The Design and Production of Ti-6Al-4V ELI Customized Dental Implants

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This paper addresses the production of customized Ti-6Al-4V ELI dental implants via electron beam melting (EBM). The melting of Ti-6Al-4V ELI powder produces implants with great biocompatibility, fine mechanical performance, and a high bone ingrowth potential. The EBM technology is used to produce one-component dental implants that mimic the exact shape of the patient's tooth, replacing the traditional, three-component, "screw-like" standardized dental implants currently used. The new generation of implants provides the possibility of simplifying pre-insertion procedures leading to faster healing time, and the potential of better and stronger osseointegration, specifically through incorporating lattice structure design.

INTRODUCTION

After years of research in bone curing and regeneration, P.I. Brånemark discovered the phenomenon of osseointegration in 1952. He defined it as "the light microscopic direct functional and structural bond between organized, vital bone and the surface of an inanimate, alloplastic material." The discovery led to the first pure titanium implant to be placed in 1965 at Gothenburg's University of Sweden. Brånemark's dental implants soon reached international recognition and his implant system has been widely used in oral implantology for the last 25 years.[1]

In 2006, the dental implant industry was estimated to be worth $2.2 billion.[2] The U.S. market offers more than 100 dental implant designs, produced by more than 25 national companies, with the number of implants increasing by a factor of 10 between 1983 and 2002.[3]

Traditional implants are produced from machined wrought titanium.[4] The classical dental implants consist of an assembly of three components: the root-form fixture that actually engages the jaw bone, the transmucosal abutment, and a connecting screw. The transmucosal abutment is the support structure where the dental prosthesis (also known as the crown) is installed. The root-form fixture is threaded, grooved, perforated, plasma sprayed or coated. The different root-form fixture designs were invented in order to produce a better preload after insertion and to encourage osseointegration by increasing the surface area. However, one of the common failures of traditional implants reportedly occurs at the fixture/abutment interface.[5]

> ### How would you…
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> **…describe the overall significance of this paper?**
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> *The production of customized Ti-6Al-4V ELI dental implants by electron beam melting technology makes it possible to mass produce customized dental implants which introduce a porous surface to promote better osseointegration. By fabricating the root-form implant and the abutment as one piece, the authors expect to eliminate fracturing at the abutment screw and prosthetic screw. This paper describes the new technology and the steps taken in the fabrication of customized dental implants.*
>
> **…describe this work to a materials science and engineering professional with no experience in your technical specialty?**
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> *This paper describes electron beam melting (EBM) technology and the steps required to produce customized dental implants from Ti-6Al-4V ELI powder. A computed tomography scan of an existing tooth was converted to a computer-aided design/computer-aided manufacturing model for fabrication by EBM. Tensile testing and microstructure analysis were performed on ASM E8 coupons built with the same parameters used to produce the dental implants.*
>
> **…describe this work to a layperson?**
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> *Dental implants provide a practical and effective replacement for lost or damaged teeth. Recent technology has enabled the production of customized dental implants which may reduce surgery and recovery times and be more cost-effective for patients. The method and steps of the production process are discussed.*

In 1986, Charles Deckard of the University of Texas in Austin filed for a patent disclosing the invention and apparatus of producing fully functional parts by combining the plurality of sintered layers. The layers are sintered using a computer-controlled laser that melts powder to cover the cross-sectional profile produced by slicing a computer-aided design model. The National Science Foundation funded Deckard's research leading to the invention of the first model of rapid manufacturing (RM), the DTM machine, producing functional metal parts out of metal powder.[6] Rapid manufacturing significantly reduces lead time and increases build flexibility for low-volume production of customized parts compared to subtractive and net-shape manufacturing techniques.[7]

Today's rapid manufacturing technologies include selective laser sintering (SLS), laser micro-sintering, selective laser melting (SLM), three-dimensional (3-D) laser cladding, electron beam melting (EBM), and electron beam sintering (EBS). Rapid manufacturing technologies lead to today's freeform fabrication machines that build parts using a wide variety of metal powder. See the sidebar for details on electron beam melting.

