Proceedings of the Estonian Academy of Sciences,
2019, **68**, 2, 191–197
https://doi.org/10.3176/proc.2019.2.11
Available online at www.eap.ee/proceedings

MATERIALS ENGINEERING

Modelling of impact-abrasive wear of ceramic, metallic, and composite materials

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Received 25 February 2019, accepted 19 March 2019, available online 23 April 2019

Abstract. The behaviour of materials was investigated using finite element modelling software (SOLIDWORKS and COMSOL). Three types of materials were studied: (1) ceramic (diamond), (2) metallic (titanium), and (3) composite (consisting of ceramic and metallic phases). Finite element modelling allows illustrating deformation and stressing the distribution of the test material during a single impact of the tribodevice with or without abrasive particles. The impact energy absorption was investigated. Real composite materials were produced by a combination of 3D printing (selective laser melting) of the lattice structure (Ti6Al4V) followed by addition of a hard ceramic phase with the help of the spark plasma sintering technique. The produced samples were tested by a laboratory impact-abrasive tribodevice. The results of modelling and laboratory testing were compared. The effect of modelling variables is illustrated. It is explained why composite materials showed better performance in impact-abrasive conditions and are suitable for tunnelling and mining applications.

Key words: additive manufacturing, spark plasma sintering, selective laser melting, impact-abrasive simulation, SOLIDWORKS software, COMSOL software, diamond–Ti6Al4V composite.

1. INTRODUCTION

Combination of computer-aided design (CAD), finite element analysis, and 3D printing of metal alloys is a high-potential additive manufacturing approach converting conventional metallurgy to modern powder metallurgy. Focus on the simulation of prototypes and experiments can lead to better results and reduced costs of manufacturing, e.g. sintering or consolidation of material powders and printer parameters as well as compressive, tensile, impact, and abrasion tests. The influence of scanning strategies (hatching and concentric) and printer parameters (laser power and pulse duration) of CoCr alloy powders for stent placement feasibility in cardiology has resulted in selective laser melting (SLM) [1]. Advantages of concentric scanning for having a fine mesh and also electrochemical polishing for post-processing are shown in this study. Manufacturability of the gyroid- and diamond-type triply periodic minimal surface (TPMS) scaffold design for biomaterials (bone implant) application is investigated in [2]. Visual and quantifiable comparisons by 3D reconstructed and 3D CAD modelled Ti6Al4V TPMS lattices show an acceptable reproduction design. Compressive strength, stress/strain distribution, and the failure occurrence mechanisms of cellular structures can be successfully analysed by the finite element method [3].

A nonlinear transient (thermo-mechanical field) model is developed via the ANSYS parametric design language (APDL) in [4]. This finite element analysis considers temperature and stress fields caused by the overhanging and floating of a 316L stainless steel layer built in a powder bed without support.

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Lightweight metallic TPMS sheets/shells (primitive, diamond, and gyroid) are fabricated by SLM and compared to body-centred cubic lattices in [5]. Simulation results illustrate uniform stress distributions for diamond- and gyroid-type lattices under compression leading. The powder spreading/distribution process is an important research field in additive manufacturing. Some simulations in this area to illustrate induced flow, velocity, solidification or discontinuous track, and temperature contours of particles in solid bed have been developed [6,7].

In this work, the modelling ability of SOLIDWORKS and COMSOL software is introduced for prototype samples under impact and abrasive loadings [8–10]. The combination of SLM (for metallic lattice) and spark plasma sintering (SPS, for reinforcing by diamond) techniques is used for preparing an optimized sample.

