Ph.D. Thesis Review

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Title: Developing Trabecular Structure.
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The use of porous structures instead of conventional bulk materials in current biomedical applications provides us with some improvements, such as better integration of bones and implants, or a more compatible implant stiffness that prevents insufficient bone resorption and implant release. Moreover, the actual bone exhibits a spatially and temporally (remodeling) variable trabecular structure. Recently, additive manufacturing has become a significant trend in the biomedical industry not only because of its popularity, but also, in conjunction with imaging methods and CAD, due to the straightforward personalization of the production of various implants. The next step is additive manufacturing of porous titanium orthopedic implants – topic of the thesis.

Meeting the objectives of the dissertation Author formulated the objectives as "1) testing the hypothesis that the AM (manufactured using additive technologies) trabecular structure mechanical properties are influenced by open-cell architecture, strut thickness, relative density, and choice of bulk materials; and 2) using the hypothesis to evaluate homogenized mechanical properties". The study consists of three basic ingredients:

- Production and post-production treatment. All experiments has been performed using 3D printed samples. Both dogbone like small specimens used to evaluate single strut response and rhombic dodecahedron trabecular cube shaped specimens $2 \times 2 \times 2$ mm for compressive test have been made from Concept laser CP-Ti Grade 2 powder with size ranging from 45 to 100 μm using selective laser melting, and left as built. Each of a set of cubic specimens $6 \times 6 \times 6$ mm made from pure titanium (TILOP) powder using SLM with printer default "island strategy" for compressive static tests, resp. made from Concept laser titanium grade 23 (CL 41TI ELI) for compressive dynamic tests has been after printing subjected to a combination of etching and/or hot isostatic pressing (HIP). Six groups of specimens (as built, HIP only treated, 3 min etched, 6 min etched, HIP treated and 3 min etched, HIP treated and 6 min etched) have been made by post-production treatment slightly different way for static, resp. dynamic compressive tests. Manufactured specimens were subjected to geometry scanning and evaluation using RedLux method and equipment or SEM before testing.

- Experiments, including experimental assessment of static response of single strut (tensile test using small samples), experimental assessment of static response of $2 \times 2 \times 2$ mm cubic specimens under compressive loading, and experimental assessment of both static and dynamic response in air or water or blood like material (BLM) of $6 \times 6 \times 6$ mm cubic specimens under compressive loading.

- Mathematical models (both analytical and FEM) to perform basic homogenization of mechanical properties have been systematically applied, developed, and verified together with experiments.

In general I can say that the objectives have been met. Specific aims declared by author (listed bellow) have been fulfilled as well.

- To determine the size effect of AM small samples on their mechanical properties.
  The aim was met performing tensile tests on set of small printed dogbone samples with cross-sectional area range $A \in \langle 0.15; 4.2 \rangle$ mm^2 oriented as perpendicular to or as parallel with 3D print layer and evaluating the dependence of mechanical properties on both A and specimen orientation (chapters 4.1, 5.1, and 6.2).
- To quantify and explain the effect of post-treatment methods on mechanical properties of AM porous structure.
  The aim was met (see chapters 4.6, 5.5, 5.6, and 6.3)
- To assess the role of environmental conditions in the human body on the mechanical behavior of the cellular structure. The objective has been met (see chapters 4.9, 5.9, and 6.6).

Author's insight on the „state of the art". The author presents an adequate knowledge in the fields covering the topic of thesis–porous structures, industrial and namely biomedical and implant industry applications and mechanical response of them. Further additive manufacturing technologies including SLM and EBM approach principles, material limitations, and biomedical application. In chapter 3 he has commented on relevant articles dealing with mentioned topics, and he found the lack of published information namely in the field of mechanical response of theoretically regular trabecular porous structures suitable to serve in orthopedic implants.

The theoretical contributions of thesis. Experimental results were systematically evaluated and statistically tested for correlation between parameters of manufacturing procedure and/or post-production treatment, and nominal mechanical properties of printed trabecular structures. This way new knowledge extending so far known facts about mechanical response of porous materials has been gained. Author has both employed known analytical formulas and performed finite element analyses of models using beam idealization to express homogenized properties of trabecular structures like relative density, elastic modulus, yield or proof stress, first maximum compressive strength and compared them each to other as well as compared both with experimental results. The numerical study was not the main aim of the work, but it shows the potential of the chosen FEM approach to homogenization of porous trabecular structure materials. Models are not described in detail in the work, in my opinion, their tuning could bring the results of the analysis closer to reality.

The thesis contribution for practice. As the experimental research has been performed on specimens made of titanium–widely used material in bio-medicine–and it has been inspired by orthopedic implants application regarding their stiffness, applied loads, and other conditions, utilization of the results in this field is relatively straightforward.

Suitability of the methods used. The methodology used in the thesis is considered to be appropriate. Author used adequate standards to design, perform and evaluate experiments as well as appropriate statistic approach to evaluate correlation between specimens production parameters and their mechanical response. By my opinion, FEM is adequate tool for mathematical modeling and homogenization of investigated porous material.

The formal level of dissertation. The formal level of the dissertation is standard. The work has logical structure. The clarity of the work would benefit if the author paid more attention to introduce the terminology used and correct utilization. The term of mechanical performance on page 8 is not introduced and its exact meaning has never been traced. Modulus of elasticity or yield stress are sometimes alternated with elastic gradient or proof stress without explanation (see

"*Figure 5.17 illustrates elastic modulus of compression test of TILOP cubical samples. Surface treatment can change mechanical properties and elastic gradient can be depended on the effectiveness of surface treatment which means 6-minute surface treatment can influence porous structure more than 3-minute surface etching. Moreover, surface treatment can decrease elastic modulus by 26%*"

on page 62).The first are material parameters, the second are connected with compressive test (see pages 37, 59, 61). The utilization of elastic gradient evaluated from compressive test according to ISO 13 314 as Young modulus of elasticity of homogenized material is correct, but mixing the terminology in text without explanation may be confusing.

Conclusion. Despite some of the above-mentioned shortcomings, I can say, that the author of the thesis performed excellent experimental work, achieved new results, and proved his ability to perform research work. **I recommend the thesis for presentation with the aim of receiving the Degree of Ph.D.**

4. 1. 2020
Miroslav Španiel

Questions

1. Please, explain the meaning of *Concept Laser* and *Required* in tables 4.1 and 4.2 on page 19.
2. Please explain the difference between *dry foam* and *wet foam* in terms of FEA or Abaqus (figure 4.33 on page 45). How did you maintain non-linear effects in your models? Is the contact between struts taken into account and, if yes, how?

3. Please explain the term *impact strength* regarding dynamic testing. You evaluate it as pure energy in joules [J]. Do You calculate it as integral of impactor displacement–force dependence? What is the integration domain? Regarding the impact tests in water or BLM, what is the influence of hydrodynamic forces on the experiment?