INSTITUTE OF **MACHINE**
AND **INDUSTRIAL DESIGN**

Faculty of Mechanical Engineering
Brno University of Technology

Review of Doctoral Thesis

1. PhD candidate
Ing. Radek Vrána / vrana@fme.vutbr.cz
2. Name of PhD programme
Design and Process Engineering
3. Title of PhD thesis
Study of Energy Absorption in Micro-Strut Lattice Structure Produced by Selective Laser Melting

4. Principal supervisor
doc. Ing. David Paloušek, Ph.D. / david.palousek@vut.cz
5. Co-supervisor
doc. Ing. Daniel Koutný, Ph.D./ daniel.koutny@vut.cz

6. Reviewer
Univ.-Prof. Dr.-Ing. Dipl. Wirt.-Ing. Johannes Henrich Schleifenbaum / Johannes.Henrich.Schleifenbaum@dap.rwth-aachen.de
Faculty of Mechanical Engineering, RWTH Aachen University

7. Overview of the scope of PhD thesis[1]
Very good
The thesis aims at developing a numerical model of the deformation behaviour of SLM-produced lattice structures out of AlSi10Mg. The main steps taken are: 1) process development (laser power, scan speed and scan strategy) for optimized density and surface roughness. 2) Design and qualification of a drop weight impact testbed for the referencing/validation of the numerical model. 3) Development and validation of numerical model including porosity, surface roughness and strut shape deviations. This is an appropriate and good approach. The analyzation of the influence of SLM process parameters on the formation of internal material defects and surface roughness during the SLM production of the lattice structure represents the largest part of the thesis. The hypothesis is that these defects degrade mechanical properties of the structure and their removal will improve the mechanical properties. (Yet, this is a bit inaccurate. We know from literature that even porosity of some percent have only little influence on static performance of bulk parts. On the other hand side the hypothesis is absolutely true for the dynamic performance). Based on the process optimization the deformation behaviour of the manufactured lattice structures is analysed on the developed drop weight impact device. The deformation behaviour is evaluated using the image analysis of a high-speed camera and a force record from a strain gauge. The results of the mechanical testing is then finally used for the validation of the developed numerical model. In that model the real shape of the produced lattice structure was implemented in the form of an elliptical

[1] Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

geometry along with the information on the real mechanical properties in the form of the developed material model. The resulting comparison of the experimental results and the numerical model prediction show a good match at the maximum load (deviation of approx. 5 %).

8. Significance of the topic and clarity of problem statement

Very good

The topic is absolutely relevant for various fields of application, such as aerospace, lightweight design in general of shock absorbing structures. The problem of porosity and especially surface roughness is well addressed. For complex lattice structures, post treatment (i.e. to reduce surface roughness) is difficult to achieve. Hence the deterministic description of those quality factors and finally the evaluation of the outcome - tensile strength, fatigue strength, etc. – are crucial for the use of such lattices in industry. The idea of a simulation driven design will help future designers to incorporate lattices into their thinking and design approaches. Besides this, the procedure can be driven further for the evaluation of thin structures (e.g. in topology optimization) in general.

9. Knowledge of existing literature

Good

Main literature sources are cited. Yet, 65 sources could be improved. Some mistakes are made throughout the theses. For example, AlSi10Mg was used in Laser Powder Bed Fusion (or SLM, as it is called here) for more than 10 years now. In the thesis it is stated, that this material is in use for not more than 3 years. On the other hand side the extend of chapter two and three (State of the art) make up to approx. 35% of the whole thesis which seems to be a bit exaggerated.

10. Choice of methods and technical soundness

Good

The choice of methods is appropriate. Especially the design and qualification of a drop weight impact testbed for the evaluation of the SLM-produced lattice structures is innovative and new. The exploitation of uCT method for the volumetric evaluation of porosity (backed by the metallographic analyzation) and the surface roughness is well chosen. The determination of the strut shape and the consequent adaption of the numerical model (ellipse instead of circular shape) by means of optical measurement methods is appropriate, too. In the field of SLM process development three main parameters are optimized (laser power, scan speed, scan strategy). Especially the "contour only" strategy is well chosen for the build up of struts. Besides this, there are many other parameters that influence porosity and surface roughness. One of the most decisive ones is the specimen position on the build plate (due to inhomogeneous atmosphere and flow conditions in the build chamber). This is not taken into consideration at all and marks a major mistake in this work.

