THE NUMERICAL MODELING OF FATIGUE PROPERTIES OF A BIO-COMPATIBLE DENTAL IMPLANT PRODUCED BY ELECTRON BEAM MELTING® (EBM)

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Abstract

Cyclic load could result in the fatigue failure of a component at stress levels below the yielding stress of material. Therefore, studying the mechanical behaviors of a dental implant structure under cyclic load is required. The numerical modeling of a cyclic load test was performed for a bio-compatible dental implant by using ANSYS® Workbench®. The fatigue test samples, made of Ti-6Al-4V were manufactured by Electron Beam Melting® (EBM) process. An abutment with octahedral lattice structure of 2 mm unit cell size was selected to design the abutment. A sinusoidal wave was used to apply the cyclic load, where the loading ratio was set at 10%. The influences of the loading force and the fatigue strength factor on the fatigue life of the octahedral lattice structure were numerically studied. According to the results, an increase in the loading force was associated with an increase in the maximum equivalent stress developed in the lattice structure. Also, the numerical results showed that applying a load above 441 N resulted in a sharp decrease in the fatigue life of the lattice structure from 10^7 cycles to 5.5×10^4 cycles. It was shown that an increase in the fatigue strength factor from 0.81 to 0.87 improved the fatigue life about 100 times. Therefore, improving the surface roughness of the bio-compatible dental implant could be one of the major factors that could increase the implant fatigue resistance and should be considered through the design optimization of the dental implant.

Keywords: Fatigue Failure, Surface Roughness, Fatigue Strength Factor, Bio-Compatible Dental Implant, Electron Beam Melting® (EBM)

1. Introduction

The mechanical behavior of a structure is one of the most important factors to consider through the optimization of a dental implant design. However, it is necessary to recall that the mechanical behavior of a structure under a static load might be noticeably different than under a cyclic load. A cyclic load could result in fatigue failure at stress levels below the yielding stress of a material. Therefore, it is required to study the mechanical behavior of an implant structure under a cyclic load. Several studies have been performed to investigate the effects of loading parameters on the fatigue properties of implants. C. K. Lee et al. [1] studied the influence of the cycling rate on the fatigue resistance of dental implants, where two different loading frequencies including 2 Hz and 30H z were used. Results showed that initial crack formation was statistically more likely at 2 Hz than at 30 Hz, while fatigue crack growth rates were almost independent of the cycling frequency. Similarly, M. Karl et al. [2] showed that both the strain rate and failure

probability depended on the loading frequency, where failure probability was higher at 2 Hz than at 30 Hz. However, strain magnitude and the fracture surface morphology were independent of the loading frequency. The effect of the implant environment was studied by [1], where two different environments including room air at 25 °C and normal saline at 37 °C were used to perform experiments. The testing environment showed no effect on the probability of crack initiation. However, at a loading frequency of 2 Hz, the fatigue crack growth rates were lower in saline than those in the air.

Other than the loading situation, dental implant design might influence the fatigue resistance. I. S. Park et al. [3] compared the fatigue properties of five different designs of implant-abutment configurations, where a considerable effect of design on fatigue life of implants was observed. The influence of implant diameter on its fatigue resistance was studied by S. R. Allum et al. [4]. According to the results, implants with diameters less than 3 mm showed a considerable decrease in maximum tolerated force.

The fatigue life of an object is a function of its surface conditions [5], such as surface roughness that is influenced by the manufacturing process. During additive manufacturing of a 3D structure, powder particles located in the vicinity of the molten pool experience a partial melting which results in the attachment of the powder particles to the solidified area. This partially sintered powder is the main cause of producing a part with highly rough surface during the additive manufacturing process based on Electron Beam Melting® (EBM). K. S. Chan et al. [6] showed that the fatigue resistance of the dental implants produced by additive manufacturing highly depends on the part surface roughness, where an increase in the part surface roughness was associated with a decrease in fatigue life. Also, H. B. Hasib [7] showed that reducing surface roughness of the lattice structure through etching resulted in a noticeable increase in fatigue life. However, no relation was found between etching time and fatigue life. Also, S. J. Li et al. [8] showed that the root of un-melted Ti- 6Al- 4V powders attached to the lattice structure surface has a very high potential for fatigue crack initiation.

Recently, the fatigue properties of dental implants produced by non-stochastic lattice structures have been investigated [8, 9]. N. W. Harbe et al. [9] used a non-stochastic lattice structure with different densities in order to reduce stress shielding at the interface between the root of the dental implant and the jawbone. Compression fatigue testing performed at 15 Hz showed that the designs were not able to meet the results obtained from the solid Ti-6Al-4V coupons. Three reasons were suggested as the possible causes of the inappropriate mechanical behavior of the lattice implant including the closed porosities within the struts, stress concentration caused by surface roughness, and acicular or martensitic microstructure of the implant. S. J. Li et al. [8] studied the effect of the lattice structure density on static strength and fatigue resistance, where both of these properties increased by increasing the lattice structure density.

