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FINITE ELEMENT SIMULATION TO ESTIMATE THE DURABILITY OF THE CUSTOMIZED IMPLANTS MADE BY SELECTIVE LASER MELTING (SLM)

Pacurar Razvan, Berce Petru, Balc Nicolae, Goagas Lucian
Technical University of Cluj-Napoca
B-dul Muncii no. 103-105, Cluj-Napoca
Romania

ABSTRACT
The paper presents a new theoretical method that has been proposed and developed at the Technical University of Cluj-Napoca (Romania) for estimating the durability of the customized implants made by Selective Laser Melting (SLM) process. Several simulations were performed within the CosmosWorks FEA software by using different working conditions on the MCP Realizer SLM 250 equipment we have in our research laboratory. Several samples were manufactured on the SLM equipment and several tests were performed afterwards, in order to determine the material's mechanical characteristics needed for the Finite Element Analysis (FEA).
Keywords: Additive Manufacturing, Selective Laser Melting (SLM), Finite Element Analysis (FEA), Customized Implants

1. INTRODUCTION
In the past, rapid prototyping has been used for preoperative planning of surgical operations [1]. Today biocompatible materials are used for soft- and hard-tissue replacement in surgery. The high-quality planning method is a useful help for complex osteotomies in maxillofacial and plastic surgery [2]. In many cases this method has dramatically improved the security and quality and reduced the surgical operation time. In the meantime, rapid prototyping processes have been developed further for plastic and metal materials to become Rapid Manufacturing (RM) Systems. This creates an exciting basis for the use of biocompatible materials and even tissue engineering in individual, pre-determined, three-dimensional replacement of bony structures in clinical applications. After the Selective Laser Sintering (SLS) Rapid Prototyping process, indirect selective laser sintering of metal, in which the metal powder particles are connected with low melting binder such as bronze or nylon and sintered afterwards, a new technology is now ready for clinical application, Selective Laser Melting (SLM). Requiring no post-processing stages, like for example infiltration with other materials or post-heat treatment, the manufactured parts are completely dense and homogenous without pores or voids inside their structures [3]. Many and varied materials and alloys can be processed by the SLM technology, such as stainless steel, tool steel, titanium, aluminum and cobalt-chrome alloys [4]. Implants and endoprostheses for repair of damaged and lost bone tissue have already produced by using the SLM technology [5]. They are constructed as spatial lattices with ordered or disordered configuration and size of the cells. Such structures provide optimal conditions for the direct bone regeneration. Porous materials offer a convenient solution to determine a fine structure of the absorbed materials that can be used as substrates to support catalysts and can act as highly selective sieves that only allow access to particles up to a certain size [6]. The current paper will not be focused on the new types of biocompatible materials that were developed within the Technical University of Cluj-Napoca (TUC-N), but will be focused on the results we have obtained at TUC-N while testing several samples manufactured from the new type of biocompatible material that has been developed for our SLM system, in close-connection to the durability issue.

2. FEA TO ESTIMATE THE DURABILITY OF AN IMPLANT MADE BY SLM

2.1. Samples manufactured by SLM and fracture strength analysis

For starting up the experiments, several samples as the ones illustrated in Figure 1 were manufactured at the Technical University of Cluj-Napoca by using the MCP Realizer SLM 250 equipment, from new types of biocompatible materials that are composite materials made from titanium and hydroxyapatite mixed together in different ratios. The technological parameters that has an important influence on the porosity issue of the samples made by SLM were varied as following:

- The laser power has been varied between 160 – 200 Watts
- The scanning speed has been varied between 0,4 – 0,8 m/s
- Hatching on the X and Y axis directions have been varied between 0,4 – 0,8 mm
- The platform has been pre-heated on 180 ˚C for 2 hours for all manufactured samples

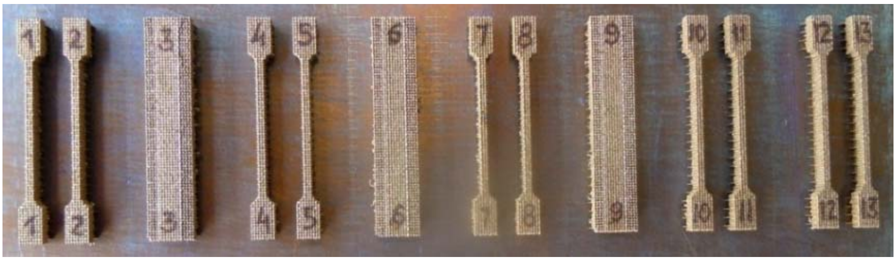

Figure. 1. A set of samples (example) manufactured by SLM from a new type of biocompatible material

