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REVIEW OF THE DOCTORAL DISSERTATION

of Alireza Kalhor, M.Sc. Eng.

entitled:

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

prepared under the supervision of:

Prof. Kinga Rodak, D.Sc., Ph.D., Eng.

1. Basis of the review

This review was prepared at the request of the Materials Engineering Discipline Council of the Silesian University of Technology.

The legal basis is Article 187 of the Act of 20 July 2018 – Law on Higher Education and Science, as amended.

The assessment of the doctoral dissertation addresses three criteria:

1) An assessment, with justification, of whether the doctoral dissertation demonstrates the Candidate's general theoretical knowledge in the discipline of materials engineering;

2) An assessment, with justification, of whether the doctoral dissertation demonstrates the Candidate's ability to conduct independent scientific research;

3) An assessment, with justification, of whether the doctoral dissertation constitutes an original solution to a scientific problem.

2. Description and characteristics of the dissertation

General remarks

The doctoral dissertation submitted by Alireza Kalhor, M.Sc. Eng., was prepared under the supervision of Prof. Kinga Rodak at the Faculty of Materials Engineering and Industrial Digitalization of the Silesian University of Technology. It addresses microstructure design and the development of mechanical and electrical properties of Cu-Mg alloys using various plastic deformation methods, including severe plastic deformation (SPD) techniques.

The development of modern technologies, particularly electrical engineering, electronics and electric power transmission systems, places increasingly demanding requirements on electrically conductive materials. In addition to high electrical conductivity, these materials should exhibit sufficiently high mechanical strength, resistance to permanent deformation and favorable ductility to enable processing and service under complex loading conditions.

A fundamental materials challenge is the trade-off between strengthening mechanisms and electrical conductivity. Developing materials that combine high strength, good ductility and high electrical conductivity requires appropriate chemical composition selection and precise control of microstructural evolution.

Cu-Mg alloys occupy an important position among such materials. Magnesium strengthens copper primarily through solid solution strengthening. Their properties can be further improved through suitable alloying additions and plastic deformation processes. SPD techniques are particularly promising because they enable substantial grain refinement, increased dislocation density and the formation of ultrafine-grained (UFG) microstructures.

However, SPD also changes the defect structure of the material, potentially reducing electrical conductivity and limiting further plastic deformability. It is therefore particularly important to identify combinations of chemical composition, heat treatment and deformation parameters that provide a favorable balance between strength, ductility and electrical conductivity.

The dissertation under review fits well within this research area. The Candidate has attempted a comprehensive assessment of the effects of chemical composition, heat treatment and various plastic deformation methods on microstructural evolution, mechanical properties and electrical conductivity of Cu-Mg-based alloys.

An important aspect is the extension of the investigation to a density-reduced Cu/Mg composite, based on a different materials design concept: combining a conductive copper matrix with continuous magnesium filaments. This approach offers the possibility of reducing material weight while retaining favorable mechanical and electrical properties.

The research concept comprises three complementary approaches: modification of Cu-Mg-based alloy composition combined with SPD; combinations of different deformation methods; and development of a density-reduced Cu/Mg composite.

This research program made it possible to relate microstructural changes and strengthening mechanisms to the mechanical properties and electrical conductivity of the investigated materials.

In my opinion, the dissertation addresses a timely and important scientific problem firmly situated within materials engineering. Particularly valuable is the attempt to simultaneously optimize three material properties that are frequently in conflict: mechanical strength, ductility and electrical conductivity.

The problem has both scientific significance, through the elucidation of mechanisms governing microstructure and properties in Cu-Mg alloys, and potential practical significance for designing modern electrically conductive materials intended for service under elevated mechanical loads.

I consider the choice of research topic appropriate and the research concept an interesting approach to identifying new materials solutions that offer a favorable combination of mechanical and electrical properties in copper alloys.

Editorial remarks

The dissertation is written in correct language. It is complete, logically structured and comprises six main chapters: Introduction, Literature Review, This Investigation, Discussion and Analysis of Research Findings, Future Outlook and Opportunities, and Summary and Conclusions. It also includes references, lists of figures and tables, abstracts in English and Polish, and a list of the Candidate's publications.