In this study, numerical modeling is used to investigate the influence of the cyclic load on the mechanical behavior of the bio-compatible dental implant. For this purpose, the octahedral lattice structure with 2 mm unit cell size is used to produce the abutment in a single-component bio-compatible dental implant. This lattice structure provided the most desirable mechanical behavior under a static load among the lattice structures that were previously studied. The

influences of the biting force level and surface roughness on the fatigue resistance of the dental implant are numerically investigated.

2. Previous Study

In the previous study, the feasibility of producing a bio-compatible dental implant by the EBM process was studied. The desired bio-compatible implant is able to mimic the behavior of a natural tooth in providing the tooth micromotion under biting force. For this purpose, three different lattice structures including cross, honeycomb, and octahedral structures with the different unit cell sizes were used to produce lattice abutments of Ti-6Al-4V. The schematic designs of the three lattice structures used for producing the dental abutment are shown in fig. 1. Also, a solid abutment with the same dimensions was produced for comparison purposes. Figure 2 shows results of compression test performed on different lattice structures, under a 400 N normal force. According to the results, because of the increase in the unit cell size, the abutments show more deformation. However, the maximum normal force tolerated decreases. Both the experimental and numerical results showed that the octahedral lattice structure with a 2-mm unit cell size presented the best mechanical behavior. In the next step, seven different angles from 0°
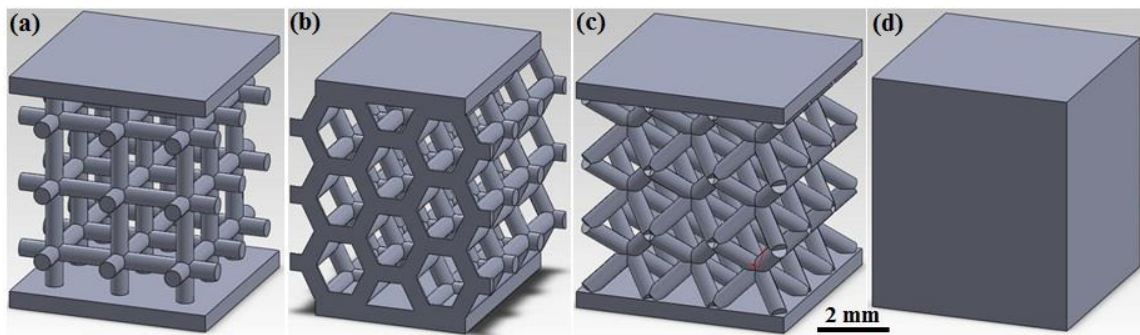

Fig. 1. Schematics of the three lattice structures with 2 mm unit cell size, a) Cross-A, b) Honeycomb-A, c) Octahedral-A, and d) The solid structure [10]
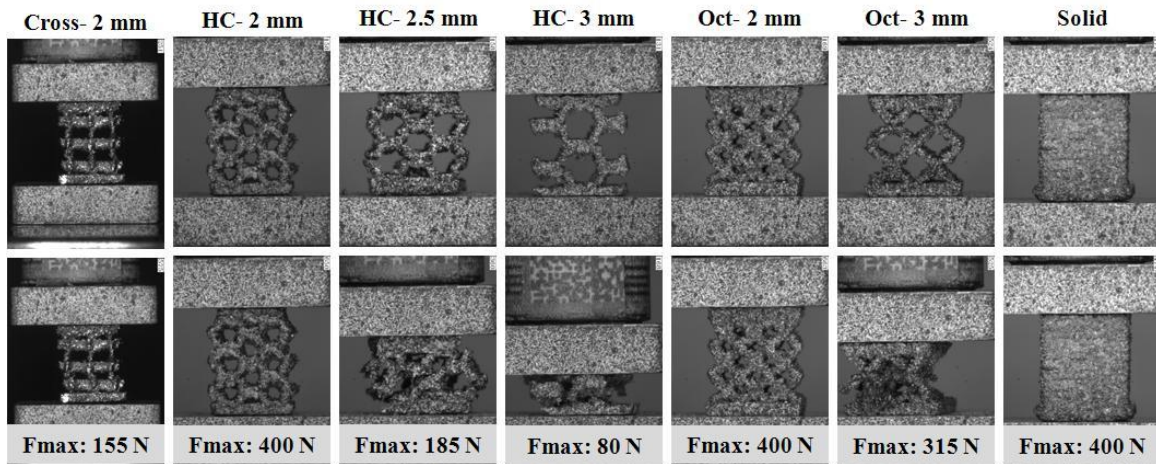

Fig. 2. The results of compression test performed on different lattice structures (HC: Honeycombs, Oct: Octahedral, F_{max}: the maximum tolerated force level) [10]

to 90° with a 15° increment are employed in order to study the effects of the biting force angle on stress development in the lattice abutment. Numerical results showed that α= 30° is a critical biting force angle, where the application of biting force at angles equal to or above α= 30° is accompanied by a considerable increase in the maximum equivalent stress developed in the abutment lattice structure. Also, numerical modeling revealed that both of the horizontal and longitudinal displacements in the lattice abutment increased by increase in the biting force angle [10].

3. Fatigue Fracture

When a metal is subjected to a cyclic load for a long time, failure might occur at stress levels much lower than failure stress under a static load. Failure of materials under cyclic load is called fatigue failure [5]. Among all of the influencing factors, two of the more important factors for the current study are described: stress concentration and surface condition.