CUSTOM DENTAL IMPLANTS: DESIGN AND PRODUCTION

Taking advantage of the versatility and practicality behind the operation of EBM in producing customized parts, the production of dental implants that mimic the exact shape of the original tooth is being suggested as an alternative to the traditional implant. By reducing the shape variance between the original tooth and the implant, the chance of preserving the loading distribution on the jaw bone is strongly increased. In addition, pre-insertion procedures such as drilling and boring can be decreased, promoting faster healing times. One other design improvement is the replacement of the three-component setup that has produced problems in traditional dental implants[5] with a one-component implant that has two interfaces: an implant /jaw bone interface and an implant/dental prosthesis interface (see Figure 1).

Electron beam melting has produced successful tailored implants such as knee, hip, jaw replacements, and maxillofacial plates. The final products only need minimal machining, if any, and the manufacturing process has lead times on the scale of a few weeks.[10] One other advantage of EBM is the ability to build implants in batches, making it possible to build several patients' implants at the same time. This drastically reduces build times in a cost-effective manner. As shown in Figure 2, several dentists treating different patients are able to combine their orders in one build-up.

The production of customized dental implants via EBM is performed through several stages of data processing, as plotted in Figure 3. First, a computed tomography scan of the patient's tooth to be extracted is captured when pictures are taken at several depths of the tooth in order to define the shape. The pictures are then converted into a stereolitography (.stl) computer-aided design (CAD) file using Mimics© from Materialise©. At this point the CAD file of the tooth takes the same path that any other parts to be manufactured via EBM take. The CAD model goes through a series of CAD manipulations, such as .stl fixing and Boolean

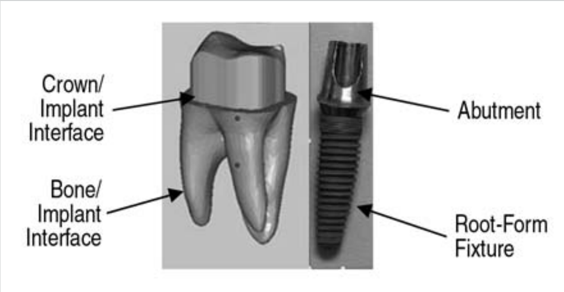


Figure 1. Customized and traditional dental implants (left to right).

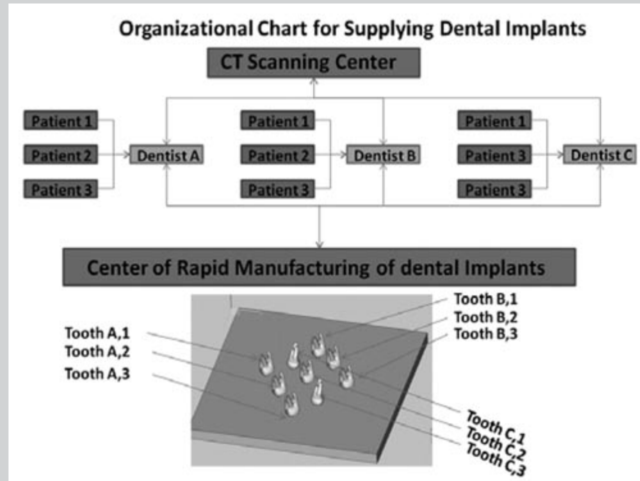


Figure 2. An organizational chart for producing dental implants.

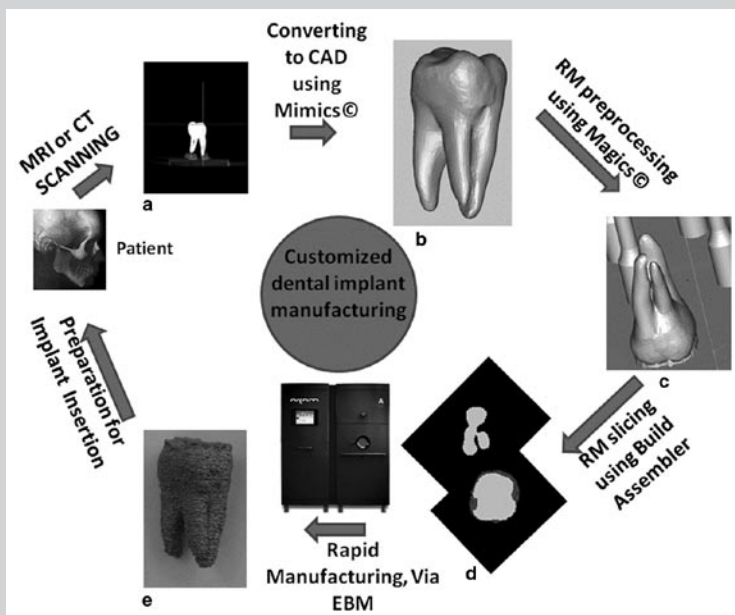


Figure 3. Steps for producing customized dental implants via EBM.

