IOP Conf. Series: Materials Science and Engineering **269** (2017) 012072 doi:10.1088/1757-899X/269/1/012072

Investigation on Tensile Fatigue Characteristics of Meshed GUM Metal Plates for Bone Graft Applications

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Abstract. GUM Metal has characteristics of lower elasticity rigidity, large elastic deformation, higher strength and biocompatibility etc. When it is used for implant applications, there is still problem like overloading on the natural-bone because of its high rigidity compared with the human bones. Therefore, the purpose of this study is to create more flexible meshed plates for implant applications from the viewpoints of elastic rigidity and volume density. Basic mesh shapes are designed, devised and applied for meshed GUM Metal plates using three dimensional (3D) CAD tools. Experimental evaluation on tensile fatigue characteristics of meshed GUM Metal plate specimens are carried out. Analytical approaches on stress evaluation are also executed through finite element method to obtain the S-N curve for fatigue characteristic evaluation.

1. Introduction

Recently in Japan, degenerative intervertebral discs have a sign of epidemic as one of diseases caused by aging and lifestyle habits. Degenerative intervertebral discs include lumber disc herniation, intervertebral disc herniation and cervical disc herniation. Table 1 shows the number of those patients having been increased year by year.

Table 1. Disc herniation the annual number of surgery (2014.4~2015.3).

Indivisual surgeries	Total case number	Average days in hospital
Surgical removal	7,152	11.5
Other surgeries	17,187	18.0
No surgeries	16,590	9.8
Total throughout the year	40,929	13.5

In this study, disc herniation as one type of disc defects is interested. Figure 1 shows some cases of the intervertebral disc protrudes beyond the normal intervertebral space to compress the nerve and cause pain. The treatment for disc herniation varies depending on different conditions. One of the currently practiced treatments is called spinal fusion surgery as also shown in figure 1. In this treatment, the upper and lower spinal cords of the defective disc are fixed using pure titanium or titanium alloy implant products. However, there is a problem that the load on the natural-bone of the human body is large and will cause overloading on healthy nature bones [1]. Therefore, in order to reduce the load on patient’s natural-bone, creation of implant products matching the mechanism such as the elasticity and rigidity of natural bones are desired as much as possible.

In this study, mesh structure [2] applications are considered for GUM Metal plates. GUM Metal is one kind of titanium alloy having relatively low elastic modulus and large elastic deformation compared with pure titanium and other titanium alloy. The purpose of this study is to design flexible meshed plate shapes and evaluate the tensile fatigue properties of meshed GUM Metal plate specimens for implant applications. Figure 2 shows the example of spinal fusion treatment using meshed GUM Metal plates.

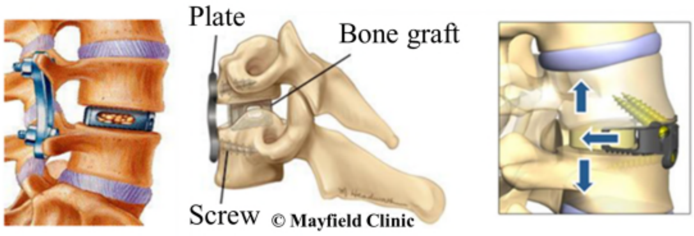

Figure 1. Fixation methods on spine for hernia of intervertebral discs using titanium implants.

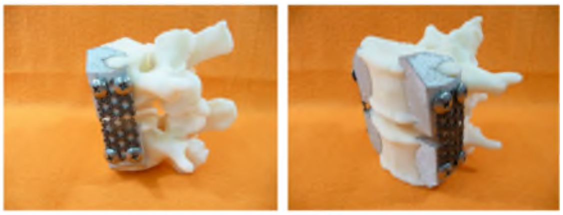

Figure 2. Sample application with meshed plates on spine for hernia of intervertebral discs.

2. Design of basic mesh shapes for meshed GUM metal plates

2.1. Mechanical properties of GUM metal

As shown in figure 3[3], GUM Metal is characterized by relatively low elasticity rigidity, high strength, large elastic deformability and high biocompatibility compared with other metals and metal alloys. Table 2 shows the mechanical properties of GUM Metal plates used in this study for experimental approach.