Fatigue resistance of a part is extremely reduced by the presence of a stress raiser in the structure. The stress could be raised by a notch or a hole caused by machining or even metallurgical defects such as porosity, and inclusions [11]. Another source of stress raisers might be the design of a part, where sharp corners result in a local stress concentration [11]. Any sharp corner on the surface of a part that is under a cyclic load could increase the fatigue failure risk [5]. One of the best ways to minimize the probability of fatigue failure is through an improved design that reduces avoidable stress raisers such as sharp corners.

Surface properties of an object could affect its fatigue resistance in three ways; by surface roughness, variation in surface strength, and variation in surface residual stress [5]. Among these three factors, the influence of the surface roughness is more of interest for this study.   P.   G. Fluck [12] studied the influence of surface roughness on the fatigue resistance of a SAE 3130 steel specimen, where a fully reversed stress at 655 MPa was used. Results showed that a grinded and polished specimen with 0.05 μm surface roughness had a fatigue life about 10 times more than a lathe-formed specimen with 2.67 μm surface roughness.

3.1. Fatigue Test of Dental Implants

The International Organization of Standardization developed the ISO 14801 standard in order to provide a procedure for the dynamic fatigue testing of dental implants. The standard desires a study to apply the worst case on an implant. The dynamic fatigue test could be performed in both a dry and wet environment. The maximum loading frequency in a wet condition is 2 Hz. Testing must be carried out until failure or 2 million cycles. In a dry condition, the maximum allowed loading frequency is 15 Hz, and testing must be performed until failure or 5 million cycles [13].

Figure 3 shows the schematic of the loading configuration on the implant. A hemispherical loading member should be designed or attached on the implant top surface in order to provide a uniform load distribution on the implant. Also, the implant shall be fixed in either a rigid fixture or embedding material with a modulus of elasticity higher than 3 GPa [13].
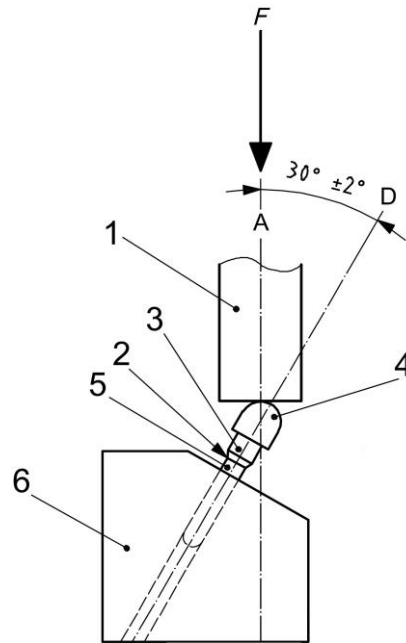
Fig. 3. The schematic for the fatigue test setup; (1: loading device, 2: nominal bone level, 3: connecting part, 4: hemispherical loading member, 5: dental implant body, 6: specimen holder) [13]

A static compression test needs to be performed by using the same loading configuration. The failure load of the static compression test would be used to select the load levels of the cyclic load test. The latter loads could be a specific percentage of the static compression failure load. During the cyclic compression test, at least two and preferably three tests must be done for any load level. Performing the fatigue test at four load levels is the minimum requirement. All loads are applied with a sinusoidal wave form with a loading ratio of 10%. During any cycle, the applied force oscillates between 10% and 100% of the desired load as the minimum and maximum loads, respectively. As shown in Fig. 3, the load is applied on the implant at a 30°± 2° angle, with the implant axis, in order to provide the worst case condition.

3.2. Experimental Setup
3.2.1. Fixture Design

In order to provide the worst case condition required by ISO 14801, a fixture is designed for the fatigue test that transfers the cyclic load onto the sample along a 30° angle. Figure 4-a shows the schematic view of the designed fixture. The lattice abutment sample is tightened inside the fixture by using screws that provide the required fixing for the cyclic test. Figure 4-b shows the sample installed on the machine and ready for test.

3.2.2. Static Compression Test

The static compression test is performed by using the produced samples and the designed fixture, where the load is applied at a 30° angle until sample failure. The maximum failure load could be used to select the loading forces required to perform the cyclic test. The force-displacement results of the static compression test are shown in Fig. 5. According to the results,

the three sample failures occurred at 610 N, 630 N, and 650 N and resulted in an average failure load of 630 N under a static compression test at a 30° angle.
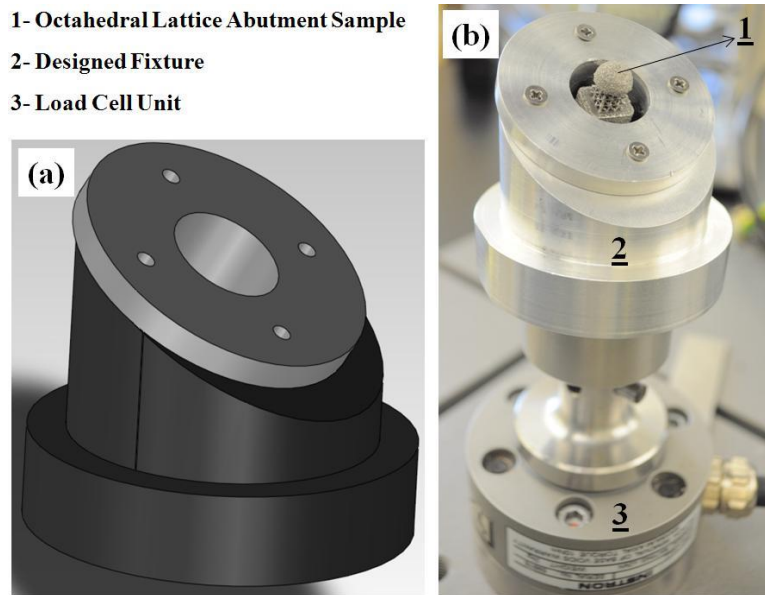