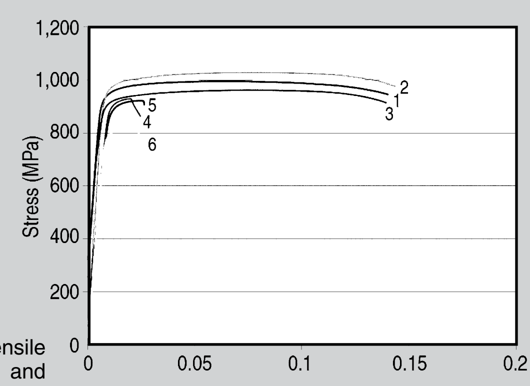


Figure 4. Tensile stress vs. tensile strain for three polished (1, 2, 3) and three unpolished (4, 5, 6) coupons.

and scaling operations, using Magics©, a software program that specializes in RM file preparation. The CAD model is then sliced using the "Build Assembler" (supplied by ARCAM AB®) into 0.1 mm layers and volume supports are created. (Volume supports are lightly sintered powder that will help to support any overhanging structures from collapsing.) The ".abf" file produced by "Build Assembler" contains all the needed information for the EBM A2 machine to build the part. The file is then transferred into the machine to go through the rapid manufacturing process where a Ti-6Al-4V ELI dental implant is produced that mimics the exact shape of the initial tooth, with a ripple surface finish. The parameters used in the process are: a filament voltage of 60 kV, a filament current of 10.81 A, 28 mA maximum preheat current, and 14,600 mm/s preheat scanning speed. The contours and squares are melted using an automatically calculated current and scanning speed, with an initial current of 12 mA and a hatch pitch of 0.24 mm for the squares. The use of the automatic calculation provokes an algorithm embedded in the EBM control software, where the parameters are varied in order to preserve the integrity and consistency of the building process. Arcam AB has not yet disclosed any information regarding the algorithm.

MECHANICAL PROPERTIES OF EBM COUPONS

Six coupons, following the ASM E8 standards for tensile coupons, were built using the EBM A2 machine. The process parameters used were similar to those used in producing the dental implants. Three of the coupons were left "as is," preserving the ripple finish. The other coupons were machined using water-jet cutting and polished using 400 μm sandpaper. Although the process parameters used to produce the coupons and the build direction are the same, a serious discrepancy in the mechanical behavior is found. Performing tensile tests at a rate of 1 mm/min., the polished coupons reached an ultimate stress of 1,028 MPa and more than 14% tensile strain exhibiting ductile behavior. The "as is" coupons reached an ultimate tensile stress of 928 MPa and a tensile strain less than 3%, manifesting brittle behavior (see Figure 4). Mechanical properties of wrought Ti-6Al-4V, ultimate tensile strength of 955 MPa, and an elongation at break of 9%[11] coincide with mechanical properties of the polished coupons obtained by EBM.

One of the serious implications of the experiment is the prominent effect of crack initiation and surface roughness on the mechanical performance of the produced parts. This is a crucial factor for the mechanical behavior of lattice structures, where the surface finish of the structures cannot be easily controlled or altered.

An SEM picture of the polished coupons taken at a magnification of 500× displayed in Figure 5 is one more indication of the ductile behavior of pol-

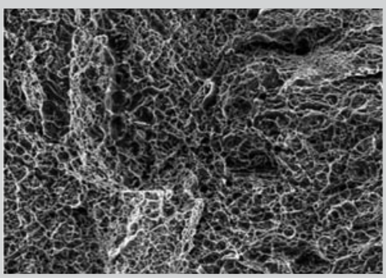


Figure 5. An SEM photograph of the fracture surface of a polished tensile test coupon at 500x magnification.