In Chapter 1, the Candidate presents the significance of copper alloys with high strength and electrical conductivity and justifies the research topic. The extensive literature review discusses Cu-Mg and Cu-Mg-Ca alloys, their strengthening mechanisms and possibilities for microstructure engineering using SPD techniques.

The core of the dissertation is Chapter 3, which presents the methodology, research findings and their analysis. It is divided into three parts corresponding to the adopted research approaches. The first examines the effects of Ca addition, heat treatment and MaxStrain processing on the microstructure and properties of Cu-Mg alloys. The second investigates combinations of deformation methods, including conventional extrusion, KoBo extrusion and MaxStrain processing. The third addresses fabrication and characterization of a density-reduced, highly conductive Cu/Mg composite.

In the subsequent chapters, the Candidate provides an overall discussion of the findings, identifies opportunities for future research and presents the summary and final conclusions.

I consider the structure of the dissertation appropriate and clear. The work is extensively illustrated with microstructural characterization results, graphs and tables.

In summary, the dissertation has been prepared carefully, and the presentation of the results is clear and meets the standards expected of scientific studies in materials engineering.

Research aim and scope

The main objective adopted by the Candidate was to develop Cu-Mg-based alloys exhibiting high strength, favorable ductility and good electrical conductivity through suitable selection of chemical composition, heat treatment and application of SPD techniques.

No research hypothesis was explicitly formulated in the dissertation. Instead, the Candidate adopted three research directions, referred to as Approaches, to achieve the main objective.

Approach 1 investigated the effects of Ca addition, heat treatment and SPD by MaxStrain processing on the microstructure, mechanical properties and electrical conductivity of Cu-Mg and Cu-Mg-Ca alloys.

Approach 2 analyzed the effects of combining different plastic deformation methods, including conventional extrusion, KoBo extrusion and MaxStrain processing, on the microstructure and properties of the Cu-0.7Mg alloy.

Approach 3 involved fabrication of a density-reduced, highly conductive Cu/Mg composite by KoBo extrusion and characterization of its microstructure and mechanical and electrical properties.

In my opinion, the Candidate correctly identified an important research problem and designed an interesting research program. The three approaches enabled different routes for tailoring the properties of copper- and magnesium-based materials to be considered. The first two focus on microstructure modification of Cu-Mg alloys, while the third extends the research concept to composite materials.

Implementing these approaches required extensive investigations involving material fabrication, heat treatment and plastic working, microstructural characterization using SEM, EBSD and TEM, mechanical testing and electrical conductivity measurements. The experiments were supplemented by numerical analyses of deformation processes.

I believe the planned research program is consistent with the main objective of the dissertation and has enabled a comprehensive analysis of the relationships between chemical composition, manufacturing technology, microstructure and the mechanical and electrical properties of the investigated materials.

In conclusion, I consider the aim and scope of the dissertation appropriately defined and fully consistent with the requirements for doctoral research in materials engineering.

Assessment of the doctoral dissertation

The dissertation by Alireza Kalhor, M.Sc. Eng., addresses a timely and important scientific problem concerning the control of microstructure and mechanical and electrical properties of copper alloys. The principal challenge in designing these materials is achieving high mechanical strength while retaining adequate ductility and high electrical conductivity. This issue is significant from both scientific and application perspectives, especially given the growing demand for advanced electrically conductive materials.

The Candidate correctly identified the research problem and proposed three experimental approaches enabling different routes to tailor the properties of Cu-Mg-based materials.

The first research approach investigated the effects of Ca addition, heat treatment and SPD by MaxStrain processing on the microstructure and properties of Cu-Mg alloys.

A valuable result is the demonstration that adding 0.1 wt.% Ca to Cu-0.7Mg leads to the formation of Cu_5Ca intermetallic particles and refinement of the as-cast microstructure. The presence of this phase contributed to a substantial increase in hardness (33%) and increases of more than 10% in yield strength (YS) and ultimate tensile strength (UTS) compared with the binary alloy. At the same time, elongation and electrical conductivity decreased by more than ten percent.