Fig. 4. The cyclic load fixture design; a) the CAD design of the fixture, b) The lattice abutment is installed in the fixture and is ready for fatigue test
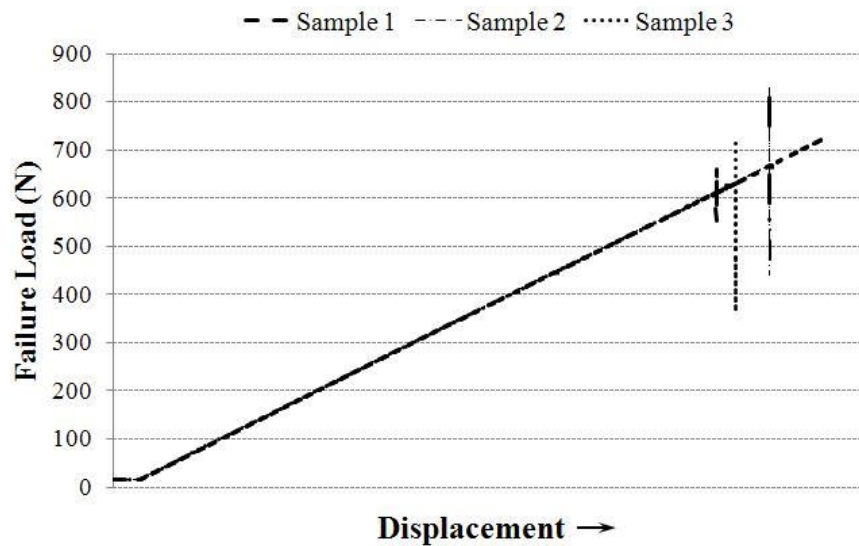

Fig. 5. The load-displacement results of the three static compression tests performed on the octahedral lattice structure at 30° angle

3.2.3. Cyclic Compression Test

Cyclic compression testing of the octahedral lattice structure with 2 mm unit cell size was performed at a 30° angle by using the Instron® E1000 data acquisition system. For this purpose,

30% of the maximum static compression failure load with the loading ratio of 0.1 is used. Therefore, the maximum and minimum loads in any cycle were selected to be equal to 10.8 N and 108 N, respectively. Also, the mean load value and load amplitude were 59.4 N and 48.6 N, respectively. The maximum loading frequency was set at 15 Hz. The fatigue tests of the octahedral lattice abutment are in progress.