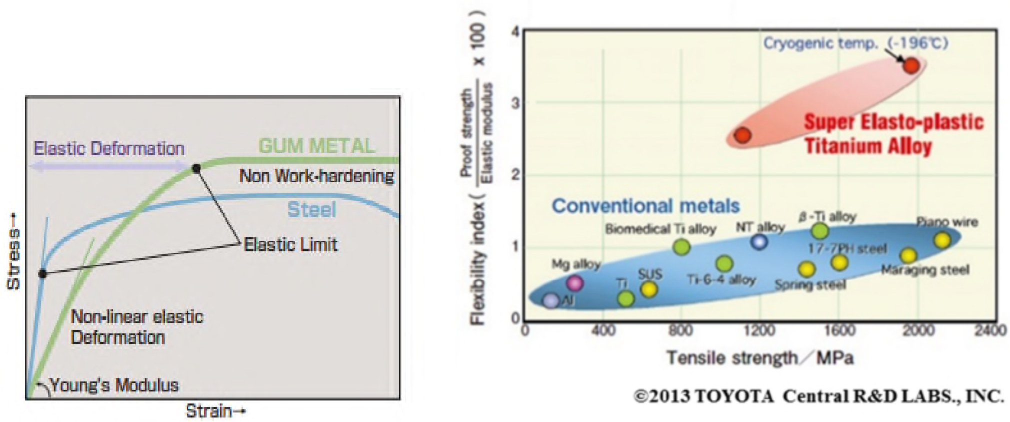

Figure 3. Comparison on tensile properties of GUM Metal with other metals and alloys.

Table 2. Mechanical property of GUM Metal.

Material property of GUM Metal	
Density [kg/m^3]	5600
Young's modulus [GPa]	91.0
Poisson's ratio	0.33

2.2. Designed basic mesh shapes and prototype model of meshed GUM metal plates.

Design concepts for basic mesh shapes are as follows considering of low cost, long life and higher flexibility etc.

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

(2) Higher 3D 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 minimize stress concentrations and lead for higher strengths and longer operating life

Basic mesh shapes based on the above design concepts are obtained using 3D CAD code Solidworks and sample ones for experimental evaluation are shown in figure 4. Two types of basic mesh shape are designed: 90° axisymmetric type based from regular tetragon and 60° axisymmetric type based from regular hexagon. For each type, three basic mesh shapes are designed having different sizes as design variables. Using these mesh basic shapes, prototype shape model of mesh GUM Metal plates are then created and shown in figure 5. These shape models are used and GUM Metal plate specimens are manufactured by laser-cutting processing. These meshed GUM Metal plate specimens are subjected to tensile fatigue experiment to evaluate their tensile fatigue characteristics and shape models are used for stress analysis.

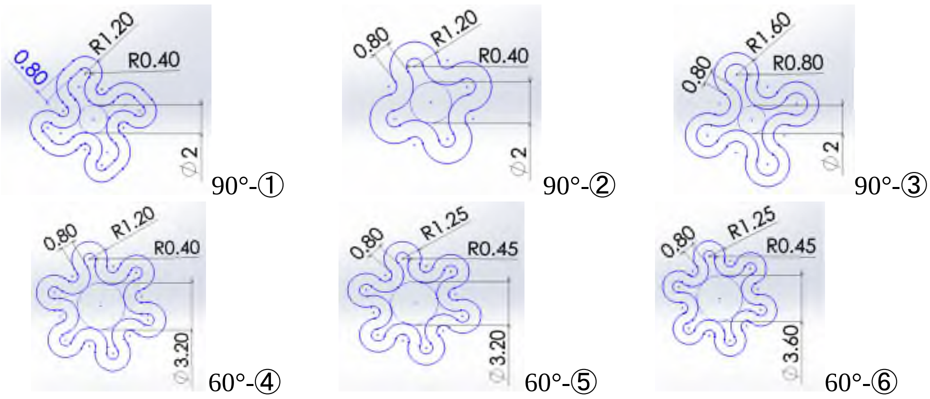

Figure 4. Basic mesh shapes for prototype meshed GUM Metal plates.

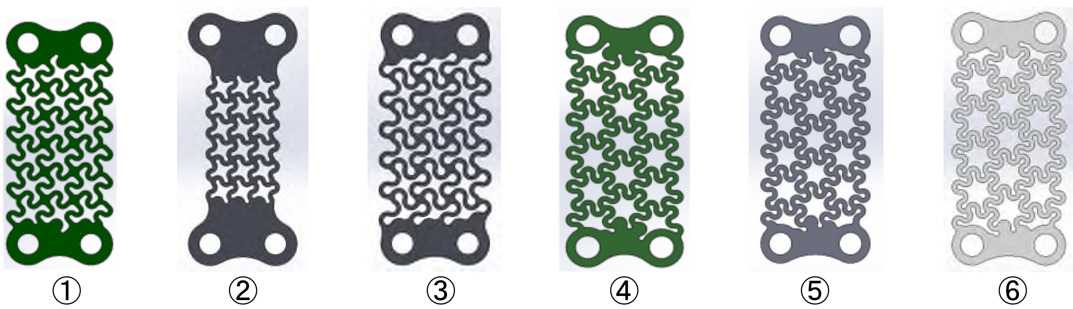

Figure 5. Meshed plate models for sample specimens (90° and 60° axisymmetric types).