2. MATERIALS, MACHINES, AND METHODS

Various Ti6Al4V cellular lattice structures were modelled by SOLIDWORKS software. These can be fabricated via SLM or 3D printing (Figs 1 and 2). A BCC-type 1 mm unit cell (diamond-type) lattice structure (Figs 1A and 2A) was printed by *Realizer SLM50* metal printer from Ti6Al4V powder in the size of 20–63 µm (supplied by SLM Solution Group) and are studied in the current work. A *FCT Systeme* SPS machine was used for adding diamond particles with the size of 40–50 µm (supplied by Vanmoppes & Sons Ltd), which filled the space between the lattice structure (Fig. 3). Wear resistance and damage tolerance of the Ti6Al4V–diamond composite were evaluated via a custom-made patented impact-abrasive tribology tester in Tallinn University of Technology [8] (Fig. 4A). During the real testing, the WC-15Co rotating wheel was driven by an electrical motor, but in the current simulation study only an impact generator was used with 1 m/s velocity and range of impact energy (Fig. 4B). The abrasive was introduced into the region between the wheel and the sample by a nozzle. The wheel diameter was 100 mm, and the cylindrical sample was modelled to be of 20 mm diameter and 10 mm height.

COMSOL software was applied for stress and displacement simulation. The surface stress distribution and deformation of the solid diamond sample with a single impact (without the abrasive particle) in the centre is shown in Fig. 5. Figure 6 illustrates the diamond

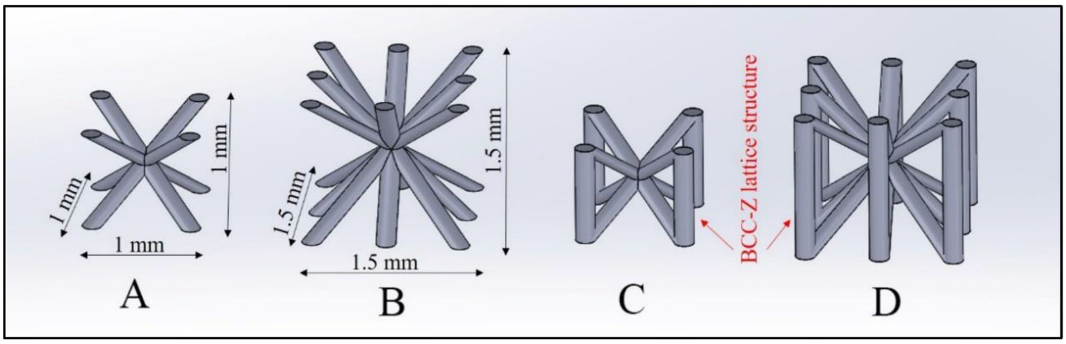

Fig. 1. Lattice structure design: (A) body-centred cubic (BCC) (diamond-type lattice), 1 mm unit cell; (B) BCC, 1.5 mm unit cell; (C) body-centred cubic with vertical scaffolds (BCC-Z), 1 mm unit cell; (D) BCC-Z, 1.5 mm unit cell.

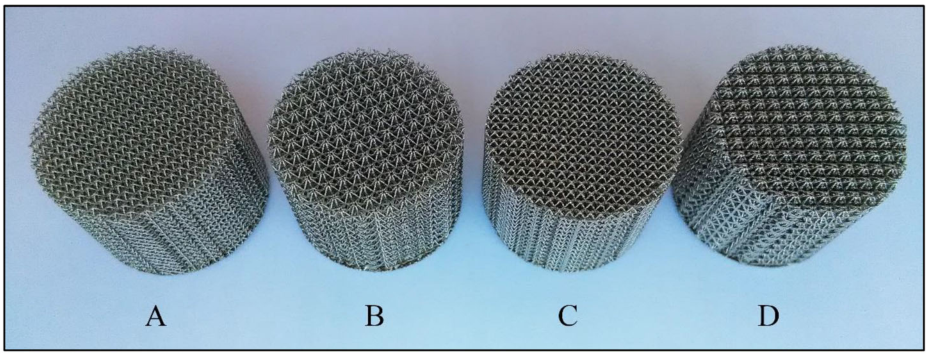

Fig. 2. Examples of cellular lattice structures: (A) BCC, 1 mm unit cell; (B) BCC, 1.5 mm unit cell; (C) BCC-Z, 1 mm unit cell; (D) BCC-Z, 1.5 mm unit cell (dimensions of printed objects are diameter 20 mm and height 15 mm).

