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prof. dr hab. inż. Michał Kuciej
Wydział Mechaniczny
Politechnika Białostocka

REVIEW

of the doctoral dissertation by M.Sc. Eng. Anil Antony Sequeira

entitled

Thermal properties and thermal residual stresses in graded Al–matrix composites reinforced with Al_2O_3 and SiC particles: experiments and numerical simulations

supervisor: prof. dr hab. inż. Michał Basista

auxiliary supervisor: dr inż. Witold Węglowski

1. Characterization of the dissertation

The doctoral dissertation comprises 138 pages of A4 format typescript and is written in English. The work consists of eight chapters, followed by a summary, table of contents, list of references, and list of symbols. It includes 89 figures, 19 tables, and 199 bibliographic entries.

The main objectives of the doctoral dissertation by M.Sc. Eng. Anil Antony Sequeira were the design, fabrication, and comprehensive evaluation of the physical, thermal, mechanical, and tribological properties of $AlSi12/Al_2O_3$ and AlSi12/SiC composites, including functionally graded materials (FGMs), in order to assess their potential applicability as lightweight brake disc materials for automotive applications.

The *chapter 1* introduces the research topic concerning aluminum matrix composites (AMMCs) and functionally graded materials (FGMs). The author presents the current state of knowledge, the motivation behind the undertaken research, and the scientific and technological rationale for developing new, lightweight, and wear-resistant materials with high thermal conductivity, particularly for automotive applications.

At the beginning of the chapter, the current state of research on metal matrix composites (MMCs) is discussed. These materials consist of a metallic matrix (e.g., aluminum) and a ceramic reinforcement (e.g., SiC, Al_2O_3, TiC), allowing the combination of the advantages of both phases – namely, the low density and high thermal conductivity of metals with the hardness and wear resistance of ceramics. For aluminum reinforced with ceramic particles, significant improvements in mechanical properties, hardness, and wear resistance can be achieved. However, as emphasized in the dissertation, increasing the ceramic content does not always enhance thermal conductivity; in fact, it often decreases due to porosity and the thermal resistance at the metal-ceramic interface.

These limitations lead to the concept of functionally graded materials (FGMs) – composites with a gradual change in composition and properties. This idea originated in Japan in the 1980s as a response to issues related to thermal stresses caused by steep temperature gradients. A gradual phase distribution allows for a reduction of residual stresses and improved structural durability. FGMs are used in aerospace, automotive, defense, and electronic industries; however, their fabrication remains challenging due to their complex microstructure.

The author highlights that the main motivation for this research is the development of a brake disc material capable of operating under extreme conditions of friction, temperature, and mechanical loading. Traditional grey cast iron provides good heat dissipation but is heavy, while aluminum is lightweight but exhibits low wear resistance. Combining these features in an Al-ceramic composite appears to be an optimal solution: an aluminum core ensures thermal conductivity and strength, while ceramic-rich surface layers provide wear and heat resistance.

The next part of the chapter discusses manufacturing techniques for FGMs, with particular emphasis on powder metallurgy (PM). Various methods are reviewed, including Hot Pressing (HP) and Spark Plasma Sintering (SPS). Both techniques enable a homogeneous distribution of ceramic particles, precise microstructural control, and high material density. The author notes that SPS, due to its rapid heating cycles and short sintering times, allows the fabrication of materials with a fine-grained structure and strong interfacial bonding, making it the preferred method in this research.

A separate section focuses on thermal residual stresses (TRS) resulting from differences in the coefficients of thermal expansion (CTE) between the metallic matrix and the ceramic reinforcement. The author provides an overview of measurement methods, both experimental (e.g., neutron diffraction, synchrotron diffraction, Raman spectroscopy) and numerical (finite element method). It is emphasized that a properly designed gradient structure can effectively reduce TRS without compromising overall thermal conductivity or mechanical integrity.

Further discussion concerns the two main types of composites studied: Al-Al_2O_3 and Al-SiC. Reinforcement with alumina improves hardness, compressive strength, and wear resistance, while silicon carbide enhances thermal conductivity and tensile strength. However, in Al-SiC systems, interfacial reactions may lead to the formation of undesirable phases such as Al_4C_3 or oxides, which deteriorate thermal properties. The dissertation references literature describing strategies to mitigate these effects, including optimization of sintering parameters, interfacial modifiers, and post-processing treatments.

The final section of the chapter addresses thermal modeling of FGMs. The author reviews analytical models (e.g., Maxwell, Bruggeman, Hashin–Shtrikman) and numerical approaches (finite element method, multi-scale modeling) used to predict thermal conductivity, the coefficients of thermal expansion and residual stresses. It is noted that most models rely on idealized microstructures, while real materials produced via powder metallurgy exhibit non-uniform porosity and irregular particle distribution. Therefore, in this dissertation, 3D modeling based on X-ray microtomography (micro-XCT) data was employed to accurately reconstruct and simulate the actual microstructure of the composites.

In summary, chapter 1 provides the theoretical and conceptual foundation of the dissertation. It outlines current challenges in the design and fabrication of Al-ceramic composites with graded structures, reviews methods for determining their characteristics, and emphasizes the need to integrate experimental studies with numerical modeling. The overarching goal of the research is to optimize AlSi12/Al_2O_3 and AlSi12/SiC composites produced by HP and SPS for their potential use as lightweight, durable materials for automotive brake discs.

