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REVIEW

Doctoral dissertation by **Alireza Kalhor**, M.Sc. (Eng.)

"Cu-Mg-Based Alloys with Strength, Ductility, and High Conductivity Achieved by the SPD Technique"

1. Basis for the Review

This review is based on a letter from the Chair of the Disciplinary Council (RDIMa.512.5.2026), Prof. Adam Grajcar, Ph.D., Eng., dated September 23, 2026, informing me that the Disciplinary Council for Materials Engineering at the Silesian University of Technology had appointed me as a reviewer of the doctoral dissertation by Alireza Kalhor, M.Sc., Eng., in a procedure conducted in the discipline of "Materials Engineering." I received the documentation on October 2, 2026.

2. General Characteristics and Structure of the Dissertation

The doctoral dissertation under review, " " by Alireza Kalhor, M.Sc. (Eng.), titled ***"Cu-Mg Based Alloys with Strength, Ductility, and High Conductivity Achieved by SPD Technique"*** was prepared under the supervision of Prof. Kinga Rodak, Ph.D., Eng. Its subject matter falls within the field of engineering and technical sciences, in the discipline of materials engineering.

The thesis is written in English, consists of 161 pages, including a six-page introduction and 155 pages numbered with Arabic numerals. The main text spans pages 1–126 and comprises six chapters, which include 73 figures and 6 tables. The thesis is supplemented by lists of figures and tables, abstracts in English and Polish, and a list of three co-authored publications in which the doctoral candidate is the first author.

The bibliography includes as many as 395 entries, including four co-authored works by the doctoral candidate—entries [3], [4], [5], and [245], published between 2023 and 2025. In all of them, he is the first author. In addition to older studies of fundamental importance to the theoretical foundations of the analyzed issues, numerous publications from the last few years (2019–2025) have been included. The selection of sources confirms the relevance of the chosen topic and the dissertation's proper placement within the current state of knowledge.

The structure of the thesis deviates somewhat from the traditional format of a doctoral dissertation, in which the literature review is followed by the formulation of the thesis's objective and thesis statement, and then separate chapters present the research methodology, the results of the Author's own research, a discussion of those results, and final conclusions. In the reviewed thesis, the Author has organized his own research into three research tasks, referred to as "*Approaches*," each of which includes a description of the methods used, a presentation of the results along with a discussion, and partial conclusions. I consider the adopted method of presentation to be appropriate, as it allows the obtained results to be directly linked to the methodology and conditions under which the individual experiments were conducted.

The Author identifies the overarching goal of the research as achieving a favorable combination of mechanical properties and electrical conductivity in Cu–Mg-based materials. The first two tasks align directly with this concept. However, the relationship between this concept and the third task—which focuses on the Cu/Mg composite, where reducing the material's density serves as an additional evaluation criterion—requires a more detailed discussion in the summary section.

The thesis by Alireza Kalhor, M.Sc. (Eng.), is coherent; the order of the chapters allows the reader to follow the course of the research, and the structure adopted is essentially logical. The title corresponds to the main focus of the research, although it does not explicitly include the section on the fabrication and characterization of the Cu/Mg composite.

3. Evaluation of the Selection of Topic, Objective, and Scope of the Thesis

The thesis addresses one of the fundamental challenges in the design of copper alloys: achieving a favorable combination of mechanical strength, ductility, and electrical conductivity. Strengthening mechanisms associated with the presence of alloying elements, dislocations, second-phase particles, and grain boundaries can simultaneously increase electron scattering. As a result, an increase in strength is often accompanied by a decrease in conductivity. An important research objective is therefore to determine how the selection of chemical composition and processing conditions allows for the formation of a microstructure that ensures the desired set of properties. This issue has both theoretical significance—related to understanding the microstructural determinants of strengthening and electrical conductivity—and practical significance for wires, connectors, and contact elements operating under mechanical load.