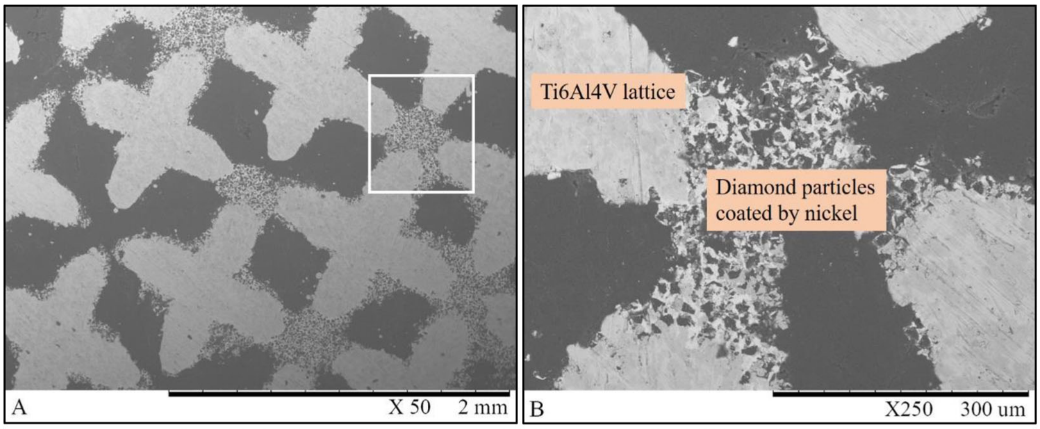

Fig. 3. SEM micrograph of diamond–Ti6Al4V sample after SPS and polishing.

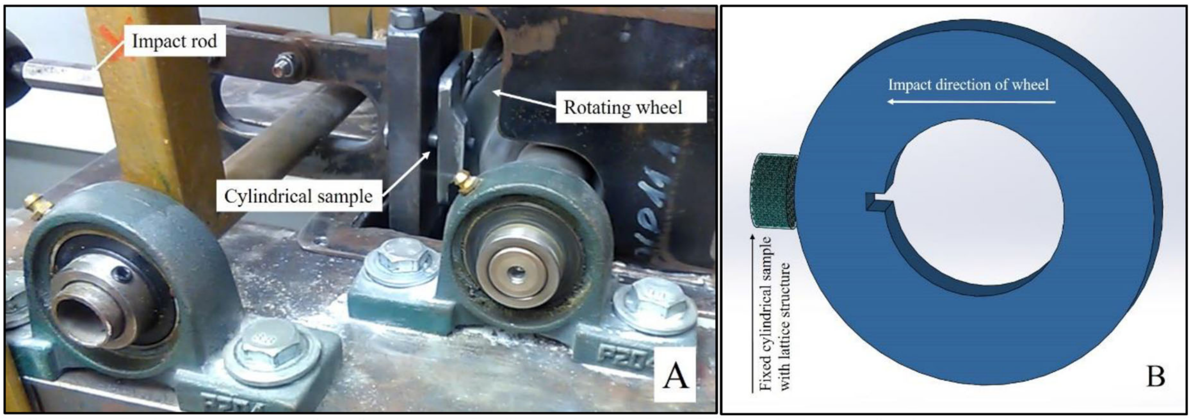

Fig. 4. (A) Position of the sample, wheel, and rod of the impacting device; (B) simulation mechanism; only horizontal impact motion [8,9].

