

Tensile behaviors of three-dimensionally free-formable titanium mesh plates for bone graft applications

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Abstract. Present metal artificial bones for bone grafts have the problems like too heavy and excessive elastic modulus compared with natural bones. In this study, three-dimensionally (3D) free-formable titanium mesh plates for bone graft applications was introduced to improve these problems. Fundamental mesh shapes and patterns were designed under different base shapes and design parameters through three dimensional CAD tools from higher flexibility and strength points of view. Based on the designed mesh shape and patterns, sample specimens of titanium mesh plates with different base shapes and design variables were manufactured through laser processing. Tensile properties of the sample titanium mesh plates like volume density, tensile elastic modulus were experimentally and analytically evaluated. Experimental results showed that such titanium mesh plates had much higher flexibility and their mechanical properties could be controlled to close to the natural bones. More details on the mechanical properties of titanium mesh plates including compression, bending, torsion and durability will be carried out in future study.

1. Introduction

Tailor-made tricalcium phosphate bone implants fabricated using a 3D ink-jet printer and used in clinical trial have mechanical properties such as very poor stiffness & fracture strength and have been applying only for the non-load implant cases (Tessier et al. 2005 [1], Eppley et al. 2005 [2], Igawa et al. 2010 [3]). Then titanium plate implants can be used as the reinforcements of such Tailor-made tricalcium phosphate bone implants for many implant cases. On the other hand, the present titanium plates for implant applications have the problems like too heavy, mismatch-elasticity and excessive-strength compared with natural bones (Sato et al. 2011 [4], Wakui et al. 2012 [5], Seki et al. 1994 [6]). In this study, improved titanium mesh plates with higher 3-dimensional flexibility (Abiko et al. 2011 [7], J. He et al. 2014 [8]) were interested to solve such kind of problems.

Fundamental mesh shapes and patterns were designed under different base shapes (triangle, quadrangle and hexagon) and design parameters through three dimensional CAD tools from higher flexibility and strength points of view. Based on the designed mesh shapes with different base shapes (triangle, quadrangle and hexagon) and mesh line widths, sample specimens of titanium mesh plates were manufactured through the laser beam machining for experimental and analytical studies. Tensile experiments on sample titanium mesh plates were carried out to evaluate the effects of design parameters on the mechanical properties like tensile elasticity and volume density etc. On the other hand, analytical approaches on mechanical properties of titanium mesh plates were also carried out using ANSYS finite element analysis code. Comparisons between experimental and analytical results are used to validate the analytical approach method.



2. Fundamental mesh shape designs for 3D free-formable titanium mesh plates

To solve the too heavy, mismatch-elasticity and excessive-strength problems compared with natural bones in the present metal plate implants, mechanical properties of improved plate implants need to be closed to the natural bones. Then fundamental mesh shapes are considered under the following structural design conceptions:

(1) Single fundamental mesh shape construction for simplification of manufacturing processing and cost-down purpose

(2) Higher three-dimensional flexibilities including expansion/contraction, bending and torsion for possibility of handily shape changes during surgery

(3) Easy-controllable mechanical properties like elastic modulus, bending stiffness etc. for approachability to natural-bone's mechanical properties

(4) Uniform mesh line width and non-angle smooth shape desired to avoid the stress concentrations and lead for higher strengths and longer operating life

Figure 1 shows three basic mesh shapes with basic five design parameters introduced in this study based on the above mentioned design conceptions.

