests for the coating were conducted using the Pull–off adhesion test to evaluate the adhesion strength of the coated layer.

5. Selected optimum coating parameters were chosen and assessed in terms of adhesion strength (with the range of more than 15 Mpa).

6. A surface roughness tester performed surface roughness evaluation of the coated and uncoated samples.

7. Vickers micro-hardness was conducted to evaluate the hardness properties of the uncoated and coated samples.

8. The tribological characteristics of the uncoated and coated samples were determined using the combination of a Linear Reciprocating Ball-on-Flat wear test followed by microscopic characterization.

9. The simulated body fluid (SBF) test was conducted to evaluate the corrosion properties of the SMAs, wherein the potentiodynamic polarization (PDP) method was used.

10. The corroded and worn surfaces of the coated SMAs were analyzed using the SEM equipped with energy dispersive X-Ray (EDX) spectroscopy.

1.7 Significance of the Study

This research aimed to gain in-depth knowledge of the microstructural, tribological, and corrosion properties of porous Ti-30 at.% Ta SMA coated with MWCNT and MWCNT/+PEEK is useful for high-performance biomedical implant applications. The proposed Ti-30 at. % Ta SMA as a substrate material with appropriate coating by biocompatible and bioactive materials contributed to developing future functional biomedical implants. It was affirmed that the microstructures, tribological, and corrosion behaviors of the porous Ti-30 at.% Ta SMA coated with MWCNT and MWCNT/+PEEK can be customized by varying the coating and deposition parameters. In short, the obtained findings of this research are expected to provide immense benefits in biomedical implants made from porous shape memory alloys materials coated with MWCNT/+PEEK. In addition, the optimum coating was shown to improve the proposed implants' overall properties (mechanical, wear, and corrosion resistance).

Moreover, it is expected to allow these materials to be used for wear and corrosion environmental without degradation and losing their properties. The optimized MWCNT/+PEEK coating on the porous Ti-30 at. % Ta SMA surface must be investigated using various other material characterization techniques before the clinical bedside from the laboratory environment.

1.8 Thesis Organization

This thesis consists of five chapters: Chapter one briefly discusses the problem background, problem statement, research questions, research objectives, research hypotheses, research scopes, research significance, and thesis organization. The literature review of this study is introduced in Chapter Two. Where it presents the background of biocompatible materials and recent progress in using Ti-based alloys for biomedical applications. Moreover, the EPD fundamentals and approaches with its literature also are clarified. Chapter three describes the research methodology utilized in conducting this research. The steps of experimental work will be described in detail and how the experiments will be performed, substrate and coating material preparation, and coating and substrate testing. Chapter four relates to experimental work results and discusses the experimental tests' findings. Finally, Chapter five summarizes the research conclusions and ends with future work recommendations.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Ahmed G. Hassan**, M.A. Mat Yajid, S.N. Saud, T.A. Abu Bakar, A. Arshad, Nurzafirah Mazlan. (2020). Effects of varying electrodeposition voltages on surface morphology and corrosion behavior of multi-walled carbon nanotube coated on porous Ti-30 at.%-Ta shape memory alloys. Surface & Coatings Technology, 401, 126257. https://doi.org/10.1016/j.surfcoat.2020.126257. **(Q1, IF:4.865)**

2. **Ahmed. G. Hassan**, M. A. Mat Yajid, S. N. Saud, T. A. Abu Bakar, Ahmed Alsakkaf. (2022). Tribological Behavior of a Multi-Walled Carbon Nanotube (MWCNT) Coated Porous Ti-Ta Shape Memory Alloy. Journal of Materials Engineering and Performance, Journal of Materials Engineering and Performance, 31, 1-13. https://doi.org/10.1007/s11665-022-07077-9. **(Q2, I.F: 2.036)**