4. Mathematical Model

Figure 6 shows the flowchart of the procedure followed in the numerical modeling of the cyclic load test. As shown, through the three initial steps, the mechanical response of the structure under the applied load is calculated. While for studying the fatigue resistance under a cyclic load, some extra parameters and settings are required to be considered. The flowchart is explained in detail in the following sections.
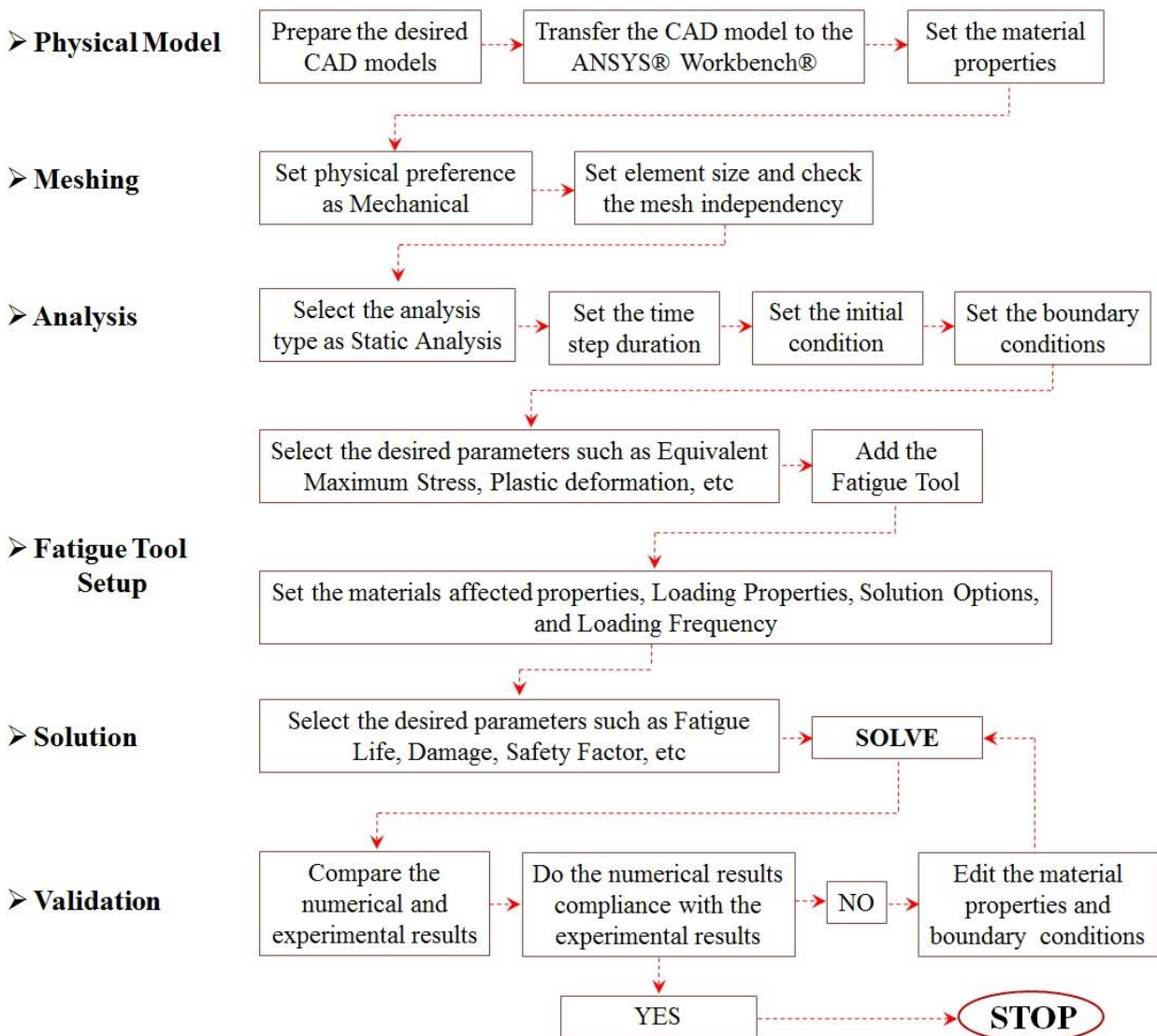

Fig. 6. The flowchart of the numerical procedure for cyclic load in ANSYS® Workbench®

4.1. Physical Model

According to the results of static compression test in the previous study, the octahedral lattice structure with 2 mm unit cell size is selected for the cyclic compression test study. According to ISO 14801, a hemispherical design was added on the top of the lattice abutment in order to provide a uniform force transformation on the structure. Also, it is assumed that the specific design of the tooth root does not have any major influence on the mechanical behavior of lattice abutment, under the cyclic load test. Therefore, the complex structure of the tooth root can be replaced by a simple cubic structure. Figure 7-a shows the 3D view of a sample geometry that is built by EBM and used for the cyclic load test. The hemisphere has a 4.65 mm radius, while the bottom cubic structure length, width, and height are 10, 12, and 12.1 mm, respectively.

4.2. Meshing

Figure 7-b shows the mesh distribution used for the octahedral lattice abutment structure during the numerical cyclic load test. As shown, a finer mesh is used in the lattice structure by using the mesh refinement Level 1. The rest of structure has a coarser mesh size to keep the total number of elements under the maximum allowable (256,000), as well as to save on the solution time.

4.3. Initial and Boundary Conditions

In this study, the mean force (discussed in section 4.4.3) is applied as the initial condition at the top of the hemi sphere component at a 30° angle with respect to the lattice abutment vertical axis. The load vector is shown in Fig. 7-c as an arrow and identified by I.C. Also, the cubic part designed at the bottom section of the sample is assumed to be a fixed. Therefore, fixed displacement is applied on all of the cubic part surfaces as the boundary condition (identified by B.C. in Fig. 7-c).
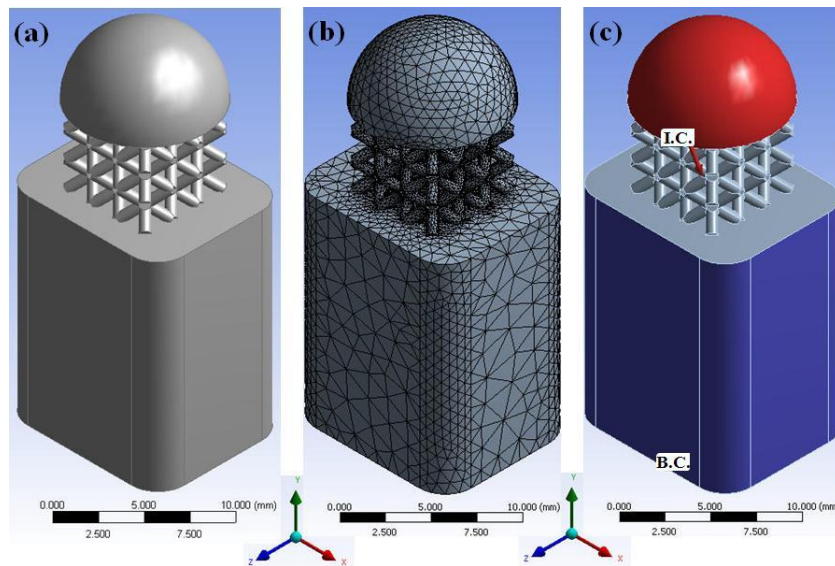

Fig. 7. The schematic view of the cyclic load test sample; a) physical model, b) sample meshing, c) initial and boundary conditions applied on the sample

4.4. Fatigue Tool Setting

In order to perform a numerical modeling of a cyclic load by using ANSYS® Workbench®, some parameters are required to be defined. The analysis type is selected to be stress life that focuses on both the crack initiation and crack propagation stages. It is suitable for high cycle fatigue (HCF) cases, where an object experiences more than 10^5 cycles [11].

