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**Review of the doctoral dissertation of Mana Nabavian Kalat, M.Sc.**


**Entitled: "Thermomechanical Properties of Additively Manufactured Shape Memory Epoxy for Advanced Shape-Morphing Applications".**

The review was prepared on the basis of the resolution adopted by Scientific Council of the Institute of Fundamental Technological Research, Polish Academy of Sciences, dated February 5, 2026 (Rada Naukowa Instytutu Podstawowych Problemów Techniki PAN).

The dissertation of Ms Mana Nabavian Kalat, M.Sc. was carried out at the of IPPT PAN in Warsaw under the supervision of Prof. Zbigniew Kowalewski and co-supervision of Prof. Andrés Diaz Lantada. The presented dissertation is in line with my scientific interests.

**Topics of the dissertation**

The dissertation deals with the manufacture of materials based on different polymeric materials – polyurethanes as well as epoxy resins and shape memory materials obtained using 3D printing technologies (FDM and SLA). The obtained materials have been characterised using several advanced techniques i.e SEM, TMA, FTiR, DSC, mechanical testing, ect.

According to the current regulation of the Minister of Science and Higher Education Art. 187 of the Act of July 20, 2018 Law on Higher Education and Science (Journal of Laws of 2023, item.742 with later changes), the reviewed dissertation qualifies for field of Science in the discipline of Material Science. The dissertation is also of an engineering nature in the field of polymer materials engineering. 

## **Dissertation layout**

The reviewed dissertation consists of 195 pages, and additional pages of acknowledgements, table of contents, declaration, dedication, list of figures, list of tables, list of abbreviations, vita, publications, conference abstracts, abstract and streszczenie. The dissertation contains bibliography that includes 164 items of literature. The cited literature represents quite new articles (from 2015-2021), but also older works (from the beginning of the 21st century) and also older ones from 1980s.

The dissertation is written in English and consists of: 6 Chapters and Conclusions:

Chapter 1. Foundation of Shape-Morphing Technologies

Chapter 2. Background of 4D printing of Shape-morphing Technologies

Chapter 3. Materials, Methods, and Experimental Workflow

Chapter 4. Results and Discussion (I): Preliminary Thermomechanical Investigation of PU-SUP

Chapter 5. Results and Discussion (II): Comprehensive Investigation of SLA 3D-Printed SMEp

Chapter 6. Results and Discussion (II): Design, 3D Printing and Training of SMEp Prototypes

Chapter 7. Conclusions.

## **Substantive evaluation**

In the thesis, the doctoral student addressed the topic of designing, fabricating, and characterizing a so-called shape-morphing device using materials printed via 3D printing techniques.

The thesis has a very interesting structure—right from the start, the doctoral student begins each chapter with a sort of abstract, summarizing what the chapter contains. This is extremely helpful in following the author's line of thinking.

The entire first chapter serves to explain why the doctoral student chose this topic in the first place, and she also discusses the objectives of the thesis, dividing the research into two main paths — one related to PU and the other to epoxy resins—and then briefly summarizes what is covered in the subsequent chapters.

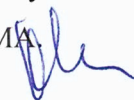
The second chapter of the thesis is a Literature Review, which is fairly concise, spanning about 40 pages, but clearly explains what Shape Memory Polymers are and compares them structurally to conventional polymers. Next, the PhD candidate presented a classification of thermo-responsive shape memory polymers and moved on to techniques for forming them using additive methods (3D printing), which she also described. The following subsection covers 4D structures. The PhD candidate also devoted considerable attention to the challenges and research gaps in 4D materials.

Chapter 3 is a fairly standard presentation of the research methodology and a description of the materials. This section also includes an explanation of why the PhD candidate switched from the originally selected PU polymer to epoxy materials. It is also worth noting and appreciating here that the PhD candidate describes each experiment in great detail and even specifies the sources of funding for the equipment and all collaborations within which the research was conducted.

The most important part of the thesis consists of chapters 4–6, where the PhD candidate compiled the results of her research. Here again, each chapter begins with a summary, with particular emphasis on the key findings.

In Chapter 4, the PhD candidate presented research on thermoplastic polyurethanes and discussed the possibility of printing using FDM technology. She devoted a significant portion of the chapter to the thermal characteristics of the material under study, concluding that it consists of both hard and flexible segments. She conducted a multi-level DSC analysis to investigate phase transitions in the material, then tested the resulting material for strength, examined the material's microstructure after deformation, and assessed the material's properties under cyclic loading, followed by an examination of the material's microstructure after repeated deformation. The chapter concludes with a characterization of the shape memory performance of a 3D-printed PU-SMP structure. Given the less-than-satisfactory properties, the PhD candidate changes the focus of her research.