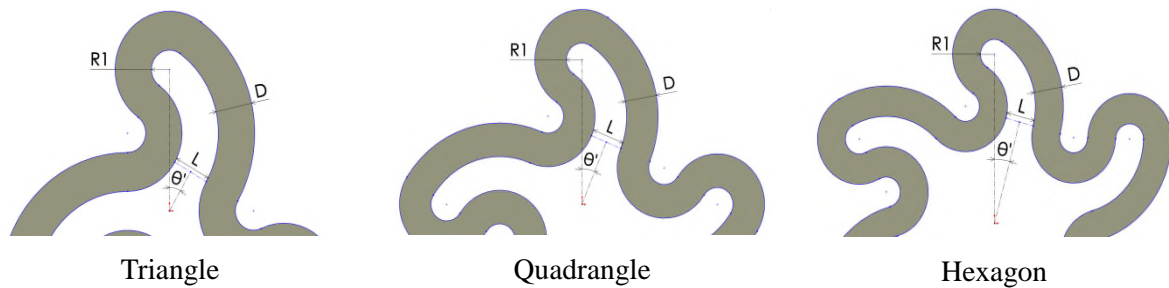


Figure 1. Mesh shapes with five basic design parameters: n: triangle=3, quadrangle=4 and hexagon=6; D: mesh line width; R1: mesh space radius; L: minimum space length; θ : bending angle.

It is possible to create different varieties of mesh shapes from these five basic design parameters as shown in figure 2a. Other dimensions shown in figure 2b can be deduced from the following equations with five basic design parameters.

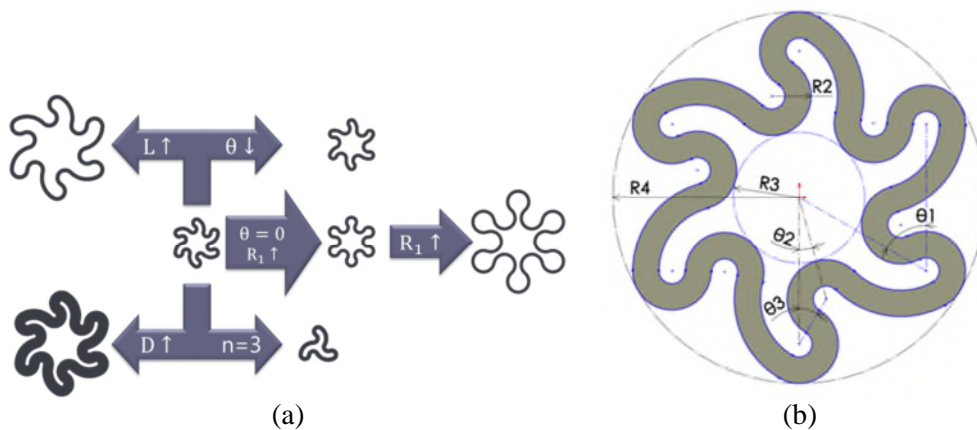


Figure 2. Different varieties and dimensions of mesh shapes.

$$R_2 = R_1 + D \quad (1)$$

$$\theta_1 = \frac{90 \cdot (n-2)}{n} \quad (2)$$

$$\theta_2 = \frac{180}{n} - \theta' \quad (3)$$

$$R_3 = \left(R_2 + \frac{L}{2}\right) \sec \theta_1 - R_2 \quad (4)$$

$$R_3 = \left(R_2 + \frac{L}{2}\right) \sec \theta_1 - R_2 \quad (5)$$

$$R_4 = (R_1 + R_2) \cos \theta_3 + (R_2 + R_3) \cos \theta_2 + R_2 \quad (6)$$

Above mentioned basic mesh shapes are designed from regular triangle, quadrangle and hexagon shapes, they have 120° , 90° and 60° axial symmetry with respect to the plate plane. Then three dimensional meshed plate models using the designed mesh shapes with two different mesh line widths (0.4 mm and 0.8 mm) are obtained and the CAD models for sample titanium mesh plates are shown in figure 3 to figure 5. From these models, one can see that the meshed plates have uniformed mesh line widths and smooth shapes just along the requirements of design conceptions.

