



University of Southern Queensland

Faculty of Engineering and Surveying

**THE PRELIMINARY STUDY ON THE
MECHANICAL PROPERTIES OF HEAT-TREATED
BOVINE BONE USING EXPERIMENTAL
AND SIMULATIONS APPROACHES**

A dissertation submitted by

Mei-ling Lau

For the award of
DOCTOR OF PHILOSOPHY

2013

ABSTRACT

A critical factor that leads to bone fracture is the deterioration of bone quality. For a severe bone fracture that incurs a loss of volume, bone is unable to recover and bone grafting may be needed. Heat-treatment of bone is proposed as one of the most reliable and simple sterilisation methods to overcome the risk of rejection and disease transfer during transplantation.

The mechanical properties of bone at the micro-structural level after heat-treatment are not well characterised. To address this, this study investigated the localised mechanical properties of micro-structural tissues with the global structural level at different pre-set temperature ranges. Bovine cortical bone was used in this study as it has similar structure and morphology to human bone.

The results of the nanoindentation test demonstrated that heat-treated cortical bones can maintain relatively high elastic modulus (E) and nanoindentation hardness (H) among values between of 90⁰C to 150⁰C as compared to those of pristine bone. A significant increase of 44% (longitudinal) and 23% (transverse) of E values were found when compared to pristine bone. Also, an increase of 43% and 38% of H values in longitudinal and transverse directions respectively were found when compared to pristine bone. Furthermore, the E and H values of interstitial lamellae in this study at various temperatures are from 18.4 to 30.5 (GPa) and 0.84 to 1.27 (GPa),

respectively. The E and H values of osteon are from 18.6 to 28.8 (GPa) and 0.83 to 1.25 (GPa), respectively.

In the current study, compressive testing was employed to measure the global stiffness (E) of the bone samples. When heated at 150°C, the bone specimens showed an increase of 60% in stiffness (E) and an increase of 26% in yield stress. On the other hand, when heated at 90°C, a slight increase of 11.4% in stiffness (E) and 21.5% in yield stress was recorded.

Backscattered Electron (BSE) imaging was conducted to examine the relationship between mineral content and mechanical strength within the nanoindentation regions. The data demonstrated that the non heat-treated bones obtained the highest calcium wt% amongst the three groups. As temperature increased, there was a slight decrease in calcium wt%; however, the changes were not severe in this study.

Thermal gravimetric analysis (TGA) was used to investigate the condition of organic constituents of the bovine cortical bone. The TGA results demonstrated that heat-treated bones had three stages of weight loss. The first stage was the loss of water, which started from room temperature to 160°C. The second stage included a weight loss of organic constituents starting from 200°C to 600°C. Upon reaching 600°C, the organic constituents were decomposed and mineral phase loss started taking place until 850°C.

Computational modeling – finite element analysis (FEA) was conducted to investigate the relationship between the porosity and the mechanical properties of two main components of the cortical bone. Varying the diameters of the Haversian canal and the distribution of Volkman’s canals in osteonal bone models showed a significant difference. This means that the increase of the porosity apparently affected the elastic modulus of cortical bone. This validated FE model is able to simulate the bone properties with the consideration of different bone porosity and its heterogeneous mechanical properties in osteonal and interstitial bone’s longitudinal and lateral directions.

Suggestions for further study of the mechanical and chemical properties of heat-treated cortical bone for clinical applications are presented.

ASSOCIATED PUBLICATIONS

The following publications were produced during the period of candidature:

Journal Papers:

Mei-Ling Lau, Kin-Tak Lau, Yan-Dong Yao Yeo, Chi-ting Au Yeung, and Joong-Hee Lee, “Measurement of Bovine Bone Properties through Surface Indentation Technique”, *Materials and Manufacturing Processes*, No. 25, 2010, pp 324–328.