All manufactured samples were tested afterwards on the Galdabini equipment from the Technical University of Cluj-Napoca, in order to determine the material curve as illustrated in Figure 2. The material properties we were interested in where the fracture strength and the material elongation. These characteristics together with other important mechanical and thermal properties of the metallic powder provided by the supplier of the SLM equipment (thermo-elastic coefficient, hardness, density, etc.) where introduced on the finite element analysis that has been performed in order to determine the durability of an implant made by Selective Laser Melting (SLM) process.

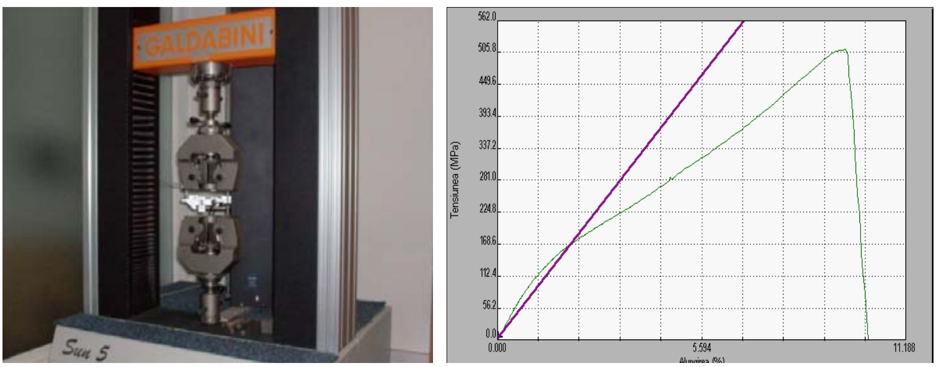

Figure 2. Testing the SLM samples on the Galdabini equipment from TUCN

2.2. Finite element analysis for testing the durability of an implant

The implant we had considered for the finite element analysis is illustrated in Figure 3 together with the materials characteristics that have been introduced on the CosmosWorks FEA programme. Further on, several restrains were applied on the analyzed model, such as motion restraints and technological restraints, related to the maximum pressure, maximum applied force, etc. (see Figure 4).

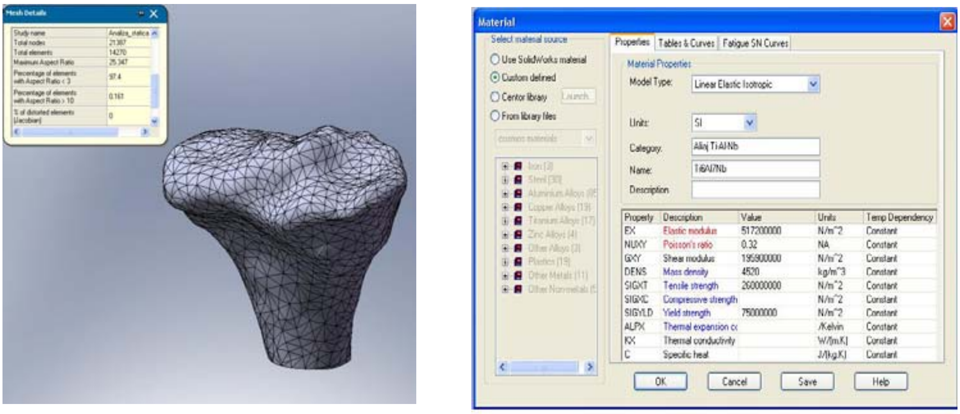

Figure 3. Customized implant (epiphysis) and materials characteristics (CosmosWorks FEA)

The loading force has been calculated as the pressure that is being applied on the surface indicated in Figure 4. The maximum pressure has been established so as the force would be equivalent to the exertion force of a person with a 150 kg in weight. The stressed area has been calculated within the ComosWorks FEA programme. Further on, the S-N curve has been defined as illustrated in Figure 4. In order to define the S-N curve, several calculus were made by taking into account the tensile strength of the material. A value of 1185 MPa corresponds for the first cycle as it could be observed in Figure 4 (this value is provided by the supplier of the SLM equipment for the titanium material). In order to determine the stress amplitude that corresponds to a number of 10^6 cycles, the tensile strength is being calculated by using the following formula:

$$\sigma_{10^6} = 0.25 * HB \qquad (1)$$

where HB is the Brinell Hardness of the new type of material we are analysing (titanium material mixed with hydroxyapatite). By doing the calculus using formula 1, the value we have obtained for the S-N curve at 10^6 cycles was 87,5 MPa.