11. Quality, originality and significance of the results

Good

Overall, the results of the thesis are good. The method is appropriate and the developed test procedures are innovative. The quality of the SLM process development is very good, the combination of an adapted scan strategy for struts with the evaluation of appropriate Line Energy is promising. Yet, this is foiled by the missing evaluation of other very important influencing factors, like positioning on the build platform. The evaluation of the energy absorption of the optimised lattice structures is innovative, this is a very good

approach. This is also the case for the newly developed material model and the adaption of strut surface and porosity equivalent. In sum, the results are very good and promising. Yet, the missing puzzle pieces (choice of influencing parameters on porosity and surface roughness, categorization / classification of defects and their impact, poor explanation of strut size choice, ..) and the blotted presentation of pictures (fuzzy, missing legends, scales, etc.) and diagrams (in some cases not readable at all) preclude a better evaluation.

12. Quality of attached papers

Very good

The papers attached to the thesis are well written and show the importance and significance of this work. Yet, there are only two papers available, this could be improved. This impression is underlined by missing information and interpretations, e.g. the development of gas pores in downskin areas. What is the condition of the powder in terms of humidity? Was there a drying process performed before the actual AM process? The grain size distribution seems to be coarse compared to "standard" 10-45 um. Why was the coarser fraction chosen? Why is the strut diameter chosen to be 0.8mm? More background information and cause-effect descriptions could be given.

13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)

Good

The thesis is well structured with a clear objective stated in the very beginning. The work is innovative and relevant. The development of the numerical model and the underlying process development is well presented. Yet, some crucial facts are missing, e.g.: 1) It is known that the position of specimen on the substrate play major role in the formation of defects, this is not touched at all in the thesis. 2) The explanation why BCC unit cells are used and the reason for the choice of the strut diameter are in need for improvement 3) The difference between thicker and thinner struts in terms of susceptibility for pores, defects compared to the absolute thickness is not sufficiently categorized 4) The indication of the influence of the degree of porosity (here to be found between approx. 0.1% ...3%) is not presented. Besides this, the quality of the pictures is in approx. 50% of all cases insufficient. Either diagrams or legends are hardly readable or legends and scales are missing completely. Some abbreviations are introduced within the text, some have to be taken from the annex, this makes the thesis hard to read at some points. Overall, there are many small mistakes throughout the text which in the end sum up and leave the impression of blotted paper work. In sum, the very good idea and work carried out in this thesis is foiled by a lack of accuracy. The thesis is between good and very good.

14. Questions and comments

Rework pictures, many of them are fuzzy and barely readable. Add scales and legends to the pictures.

15. Conclusion

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.

YES

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FME

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Review of Doctoral Thesis

1. PhD candidate

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2. Name of PhD programme

Name

3. Title of PhD thesis

Study of Energy Absorption in Micro-Strut Lattice Structure Produced by Selective Laser Melting

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6. Reviewer

Dr Eng. Mateusz Skalon / mateusz.skalon@tugraz.at

Graz University of Technology

7. Overview of the scope of PhD thesis[1]

Excellent

The scope of the thesis is focused on delivering the accurate description of energy absorption behaviour of lattice structures manufactured from AlSi10Mg by Selective Laser Melting technique. The scope is very broad however, it circles in an organised manner around one and well defined topic. Both the experimental approach and the research plan are of high quality and leave no space for uncertainties. The influence of the main SLM parameters on the printed single-melt-track properties are investigated. In the next step the influence of both the process parameters and contour strategy on the structure and quality of the struts are investigated. Basing on the received data the numerical model of the lattice deformation is developed. The model is then confronted with a real-life data retrieved from the self-designed test stand. As a result, the Thesis delivers a description of manufacturing process of lattice structures produced from AlSi10Mg along with its behaviour during local impact.

8. Significance of the topic and clarity of problem statement

Very good

The presented topic is well described and the problem properly motivated. Since the lattice structures may be produced only via SLM process the presented topic is of high importance to all further understanding of

[1] Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

its failure mechanism, prediction of its behaviour and finally to industrial application. The presented topic is of a great importance due to rapidly growing amount of SLM systems being is use. The problem of the Thesis was stated in a clear manner. The aim of the Thesis was presented thoroughly by listing 7 main tasks. The tasks were designed in order to answer the stated Hypotheses and Scientific Questions. Finally, the Hypotheses are well defined and presented in clear and concise way.

9. Knowledge of existing literature

Excellent

The references are properly used, well-structured and properly described. Cited documents refer to relevant and up-to-date documents supporting intentions of the candidate. They are used in a proper and not excessive number. More than 80% of used references cite manuscripts not older than 2012. What is natural some of the references are used both in the Thesis and in the appended manuscripts. As a part of good practices, as a source of knowledge beside the scientific manuscripts also the previous works of the candidate are mentioned and consist coherent background for the thesis. It is worth highlighting that the candidate used diversified sources i.e.: patents, websites and conference papers. The knowledge of the candidate concerning the existing literature is at a very high level.