Mei-Ling Lau, Kin-Tak Lau, Harry Ku, Debes Bahattacharyya and Yan-Dong Yao, “Measurements of Heat treatment Effects on Bovine Cortical Bones by Nanoindentation and Compression Testing”, *Journal of Biomaterials and Nanobiotechnology*, No. 3, 2012, pp 105-113

Mei-Ling Lau, Kin-Tak Lau, Harry Ku, Francisco Cardona and Joong-Hee Lee, “Analysis of Heat-treated Bovine Cortical Bone by Thermal Gravimetric and Nanoindentation”, *Composites B (Accepted)*

Mei-Ling Lau, Kin-Tak Lau, Harry Ku, “Mechanical Properties of Heat-treated Bovine Cortical Bones by Nanoindentation”, *Bones (Under reviewing)*

Mei-Ling Lau, Kin-Tak Lau, Yan-Sheng Yin, Lan Li, May Wong, Kevin Chan, and William Chen, “A Shape Memory Alloy Energy Absorber for Backpack Design”, *Materials and Manufacturing Processes*, No.25, 2010, pp 281–286.

Conference Paper:

Mei-Ling Lau, Kin-Tak Lau and Yan-Dong Yao Yeo, “Experimental Measurement of Cortical Bone Properties”, *The 17th International Conference on Composites or Nano Engineering (ICCE-17)*, Hawaii, U.S., July 2009.

Mei-Ling Lau, Kin-Tak Lau, Yan-Dong Yao and Debes Bahattacharyya, “A Study on Bone Properties using Nanoindentation Technique”, *Processing and Fabrication of Advanced Materials XIX (PFAM-19)*, New Zealand, January 2011.

Mei-Ling Lau, Kin-Tak Lau, Harry Ku, Debes Bahattacharyya and Joong-Hee Lee “Assessing Heat-treatment Effects on Bovine Cortical Bones by Nanoindentation”, *Processing and Fabrication of Advanced Materials XX (PFAM-20)*, December 2011.

CERTIFICATION OF DISSERTATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Sindy, Mei Ling Lau

0061014581

Signature of Candidate

Date

ENDORSEMENT

Signature of Principle Supervisor

Date

Signature of Associate Supervisor

27/02/2013

Date



ACKNOWLEDGEMENTS

I would like to express my most sincere appreciation to my PhD project supervisors Dr. Harry Ku and Prof. Alan Kin-Tak Lau for all their support, encouragement, valuable inputs and guidance provided at every stage of this thesis. I would also like to extend my gratitude toward the entire departmental and technical staffs, including Dr. Francisco Cardona and Mohan Trada for their assistance and support in using facilities and materials for conducting the experimental work. Special thanks to Annmaree Jackson for her contribution to edit the thesis and to all people who have been actively involved in carrying out this thesis and those who have given me this opportunity to do this thesis.

In addition, I wish to express my deepest appreciation to my family and sisters Kit Hing, Mei Lan and Mei To for their constant support throughout the study. I would like to extend my appreciation to my friends for their encouragement. Special thankful and grateful to Ahmed Naji for his supported and encouraged me all these days.

A particular appreciation is also extended to the University of Southern Queensland and the Centre of Excellence in Engineered Fibre Composites for financial support.

TABLE OF CONTENTS

| | |
|---|--------------|
| Abstract..... | i |
| Associated Publications..... | iv |
| Certification of Dissertation..... | v |
| Acknowledgments..... | vi |
| Table of Contents..... | vii |
| List of Figures..... | x |
| List of Tables..... | xvi |
| List of Abbreviations..... | xviii |
| Chapter 1 Introduction..... | 1 |
| 1.1 Aim and Objectives..... | 7 |
| 1.2 Outline of Thesis..... | 9 |
| Chapter 2 Bone Structure, Composition and Mechanics..... | 12 |
| 2.1 Introduction..... | 12 |
| 2.2 Bone Structure..... | 14 |
| 2.2.1 Shapes of bones..... | 14 |
| 2.2.2 Hierarchical structural of bone..... | 16 |
| 2.3 Bone Composition and Remodeling..... | 22 |
| 2.3.1 Basic components of bone matrix..... | 22 |
| 2.3.2 Bone cells..... | 25 |
| 2.3.3 Modeling and remodeling of bone..... | 27 |
| 2.4 Bone Mechanics..... | 28 |
| Chapter 3 Literature Review..... | 31 |
| 3.1 Bone Mechanical Properties..... | 31 |
| 3.1.1 Material and structural properties of bone..... | 32 |