ELECTRON BEAM MELTING

Electron beam melting (EBM) is a rapid manufacturing technology invented and implemented by ARCAM AB® in Sweden.[8] The latest model, the EBM A2 machine, was introduced to the market in May 2007. Compared to laser sintering, EBM provides faster build-up time due to higher beam efficiency, faster scanning speed, and minimal reflection. The EBM A2's double-stage pumping system produces a vacuum on the order of 10^{-10} mPa in the chamber and 10^{-10} MPa in the electron beam gun. This provides the conditions to form a high-quality beam, reducing oxidation and contamination of the melted metal in the chamber (see Figure A). The EBM A2 specialized in titanium alloys and chromium cobalt. The first attempt at producing customized implants used Ti 6Al-4V ELI, an alloy commonly used in modern implantology.

The electron beam process starts with a computer-aided design (CAD) model expressed in the stereolitography form (.stl). The solid model is sliced into thin layers varying from 0.1 mm to 0.25 mm. Each layer contains the information needed for the machine to melt the required profile, the same way that the aggregation of the layers produces the CAD model; the stacked melted profiles will form the three-dimensional (3-D) part. The data of the sliced layers are then transferred into the machine. The part is built on a stainless steel plate 10 mm thick. The difference in the thermal expansion coefficient between the titanium alloy and stainless steel will make the part detach from the plate, only leaving marks of around 0.5 mm of intermetallic diffusion. The plate is initially preheated to 770ºC. In fact, the whole melting process will be conducted at a high overall temperature in order to eliminate the formation of thermal stresses, which might endanger the part's integrity during the build-up and its performance after its manufacturing. The first layer of powder is spread using an auto-calibrating rake that employs powder-flow sensors for feedback control. The layer is then preheated using a ramping beam current in order to slightly sinter the powder. The preheat step proves to be very crucial in both maintaining the system's temperature and in preventing any powder spreading that occurs in electron beam sintering of powder.[9]

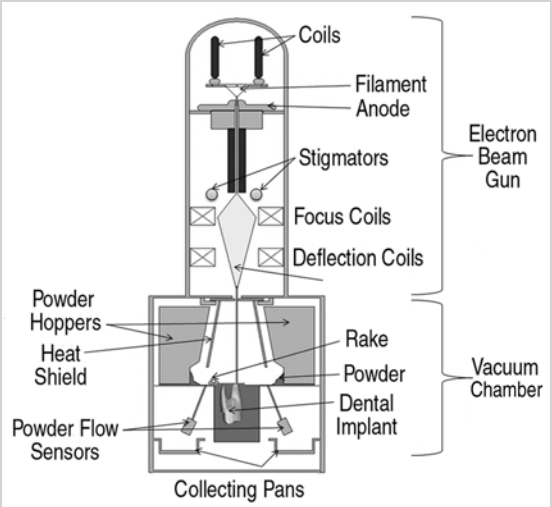


Figure A. A sketch of the electron beam melting setup.

ished EBM Ti-6Al-4V ELI. The sponge-like surface covering the fracture face is noticeable.

MICROSTRUCTURE OF EBM TI-6AL-4V

Using the same parameters mentioned earlier, a 25.4 mm diameter rod was manufactured by EBM and cut by water jet in the longitudinal (along the buildup) direction and in the cross-sectional direction (normal to the buildup direction). The pieces were installed in a resin fixation setup and polished down to 1 μm, producing a mirror-like finish. After exposing the setup to etchant Keller's solution for 10 seconds, micrographs were captured. The titanium alloy exhibits a basket weave α and β lamellar structure (see Figure 6). The very fine structure is proof of rapid cooling. Columnar growth of grain boundaries can be seen in the longitudinal cut.

Inspecting the cross-sectional cut, the α structures are smaller than the β structures, porosity is very rare, and the titanium alloy is fully melted (i.e., no signs of the layering process).

DESIGN AND OPTIMIZATION OF LATTICE STRUCTURE

According to Wolff's "Law of Bone Remodeling," human bone remodels its internal architecture based on the load distribution exerted on it.[12] By inserting a metal implant, which is stiffer than bone, the load transfers to the implant. This reduces the loading on the surrounding bone leading to stress shielding—a phenomenon of weakening bone due to reduced stress. Stress shielding causes implant loosening, hence, implantation failure. On the other hand, the implant might produce higher stresses due to pinching or high preloading effects, which may lead to osteonecrosis.[12] The use of lattice structure design may help control the stiffness of the implant. By mimicking the human bone's stiffness, stress shielding is less likely to happen. In addition, the lattice structure design reduces weight and larger surface area potentially leading to better osseointegration.