Also, among the three classical theories including Gerber, Goodman, and Soderberg, according to the brittle behavior of lattice structures during compression testing, the Goodman theory is selected for considering the effect of mean stress on fatigue life.

There are several standards that provide approved procedures for the preparation of test samples or test conditions. However, there could be some differences between the controlled experiments and the functioning situations. These differences could result in different mechanical behaviors of a part during the experiment rather than real functioning life. These differences could be accounted for by introducing a modification factor, called as fatigue strength factor (K_f). The fatigue strength factor has a value less than one, is multiplied to the alternating stress, and results in the reduction in fatigue resistance. Surface roughness could be one of the parameters that might cause differences between the fatigue properties of Ti- 6Al- 4V under controlled test conditions and those parts produced by EBM [14].

4.5. Fatigue Analysis Results

Through the available information provided by fatigue testing, the following three parameters are studied: fatigue life, fatigue safety, and biaxiality indication. Fatigue life shows the number of cycles that a structure with specific properties can survive under the defined conditions. The fatigue safety factor is calculated by dividing the available life of a given design life. This parameter is plotted over the structure and provides an overview of the most probable areas for failure as well as the safest part of the structure. The maximum value of a fatigue safety factor is 15, while values between zero and one represent areas that experience failure before reaching the design life [14]. Biaxiality indication is defined as the ratio of the smallest principal stress to the largest principal stress. This parameter varies between -1 and 1, where -1 is representative of pure shear, and 1 indicates the pure biaxial state. Under a uniaxial stress state, the biaxiality indication is equal to zero. Biaxiality indication could provide an understanding of the distribution of both tensile and compressive stresses inside the structure [14].

4.6. Numerical Modeling Parameters

Two parameters including loading force and fatigue strength factor are selected to investigate their influences on the fatigue resistance of a lattice dental abutment.

The average maximum failure load for the octahedral lattice structure under static compression testing at a 30° angle was measured to be equal to 630 N. Eight levels of force from 10% to 80% with 10% increments were used to calculate the numerical fatigue resistance of the mentioned structure. The loading ratio was set equal to 10% and a sinusoidal wave was used to define the loading cycle. Also, the fatigue strength factor of the lattice abutment produced by EBM was assumed to be 0.85.

As described earlier, the surface roughness of parts produced by EBM might causes differences between the mechanical results obtained under the controlled test conditions and the real functioning situation. Therefore, in order to take into account the influence of surface roughness of the lattice abutment trusses on its fatigue resistance, eight levels of fatigue strength factor from 0.81 to 0.88 with 0.01 increments are studied, while the loading force is set at 504 N (80% of the static compression failure load) with a loading ratio of 10%.