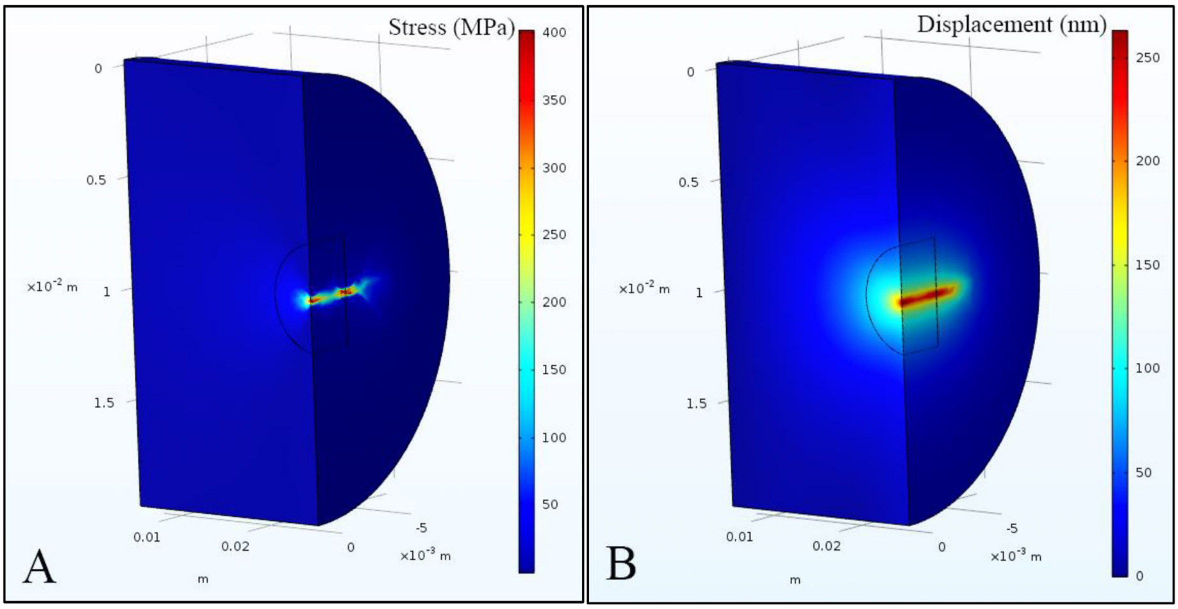

Fig. 5. (A) Stress and (B) deformation resulting from impact simulation of a solid diamond (without the abrasive particle).

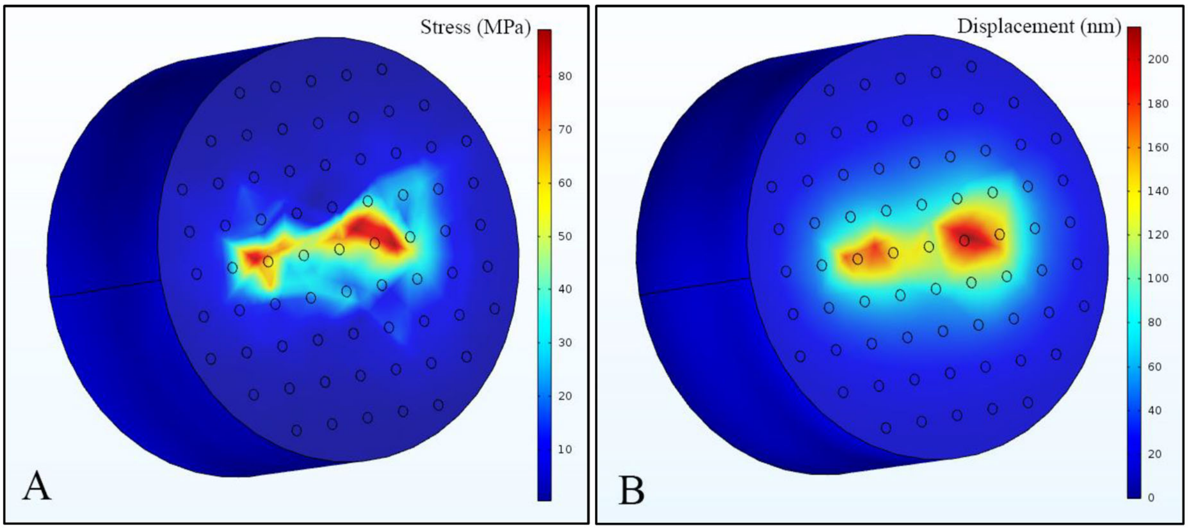

Fig. 6. (A) Stress and (B) deformation resulting from the impact simulation of the diamond embedded lattice structure (without the abrasive particle).