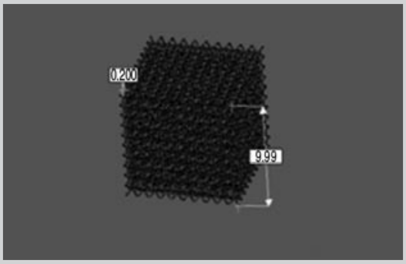
The tooth produced by the EBM process depicted earlier is proof of the ability of the procedure to produce a part that possesses acceptable feature definition at a small scale. The actual dental implant does not have the crown part as modeled previously; it will have an implant/bone interface and an implant/dental prosthesis interface, as shown in Figure 7. Figure 7 shows two configurations of customized dental implants: the bone/implant interface can be solid or it can have a lattice structure outer-layer with a solid core.

Next, the layer is scanned using high-beam power following the profile of the slice corresponding to the layer's height; the process is called melting. Melting is applied on two areas of the profile at different parameters: the contour, which is melted independently in order to ensure a rigid and well-defined shell of the part, and the squares, covering the inside of the profile, which are melted at automatically calculated beam current and scanning speed and a preset hatch pitch. The melting beam current slightly decreases after every layer, which is crucial to compensate for the increasing initial temperature of each layer as the process proceeds to higher layers. A very high initial temperature leads to local overheating of the layer, which causes evaporation and swelling of the buildup.

The electron beam is produced by a 4 kW gun that operates at 60 kV and 11 A. The beam goes through two stigmators that will compensate for the projection effect of the beam in order to conserve the circular shape of the beam spot. A magnetic focus field converges the beam, and two magnetic deflection stations that operate in the X and the Y direction redirect the beam with scanning speeds that can reach 1,000 m/s with a positioning accuracy of ±0.025 mm. The machine has two interchangeable chambers: a tall chamber that produced parts up to 200 mm × 200 mm × 350 mm, and a wide circular chamber with a maximum build size of Ø 300 mm × 200 mm. The final product has a ripple finish and is a fully dense part due to the fact that the powder is fully melted.

The EBM A2 machine is the most recent manifestation of the freeform fabrication technology; the machine is able to produce complex customized parts with part tolerance of ± 0.3 mm. The EBM process is characterized by the unique capability to generate lattice structures with controllable features, which provides an opportunity to produce hybrid structures that consist of a combination of solid regions and lattice structures or meshed regions. That unique capability offers the option to design and produce lighter structures, filters, heat exchangers, and scaffolds.

A 10 mm cube made of octahedron lattice cells (Figure B) has a volume of 28.26450448 mm^3 compared to 1,000 mm^3 of a solid cube, a 97.17% volume and weight reduction. On the other side the total surface area is 1527.5076 mm^2 compared to 600 mm^2 of a solid cube, a 154.6% increase, which may prove helpful in inducing better osseointegration and better mechanical bonding between lattice structure and bone.



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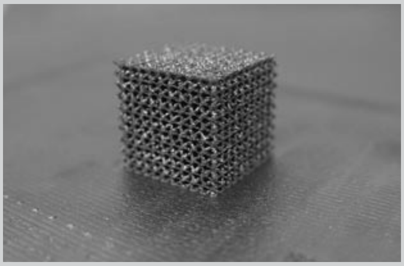
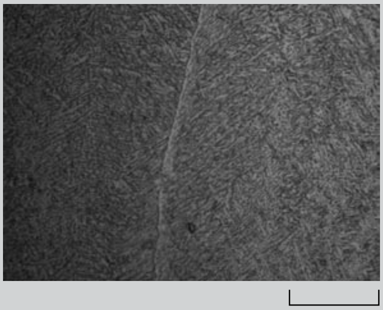
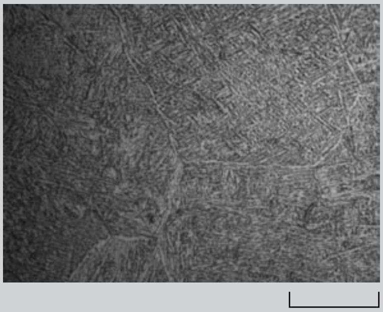


b

Figure B. The lattice structure of a 1,000 cell octahedron structure. (a) Model (b) actual structure.



a 60 μm



b 60 μm

Figure 6. A micrograph of (a) a longitudinal cut and (b) a cross-sectional cut.