10. Choice of methods and technical soundness

Excellent

The candidate proved to be able to select the experimental methodology in a way to leave no space for uncertainty in respect to obtained results. He is aware of the drawbacks emerging from using each of testing methods therefore the best possible means were harnessed in order to prevent drawbacks or at least to minimise them e.g. Few methods of roughness check and cross-validating of the impactor move or Paper B where the mass check of the lattice was used as a base for checking the printed shape correctness. All values selected for performing experiments and tests are based on thorough preparation and are well justified. Additionally, the Candidate proved to be able to design and build both the testing hardware and software extending his research capabilities. Both the parameters selection algorithm and the constructing the Impact Test Stand coupled with measurement system merits recognition. The FEM simulation were prepared carefully in agreement with the best scientific practice. The Candidate has proved to be fluent in methods' selection and modification and making correct interpretation of results.

11. Quality, originality and significance of the results

Excellent

The delivered results are of high quality due to the joint effect of the detailed preparation of each experiment and a high number of tested repetitions. Comprehensive research approach where a broad experimental part is supported with a Finite Element Analysis and a proper explanation of each observed phenomenon further supports the results' quality. Algorithm allowing for design the lattice structures of desired properties is a significant an important step towards an applicative outcome. Static behaviour of the SLM printed lattice structures is already well known. This work however, complements current state-of-art with a detailed explanation of lattices' behaviour and failure mechanism under low-speed impact. The results consist an original piece of work.

12. Quality of attached papers

Very good

There are two peer-reviewed papers appended to the Thesis. Both were published in Open Access journal Materials (MDPI) specializing in area of „Materials Science and Multidisciplinary ". The journal is ranked as 111/285 according to JCR and has an assigned Impact Factor of 2.467 (2018) what positions it as a publishing platform for high-impact and high-quality research. Both papers were published in second half of 2018 and already have been cited already three times in total. Both have thoroughly described methodology so the experiments can be easily repeated. Presented results consist pieces of the Thesis. Performed experiments are well designed and conclusions are clear and properly concluded. The first one: Selective Laser Melting Laser Strategy for Fabrication of Thin Struts Usable in Lattice Structures" presents the background for the initial part of the Thesis. The second one:" Dynamic Loading of Lattice Structure Made by Selective Laser Melting - Numerical Model with Substitution of Geometrical Imperfections" supports the second part of the Thesis. The papers are of high quality and present the sound results along with a thorough interpretation.

13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)

Excellent

Clearly, the preparation of the Thesis consumed a lot of time and effort. The Thesis coupled with appended papers reflects the high volume of know-how created along the work. The Thesis is prepared with a great care and with attention on details. There are only few typos in the whole document what reflects that great care about details. The major advantages were: a) versatile approach in order to answer stated questions, b) use of self-designed test stand and algorithm, c) multiple check of each result or obtained data. Another feature deserving recognition is a proper use and interpretation of each method. The candidate proves to understand the technical limits of research tools. The only drawback is that Thesis treats the material as homogeneous entity where pores are the main reason of change in mechanical response of the materials. Therefore, there is a lack of metallographic investigation describing the changes (or lack of changes) in the material microstructure. This, on the other hand, was managed by checking directly the mechanical properties of struts which is also acceptable.

14. Other comments

15. Conclusion

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.

YES

16. Date and signature

14/03/2019

Please note

A. *Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.*
B. *E-mail the completed form to: Klara.Javorcekova@vut.cz*

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FME

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Principal supervisor's final report on the PhD study

1. PhD candidate
Ing. Radek Vrána / Radek.Vrana@vut.cz
2. Name of PhD programme
Design and Process Engineering
3. Title of PhD thesis
Study of Energy Absorption in Micro-Strut Lattice Structure Produced by Selective Laser Melting

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doc. Ing. Daniel Koutný, Ph.D. / Daniel.Koutny@vut.cz

6. Stays at other institutions (min. 7 days)
Rheinisch-Westfälische Technische Hochschule Aachen (RWTH Aachen)/ Germany / **01/06/2018 / 30/11/2018**

7. Teaching activities
3CD, 4KC, ZAT, ZPP, ZM1, ZM2, ZKP, ZIP

8. List of main publications
VRÁNA, R.; KOUTNÝ, D., PALOUŠEK, D., PANTĚLEJEV, L., JAROŠ, J., ZIKMUND, T. and KAISER, J. Selective Laser Melting Laser Strategy for Fabrication of Thin Struts Usable in Lattice Structures. *Materials* 2018, 11 (9), ISSN 1996-1944. IF=2.467
VRÁNA, R.; ČERVINEK, O., MAŇAS, P., KOUTNÝ, D. and PALOUŠEK, D. Dynamic Loading of Lattice Structure Made by Selective Laser Melting - Numerical Model with Substitution of Geometrical Imperfections. *Materials* 2018, 11(11), ISSN 1996-1944.IF=2.467
VRANA, R.; KOUTNY, D.; PALOUSEK, D.; ZIKMUND, T. Impact Resistance of Lattice Structure Made by Selective Laser Melting from Alsi12 Alloy. *MM Science Journal*, 2015, 2015 (4), s. 852-855. ISSN: 1805-0476.