I consider research on Cu–Mg and Cu–Mg–Ca alloys to be justified by the possibility of combining solid-solution strengthening with the interaction of second-phase particles and microstructural refinement. Magnesium provides strengthening of the copper matrix, while a small addition of calcium leads to the formation of particles rich in Cu and Ca, which can influence the deformation behavior and grain boundary distribution. Repeated compression in two perpendicular directions, performed in the MaxStrain module, and extrusion with a double-sided oscillating die using the KoBo method allow for the evaluation of the influence of various plastic deformation sequences on the development of the dislocation substructure, high-angle boundaries, and fine-grained microstructure. The value of such a program lies in its ability to consider the effectiveness of strengthening in conjunction with changes in elongation and electrical conductivity.

An interesting extension of the research is the section on the Cu/Mg composite. A different material concept was applied here: a continuous copper matrix ensures high conductivity, while magnesium filaments serve to reduce density. The originality of this section lies in the implementation and characterization of the adopted composite architecture under specific KoBo extrusion conditions, rather than in the mere idea of combining copper with magnesium. The connection between this project and alloy research stems from a shared goal of achieving favorable mechanical and electrical properties, while introducing an additional criterion: material mass.

The overarching goal of this dissertation, as indicated in the summary of the literature review and the comprehensive discussion, is to develop Cu–Mg-based materials with a favorable combination of mechanical properties and electrical conductivity. This goal is pursued through three tasks: the selection of composition and processing conditions, deformation modeling, microstructural characterization, and property measurements. I consider this scope appropriate for the subject matter at hand. It allows for a comparison of the effects of the applied processing sequences and identifies the relationships between microstructure and properties. However, a more comprehensive justification of the quantitative contribution of individual mechanisms and an assessment of practical applicability require broader verification than merely demonstrating favorable results for selected material states.

I view the selection of the topic and the fundamental scope of the research positively. I see the greatest cognitive value of the work in the comparison of the effects of various methods of microstructure control and the identification of their associated benefits and limitations.

4. Substantive Evaluation of the Doctoral Dissertation

4.1. Assessment of the current state of knowledge

The literature review covers topics relevant to the thesis's subject matter. The Author begins with a characterization of copper and the basic groups of its alloys, and then focuses on Cu–Mg and Cu–Mg–Ca alloys. He discusses the mechanisms of solution, precipitation, dispersion, and strain hardening, as well as the importance of grain refinement. He also presents methods of severe plastic deformation (SPD), including equiangular channel pressing (ECAP), high-pressure twisting (HPT), and repeated rolling with bonding (ARB), MaxStrain deformation, and KoBo extrusion, as well as the relationships between microstructure and electrical conductivity.

I consider the summary of previous research results on Cu–Mg and Cu–Mg–Ca alloys to be particularly valuable. It allows for an assessment of the potential for using alloying elements, heat treatment, and plastic deformation to increase strength while maintaining high electrical conductivity. The examples cited provide an appropriate basis for justifying the proposed research program.

The selection of literature reflects the current state of knowledge and demonstrates the doctoral candidate's sound understanding of the subject matter. In some places, however, the discussion is overly descriptive. A critical comparison of known solutions—highlighting the limitations of previous research and unresolved issues—would be more valuable than a broad presentation of these solutions.

I evaluate the literature review positively as a foundation for research into the microstructure and properties of Cu–Mg and Cu–Mg–Ca alloys. However, the justification for the thesis's concept would benefit from a more precise definition of the research gap, particularly with regard to the effect of calcium addition and the heat treatment and plastic deformation sequences employed. The need to increase strength while maintaining high conductivity defines the general direction of the research; however, identifying relevant, insufficiently understood relationships would allow for a clearer assessment of the originality of the doctoral candidate's research program.