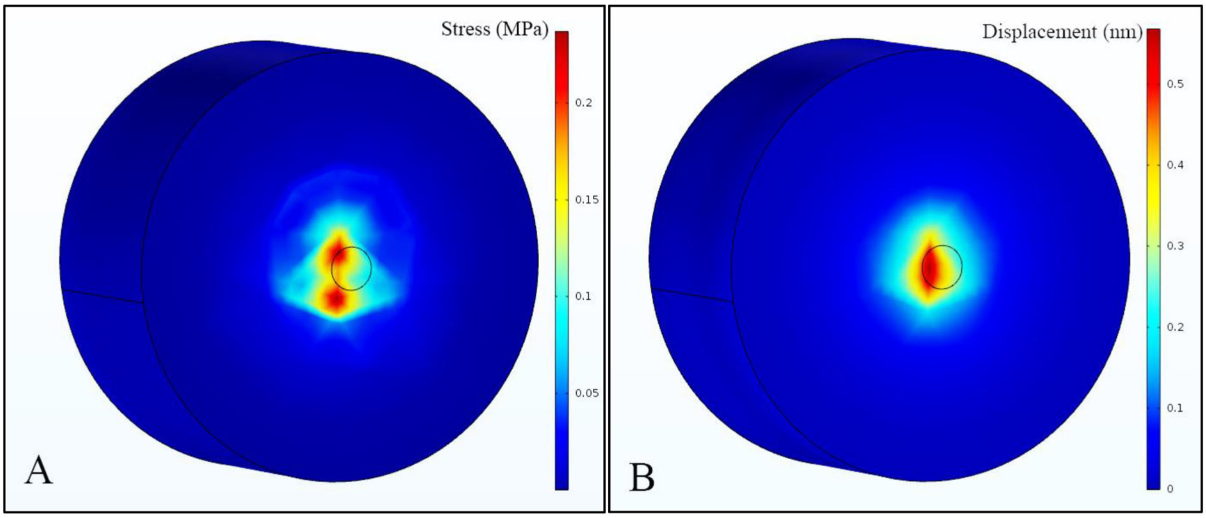

Fig. 7. (A) Stress and (B) deformation resulting from the impact simulation of a solid diamond in contact with the abrasive particle.

sample reinforced by a Ti6Al4V lattice structure. The modelling of the impact of the SiO_2 abrasive particle with a diameter of 2 mm, trapped between the wheel and the sample, is depicted in Fig. 7.

3. RESULTS AND DISCUSSION

Three simulations of composite samples were considered for the assessment of wear resistance, impact energy absorption, and damage tolerance, respectively, of a solid diamond, a diamond embedded Ti6Al4V lattice structure, and a diamond in contact with a SiO_2 abrasive particle. The von Mises equivalent stress distribution and displacement of samples are shown in Figs 5–7. For the solid diamond, symmetry of the model is used to save time and to obtain a finer mesh configuration (Fig. 8). However, in the two next simulations, a complete model was preferred for consideration because of the boundary condition of the lattice and the sample and the triply contact of the wheel/sample/particle. The possibility of applying a wide range of metals, ceramics, and composites, different diameters and shapes of the samples and abrasive particles, and varied velocity/