| | | |
|-------|--|----|
| 3.1.2 | Measuring the properties of bone..... | 35 |
| 3.1.3 | Evaluation for architectural properties of bone..... | 46 |
| 3.2 | Computational Modeling of Bone..... | 51 |
| 3.2.1 | Modeling of whole bone..... | 51 |
| 3.2.2 | Modeling of trabecular bone..... | 53 |
| 3.2.3 | Prediction of crack propagation..... | 54 |
| 3.3 | Bone Grafting Technology..... | 56 |
| 3.3.1 | Bone graft materials..... | 57 |
| 3.3.2 | Temperature-dependent properties of bone..... | 62 |

Chapter 4 Mechanical Properties of Heat-treated Bovine

| | | |
|-------|--|-----------|
| | Cortical Bone..... | 64 |
| 4.1 | Introduction..... | 64 |
| 4.2 | Mechanical Properties of Heat-treated Bovine Cortical Bone by Nanoindentation Test..... | 65 |
| 4.2.1 | Fabrication methodologies..... | 65 |
| 4.2.2 | Nanoindentation tests..... | 72 |
| 4.2.3 | Nanoindentation test results..... | 75 |
| 4.2.4 | Nanoindentation test discussion..... | 82 |
| 4.3 | Mechanical Properties of Heat-treated Bovine Cortical Bone by Compressive Test..... | 85 |
| 4.3.1 | Fabrication methodologies..... | 85 |
| 4.3.2 | Mechanical properties measured by compressive tests..... | 87 |
| 4.3.3 | Compressive test results..... | 89 |
| 4.3.4 | Compressive test discussion..... | 90 |
| 4.4 | Examine Mineral Content by Backscattered Electron (BSE) Imaging..... | 92 |
| 4.4.1 | Fabrication methodologies..... | 92 |
| 4.4.2 | Examination of mineral content by BSE imaging..... | 93 |
| 4.4.3 | BSE imaging results..... | 94 |
| 4.4.4 | BSE imaging discussion..... | 99 |

| | | |
|------------------|--|------------|
| 4.5 | Thermal Gravimetric Analysis (TGA) of Bovine Cortical..... | 100 |
| 4.5.1 | Fabrication methodologies..... | 100 |
| 4.5.2 | TGA Test..... | 101 |
| 4.5.3 | TGA measurement results..... | 101 |
| 4.5.4 | TGA measurement discussion..... | 104 |
| Chapter 5 | Finite Element Analysis (FEA) on Microstructure..... | 109 |
| 5.1 | Introduction..... | 109 |
| 5.2 | Finite Element(FE) Model of Cortical Bone Microstructure..... | 116 |
| 5.2.1 | Basic assumptions..... | 116 |
| 5.2.2 | Model geometry..... | 118 |
| 5.2.3 | Materials Properties..... | 131 |
| 5.2.4 | Elements and meshing..... | 131 |
| 5.2.5 | Boundary conditions..... | 134 |
| 5.3 | FEA Simulation Results..... | 135 |
| 5.3.1 | Osteonal bone porosity..... | 136 |
| 5.3.2 | Interstitial bone porosity..... | 137 |
| 5.3.3 | Microstructural stress and strain fields..... | 138 |
| 5.4 | FEA Simulation Discussion..... | 150 |
| Chapter 6 | Concluding Remarks and Suggestions for Future Research..... | 155 |
| 6.1 | Conclusion..... | 155 |
| 6.2 | Suggestions for Future research..... | 158 |
| | References..... | 160 |
| | Appendix..... | 170 |