3. Tensile fatigue characteristics of prototype meshed GUM metal plates

3.1. Tensile fatigue experiment of prototype meshed GUM metal plates.

Tensile fatigue tests were carried out on prototype meshed GUM Metal plate specimens. Total 36 specimens of 6 type of meshed GUM Metal plates are tested as shown in figure 6 with testing machine (Asahi Seisakusho FRS-20) and specimen installation. Tensile loads of 45N, 55N, 65N, 75N, 85N and 95N are applied for experimental investigation.

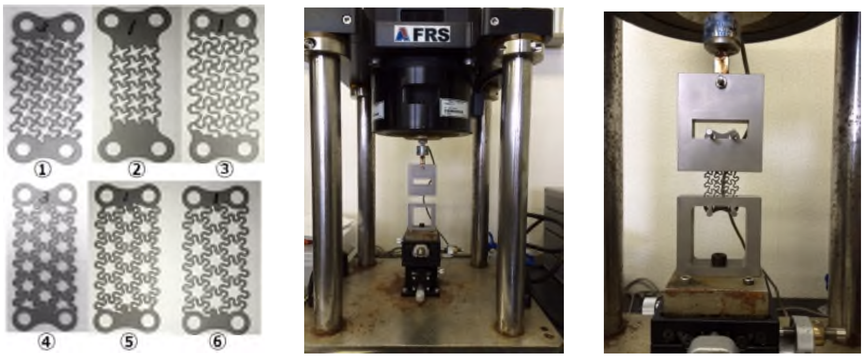

Figure 6. Sample specimens of meshed GUM Metal plates with fixtures and testing machine.

3.2. Stress evaluation of prototype meshed GUM Metal plates under tensile loading.

It is difficult to use the effective cross-sectional area of the prototype meshed plates for stress evaluation because of the complex shapes. Thus, ANSYS finite element analysis code were introduced and stress analyses were carried out in order to grasp the maximum Von Mises stress under the tensile loading of the tensile fatigue tests. Figure 7 shows an example model of the tensile fatigue test on meshed GUM Metal plate with the loading/constraint conditions and the stress contour plot of a 60° axisymmetric specimen. Table 3 shows the fixed finite element mesh for two type of meshed GUM Metal specimens. Material properties shown in table 2 are used for analytical approach. Stress results as shown in figure 7 confirmed that the locations where stress concentrations occurred didn't change under different tensile loading. Maximum Von Mises stress with respect to tensile loads is shown in figure 8.

Table 3. Analytical conditions for meshed GUM Metal plates.

	90° axisymmetric model	60° axisymmetric model
Element size [mm]	0.128	0.125
Number of mesh elements	220,836	248,500
Number of mesh nodes	169,235	194,454

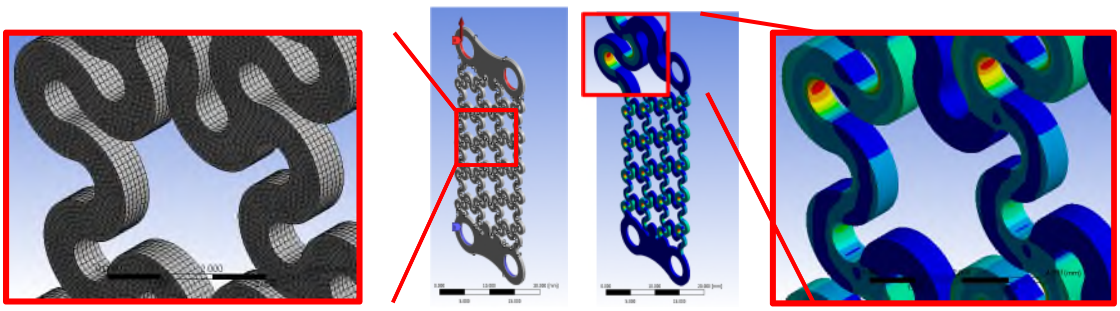

Figure 7. Stress analysis of prototype meshed GUM Metal plate (60° axisymmetric model).

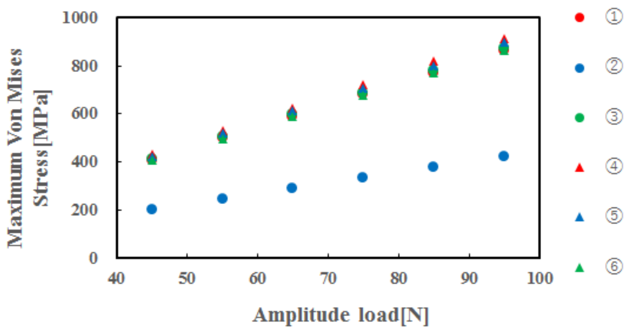

Figure 8. Maximum Von Mises stress results with respect to tensile loading.