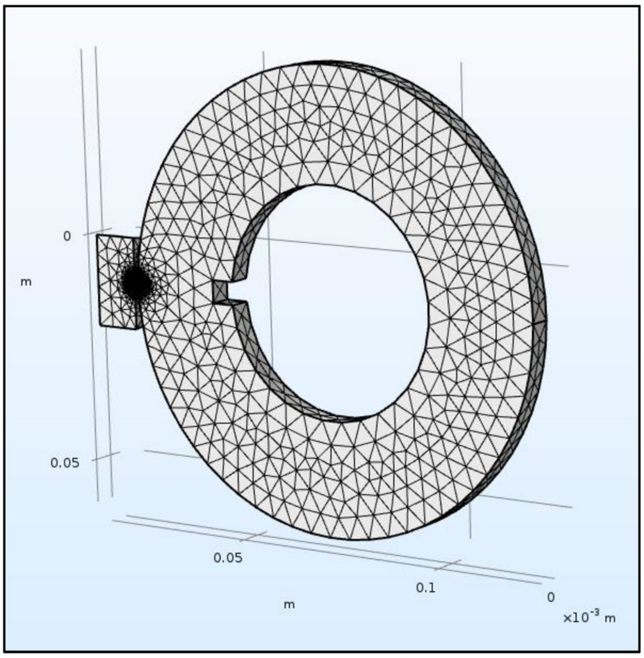

Fig. 8. Mesh configuration of symmetry of the model with a finer mesh in the contact region.

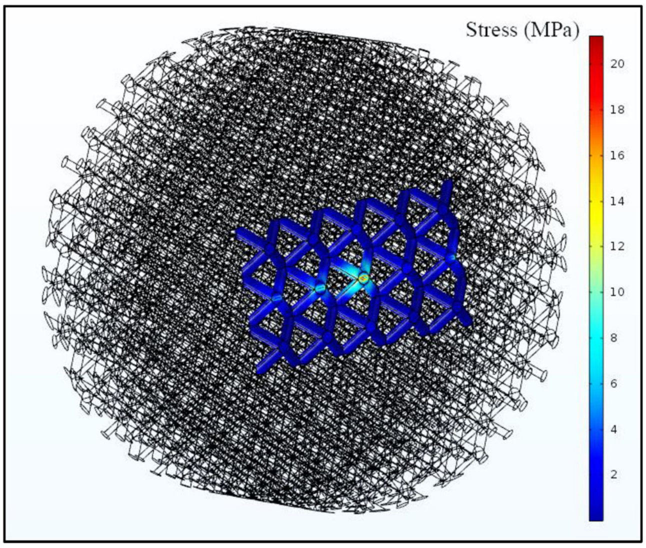

Fig. 9. Stress distribution of the lattice structure under impact in the contact region.

energy of impact and using finite element is an advantage of this method. Horizontal and linear distribution of the stress/deformation is the reason of the cracking/splitting of solid diamond samples under high impact rates (see Fig. 5).

The pivotal role of the lattice structure in impact absorption and in increasing damage tolerance is considered in Figs 6 and 9. Comparison of Figs 5 and 6 demonstrates a significant reduction of stress in the solid sample. Figures 10–12 illustrate statistical comparison of solid diamond and diamond embedded Ti6Al4V lattice. Either decrease of stress and deformation or increase of impact energy absorption is clear in the graphs.

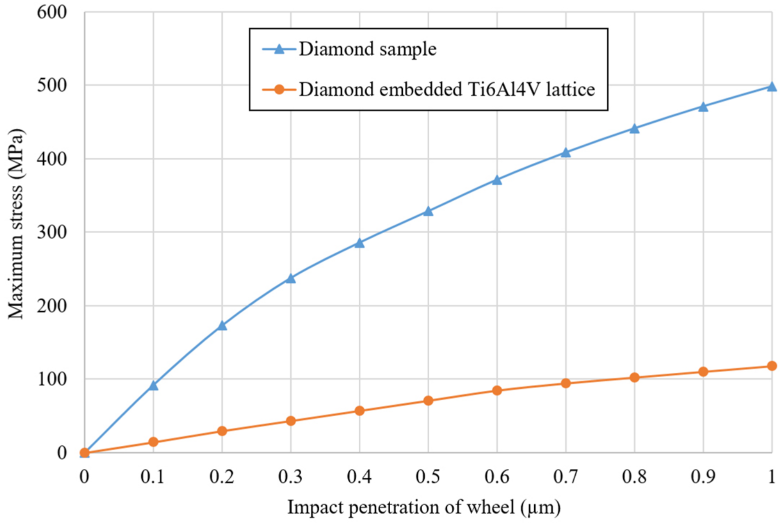

Fig. 10. Comparison of maximum stress of diamond and diamond–Ti6Al4V samples during impacting.