In Chapter 5, the PhD candidate describes printed shape-memory systems based on epoxy resins manufactured using stereolithography. In this case, the PhD candidate produces dog-bone specimens with varying print orientations, which, she claims, affects the materials' properties. The PhD candidate conducted microstructural analysis (SEM), examined material swelling and water absorption, characterized the material structure using FTIR, assessed thermal stability (TGA), the presence of phase transitions (DSC), as well as thermal expansion using TMA.



Subsequently, the PhD student performed, among other things, shape memory evaluation using thermomechanical cycle testing and a comparison of thermomechanical parameters of printed parts with different geometries. The chapter concludes with considerations regarding potential applications (aerospace or biomedical engineering applications, precision micro-mechanisms).

Chapter 6 covers research on printed prototypes and is a direct continuation of the research in Chapter 5. The PhD student prepared prototype designs in collaboration with a research group from the Polytechnic University of Madrid, then fabricated the prototypes using SLA technology, and subsequently conducted advanced studies on shape recovery in 4D-printed prototypes. The chapter concludes once again with a discussion of potential applications (soft robotics, deployable structures, biomedical devices, energy-efficient actuation).

Chapter 7 summarizes the results obtained throughout the thesis, where the PhD candidate highlights the most important achievements of the work, namely thermomechanical behavior and cyclic durability, as well as the shape memory of PU and epoxy resin.

The thesis is executed with great care. The visual presentation of the thesis deserves praise, featuring clear and highly professional graphs and illustrations that facilitate understanding of the experiments. The experiments themselves are conducted with great precision, and every aspect of the research is thoroughly described. The structure of the thesis is also interesting—each chapter begins with an abstract and concludes with a summary. Also noteworthy is the PhD candidate's critical approach to her research and her identification of the shortcomings and directions for further development of the materials under study.

### **Comments and questions**

It can be seen that Mrs. Mana Nabavian-Kalat put a lot of work into the conducted experiments, as well as in describing them in the dissertation. Generally, the work is really good, well described. However, a few things could have been presented or described better.

Below are some of my comments and questions for the Doctoral Student:

1. DSC experiments were performed using several steps, as shown in Figure 24. Why were these steps chosen? Did you conduct a preliminary study to determine these steps?
2. The results of the mechanical tests (Table 5) are given to two decimal places without any statistical information. It seems that, for example, at an elongation of 194.52%, the measurement error could be as high as 5–10%, so providing such precision does not make much sense. Are the results given in the table averages? A similar comment

applies to Table 6; in this case, the standard deviation is provided, but it would also be helpful to round the results to significant figures.

3. In the work, the PhD candidate uses commercially available materials, which means they are likely quite well-studied, and the candidate did not perform any chemical modifications on them that could have improved certain parameters. Why did the PhD candidate not undertake the design and production of a new material with a structure that would perform even better in 4D applications?
4. Why did the PhD candidate use only two research materials? Were any preliminary studies or material selection processes conducted?

### **Final evaluation**

The subject matter undertaken in the dissertation is interesting and original. The doctoral student has set a clear goal of the work. The research methodology used and the form of presentation of results is correct. The doctoral student demonstrated a good knowledge of the state of the art in the subject matter, as well as knowledge of advanced research techniques, which he used correctly. Despite the reviewer's comments, it should be stated that the dissertation submitted by Mana Nabavian-Kalat, M.Sc. has the necessary elements required in doctoral theses.

The manner in which the research was carried out, the number of experiments, testifies to the good preparation of the Doctoral Student for scientific work in the field of Material Science.

The doctoral student is a co-author of four publications in reputable international journals, including the European Polymer Journal and Materials and Design, where she is the first author. Her research and academic achievements also attest to the high quality of her work.

I conclude that the reviewed dissertation meets the requirements for doctoral theses specified in Art. 187 of the Act of July 20, 2018 Law on Higher Education and Science (Journal of Laws of 2023, item.742 with later changes), Ph.D. candidate:

1. Has achieved learning outcomes at Level 8 of the Polish Qualifications Framework;
2. She submitted a doctoral thesis containing original scientific results and addressing a scientific problem; in this case, it involves an in-depth thermomechanical characterization of shape memory materials with particular emphasis on print

orientation, as well as the fabrication of monolithic prototypes using the 4D SLA method.

3. She demonstrated depth in the analysis of research data,
4. Additionally, she is a co-author of 4 scientific article (with IF).

therefore I am recommending the admission of Mana Nabavian-Kalat to the next stages of the doctoral process.

Sincerely

A handwritten signature in blue ink, appearing to read 'H. S. S. S. S.', is written in a cursive style.