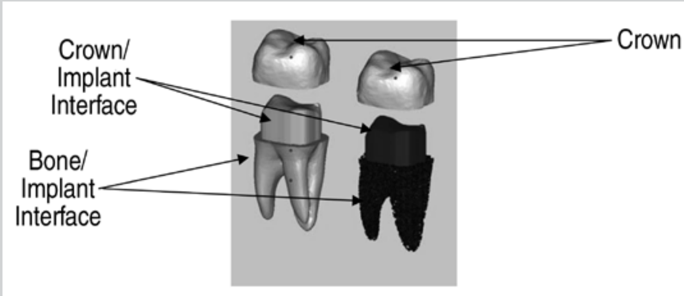


Figure 7. Two possible design configurations of customized dental implants.

The crown/implant interface, on the other hand, is required to be solid to connect to the cemented crown.

Lattice structure design optimization can be conducted by varying the following properties: lattice type or structure configuration, the ratio between beam thickness and beam length, and the lattice's density. In the following simulation, a 10 mm × 10 mm × 10 mm volume is filled with an octahedron lattice structure. The beam thickness to beam length is preserved, maintaining a constant relative volume of 2.8%. (Relative volume is the ratio of the lattice structure's volume in respect to the volume of the solid it is occupying. It is strongly dependent on the beam thickness to beam length ratio.) The only varying property is the number of cells occupying the fixed volume. Using NX6 (Siemens PLM software), five lattice structures were modeled comprising 1, 8, 27, 64, and 125 elements, respectively. The total surface area was calculated using geometry evaluation. It was found that the total surface area increases with the number of the structures, surpassing the 600 mm^2 mark provided by a solid structure at 64 cells (see Figure 8) and reaching almost 800 mm^2 at 125 cells. It is not of interest to show that some cell populations offer less surface area than the solid volume, such as at 1–27 cells per 1,000 mm^3. However, this is an indication that by increasing the number of cells, the total surface area increases. One other benefit of lattice structures is that they offer three-dimensional osseointegration, which may lead to a stronger mechanical adhesion.

The next step is to evaluate the mechanical behavior of the lattice structures. Using the NX Nastran extension in NX6, a simulation model is created where a force of 100 N is exerted on every structure from 1–64 cells/1,000 mm^3. The maximum displacement is then evaluated. The ratio of the modulus of elasticity is calculated using the following equation:

$$\frac{E}{E_S} = \frac{100(N)/A(m^2)}{\in} / E_S$$

In this equation, E is the lattice structure relative modulus of elasticity, A is the surface area corresponding to the volume's top surface (100 mm^2), $\in = \frac{\Delta x}{l}$ is relative strain, E_s is the modulus of elasticity of the base material (1.21 × 10^8 Pa), ∈ is the relative strain, Δx is the maximum displacement, and *l* is the length of the volume corresponding to 10 mm. Figure 9 displays the simulation results of the 64 cell lattice structure. The maximum displacement is recorded to be 0.0182 mm, depicting a modulus of elasticity ratio of 7.63%.

Plotting the ratio of the modulus of elasticity of the first four structures (1, 8, 27, and 64 cells, respectively), the ratio increases from 4.3% to 7.63% as the number of cells increases (see Figure 10). This demonstrates that the stiffness of the structure is controlled by varying the cell population.

A dental implant that possesses a meshed (1.1 mm cell size) bone/implant interface was produced via EBM. Compared to the solid shape, it should be noted that the shape of the root is preserved and the lattice structure is of accepteble definition (Figure 11).

CONCLUSION

The tensile testing shows that polished Ti-6Al-4V ELI coupons present outstanding mechanical strength and elongation, easily comparable with

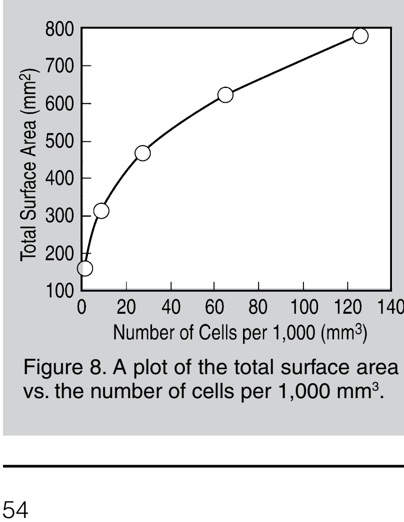


Figure 8. A plot of the total surface area vs. the number of cells per 1,000 mm^3.