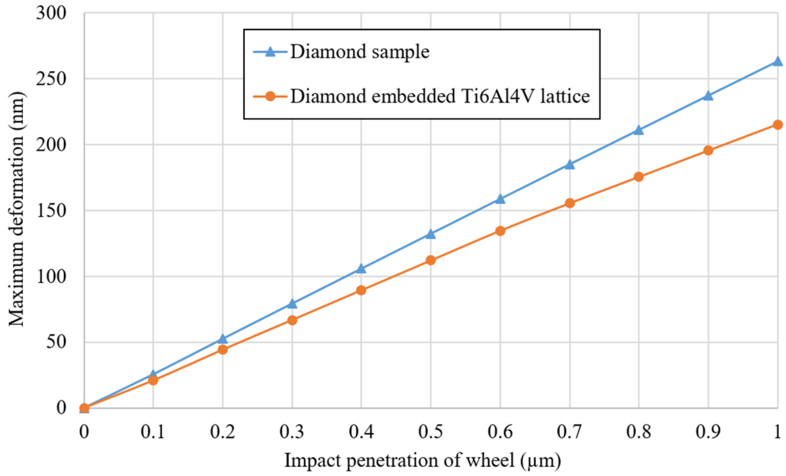

Fig. 11. Comparison of maximum deformation of diamond and diamond–Ti6Al4V samples during impacting.

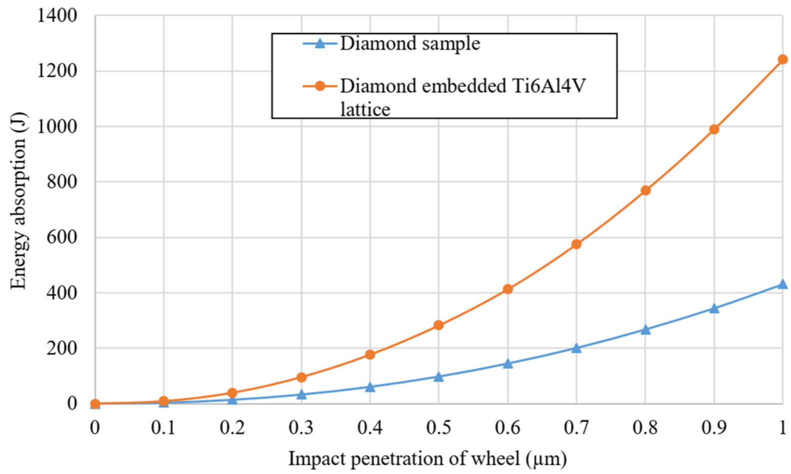

Fig. 12. Comparison of energy absorption of diamond and diamond–Ti6Al4V samples during impacting.

4. CONCLUSIONS

This study describes three cases of the simulation of impact-abrasive wear, namely, of solid diamond, Ti6Al4V lattice structure with diamond, and diamond in contact with an abrasive particle. Combination of laser melting and spark plasma sintering is a novel method, which can be considered for any kind of ceramics and composites.

- SOLIDWORKS and COMSOL finite element software help to design samples for 3D printing and to predict the behaviour of composite materials (deformation and stress distribution) before production. All steps of the additive manufacturing process starting from design, 3D metal printing, impact-abrasive tests, and custom-made modelling can be improved with the help of finite element simulation.
- Metallic lattice performs as an impact absorption structure to decrease local stress/deformation and delays plastic deformation in comparison with the lattice-free sample. Use of the cellular lattice structure decreases downtime required for changing parts due to improved wear resistance.
- It was found that traditional powder metallurgy can be substituted by a combination of SLM and SPS methods to produce wear-resistant parts for impact-abrasive applications. More than four times reduction of the stress level in the diamond sample was achieved as a result of applying the Ti6Al4V lattice structure.