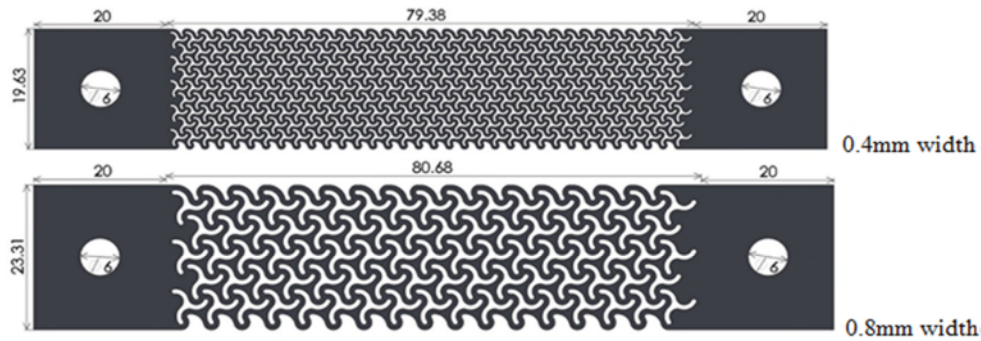


Figure 3. Meshed plate model from triangle shape.

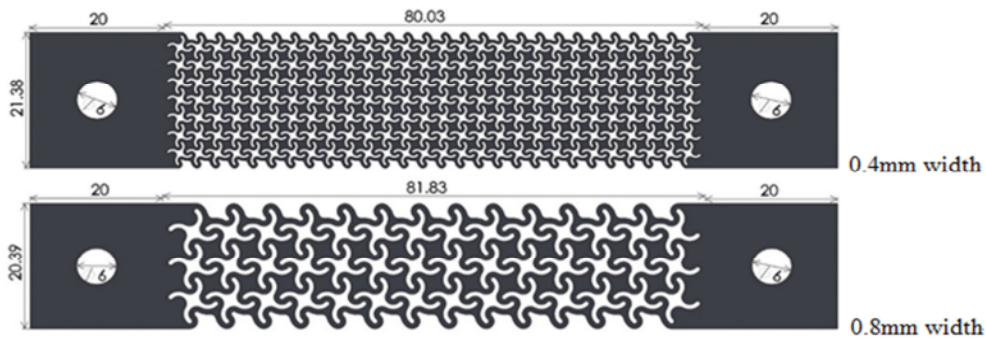


Figure 4. Meshed plate model from quadrangle shape.

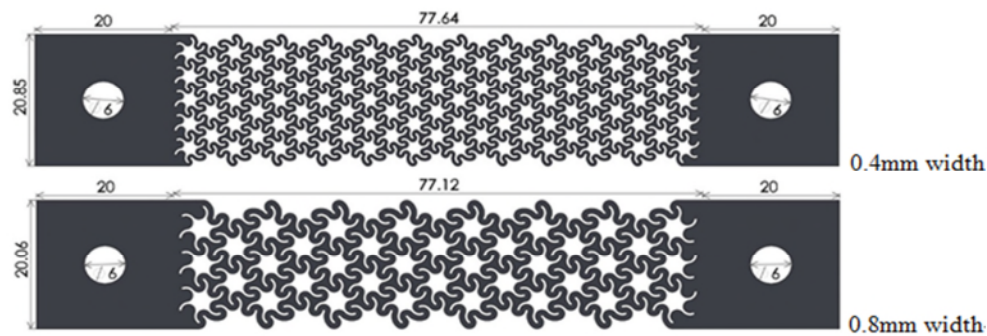


Figure 5. Meshed plate model from hexagon shape.

3. Experimental evaluations on mechanical properties of sample titanium mesh plates

Based on the mesh shapes shown from figure 3 to figure 5, sample titanium mesh plate specimens with 0.6 mm plate thickness are fabricated for experimental evaluations by laser cutting processing. Six kinds of titanium mesh plate specimens are shown in figure 6. Volume densities of these sample titanium mesh plates are then obtained by dividing the specimen's total weight with the corresponding total unmeshed plate volume and taking the area ratio of the meshed part to total specimens and the results are shown in

figure 7. The comparison results of the volume densities shown in figure 10 indicate that the volume densities of sample titanium mesh plates are reduced to about 30% of same titanium plate and can be controlled to close to the natural bone's densities ranged from 0.5 g/cm^3 to 1.1 g/cm^3 .

