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REVIEW
of the doctoral dissertation of Mr. Upadesh Subedi, M.Sc., Eng. entitled "Towards Digital Twins for Quantifying Laser-Microstructure Interface in Multicomponent Alloys Using Thermodynamic Tensor Model"

Supervisor of the Dissertation:
Prof. Tomasz Tański, Ph.D., D.Sc., Eng.
Auxiliary Supervisor:
Dr. Anil Kunwar, Ph.D., Eng.

Basis for the Review
This review has been prepared on the basis of a resolution of the Scientific Discipline Council of Materials Engineering of the Silesian University of Technology appointing reviewers in the proceedings for the award of the degree of Doctor of Engineering and Technical Sciences to Mr. Upadesh Subedi, M.Sc., Eng.
The subject of this review is the doctoral dissertation prepared at the Faculty of Mechanical Engineering of the Silesian University of Technology under the supervision of Prof. Tomasz Tański, Ph.D., D.Sc., Eng., and the auxiliary supervision of Dr. Anil Kunwar, Ph.D., Eng..

Evaluation of the Research Topic

The development of additive manufacturing technologies, laser processing techniques, and advanced computational methods currently represents one of the most rapidly developing areas of research in Materials Engineering. In recent years, particular attention has been devoted to artificial intelligence, machine learning, and Digital Twin technologies, which are increasingly being applied to the design and optimization of advanced materials and manufacturing processes.

The topic undertaken by the Doctoral Candidate concerns the quantitative description of laser–microstructure interactions in multicomponent alloy systems and the development of computational methodologies enabling the construction of Digital Twins for such processes. The research area is highly relevant, scientifically important, and fully consistent with current international research trends.

Despite the considerable progress achieved in computational materials science, a substantial gap still exists between high-fidelity numerical simulations and their implementation in real-time manufacturing environments. The integration of phase-field modeling, tensor-based data representation, and machine-learning techniques proposed in the dissertation constitutes an innovative and valuable scientific approach.

In my opinion, the selected research topic is highly relevant and fully consistent with current directions of development in Materials Engineering. The undertaken research possesses both significant scientific value and considerable application potential.

General Characteristics of the Dissertation

The dissertation has been prepared in the form of a collection of five thematically related scientific publications published in internationally recognized journals indexed in the Web of Science and Scopus databases.

The dissertation consists of 141 pages and includes an introduction, research objectives, scientific hypotheses, discussion of the scientific problem, and a synthesis of the results obtained within the framework of the published papers.

The publications forming the basis of the dissertation were published in:

1. Scripta Materialia (2024),
2. Materials & Design (2024),
3. Engineering with Computers (2025),
4. Computational Materials Science (2025),
5. Computational Materials Science (2025).

It should be emphasized that all publications were published in reputable international journals indexed in the Web of Science and Scopus databases.

The dissertation is logically organized and clearly written. The structure of the manuscript allows the reader to follow the development of the scientific concept from theoretical foundations through numerical implementation to predictive modeling.

The bibliography is appropriate and covers the major scientific areas addressed in the dissertation, including phase-field modeling, computational thermodynamics, laser processing, machine learning, and Digital Twin concepts. The literature review demonstrates a good understanding of the current state of knowledge.

The selection of references should be considered appropriate and reflects the current state of knowledge in the field. No significant shortcomings in the choice of literature were identified.

Objectives of the Dissertation

The main objective of the dissertation was to develop methods for the representation, compression, reconstruction, and prediction of microstructural evolution in laser-processed materials using phase-field modeling, thermodynamic calculations, and machine-learning techniques.

The Doctoral Candidate hypothesized that a thermodynamically informed tensor representation could preserve the essential features of microstructural evolution while significantly reducing computational complexity. Additionally, it was assumed that machine-learning methods could be successfully applied to predict microstructural evolution and melt-pool characteristics.

The objectives and hypotheses were formulated clearly and consistently addressed throughout the dissertation.

Scientific Evaluation of the Dissertation

The dissertation represents a modern and interdisciplinary scientific study combining materials engineering, computational thermodynamics, phase-field modeling and artificial intelligence methods. The Doctoral Candidate undertook a complex research problem located at the interface of materials science, numerical modeling and machine learning.

The first publication presents a tensor-based representation of microstructural evolution data for Ti-Cr alloys. The proposed approach allows significant reduction of data size while preserving essential information describing the evolution of the simulated microstructures. In my opinion, this work constitutes a valuable contribution to the development of digital materials design methodologies.

The second publication concerns the modeling of Ti_2Cu intermetallic phase growth in Ti-6Al-4V alloys subjected to laser processing. The obtained results improve understanding of the relationship between processing parameters and intermetallic phase formation, which is important for the further development of additive manufacturing technologies.