ACKNOWLEDGEMENTS

This research was supported by the Estonian Ministry of Education and Research under projects IUT19-29 and ETAG18012 and by base finance project B56 and SS427 of Tallinn University of Technology. The publication costs of this article were covered by the Estonian Academy of Sciences.

REFERENCES

1. Demir, A. G. and Previtali, B. Additive manufacturing of cardiovascular CoCr stents by selective laser melting. *Mater. Design*, 2017, **119**, 338–350.
2. Yan, C., Hao, L., Hussein, A., and Young, P. Ti-6Al-4V triply periodic minimal surface structures for bone implants fabricated via selective laser melting. *J. Mech. Behav. Biomed. Mater.*, 2015, **51**, 61–73.
3. Yang, L., Yan, C., Han, C., Chen, P., Yang, S., and Shi, Y. Mechanical response of a triply periodic minimal surface cellular structures manufactured by selective laser melting. *Int. J. Mech. Sci.*, 2018, **148**, 149–157.
4. Hussein, A., Hao, L., Yan, C., and Everson, R. Finite element simulation of the temperature and stress fields in single layers built without-support in selective laser melting. *Mater. Design*, 2013, **52**, 638–647.
5. Zhang, L., Feih, S., Daynes, S., Chang, S., Wang, M. Y., Wei, J., and Lu, W. F. Energy absorption characteristics of metallic triply periodic minimal surface sheet structures under compressive loading. *Addit. Manuf.*, 2018, **23**, 505–515.
6. Haeri, S., Wang, Y., Ghita, O., and Sun, J. Discrete element simulation and experimental study of powder spreading process in additive manufacturing. *Powder Technol.*, 2016, **306**, 45–54.
7. Khairallah, S. A. and Anderson, A. Mesoscopic simulation model of selective laser melting of stainless steel powder. *J. Mater. Process. Tech.*, 2014, **214**, 2627–2636.
8. Antonov, M., Veinthal, R., Yung, D. L., Katušin, D., and Hussainova, I. Mapping of impact-abrasive wear performance of WC–Co cemented carbides. *Wear*, 2015, **332**, 971–978.
9. Rahmani, R., Antonov, M., and Kollo, L. Wear resistance of (diamond-Ni)-Ti6Al4V gradient materials prepared by combined selective laser melting and spark plasma sintering techniques. *Adv. Tribol.*, **2019**, article ID 5415897.
10. Badisch, E., Ilo, S., and Polak, R. Multivariable modeling of impact-abrasion wear rates in metal matrix-carbide composite materials. *Tribol. Lett.*, 2009, **36**, 55–62.

Keraamiliste, metalsete ja komposiitmaterjalide abrasiivkulumise modelleerimine

Ramin Rahmani, Maksim Antonov ja Nikhil Kamboj

Käesolevas uuringus oli vaatluse all materjalide käitumine, kasutades lõplike elementide modelleerimise tarkvara (SOLIDWORKS ja COMSOL). Uuriti kolme liiki materjale: 1) keraamika (teemant), 2) metall (titaan) ja 3) komposiit (keraamilis-metalne). Modelleerimine lõplike elementide meetodil võimaldab näidata deformatsiooni ja pingete jaotust uuritavas materjalis üksiklöögi toimel triboseadmes abrasiivosakesega ning ilma. Uuriti löögienergia neeldumist. Reaalsed materjalid olid valmistatud titaanisulamist Ti6Al4V võrestruktuuri 3D printimise ja sellesse järgneva kõva keraamikafaasi lisandamisega sädeplasmapaagutuse teel. Valmistatud proovikehi katsetati laboratoorsel löök-abrasiivtriboseadmel. Võrreldi modelleerimise ja laboratoorsete katsetuste tulemusi. Muutujate mõju modelleerimisel on illustreeritud vastavate diagrammidega. On välja selgitatud, miks komposiitmaterjalidel on löökabrasiivkulumise tingimustes parem vastupanu ja on sobivad kasutamiseks tunneliehituses ning kaevandamisel.