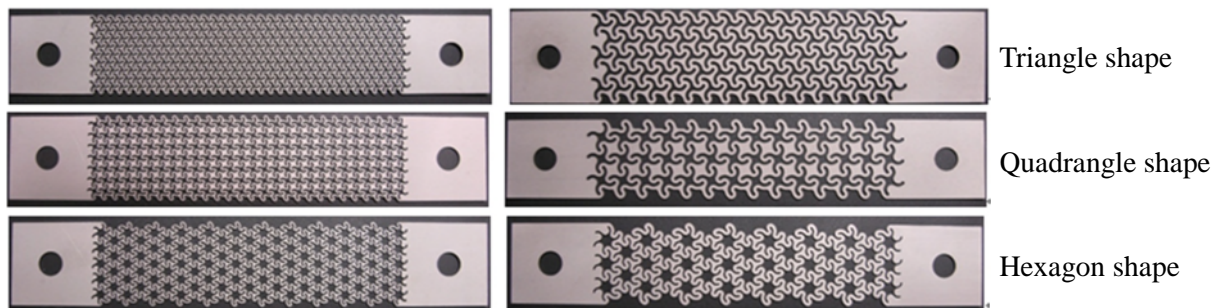


Figure 6. Tensile specimens of titanium mesh plates (0.4mm width and 0.8mm width).

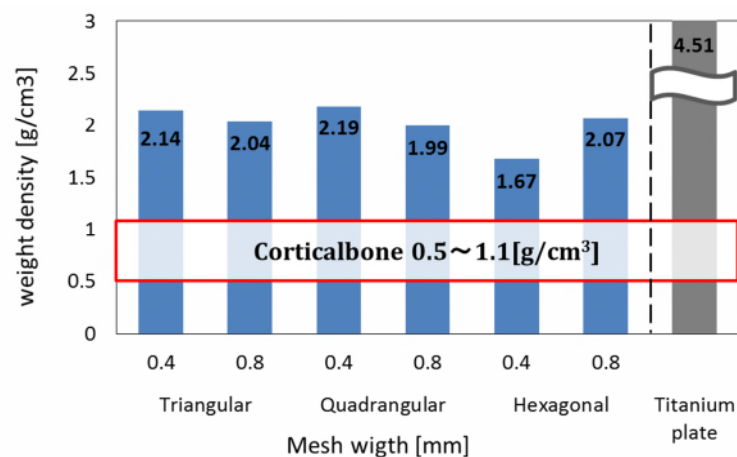


Figure 7. Volume densities of titanium mesh plates.

Tensile properties of sample titanium mesh plates such as elastic stiffness and elastic modulus are evaluated through tensile tests. Figure 8(a) shows typical measured load-displacement diagram of sample titanium mesh plates obtained from triangle shape specimen's experiment and figure 8(b) shows the approached tensile elastic modulus of sample titanium mesh plates obtained by using the unmeshed cross-sectional areas.