LIST OF FIGURES

| | | |
|-------------|---|----|
| Figure 2.1 | Internal structure of a long bone..... | 14 |
| Figure 2.2 | Metacarpal are an example of short bones..... | 15 |
| Figure 2.3 | Scapular is an example of a flat bone..... | 15 |
| Figure 2.4 | Vertebrae are an example of an irregular bones..... | 16 |
| Figure 2.5 | Hierarchical structure of bone in various levels: macrostructure, microstructure, sub-microstructure, nanostructure and sub-nanostructure (Rho et al. 1998)..... | 17 |
| Figure 2.6 | Diagram of some of the microstructure of cortical and trabecular bones (Khan et al. 2001)..... | 18 |
| Figure 2.7 | Trabecular structure in the calcaneus of a 24 years old man (feppd.org, viewed on February 2011)..... | 19 |
| Figure 2.8 | Lamellar structure of Haversian systems (osteons) in a cortical bone(feppd.org, viewed on February 2011)..... | 20 |
| Figure 2.9 | Schematic diagram of the assembly of collagen fibrils and fibers (http://hk.image.search.yahoo.com/search/images , viewed on February 2011)..... | 23 |
| Figure 2.10 | Bone deposition (feppd.org, viewed on February 2011)..... | 25 |
| Figure 2.11 | Bone resorption(feppd.org, viewed on February 2011)..... | 26 |
| Figure 3.1 | Schematic diagram of compression test for bone Structure (Shin et al. 2005) | 36 |
| Figure 3.2 | Schematic diagram of torsion test for bone structure (Shin et al. 2005)..... | 38 |
| Figure 3.3 | Schematic diagram of tensile test for cortical bone (An et al. 2001)..... | 39 |
| Figure 3.4 | Schematic diagram of tensile test for trabecular bone (Cowin et al. 2001)..... | 39 |
| Figure 3.5 | Schematic diagram of bending test for bone structure. (a) Three-point bending and (b) four-point bending test (Cowin et al. 2001)..... | 40 |
| Figure 3.6 | MultiRange Nanoprobe head attached to the TriboScratch system(TriboScratch® user manual 2006)..... | 43 |
| Figure 3.7 | Load-displacement curve (TriboScratch® user manual 2006)..... | 43 |
| Figure 3.8 | SEM images of partially crushed, boiled trabecular bone. (a) Low magnification view of the deformed trabeculae. The bone shows less breaks than the untreated or baked bone. (b) A crack formation seen from the surface and from the cross section, showing the multiple cracks that form the fractures. | |

| | | |
|-------------|--|----|
| | (c and d) High magnification view of the crack. Many filaments span the microcracks. The crack surface become hard to distinguish. (Fantner et al. 2004)..... | 47 |
| Figure 3.9 | Backscattered scanning electron micrographs of 92-year-old male in carbon coated section (at 25kV) (Rho et al. 2002)..... | 48 |
| Figure 3.10 | TGA results in air. Curves represent results in order (from top to bottom): porpoise ear bone, whale tympanic bulla, whale ear bone, whale periodic fin bone, deer antler, and cod clythrum. Masses were divided by the initial mass to give a relative mass, and are plotted against temperature (Mkukuma et al. 2004)..... | 50 |
| Figure 3.11 | Five different FE meshes (10-node parabolic tetrahedral elements) of the femur used for convergence analysis. Models A-E are shown from left to right (Helgason et al. 2008)..... | 52 |
| Figure 3.12 | Assigning material properties from CT dataset to a Gauss integration point. (a) The FE geometry imported into ABAQUS. The arrows indicate the four points where loading was applied and (b) an integration point in a pixel (Chen et al. 2010)..... | 53 |
| Figure 3.13 | FE models of the femoral head specimen created at a voxel resolution of 84 μ m (left) and 168 μ m (right) using either the hexahedron (top) or the tetrahedron meshing approach (bottom) (Ulrich et al. 1998)..... | 54 |
| Figure 3.14 | (a) An undeformed finite element mesh of CT specimen showing the location of the cohesive elements marked by the white line; (b) a deformed mesh of CT specimen with a propagation crack. Note that displacement magnification factor is 5; (c) A schematic representation of the cohesive zone (Ural et al. 2006)..... | 55 |
| Figure 4.1 | Mekton, resin bonded diamond cut-off wheels for machining the specimens..... | 66 |
| Figure 4.2 | Bovine cortical bones from ribs were machined and divided into 3 groups, (a) pristine; (b) heat-treated at 90°C; (c) heat-treated at 150°C..... | 66 |
| Figure 4.3 | Bovine cortical bones from femur were machined and divided into 5 groups, (a) pristine; (b) heat-treated at 37°C; (c) heat-treated at 90°C; (d) heat-treated at 120°C; and (e) heat-treated at 160°C..... | 67 |
| Figure 4.4 | Bovine cortical bone from ribs were embedded into epoxy resin without being vacuumed to provide support..... | 69 |