4. 2. Evaluation of the Research Methodology

The research methodology was broadly planned and, for the most part, appropriate for the tasks at hand. In the initial approach, alloys were produced from high-purity Cu, Mg, and Ca using induction melting in a graphite crucible coated with a layer of boron nitride (BN) under an argon atmosphere. The composition of the materials was determined using the EDS method with PROZA correction and reference to standard samples. Thermal behavior was investigated using DSC, which enabled the selection of the heat treatment temperature.

The MaxStrain process was conducted under conditions of repeated deformation, using 20 or 40 cycles. I consider the monitoring of sample temperatures during the process to be positive. The recorded average temperature was approximately 32.5°C, and the maximum was approximately 37°C, indicating no significant heat accumulation under the test conditions used. The strain distribution was analyzed numerically, and the modeling results were then compared with the local hardness distribution and EBSD results.

Light microscopy, scanning electron microscopy (SEM) with chemical composition analysis using energy-dispersive X-ray spectroscopy (EDS), and electron backscatter diffraction (EBSD) were used to characterize the microstructure. In the third research task, this scope was expanded to include transmission electron microscopy (TEM), scanning transmission electron microscopy (STEM), and X-ray computed tomography (XCT).

EBSD analyses enabled the assessment of grain size, the fraction of low-angle and high-angle grain boundaries (LAGB and HAGB), local disorientation (KAM), grain-internal orientation spread (GOS), and crystallographic texture. TEM/STEM observations provided information on the dislocation substructure of the copper matrix and the microstructure of the magnesium filaments. The use of XCT, in turn, allowed for the evaluation of their spatial distribution and continuity within the examined volume. Mechanical properties were evaluated based on hardness measurements and static tensile testing; for the material after MaxStrain, miniature specimens were taken from the central part of the zone of maximum strain. Three tests were performed for each condition at a strain rate of 10^{-3} s^{-1}. Compression tests were additionally performed on the Cu/Mg composite. Electrical conductivity was measured using the four-wire Kelvin method, which is suitable for materials with very low resistance.

I particularly appreciate the comprehensiveness of the methodology employed. The Author does not limit himself to merely measuring the properties but seeks to explain their changes through the results of microstructural analyses and process modeling. The research methods are therefore appropriately selected to achieve the fundamental objectives of the dissertation.

4.3. Evaluation of the Research Results and Their Discussion

The results obtained in the first research approach made it possible to determine the effect of a small calcium addition on the microstructure and properties of the Cu–0.7Mg alloy. In the alloy containing approximately 0.1% by mass Ca, particles rich in Cu and Ca—interpreted as the Cu_5Ca phase—were observed, along with a change in grain morphology from columnar to predominantly equiaxed in the as-cast state. Compared to the binary alloy, an increase in hardness of approximately 33% and tensile strength of approximately 13% was observed, accompanied by a decrease in elongation and electrical conductivity. The value of this comparison lies in identifying both the benefits resulting from the modification of the chemical composition and its limitations. In the case of conductive materials, evaluating the effectiveness of strengthening requires simultaneous consideration of changes in electrical properties and plasticity.

The results concerning heat treatment prior to deformation are also of interest. Observations following annealing at 650°C for 75 and 90 minutes, followed by water quenching, indicate partial spheroidization of the particles in the ternary alloy. The Author attributes the changes in mechanical properties to the homogenization of the matrix, changes in particle morphology, and the formation of residual stresses and an increase in dislocation density during cooling. Microscopic documentation confirms a change in the shape of some particles, whereas the degree of homogenization of the chemical composition, dislocation density, and stress state were not directly determined. Their contribution should therefore be treated as a proposed explanation for the observed effects. The simultaneous variation of annealing time and cooling method in the 75 min/water and 15 min/air variants allows for a comparison of the entire heat treatment sequences but does not permit an unambiguous separation of the effects of both parameters.