3.3. Experimental and analytical results of tensile fatigue tests.

Figure 9 shows the fractured prototype meshed plates under different tensile loading after tensile fatigue tests. Comparing 90° with 60° axisymmetric prototype meshed plates, fractures are occurred at the inflectional locations with large curvature for both type of the specimens. These are coincident with the stress analysis results as shown in figure 7. Thus, it was possible to evaluate the tensile fatigue properties of meshed plates combined with experimental and analytical approaches introduced in this study.

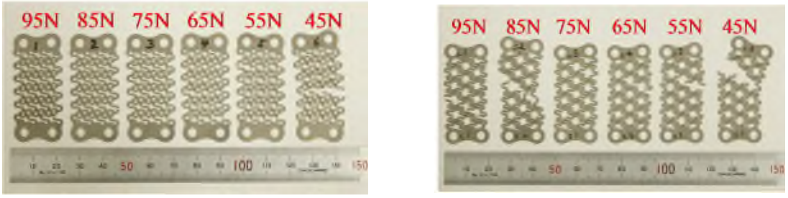

Figure 9. Typical meshed plate specimens after tensile fatigue tests (left: 90° specimen, right: 60° specimen).

S-N plots combined with analytical maximum Von Mises stress results of prototype meshed GUM Metal plates and tensile fatigue test results are then shown in figure 10. Horizontal axis represents the loading iteration number obtained from experiments and vertical axis shows the maximum Von Mises stresses under 45N, 55N, 65N, 75N, 85N and 95N tensile loads obtained from analysis.

From these results, one can see first that 90° axisymmetric specimen ② has most long life performance compared with other 5 models. Compared basic mesh shapes of prototype meshed GUM Metal plates as shown in figure 4, one can see that the curvature change in shape ② is the smallest one. Also from maximum Von Mises stress results with respect to tensile loading as shown in figure 8, 90° axisymmetric specimen ② shows the lowest stress value, which means that the curvature change in basic mesh shape will greatly affect the maximum Von Mises stress.

Additionally, if the maximum Von Mises stress under tensile loading shows near 200.0 MPa, it can endure approximately 10^6 times of tensile loading cycles. Therefore, the tensile fatigue limits of prototype meshed GUM Metal plates are under 200.0 MPa. Furthermore, in the results of the 60° axisymmetric meshed plate specimens, the difference in tensile fatigue endurance times due to the difference in basic mesh shape is small. However, it was found that changing the size (center radius) of the basic mesh shape does not significantly affect the tensile fatigue characteristics of meshed plates. Thus, it can be considered that reducing the curvature change of basic mesh shape will be most useful way to reach the tensile fatigue limit of meshed plates.

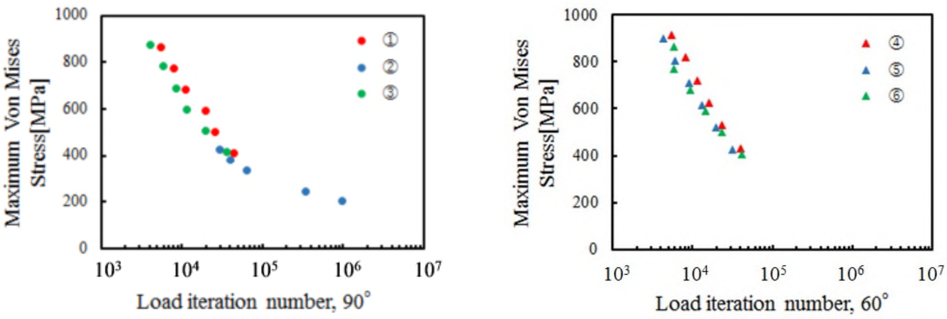

Figure 10. S-N curve of prototype 90° and 60° axisymmetric meshed plates.

4. Summary

Experimental and analytical evaluations on tensile fatigue characteristics of prototype meshed GUM Metal plates were executed. From the experimental and analytical results,

(1) Fractures were occurred at the inflectional locations with large curvatures for both type of the specimens, and coincident with the stress concentration locations obtained from analytical results.

(2) The change in curvatures of basic mesh shapes was found to greatly affect the maximum tensile stress results and then affect the tensile fatigue properties of the meshed plates.

(3) It was found that changing center radius of basic mesh shape would hardly affect the tensile fatigue characteristics of meshed plates.

Therefore, the curvature changes in the basic mesh shape are effective for improving the fatigue resistance characteristics of meshed plates under tensile loading.

5. References

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[3] Introduction of GUM METAL http://www.nissey-sabae.co.jp/wp/wp-content/uploads/GUM METAL.pdf