| | | |
|--------------|--|----|
| Figure 4.5 | Bovine cortical bone from femur were embedded into epoxy resin without being vacuumed to provide support..... | 69 |
| Figure 4.6 | Optical microscope (Nikon, Model EPIPHOT200)..... | 70 |
| Figure 4.7 | Optical micrographs of the rib cortical bone sample, (a, b) pristine bone in longitudinal and transverse directions respectively, (c, d) heat-treated at 90°C in longitudinal and transverse directions respectively, (e, f) heat-treated at 150°C in longitudinal and transverse directions respectively..... | 71 |
| Figure 4.8 | (a) Nanoindenter (TriboScratch; Hysitron, Inc., Minneapolis, MN) and (b) Berkovich diamond indenter tip attached to the TriboScratch system..... | 72 |
| Figure 4.9 A | A total of 75 indentations were produced in longitudinal direction of an intact bovine cortical bone..... | 76 |
| Figure 4.9 B | A total of 118 indentations were produced in transverse direction of an intact bovine cortical bone..... | 76 |
| Figure 4.10A | A total of 116 indentations were produced in longitudinal direction of heat-treated cortical bone at 90°C..... | 77 |
| Figure 4.10B | A total of 120 indentations were produced in transverse direction of heat-treated cortical bone at 90°C..... | 77 |
| Figure 4.11A | A total of 108 indentations were produced in longitudinal direction of heat-treated cortical bone at 150°C..... | 78 |
| Figure 4.11B | A total of 105 indentations were produced in transverse direction of heat-treated cortical bone at 150°C..... | 78 |
| Figure 4.12 | Load-displacement curve of heat-treated rib bone at 90°C. S is the contact stiffness, P is the applied load and h is the depth. S ₀ is the slope of the initial portion of unloading curve..... | 78 |
| Figure 4.13A | Specimens of bovine cortical bone from femur were heat-treated at five different temperature ranges from (a) pristine, (b) 37°C, (c) 90°C, (d) 120°C and (e) 160°C. Nanoindentation marks were impressed around Haversian canal..... | 79 |
| Figure 4.13B | Specimens of bovine cortical bone from femur were heat-treated at five different temperature ranges from (a) pristine, (b) 37°C, (c) 90°C, (d) 120°C. Nanoindentation marks were impressed around interstitial lamellae..... | 80 |
| Figure 4.14 | Specimens of bovine cortical bone from rib were machined for compressive test. (a) pristine as a control group; (b) heat-treated at 90°C; and (c) heat-treated at 150°C..... | 86 |
| Figure 4.15 | The specimen was placed between two parallel stainless steel | |