Repeated compression in two perpendicular directions, performed in the MaxStrain module, led to significant strengthening and grain refinement. After 40 passes, the average grain size was 5.6 and 4.0 μm, respectively, in the binary alloy, and 1.8 and 1.5 μm in the ternary alloy, both before and after heat treatment. The results thus indicate a finer grain size in the final states of the calcium-containing alloy. Electron backscatter diffraction (EBSD) studies also revealed microstructural heterogeneity, including fine-grained regions and larger deformed grains, as well as differences in the proportion of high-angle boundaries.

The Author interprets these changes as the result of grain subdivision and partial dynamic continuous recrystallization. While this is a possible explanation, the orientation maps obtained for the final states of the material do not allow for an unambiguous reconstruction of the microstructural evolution. Particular caution is required when equating the proportion of grains with a GOS orientation spread below 2° with the proportion of grains formed as a result of recrystallization. This is because slight variations in orientation within a grain do not unambiguously identify the mechanism of its formation. The best-documented finding remains the final degree of grain refinement and the microstructural differences between the examined variants.

An important element of the first approach is the consideration of strain heterogeneity. Numerical modeling indicates a concentration of strain in the central part of the deformed zone,

while hardness measurements confirm spatial variations in hardening. The combination of these results provides a valuable basis for interpreting the local material response. Qualitative agreement, however, is not sufficient confirmation of the accuracy of the calculated strain values. Since microstructure examinations and tensile tests primarily concern the central zone, the obtained results should not be directly extrapolated to the entire volume of the specimen.

The second research approach demonstrated the importance of prior extrusion for the effects of subsequent multiple compressions. A Cu–Mg alloy was compared without prior extrusion and after co-extrusion at 400°C and using the KoBo method starting at room temperature. After completion of the processing sequence, the average grain size was approximately 5.8 μm for the AM variant, 1.4 μm for FM, and 2.0 μm for KM. The results confirm that the final microstructure depends on the entire sequence of processing operations, not solely on the final deformation stage.

The microstructural changes were accompanied by distinct differences in properties. The tensile strength was 452 MPa for AM, 513 MPa for FM, and 624 MPa for KM, with electrical conductivity of 37.9, 35.6, and 32.0 MS/m, respectively. For the KM variant, an elongation of 26% was obtained. I consider it a significant result to have obtained this set of properties and to have demonstrated that the sequences used yield different relationships between strength, elongation, and electrical conductivity. However, no variant was obtained that was optimal according to all these criteria.

Of particular interest is the higher strength of the KM variant compared to the FM variant, despite its larger average grain size. This observation indicates that grain refinement alone is not sufficient to explain the obtained properties. The role of the dislocation substructure, texture, and strain inhomogeneity requires further discussion. A separate issue is the need to clarify the method for determining the yield strength in the first two approaches, as the description of the post-fracture elongation measurement does not explain this procedure. This reservation does not, in and of itself, undermine the hardness and tensile strength results, which confirm the fundamental strengthening effect.

The third approach expands the scope of the dissertation to include the production of a Cu/Mg composite using the KoBo method. Observations using scanning electron microscopy and X-ray computed tomography confirmed the preservation of the fundamental distribution and continuity of the magnesium filaments within the analyzed volume. This constitutes a valuable finding regarding the processability of the adopted component configuration. Line-scan EDS analyses revealed a distinct change in composition at the interface between the Cu matrix and the Mg filaments, without revealing a transition zone within the spatial resolution limits of the method used. This result does not rule out mutual diffusion on a smaller scale or the presence of a thin reaction layer. Nor does it determine the nature and strength of the interphase bond.

EBSD studies of the copper matrix indicate the presence of grains with little variation in internal orientation, while observations using transmission and scanning transmission electron microscopy (TEM/STEM) reveal dislocation cells and subgrains. These results support a discussion of the role of healing and recrystallization; however, they require consideration of differences in scale and observation location, particularly the deliberate selection of heavily

deformed regions for transmission studies. For magnesium, the average grain size was determined to be 354 ± 119 nm. When interpreting this result, the prior extrusion of the Mg rods must be taken into account so as not to attribute the entire grain refinement effect solely to the KoBo composite processing method.