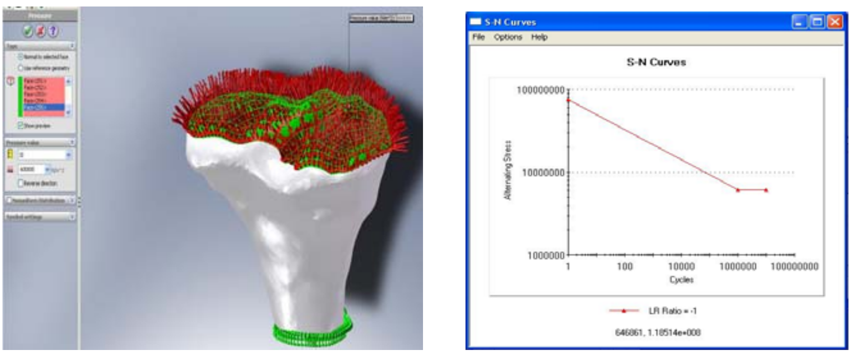

Figure 4. Technological restrains and S-N curve (CosmosWorks FEA)

The fatigue strength analysis we have performed within the CosmosWorks finite element analysis programme has been a very useful tool to determine what type of new developed powder material corresponds by the durability point of view in the case of customized implants manufactured by SLM technology and what type of powder material does not corresponds at all. The number of cycles varies from hundred of thousands of cycles to billions of cycles, depending on the type of powder material we were analyzing with (see Figure 5). The heat treatments that were made with the new types of powder materials that have been developed proved to be decisive, affecting seriously the mechanical properties of the manufactured implants made by the Selective Laser Melting (SLM) technology.

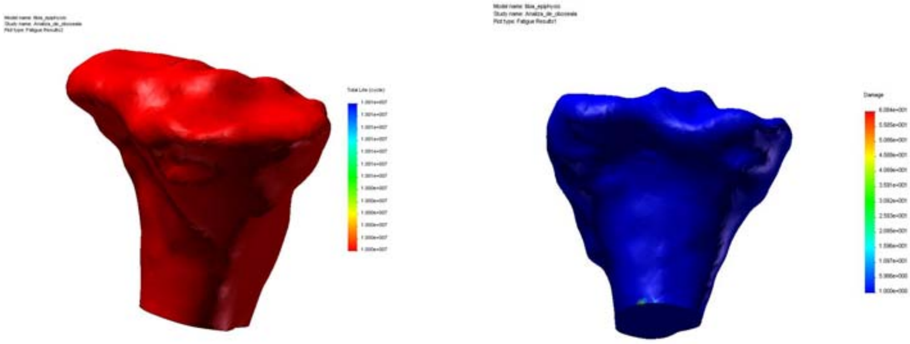

Figure 5. Durability of the implants made by SLM (CosmosWorks FEA)

3. CONCLUSIONS

A new way of approaching the field of customized implants made by the Selective Laser Melting (SLM) technology has been approached in the paper. Several samples were manufactured from new types of biocompatible materials (titanium and hydroxyapatite powders mixed in different ratios) on the MCP Realizer SLM 250 equipment from the Technical University of Cluj-Napoca and several tests were performed afterwards in order to determine the mechanical properties, such as the fracture strength and the elongation of the new developed materials. These characteristics and other thermal and mechanical properties of the material, as provided by the supplier of the SLM equipment for the titanium material, were introduced in the finite element analysis that has been done within the CosmosWorks FEA programme in order to determine the durability of an customized implant (an epiphysis) made from metallic powders by SLM. The fatigue strength analysis that has been made proved to be a very useful tool in order to determine what type of new developed powder materials corresponds and what type of powder materials does not corresponds at all by the durability point of view, in the case of customized implants made by SLM technology. Research still needs to be done in the future in this field, focusing on others characteristics of the customized implants made by SLM (such as the porosity, hardness, roughness, etc). There are also other important aspects that have to be analyzed related to the powder material characteristics (such as the powder aspect, mixing ratios or fluidity) or related to the material's biocompatibility (different tests are needed to be done in the future in vivo and in vitro on some bone cells that must grow on samples made by SLM from the new types of materials developed at the Technical University of Cluj-Napoca - TUCN).

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