These findings confirm the important role of second-phase particles in strengthening Cu-Mg alloys while also revealing limitations arising from reduced ductility and electrical conductivity.

The analysis of the effects of heat treatment on the microstructure and properties of the investigated alloys is also noteworthy. The Candidate demonstrated that appropriately selected annealing and cooling parameters affect the distribution of Mg atoms in the matrix and the morphology of Cu_5Ca particles, enabling modification of the mechanical properties.

An important part of this research is the application of SPD through MaxStrain processing. The results showed substantial grain refinement and an increased fraction of high-angle grain boundaries (HAGBs), particularly in the ternary Cu-Mg-Ca alloy. The Candidate related these changes to continuous dynamic recrystallization (CDRX) and interactions between intermetallic particles and moving dislocations.

The second research approach investigated the effects of combining different plastic deformation methods on the microstructure and properties of the Cu-0.7Mg alloy.

I consider it particularly valuable that the Candidate demonstrated that conventional or KoBo extrusion prior to MaxStrain processing produces considerably greater grain refinement than MaxStrain processing alone.

Depending on the deformation sequence, a substantial reduction in grain size was achieved relative to the material subjected only to MaxStrain processing. These changes resulted in a marked increase in strength: YS increased approximately threefold and UTS more than doubled compared with the annealed material.

These results clearly demonstrate the effectiveness of combining different plastic deformation methods to tailor the microstructure and mechanical properties of Cu-Mg alloys.

The analysis of the strengthening mechanisms is particularly interesting. The Candidate showed that the increase in strength results from the combined effects of strain hardening, grain refinement and changes in grain-boundary character associated with dynamic recrystallization.

Another important finding is that, despite the considerable increase in mechanical strength, the electrical conductivity of the investigated alloys remained relatively high.

This indicates that SPD can substantially improve mechanical properties with a relatively limited reduction in electrical conductivity.

In my opinion, this is one of the dissertation's most important scientific findings, demonstrating the possibility of obtaining a favorable combination of mechanical and electrical properties through appropriate selection of plastic deformation sequences.

The third research approach concerned the development of a density-reduced, highly conductive Cu/Mg composite.

In this part, the Candidate adopted a different materials concept, combining a pure copper matrix with continuous magnesium filaments. KoBo extrusion was used to fabricate the composite.

A valuable outcome is the demonstration that a composite with continuous magnesium filaments can be obtained while maintaining their continuity during SPD. Microstructural characterization also showed substantial refinement of magnesium grains, with an average size of approximately 0.3 μm. The resulting composite exhibited a lower density than copper while maintaining electrical conductivity close to that of pure copper.

I assess this research approach positively, particularly in terms of its potential for developing lightweight electrically conductive materials. However, the findings primarily demonstrate the technological feasibility of fabricating such a composite. In my opinion, a full assessment of its application potential would require further investigations, including mechanical properties under different loading conditions, durability of the interfacial bond and structural stability during service.

The comprehensive nature of the research should be emphasized. The Candidate employed advanced microstructural characterization techniques, including EBSD and TEM, and related the results to strengthening mechanisms and electrical conduction. This demonstrates a sound understanding of physical metallurgy, metal forming and the physical foundations of metallic material properties.

In my assessment, the most important scientific contribution of the dissertation is the demonstration of how different SPD processing routes affect microstructural evolution in Cu-Mg alloys and the identification of relationships among grain refinement, strengthening mechanisms and electrical conductivity.

The application potential of the results lies primarily in developing copper alloys with increased mechanical strength and good electrical conductivity, as well as density-reduced composite materials.

The findings presented in the dissertation demonstrate that the Candidate is capable of properly planning and conducting scientific experiments, selecting appropriate research methods and interpreting the results based on current knowledge in materials engineering.

In summary, Alireza Kalhor, M.Sc. Eng., completed an extensive and ambitious research program and obtained valuable results of scientific and potential practical significance. The investigations contribute new knowledge regarding the tailoring of microstructure and mechanical and electrical properties of Cu-Mg alloys and Cu/Mg composites.