| | | |
|-------------|---|-------|
| | platens to conduct compressive test..... | 87 |
| Figure 4.16 | All specimens were tested to failure: (a) pristine as a control group; (b) heat-treated at 90°C; and (c) heat-treated at 150°C..... | 88 |
| Figure 4.17 | Stress-strain curve of heat-treated bone at 90°C..... | 90 |
| Figure 4.18 | Compressive test results for mechanical properties: (a) Young's modulus vs heating temperature; (b) yield stress (σ_y) vs heating temperature..... | 90 |
| Figure 4.19 | The surface of the bone specimen was coated in a thin layer of carbon for BSE imaging..... | 93 |
| Figure 4.20 | Scanning Electron Microscope..... | 94 |
| Figure 4.21 | Backscattered scanning electron (BSE) images of bovine cortical bone. Light and dark gray regions represented the higher and lower mineral content respectively..... | 95 |
| Figure 4.22 | (a-f) is the BSE scanned regions of the pristine group; (g-l) is the BSE scanned regions of heat-treated in 90°C; (m-r) is the BSE scanned regions of heat-treated in 150°C..... | 96-98 |
| Figure 4.23 | TA instruments Q500 thermal analyser is used to perform the test..... | 101 |
| Figure 4.24 | Untreated and treated with PBS of bovine cortical bone from femur..... | 102 |
| Figure 4.25 | Untreated and treated with PBS of bovine cortical bone from rib..... | 102 |
| Figure 4.26 | TGA results of femur and rib cortical bones treated without PBS as heated from room temperature to 850°C..... | 105 |
| Figure 4.27 | TGA results of femur and rib cortical bones treated with PBS as heated from room temperature to 850°C..... | 106 |
| Figure 5.1 | The hierarchical structure of cortical bone (Hambli et al. 2012)... | 110 |
| Figure 5.2 | A schematic diagram illustrating the assembly of collagen fibrils and fibers and bone mineral crystals. The well known 67 nm periodic pattern results from the presence of adjacent hole (40 nm) and overlap (27 nm) regions of the assembled molecules.(Rho et al. 1988a)..... | 111 |
| Figure 5.3 | Element shapes (Abaqus / CAE User's Manual version 6.5)..... | 113 |
| Figure 5.4 | (a) mesh generated with tetrahedral elements (b) mesh generated with hexahedral elements (Abaqus / CAE User's Manual version 6.5)..... | 114 |

| | | |
|-------------|---|---------|
| Figure 5.5 | (a) BSE scanned image of osteons; (b) microstructure of the osteonal cortical bone, canals and osteons are not to scale (http://hk.image.search.yahoo.com ; viewed on 23/12/2012)..... | 116 |
| Figure 5.6 | (a) BSE image used as a reference to generate the model; the red square shows the osteon and interstitial bone; (b & c) Schematic diagram of simplified model of osteons and interstitial bone from BSE image..... | 119 |
| Figure 5.7 | (a) Top view of the single osteon model (O3 A and B), the diameter of the Haversian canal is changed from 40 μm to 60 μm ; (b) Schematic side view of the single osteon model (O3A), Volkman's canals are evenly distributed; (c) side view of the single osteon model (O3B), Volkman's canals are randomly distributed | 120-121 |
| Figure 5.8 | (a) Top view of the single interstitial model (I4A and B), the diameter of the osteon is 200 μm ; (b) Schematic side view of the single interstitial bone model (I4A), Volkman's canals are evenly distributed; (c) side view of the single interstitial bone model (I4B), Volkman's canals are randomly distributed..... | 122-123 |
| Figure 5.9 | (a) Schematic top view of the osteon pattern model (OP3A); (b) side view of the osteon pattern model (OP3A), Volkman's canals are evenly distributed..... | 125 |
| Figure 5.10 | (a) Schematic top view of the interstitial pattern model (IP1A); (b) side view of the evenly distributed Volkman's canals; (c) Schematic top view of the interstitial pattern model (IP3B); (d) side view of the randomly distributed Volkman's canals; (e) Schematic top view of the interstitial pattern model (IP6A), the osteons are evenly distributed and the diameters are set from 200-240 μm in diameter; (f) side view of the evenly distributed Volkman's canals, the diameters are set from 10-12 μm ; (g) Schematic top view of the interstitial pattern model (IP6B), the osteons are randomly distributed and the diameters are set from 200-240 μm in diameter; (h) side view of the randomly distributed Volkman's canals, the diameters are set from 10-12 μm | 127-130 |
| Figure 5.11 | Typical mesh showing the single unit cell of osteonal and interstitial bone model. (a) osteon with Haversian canal and randomly distributed Volkman's canal, (b) interstitial bone with osteon and evenly distributed Volkman's canals..... | 133 |
| Figure 5.12 | Boundary conditions of the compressive simulation. A compressive force is applied on the top surface and bottom surface is fixed..... | 134 |
| Figure 5.13 | The maximum principal stress of osteonal model A and B..... | 137 |