5. Results and Discussion
5.1. The Effect of Loading Force on Fatigue Resistance

Figure 8-a shows the effect of loading forces applied along a 30° angle on the maximum equivalent stress developed in the octahedral lattice structure. As shown, an increase in the loading force was associated with an increase in the maximum equivalent stress in the lattice structure. A load of 252 N and above contributed to stresses larger than the yield stress, leading to the plastic deformation. The influence of loading forces on the fatigue resistance of the octahedral lattice structure is shown in Fig. 8-b. According to ISO 14801, dental implants tested at loading frequencies above 2 Hz are supposed to resist 5×10^6 cycles. According to the numerical modeling results shown in Fig. 8-b, the octahedral lattice abutment could meet the ISO 14801 requirement and tolerate 5×10^6 cycles for loading forces up to 70% of the average failure
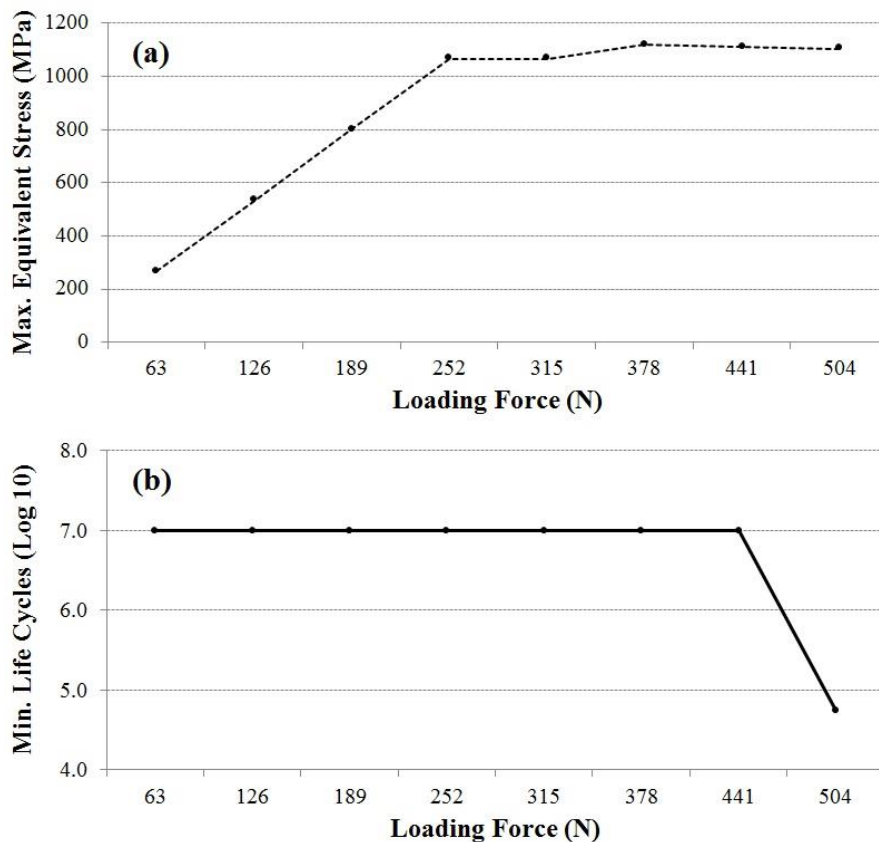
Fig. 8. The effect of loading forces at 15 Hz applied along 30° angle on a) the maximum equivalent stress developed in the octahedral lattice abutment, b) the minimum cyclic life of the octahedral lattice structure

load equal to 441 N. The application of forces above that level could result in failure before 5×10^{6} cycles are reached.

Figure 9 compares the distributions of maximum equivalent stress, equivalent elastic strain, biaxiality indication, and safety factor inside the lattice structure, caused by the application of a cyclic force of 504 N along a 30° angle. As shown, the highest value of equivalent stress is concentrated at the sharp corners of the design (Fig. 9-a). Therefore, the highest elastic strain is expected to be experienced at these sharp corners as well (Fig. 9-b). The biaxiality indication iso-surfaces inside the lattice structure provide an understanding of the distribution of the compressive or tensile stresses inside the lattice structure (Fig. 9-c). As shown, the maximum compressive stress is concentrated at the sharp corners, while the lattice structure trusses are under tensile stresses. Accordingly, it seems that the sharp corners of the octahedral lattice structure are carrying the largest portion of the applied load. This observation could be confirmed by studying the safety factor distribution of the lattice structure after experiencing the fatigue test (Fig. 9-d). As shown, the sharp corners of the design have an orange color that indicates the minimum safety factor of the design. Therefore, the sharp corners might be the most susceptible locations for any failure.
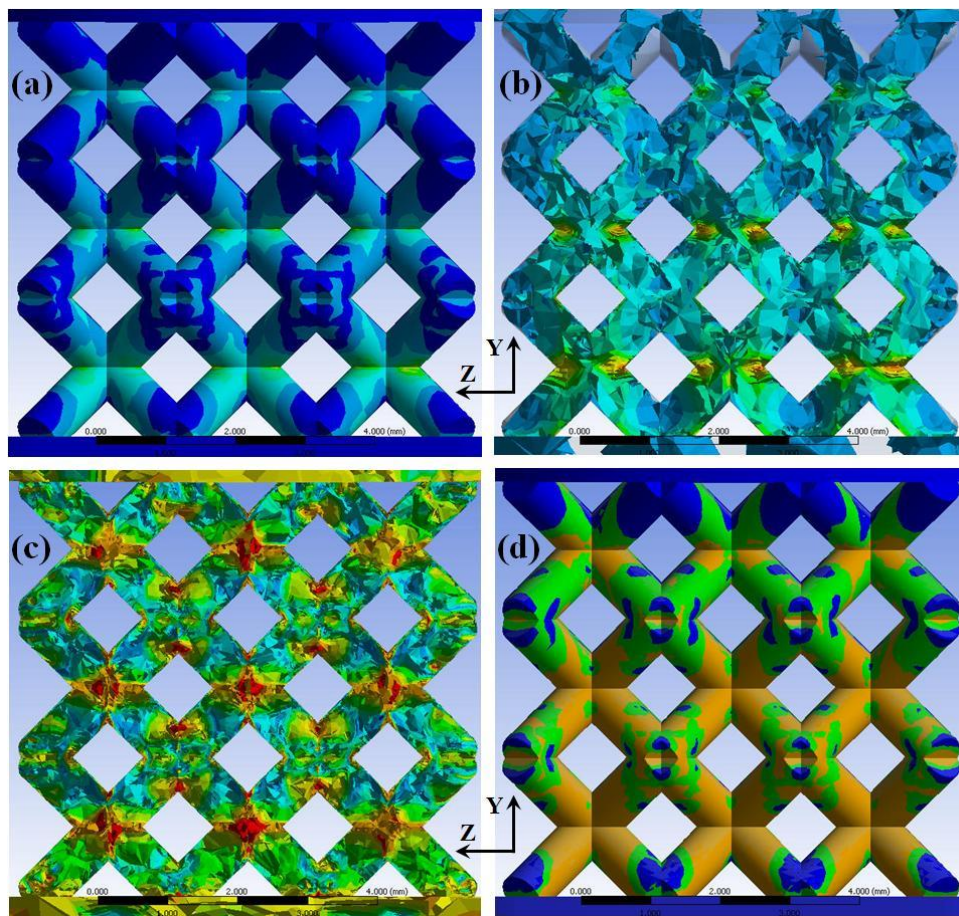