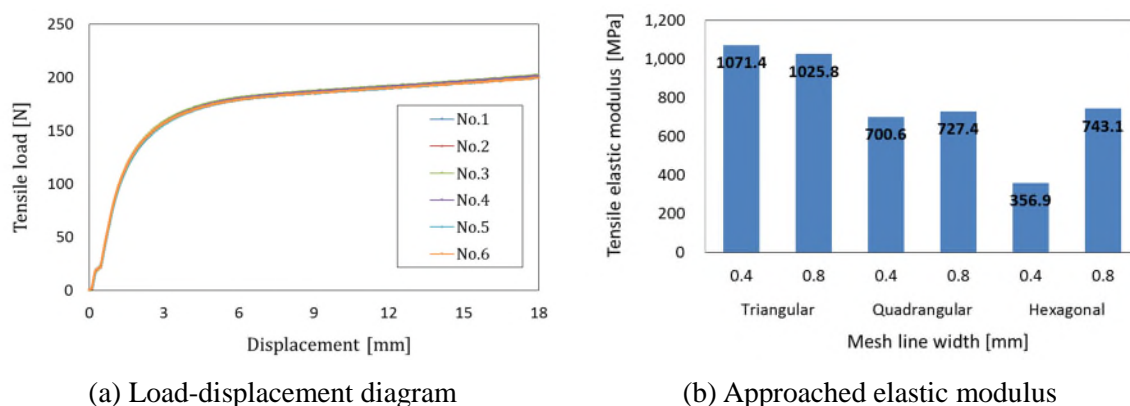


Figure 8. Typical tensile experimental results (triangle 0.4 mm width specimen).

4. Analytical approaches on tensile properties of sample titanium mesh plates

Analytical approaches on tensile experiments of the sample titanium mesh plates are carried out here using Solidworks 3D CAD software and ANSYS finite element analysis code. 3D meshed plate models with the same shapes and sizes of sample titanium mesh plate specimens on experimental evaluations are used and material properties of titanium plate shown in table 1 are used for analytical inputs. Figure 9 shows the loading and boundary conditions of the analysis model.

Table 1. Material property input for analysis.

Material	Elastic modulus (GPa)	Poisson's ratio	Density (kg/mm ³)
Titanium	105.0	0.3	4.514

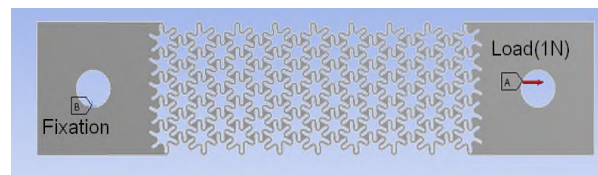


Figure 9. 3D analytical model on titanium mesh plate tensile tests.

Comparisons with experimental and analytical results on tensile properties of sample titanium mesh plates are shown in figure 10. From these results, more than 10% deviations between experimental and analytical tensile elastic modulus of titanium mesh plates are existed and these indicated that improvements of analytical method are needed in further study.

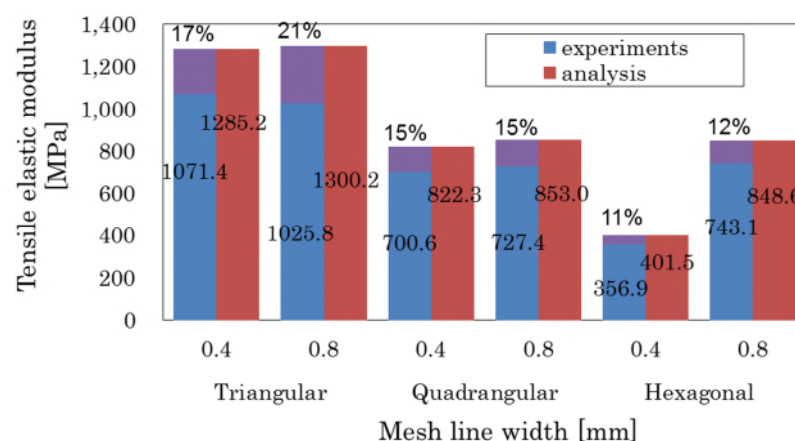


Figure 10. Comparisons on tensile elastic modulus of titanium mesh plates.

5. Summary

Experimental and analytical assessments of tensile properties on sample titanium mesh plates with higher 3-dimensional flexibility were executed and the following conclusions are obtained.

(1) Mesh plates with volume densities closed to natural bone's densities can be obtained by changing the fundamental design parameters of basic mesh shapes.

(2) Experimental tensile elasticity results of sample titanium mesh plates show the higher flexibility compared with unmeshed titanium plates and natural bones. It shows the possibility to controll the mechanical properties of such titanium mesh plates to close to natural cortical bones.

(3) Analytical approach methods for tensile property evaluations of titanium mesh plates are introduced. Comparisons between experimental and analytical results indicate that improvement of analytical approach method need to be done in future study.

6. References

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