The hardness of the Cu matrix increased from 47.1 ± 6.3 to 67.5 ± 1.8 HV. For Mg, the change from 34.5 ± 3.8 to 38.2 ± 3.6 HV was significantly smaller and requires careful evaluation in light of the spread of the results. The composite was reported to have an electrical conductivity of 52.6 ± 1.2 MS/m and a density of approximately 7.85 g/cm^3. These values indicate the possibility of reducing the material's density while maintaining high conductivity. However, a precise comparison with copper requires determining the actual composition, the uncertainty in density measurement, and an appropriate reference condition. Compression tests supplement the mechanical characterization of the composite but are insufficient to confirm its suitability under tensile loading or the claimed improvement in specific strength.

Among the strengths of the dissertation, I would highlight the combination of comparative studies of various processing sequences with microstructural characterization and property measurements. The methods employed provide complementary information and allow for the demonstration of fundamental processing effects. A weakness of the discussion is the at times overly categorical attribution of observed changes to specific mechanisms and insufficient consideration of uncertainty when interpreting minor differences. This applies in particular to the identification of the Cu_5Ca phase, the recognition of recrystallization, the effects of cooling after annealing, and small changes in electrical conductivity. A clearer distinction between the observations and the proposed explanations, along with a comprehensive comparison of the properties that takes into account the complexity of the applied processing, would allow for a more complete assessment of the scientific and practical significance of the obtained results.

I consider the most important achievements presented in this section of the dissertation to be the determination of the effect of calcium addition, as well as the sequence of heat treatment and plastic deformation, on grain refinement and the properties of Cu–Mg and Cu–Mg–Ca alloys. Of particular value is the achievement of a significant increase in strength while maintaining favorable elongation and relatively high electrical conductivity, as well as the demonstration of spatial variations in the material's hardening. A separate achievement is the production of a Cu/Mg composite with reduced density and high conductivity, as well as the documentation of the continuity of magnesium filaments within the tested volume. These results expand our understanding of the possibilities for shaping the properties of copper-based materials by selecting their composition, microstructure, and processing conditions.

4.4. Discussion and Detailed Comments

I evaluate the doctoral dissertation of Mr. Alireza Kalhor, M.Sc. (Eng.), positively, recognizing the scope of the research conducted and the value of the results obtained. However, reading the thesis raises certain doubts regarding the methodology used and the interpretation of the results. Below, I present critical comments and questions to which I ask the doctoral candidate to respond during the public defense. The specific questions are presented below:

1. The chemical composition of the alloys was determined using the ESM/EDS method, even though the Ca content is approximately 0.1% by mass. The Author applied PROZA calibration

and correction, which increases the reliability of the measurement; however, at such a low concentration, the relative uncertainty remains high. Was the composition verified using a volumetric method, such as ICP-OES or OES, and if not, how does the Author assess the limitations of EDS in this regard?

2. On what basis did the Author consider the identification of calcium-rich particles as the Cu_5Ca phase to be unambiguous? The presented EDS analysis results and the phase equilibrium diagram support this assumption but do not replace crystallographic identification. Furthermore, the determined Cu/Ca atomic ratio was 4.18, whereas for Cu_5Ca it is 5. Has the presence of this phase been confirmed by diffraction studies, such as X-ray diffraction or electron diffraction in a transmission electron microscope? If not, the categorical phase assignment should be qualified, and Cu_5Ca should be designated as a probable phase, taking into account the uncertainty of the EDS analysis and the possible contribution of the lattice signal.

3. After heat treatment, a change in particle morphology was observed, interpreted as their partial spheroidization. In the Author's opinion, could these changes also have been accompanied by a change in chemical composition? In the as-cast state, the Cu/Ca atomic ratio determined by EDS was 4.18 and deviated from the stoichiometric value for Cu_5Ca. How does the Author assess the possibility that the composition of the particles could have approached this ratio as a result of diffusion processes occurring during annealing?