The third publication introduces a Conv-LSTM-based framework for predicting microstructural evolution. This topic belongs to one of the most rapidly developing areas of computational materials science. The obtained results indicate that machine-learning methods can significantly accelerate numerical calculations while preserving the essential characteristics of microstructural evolution.

The fourth publication presents a non-isothermal multiphase-field model describing laser interaction with Ti-Au alloys. The model combines heat transfer, diffusion and phase transformation phenomena within a single computational framework. In my opinion, this publication constitutes one of the strongest scientific elements of the dissertation.

The fifth publication constitutes a continuation of the previous studies and focuses on the prediction of meltpool morphology and fluid-flow behavior during laser processing using a phase-field informed U-Net framework. The obtained results demonstrate that machine-learning models can successfully reproduce phase distributions and velocity fields while significantly reducing computational costs. The obtained results confirm the applicability of machine-learning methods in the development of future Digital Twin systems for laser-processing technologies.

In my opinion, the most important scientific achievement of the Doctoral Candidate is the development of the original Thermodynamic Tensor Model. The proposed concept enables efficient representation of microstructural evolution while maintaining the physical meaning of the simulated processes. This achievement constitutes an original scientific contribution with significant potential for further development.

Particular attention should be paid to the broad methodological competencies demonstrated by the Doctoral Candidate and to his ability to combine advanced numerical methods with modern artificial intelligence techniques. The research required the application of phase-field modeling, finite-element methods, CALPHAD thermodynamics, tensor analysis, and machine-learning algorithms.

The obtained results are original and constitute a valuable contribution to the development of computational materials engineering and Digital Twin methodologies for laser-processed materials. The scientific level of the presented research should be assessed highly and confirms the Doctoral Candidate's ability to independently formulate and solve complex scientific problems.

Evaluation of the Publication Output

The scientific achievement consists of five publications with a total score of 760 points in the Polish Ministry evaluation system and a cumulative Impact Factor of approximately 29.3.

No.	Journal	Year	Ministry Evaluation Points*	Impact Factor
I	*Scripta Materialia*	2024	200	6.3
II	*Materials & Design*	2024	140	8.4
III	*Engineering with Computers*	2025	140	8.0
IV	*Computational Materials Science*	2025	140	3.3
V	*Computational Materials Science*	2025	140	3.3

It should be emphasized that the journals in which the papers were published belong to the leading international journals in the fields of materials engineering, computational materials science and numerical modeling.

Particularly noteworthy is the fact that the Doctoral Candidate is the first author of four out of five publications included in the dissertation.

His declared contributions amount to:
Article I – 71%
Article II – 16%
Article III – 72%
Article IV – 70%
Article V – 60%

Although the contribution to Article II is lower than in the remaining papers, the overall publication portfolio clearly demonstrates the Candidate's leading role in the conducted research. This is evidenced by his dominant contribution to four publications and his responsibility for conceptualization, numerical implementation, data analysis, interpretation of the results, and manuscript preparation.

In my opinion, the quality of the publications forming the basis of the doctoral dissertation should be regarded as very high and significantly exceeding the minimum requirements typically expected of candidates applying for the degree of Doctor of Engineering and Technical Sciences.

Critical Remarks

Despite the overall high quality of the dissertation, several remarks should be made:

1. A substantial part of the dissertation is based on computational modeling, while the scope of experimental validation could have been broader.
2. In some parts of the dissertation, the Digital Twin concept is discussed more from a future-oriented perspective than from the viewpoint of practical implementation.
3. Greater attention could have been devoted to limitations resulting from real industrial processing conditions.

4. The transferability of the developed machine-learning models to other material systems could have been discussed in greater detail.

The above remarks are of a discussion character and do not affect the positive evaluation of the dissertation.

Final Assessment and Recommendation

The doctoral dissertation entitled *"Towards Digital Twins for Quantifying Laser-Microstructure Interface in Multicomponent Alloys Using Thermodynamic Tensor Model"* constitutes an original solution to an important scientific problem within the discipline of Materials Engineering.

The Doctoral Candidate has demonstrated the ability to conduct independent scientific research, a very good command of advanced computational methods, and the capability to critically analyze scientific results.

In my opinion, the scientific achievements presented in the dissertation clearly exceed the level typically expected from doctoral candidates and therefore the dissertation deserves distinction.

I conclude that the dissertation fulfills the requirements specified in Article 187 of the Act of 20 July 2018 – Law on Higher Education and Science.

Therefore, I recommend that **Mr. Upadesh Subedi, M.Sc., Eng.** be admitted to the subsequent stages of the doctoral proceedings leading to the award of the degree of **Doctor of Engineering and Technical Sciences in the discipline of Materials Engineering**.

Prof. Marcin Nabiałek, D.Sc., Ph.D.