VRANA, R.; KOUTNY, D.; PALOUSEK, D. Impact Resistance of Different Types of Lattice Structures manufactured by SLM. *MM Science Journal*, 2016, roč. 2016, č. 6, s. 1579-1585. ISSN: 1803-1269.

VRANA, R.; PALOUSEK, D.; KOUTNY, D.; KOUKAL, O.; ZIKMUND, T.; KREJCI, P. Impact resistance of lattice structure made by Selective Laser Melting technology. In *Euro PM2015 Proceedings*. Reims, France, 2015. s. 1-6. ISBN: 978-1-899072-47-7.

VRANA, R.; KOUTNY, D.; PALOUSEK, D.; ZIKMUND, T. Influence of Selective Laser Melting Process Parameters on Impact Resistance of Lattice Structure made from AlSi10Mg. In *World PM2016 Proceedings*. Hamburk, Germany, 2016, ISBN: 978-189907248-4.

VRANA, R.; VOSYNEK, P., KOUTNY, D., NAVRAT, T., PALOUSEK, D. Evaluation of mechanical behaviour of 3D printed lattice structure by SLM: Experiment and FEA. In *EAN 2018 Proceedings*. Harachov, Czech Republic, 2018. s. 443-449. ISBN: 978-802704062-9

MANAS, P.; **VRANA, R.**; HEJMAL, Z.; DUBEC, B. Determination of the material properties of recycled rubber for explicit FEM simulation. In *ICSMESP 2017 Proceedings*. Prague, Czech Republic, 2017. s. 1-7. ISSN: 2367-2544.

KOUTNY, D.; **VRANA, R.**; PALOUSEK, D. Dimensional accuracy of single beams of AlSi10Mg alloy and 316L stainless steel manufactured by SLM. In *5th International Conference on Additive Technologies iCAT2014*. Ljubljana: Interesansa, 2014. s. 142-147. ISBN: 978-961-281-579-0.

9. Assessment of the supervision process

Very good

Ing. Radek Vrána systematically worked on the dissertation thesis during entire doctoral study. In the first few years, he studied previous articles aimed at the SLM technology and its process parameters, energy absorption in porous materials and numerical modelling of the lattice structure deformation. Based on it, he could design a drop weight impact tester which was used for validation of the FEM model. During an entire study, he published eight paper as the main author and four papers as co-author and regularly attended international conferences where he presented his work. Individual sub-steps of research were always discussed. The expectations of the supervisor have been met.

10. Assessment of the candidate's ability to work independently

Very good

Ing. Radek Vrána is able to work independently. It documented two prepared IF papers during 6-monts internship at RWTH Aachen university last year or many projects where independently participated as investigator or co-investigator – e.g. ESA Contract (2014-2017) Design of spacecraft components for additive manufacturing (no.4000109548/13/NL/MV), co-investigator; TAČR TH02010514 (2017-2019) Development of 3D printing for selected materials and topology optimization of components for aerospace industry, co-investigator or Innovation of ZAT course - "Additive technologies" about topology and mechanical optimization tasks (project FV 17-20 (2017)), investigator.

11. Assessment of the contribution that the research makes to knowledge in the field

Very good
Ing. Radek Vrána worked on two main goals which are both innovative. The first, the numerical model of lattice structure deformation supplement with lattice structure material model and elliptical strut geometry and the second, the contour laser strategy for lattice structure production without material imperfection and in higher dimensional accuracy. Both areas are new and have not been published before the dissertation.

12. Other comments
Ing. Radek Vrána was also active in supervising of the bachelors and master's theses, was responsible for finishing a lot of commercial contracts in the field of SLM for companies as Honeywell, Brose, Siemens, Hannon, etc. and participated in the presentation of the department of Industrial design and REAT group on many events.

13. Conclusion
PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.
YES

16. Date and signature
19/12/2018

Please note

A. *Evaluate categories 9 to 11 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent.*
B. *In each category 9 to 11 explain reasons for evaluation using between 100–200 words.*
C. *E-mail the completed form to: Klara.Javorcekova@vut.cz*