| | | |
|-------------|--|-----|
| Figure 5.14 | The maximum principal stress of interstitial model A and B..... | 138 |
| Figure 5.15 | Sectioned model O3A, typical stress (a); typical strain (b), found in osteonal bone under compressive loading. The Volkman's canals evenly distributed..... | 139 |
| Figure 5.16 | Sectioned model O4B, typical stress (a); typical strain (b), found in osteonal bone under compressive loading. The Volkman's canals are randomly distributed..... | 140 |
| Figure 5.17 | Maximum principal strain of osteonal bone model OA and OB..... | 141 |
| Figure 5.18 | Sectioned model OP5A, typical stress, (a) and strain (b), found in osteonal bone under compressive loading. The Volkman's canals are evenly distributed..... | 142 |
| Figure 5.19 | Maximum principal strain of osteonal bone model OPA and OPB..... | 143 |
| Figure 5.20 | Sectioned model I3A, typical stress, (a) and strain (b), found in interstitial bone under compressive loading. The diameter of osteonal and Volkman's canals are varied and Volkman's canals are evenly distributed..... | 144 |
| Figure 5.21 | Sectioned model I3B, typical stress, (a) and strain (b), found in interstitial bone under compressive loading. Varying diameter in osteonal and Volkman's canals, and Volkman's canals are randomly distributed..... | 145 |
| Figure 5.22 | Maximum principal strain of single interstitial bone model IA and IB..... | 146 |
| Figure 5.23 | Sectioned model IP5A, typical stress, (a) and strain (b), found in interstitial bone pattern under compressive loading. Varying diameter in osteonal and Volkman's canals, and Volkman's canals are evenly distributed..... | 147 |
| Figure 5.24 | Sectioned model IP5B, typical stress, (a) and strain (b), found in interstitial bone pattern under compressive loading. Varying diameter in osteonal and Volkman's canals, and Volkman's canals are randomly distributed..... | 148 |
| Figure 5.25 | Maximum principal stain of interstitial bone pattern model IPA and B..... | 149 |
| Figure 5.26 | Maximum principal stress of osteonal pattern model OPA and B..... | 152 |

LIST OF TABLES

| | | |
|-----------|---|-----|
| Table 2.1 | Modeling and remodeling of osteoclasts and osteoblasts (Martin et al. 1998)..... | 28 |
| Table 3.1 | The Hierarchical levels of bone (An et al. 2000)..... | 34 |
| Table 3.2 | Compression and tensile results from various researchers..... | 41 |
| Table 3.3 | Summary of nanoindentation results from various researchers..... | 45 |
| Table 3.4 | Phases in the normal fractures healing sequence (Kenley et al. 1993..... | 57 |
| Table 3.5 | Approved materials for bone grafting (Kenley et al. 1993)..... | 58 |
| Table 3.6 | Classification of biomaterials for bone grafting (Murugan et al. 2005)..... | 61 |
| Table 4.1 | Group and temperature ranges of bovine cortical bone from rib..... | 67 |
| Table 4.2 | Group and temperature ranges of bovine cortical bone from femur..... | 68 |
| Table 4.3 | Average elastic moduli and hardness values of rib's cortical bovine bone in various temperatures..... | 76 |
| Table 4.4 | Average elastic moduli and hardness of femur's cortical bovine bone in various temperatures (Standard deviations are shown)..... | 81 |
| Table 4.5 | ANOVA is employed to analysis the statistically differences of elastic moduli and hardness of osteonal and interstitial lamellae at various temperatures..... | 82 |
| Table 4.6 | Average elastic modulus, stress and stain at various temperature ranges..... | 89 |
| Table 4.7 | Summary of Ca/P ratios in different regions..... | 99 |
| Table 4.8 | Two groups of bone specimens were untreated with PBS; while 2 groups of specimens were treated with PBS..... | 100 |
| Table 4.9 | TGA results of femur and rib cortical bone as heated from room temperature to 850°C..... | 103 |
| Table 5.1 | Summary of meshing system by various researchers..... | 115 |
| Table 5.2 | Summary of the osteon model parameters..... | 120 |
| Table 5.3 | Summary of the interstitial bone model parameters..... | 122 |
| Table 5.4 | Summary of the osteon pattern model parameters..... | 124 |