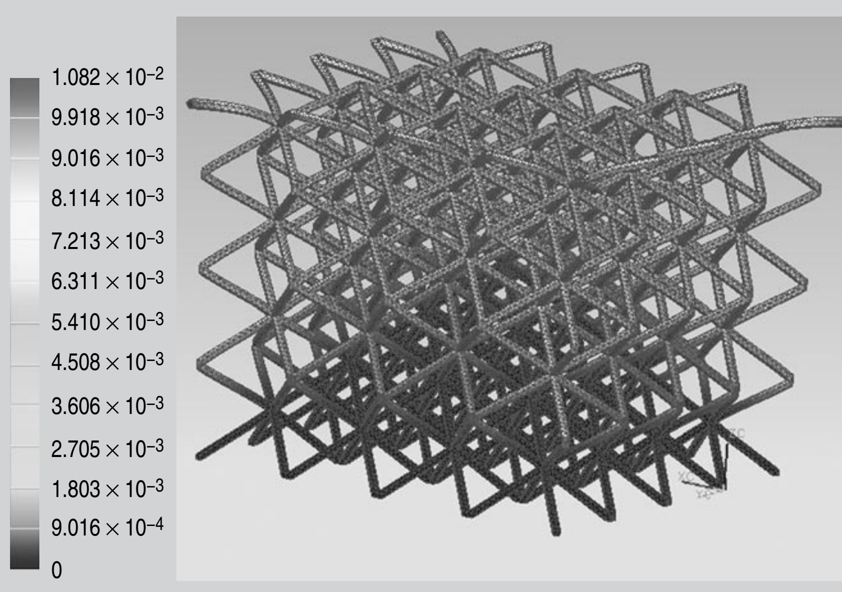


Figure 9. A simulation of a 64 elements/1,000 mm^3 under a load of 100 N.

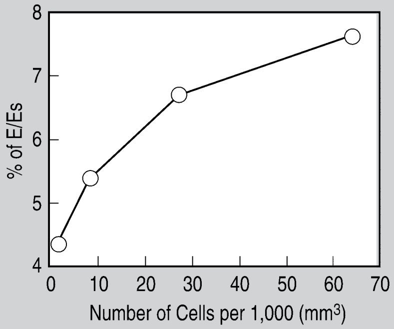


Figure 10. A plot of stiffness modulus ratio vs. the number of cells per 1,000 mm^3.

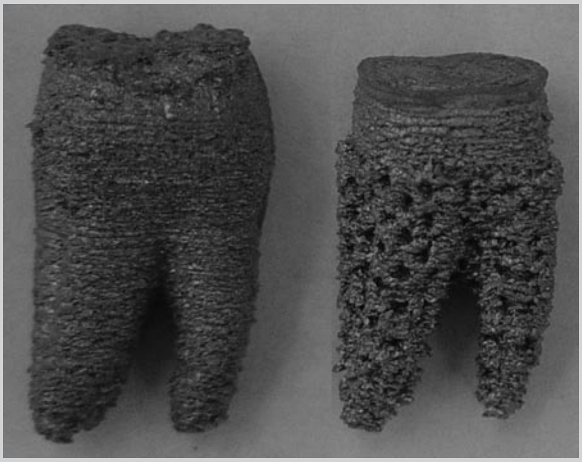


Figure 11. A solid dental implant (left) and meshed bone/implant interface (right).

those of wrought Ti-6Al-4V. However, ripple-finished Ti-6Al-4V ELI coupons had poor ductility and reduced strength. Microstructural analysis of a Ti-6Al-4V ELI part produced by EBM shows very rare porosity with very fine grain size, depicting a fast cooling rate and columnar growth parallel to the direction of build-up. Numerical simulation of lattice structures with different cell populations shows increasing total surface area and increasing stiffness with an increasing number of cells in a given volume.

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