Fig. 9. The comparison of the distributions of a) equivalent stress, b) isosurfaces of equivalent elastic strain, c) isosurfaces of biaxiality indication, and d) safety factor caused by applying a loading force of 504 N along 30° angle on the octahedral lattice structure
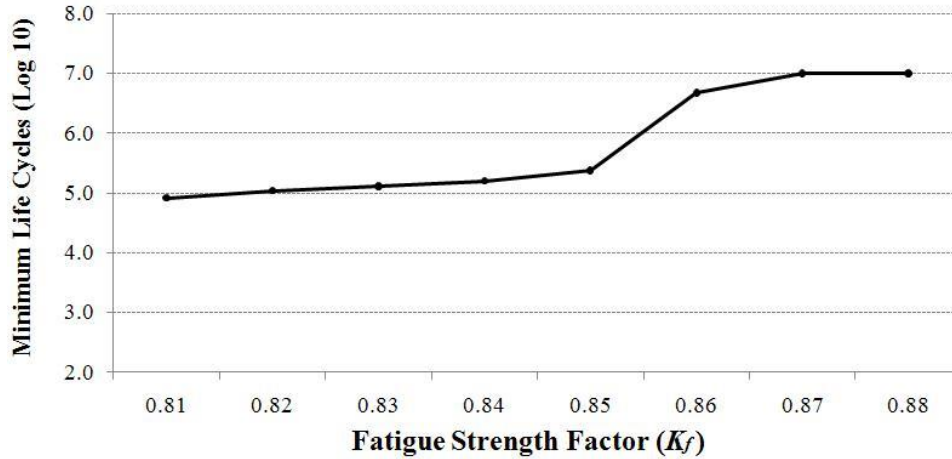
Fig. 10. The effect of fatigue strength factor influenced by surface roughness on the fatigue life of the lattice abutment

5.2. The Effect of Truss Roughness on Fatigue Resistance

The influence of EBM parts surface roughness on their corresponding fatigue resistance was studied. It is assumed that the fatigue strength factor (K_f) could be a suitable representative at the surface roughness of the octahedral lattice structure. Eight values of fatigue strength factor (K_f) were used to numerically calculate the fatigue life of the lattice structure, where the largest value of the fatigue strength factor (K_f) is representative of the smoothest surface. Figure 10 shows the influence of the fatigue strength factor (K_f) on the minimum life cycle of the lattice structure. The loading force was set at 504 N and was applied along a 30° angle to the lattice structure vertical axis. As shown, an increase in the fatigue strength factor (K_f) from 0.81 to 0.87 improved the fatigue life of the structure 100 times, from 109,920 cycles to 10,000,000 cycles. Therefore, according to the numerical results, an increase in the fatigue strength factor (K_f) through the improvement of the lattice abutment surface roughness could result in an increase in the fatigue life of the dental implant.

6. Conclusions

The numerical modeling of the cyclic load test was performed for a bio-compatible dental implant with a lattice abutment. An octahedral lattice structure with 2 mm unit cell size was selected among other designs in order to produce the fatigue test samples of a bio-compatible dental implant by using Electron Beam Melting® (EBM). According to ISO 14801, a fixture was designed and built that provides a 30° angle between the loading force direction and the implant vertical axis. This angle could provide the most severe case for the dental implant, based on ISO 14801. A series of static compression tests were performed to determine the maximum static failure load of the structure that reached a level of 630 N. A sinusoidal wave was used for applying the cyclic load, where the loading ratio was set at 10%. It was assumed that the fatigue strength factor could be a suitable representative of the influence of the surface roughness on the structure fatigue resistance. The influences of two parameters were numerically studied including loading force as well as fatigue strength factor on the fatigue life of the octahedral lattice structure. According to the results of the numerical modeling, the following could be concluded:

1. An increase in the loading force was associated with an increase in the maximum equivalent stress developed in the lattice structure. However, applying a loading force above 252 N could result in stresses above the yield stress causing plastic deformation.

2. Loading forces up to 70% of the static failure load (441 N), could meet the ISO 14801 requirement for 5×10^6 cycles, while applying a load above 441 N resulted to a sharp decrease in the fatigue life of the lattice structure from 10^7 cycles to 5.5×10^4 cycles.

3. It was assumed that the influence of the EBM parts surface roughness could be numerically studied by using the fatigue strength factor. It was shown that an increase in the fatigue strength factor from 0.81 to 0.87 increased the fatigue life about 100 times.

4. According to the numerical results, improving the surface roughness of the bio-compatible dental implant could be one of the major factors that could increase the implant fatigue resistance.

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