| | | |
|-----------|---|---------|
| Table 5.5 | Summary of the interstitial pattern model parameters..... | 126 |
| Table 5.6 | Summary of elastic modulus and Poisson's ration used in several FE simulation..... | 131 |
| Table 5.7 | Summary of the elements and nodes of the models..... | 132 |
| Table 5.8 | Summary the maximum principal stress, Von Mises stress and maximum strain of all models..... | 135-136 |

LIST OF ABBREVIATIONS

| | |
|------------|--|
| 2-D | Two-dimensional |
| 3-D | Three-dimensional |
| AFM | Atomic force microscopy |
| ANOVA | Analysis of variance |
| BMU | Basic multicellular unit |
| BSE | Backscattered electron |
| Ca | Calcium |
| Co-Cr | Cobalt-chromium alloy |
| CT | Computed tomography |
| <i>d</i> | Gauge diameter |
| DOF | Degree of Freedom |
| E | Young's modulus or modulus of elasticity |
| EDX or EDS | Energy dispersive X-ray spectroscopy |
| FEA | Finite element analysis |
| FEM | Finite element modeling |
| GH | Growth hormone |
| H | Hardness |
| HA | Hydroxyapatite |
| HIV | Human immunodeficiency virus |
| IOF | International Osteoporosis Foundation |
| L | Longitudinal |

| | |
|---------|---|
| MR | Magnetic resonance |
| NI | Nodal interpolation |
| OI | Osteogenesis imperfect |
| P | Phosphorous |
| PBS | Phosphate-buffered Saline |
| PCL | Polycaprolactone |
| PE | Polyethylene |
| PGA | Poly (glycolic acid) |
| PLA | Poly (lactic acid) |
| PLGA | Poly (lactic- <i>co</i> -glycolic acid) |
| PLLA | Poly- L-lactic acid |
| PMMA | Polymethyl methacrylate |
| pQCT | Peripheral quantitative computed tomography |
| PTH | Parathyroid hormone |
| QCT | Quantitatively computed tomography |
| R-curve | Propagation toughness |
| RT | Room temperature |
| SD | Standard deviation |
| SEM | Scanning electron microscope |
| SHPB | Split Hopkinson Pressure Bar |
| T | Transverse |
| Ti | Titanium alloy |
| TCP | Tricalcium phosphate |
| TEM | Transmission electron microscopy |

| | |
|-----|------------------------------|
| TFB | Treated femur bone |
| TRB | Treated rib bone |
| TGA | Thermal gravimetric analysis |
| UFB | Untreated femur bone |
| URB | Untreated rib bone |
| USA | United States of America |
| XRD | X-ray diffraction |

Equation parameters:

| | |
|--------------------|-----------------------------|
| A | Area |
| A_c | Projected contact area |
| E_r | Reduce modulus |
| E_i | Elastic modulus of indenter |
| E_s | Elastic modulus of specimen |
| ν_i | Poisson's ratio of indenter |
| ν_s | Poisson's ratio of specimen |
| P_{max} | maximum indentation force |
| σ | Compressive stress |
| ϵ | Compressive strain |
| P | Applied force |
| S | Contact stiffness |
| ξ, η, ζ | Global degree of freedom |
| u, v, w | Local degree of freedom |

Unit:

| | |
|----------------------|-----------------------------|
| % | Percent |
| ° | Degree |
| °C | Degree Celsius |
| cm | Centimeter |
| cm ³ /min | Cubic centimeter per minute |
| GPa | Giga pascal |
| kN | Kilo-newton |
| mg/dl | Milligrams per deciliter |
| mm | Millimeter |
| mm ³ | Cubic millimeter |
| mN | Millinewton |
| µm | Micron-meter |
| MPa | Mega pascal |
| Nm | Nanometer |
| wt% | Weight percent |