4. The Author justifies the choice of an annealing temperature of 650°C based on DSC analysis results. However, the thermogram shown in Fig. 22 suggests that a higher temperature could have been considered, since an additional endothermic effect during heating does not occur until approximately 856°C. Why, then, was 650°C specifically chosen? Was this choice based on literature data, preliminary studies, or the need to limit microstructural changes?

5. What considerations led to the decision to use 15 minutes of annealing followed by air cooling in variant (iii)? The general rationale for limiting the processing time, presented on p. 43, does not explain the choice of these conditions. Furthermore, the simultaneous change in annealing time and cooling method compared to variant (ii) makes it difficult to distinguish the effects of both factors on the microstructure and properties of the material. Why were the results of microscopic observations immediately following this treatment not presented in the paper, as was done for variants (i) and (ii)? A similar situation arises when comparing 20 and 40 MaxStrain passes, given the differences in the preceding heat treatment conditions.

6. On what basis was the dominant influence on the reduction in conductivity of the ternary alloy attributed to Cu_5Ca particles? Do the presented results allow for distinguishing the effects of the particles, the chemical composition of the matrix, and defects in the crystal structure?

7. In Section 3.1.2.7, on p. 63, the Author wrote: "….the use of an extensometer for direct displacement measurement was not feasible." The method for determining elongation based on measurements of fragments of the fractured specimen was then presented. However, the determination of YS was not explained unambiguously, even though this parameter forms the basis for numerous comparisons and conclusions. It is unclear how deformation was recorded during loading, what criterion was used to determine the yield point, and whether the compliance of the measurement system was taken into account. With regard to elongation, it was not clearly specified whether the original measurement base length was restored after fracture or whether the total length of the assembled fragments was measured. These issues require clarification by the doctoral candidate, especially given the measurement length of only 2.5 mm. When comparing the elongation with results from the literature, the influence of the specimen geometry should also have been taken into account.

8. In Section 3.2.2.2, on pp. 85–86, the average grain size is given as 1.4 μm for FM and 2.0 μm for KM. At the same time, the KM specimen exhibits higher YS and UTS—547 and 624 MPa, respectively—than FM, for which values of 462 and 513 MPa were obtained, despite a slightly lower maximum hardness in the central part of the specimen. This is not a physical contradiction, but it indicates that differences in grain size alone do not explain the observed properties. Texture, dislocation substructure, strain inhomogeneity, and the direction of sampling may play a role. A general reference to grain refinement and strain hardening is insufficient in this case. I ask the Ph.D. candidate to explain which factors he considers decisive for the higher strength of the KM sample and which of them are confirmed by the presented results?

9. In Section 3.3.1.1, on p. 99, reference is made to an earlier conductivity measurement procedure described for specimens with a cross-sectional area of approximately 2 mm². The composite, however, is in the form of a rod with a diameter of 8 mm containing seven filaments—Mg fibers. It is not clearly specified whether the entire cross-section of the rod was tested or just a portion of it, what the direction of current flow was, and whether the tested volume contained a representative proportion of both components. This information is essential for the correct interpretation of the value 52.6 ± 1.2 MS/m as the conductivity of the entire composite. The doctoral candidate should clarify the sample geometry and measurement configuration and relate the result to the material's directional structure.

10. Which of the three proposed approaches does the Author consider to have the greatest industrial potential: modification of the Cu-Mg alloy with Ca, sequential deformation using MaxStrain/KoBo, or the Cu/Mg composite? Please consider not only the properties achieved, but also scalability, process cost, and production reproducibility.