In my opinion, the dissertation constitutes an original solution to a scientific problem concerning the design of copper-based materials with a favorable combination of mechanical strength, ductility and electrical conductivity. The Candidate has demonstrated adequate theoretical knowledge in materials engineering and the ability to conduct independent scientific research.

Comments and questions

1. The Candidate investigated several technological routes involving chemical composition modification, heat treatment and different plastic deformation sequences for Cu-Mg alloys.

Based on the investigations and conclusions, is it possible to identify unambiguously the most favorable manufacturing route for high-strength and high-conductivity Cu-Mg alloys?

Which of the investigated processing routes would the Candidate consider optimal?

2. Considering the technological aspects of the proposed Cu-Mg alloy manufacturing methods, the question arises whether the improvements in material properties justify the increased number of processing operations and production costs.

Could comparable properties be achieved using simpler plastic working methods that are more readily applicable on an industrial scale?

Which of the investigated methods does the Candidate believe have the greatest potential for practical industrial implementation?

3. The results showed that adding 0.1 wt.% Ca to Cu-0.7Mg leads to grain refinement and formation of Cu_5Ca particles, which contribute to increased strength. At the same time, ductility and electrical conductivity deteriorate.

Since only one Ca concentration was investigated, I believe it would be interesting to consider the possibilities for further chemical composition optimization.

Would it be possible to determine the optimum Ca content and control the morphology and distribution of the Cu_5Ca phase so as to obtain greater strengthening while limiting the adverse effect on electrical conductivity?

4. How does the Candidate assess the long-term stability of the mechanical and electrical properties achieved, particularly at elevated service temperatures? Could recovery and recrystallization during service lead to a gradual loss of the strengthening effect?

5. How does the Candidate assess the application prospects of the developed Cu/Mg composite? Is the reduction in density while maintaining high electrical conductivity sufficient to justify using this solution instead of conventional copper conductors or Cu-Mg alloys? Which industrial applications would the Candidate consider most promising?

6. In the Candidate's opinion, in which directions should future materials and processing research proceed to achieve an even more favorable combination of high-strength and high-conductivity (HSHC) properties in Cu-Mg alloys?

Does the greater development potential lie in further optimization of chemical composition and alloying additions, or rather in the manufacturing and processing route?

3. Final conclusion

The doctoral dissertation submitted for review by Alireza Kalhor, M.Sc. Eng., entitled "Cu-Mg Based Alloys with Strength, Ductility, and High Conductivity Achieved by SPD Technique", is a valuable and original scientific study concerning the control of microstructure and mechanical and electrical properties of copper alloys and Cu/Mg composites.

The assessment of the dissertation confirms that the Candidate possesses extensive knowledge in the discipline of materials engineering. This is evidenced by the comprehensive and critical literature review and the detailed discussion of the research

findings in the context of the current state of knowledge in the field covered by the dissertation.

The Candidate has also demonstrated the ability to conduct independent scientific research. He correctly identified the research problem, designed and completed an extensive experimental program using modern techniques for characterizing microstructure and material properties. He demonstrated the ability to analyze the findings in depth, interpret them and formulate scientific conclusions.

The results constitute a valuable contribution to the development of knowledge in materials engineering, while their potential use in designing modern electrically conductive materials also gives the dissertation significant application relevance.

I therefore conclude that the doctoral dissertation by Alireza Kalhor, M.Sc. Eng., meets the requirements laid down in Article 187 of the Act of 20 July 2018 – Law on Higher Education and Science, as amended. Accordingly, I recommend that Alireza Kalhor, M.Sc. Eng., be admitted to the subsequent stages of the procedure for awarding the doctoral degree in the discipline of materials engineering.

Furthermore, considering the high scientific quality of the dissertation, the originality of the findings, the extensive and comprehensive scope of the investigations and their scientific and practical significance, I recommend that the doctoral dissertation by Alireza Kalhor, M.Sc. Eng., be awarded a distinction.

In my assessment, a particularly strong justification for this recommendation is the demonstration that combining different severe plastic deformation methods is effective in achieving a favorable combination of mechanical and electrical properties in Cu-Mg alloys. This represents a significant scientific achievement in the design of advanced structural and functional materials.

Podpisał: prof. dr hab. inż. Jarosław Mizera