The comments presented primarily point to the need for a more cautious interpretation of some of the results and more precise documentation of the methodology. Not all of these reservations imply that the proposed mechanisms are incorrect; in many cases, the issue lies in the degree of certainty with which the doctoral candidate presents them. The comments raised are primarily of a discursive and organizational nature and therefore do not detract from my positive evaluation of the doctoral dissertation by Alireza Kalhor, M.Sc. Eng.

5. Formal Aspects of the Thesis and Editorial Comments

I assess the dissertation as carefully prepared in terms of form and structure. The logical sequence of chapters, clear diagrams of the research program, and precise explanations of sample designations significantly facilitate the analysis of the experimental work carried out. The thesis's documentation is also of a high standard—the illustrative material, including microscopic images, graphs, and tables, is highly clear and has been appropriately linked to the text. A minor shortcoming is the presence of overly elaborate descriptions and repetitions. This observation applies in particular to the summary discussion and conclusions, in which the Author unnecessarily reiterates arguments already presented in the discussion of the partial results. It should be emphasized that in a doctoral dissertation, the discussion chapter should serve primarily to provide an in-depth synthesis of the obtained data, while the final conclusions should constitute a concise, precise summary of the most important findings resulting from the conducted research. I present a few detailed editorial comments below:

1. On p. 35, the Author incorrectly uses a unit of energy instead of voltage. The notation "accelerating voltage of 15 keV" is incorrect and should be replaced with the value 15 kV.

2. When specifying the load during the hardness measurement, the Author uses a unit of mass instead of force: "under a load of 1 kg (HV1)" — p. 36. The correct notation is a load of 9.807 N, corresponding to 1 kgf and the designation HV1.
3. The wording of the title of Chapter 3 ("This Investigation") is too laconic. A more precise title would be one indicating the Author's own research.
4. The figure captions must be reconciled with the list of figures. The caption for Fig. 2 refers to item [36], while the list of figures lists [41]. For Fig. 4, the discrepancy is the opposite. Furthermore, in the text on p. 3, the Cu–Ca phase diagram shown in Fig. 4 is linked to reference [3], while the figure caption indicates [41]. These references should be reconciled.
5. The citation of ASTM E9 on page 101 refers to item [345], which is a scientific article rather than a bibliographic description of the standard. Similarly, entry [369] should include an unambiguous identifier and the year of publication for ASTM E8/E8M instead of the incomplete description "(n.d.)".
6. In the Polish abstract, the term "dynamiczne odzyskiwanie" (page 154) should be replaced with "zdrowienie dynamiczne."

The noted shortcomings do not fundamentally impair the readability of the dissertation; however, correcting them would improve the precision of the wording and the clarity of the presentation of the results. In terms of form and editing, the work meets the requirements for doctoral dissertations.

6. Summary and Final Conclusion

Despite the comments presented, I assess the reviewed dissertation as scientifically valuable and addressing current issues in materials engineering. The doctoral candidate obtained original results concerning the control of microstructure as well as the mechanical and electrical properties of Cu–Mg and Cu–Mg–Ca alloys, supplemented by studies of a Cu/Mg composite. He demonstrated a good command of the dissertation's subject matter, as well as the ability to plan and conduct research and analyze its results. He has also mastered a wide range of research methods and was able to apply them to evaluate the relationships between processing conditions, microstructure, and material properties.

I conclude that the doctoral dissertation of Mr. Alireza Kalhor, M.Sc. (Eng.), titled "Cu-Mg-Based Alloys with Strength, Ductility, and High Conductivity Achieved by the SPD Technique" demonstrates the doctoral candidate's general theoretical knowledge in the field of materials engineering, confirms his ability to independently conduct scientific research, and presents an original solution to a scientific problem. Thus, in my assessment, it meets the requirements for doctoral dissertations specified in Article 187 of the Act of 20 July 2018 (Law on Higher Education and Science, consolidated text: Journal of Laws of 2024, item 1571).

I therefore move that Mr. Alireza Kalhor, M.Sc. (Eng.), be admitted to the public defense of his doctoral dissertation.

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