In the *chapter 2*, the motivation for undertaking the research is discussed, the objectives of the work are formulated, and the research hypotheses are presented. The author justifies the need to analyze the thermal properties and residual stresses in aluminum matrix composites reinforced with Al_2O_3 and SiC particles, indicating their potential application in the automotive industry, especially in the design of brake discs. It is emphasized that traditionally used grey cast iron often suffers from thermal cracking, and the use of metal-ceramic composites with a graded structure may significantly improve wear resistance, thermal conductivity, and the durability of components operating under high-temperature loads.

In the further part of the chapter, the main research objectives of the work are presented, including the fabrication of layered AlSi12/Al_2O_3 and AlSi12/SiC composites using hot pressing (HP) and spark plasma sintering (SPS) methods, as well as the evaluation of their thermal conductivity, residual stresses, and wear resistance. The author draws attention to the importance of comparing the results obtained for different sintering techniques and to the need for developing numerical models reproducing the actual microstructure of the material based on X-ray microtomography (micro-XCT) data.

The chapter also defines detailed experimental and modeling objectives, including the preparation of samples with different fractions of the ceramic phase, microstructure characterization using SEM and micro-XCT methods, measurements of thermal conductivity in a wide temperature range, determination of residual stresses by neutron diffraction, and surface wear analysis. Research hypotheses are also defined, assuming, among others, that composites with a graded structure are characterized by lower residual stresses than homogeneous materials, and that the microstructure and interfacial phases formed during sintering affect thermal conductivity. The entire chapter serves as an introduction to the further part of the dissertation, defining the direction of the research and the methodology of its implementation.

Chapter 3 presents the detailed research methodology applied in the dissertation, covering the successive stages of the research process from material preparation, through characterization, to numerical modeling and computer simulations. The dissertation emphasizes that these studies form an integrated system of actions: "processing – characterization – modeling", aimed at a full understanding of the influence of the structure of functionally graded composites (FGMs) on their thermal conductivity and the generated residual stresses.

In the section devoted to materials, the author describes the materials used - AlSi12 alloy as the matrix and Al_2O_3 and SiC particles as the reinforcing phases. The criteria for their selection are explained, based on the differences in thermal conductivity, which are crucial for applications in the automotive industry. The preparation of both homogeneous and layered composite samples is described, including powder mixing in a protective atmosphere, compaction of green bodies, and sintering performed using two techniques – Hot Pressing (HP) and Spark Plasma Sintering (SPS). The technological parameters of the processes and their optimization are also presented, aiming to achieve high material density.

The following subsections concern the methods of microstructural and thermal characterization. The density measurements were carried out using the Archimedes method; the microstructure was examined by scanning electron microscopy (SEM), and three-dimensional reconstruction of the microstructure was performed using X-ray microtomography (micro-XCT). Thermal conductivity was determined using the laser flash method, and the coefficient of thermal expansion (CTE) was measured by dilatometry. Residual stresses were determined using the neutron diffraction (ND) technique, which enables the analysis of stress distribution within different layers of the composites. Additionally, the procedure for preliminary tribological wear tests was described, performed using a pin–on–flat configuration, serving as a supporting test in the context of brake disc applications.

The final part of the chapter concerns the numerical modeling of thermal conductivity and residual stresses using the finite element method (FEM). The models were developed on the basis of real microstructural data obtained from micro-XCT, which allowed for the accurate representation of the shape, distribution, and volume of ceramic particles. The procedure for generating finite element meshes, the inclusion of porosity, interfacial thermal resistance, and boundary conditions applied in the simulations are described. The equations and parameters used for the calculation of thermal conductivity and thermal stresses, as well as the averaging procedure applied in the model, are also presented.

The entire chapter provides a detailed description of the experimental and computational methods employed in the research, forming the foundation for the analysis and discussion of the results presented in the subsequent chapters of the dissertation.

Chapter 4 presents the results of density, microstructure, thermal conductivity, and residual stress measurements for AlSi12/Al_2O_3 composites and functionally graded materials (FGMs) fabricated by Hot Pressing (HP) and Spark Plasma Sintering (SPS).

At the beginning of the chapter, the results of density and porosity measurements are discussed. The composites produced by the HP method achieved a very high relative density (over 99.6%), while the SPS samples showed slightly lower values, particularly for 30 vol.% Al_2O_3, which was attributed to the lower sintering temperature and the rapid heating rate. Gas adsorption analysis confirmed the presence of nanopores mainly in the AlSi12 matrix, which was later used in the numerical modeling of thermal conductivity.

In the section devoted to microstructural analysis, it is shown that all composites exhibit a uniform distribution of ceramic phases and good quality of the metal-ceramic interfaces. In samples produced by HP, no micropores or cracks were observed, whereas in those fabricated by SPS, local voids appeared between Al_2O_3 grains. For gradient materials (FGMs), continuous transitions between the layers were confirmed, along with the formation of metallurgical bonds ensuring structural integrity.

The next part of the chapter describes the temperature dependence of thermal conductivity (25-300 °C). It was found that samples fabricated by HP exhibited higher thermal conductivity than those produced by SPS, while increasing the Al_2O_3 content led to a systematic decrease in conductivity. For layered composites and FGMs, thermal conductivity remained stable throughout the tested temperature range. The three-layer FGM exhibited the highest conductivity among all tested materials.

Subsequently, the author presents both analytical and numerical analyses of thermal conductivity. The experimental data were compared with classical theoretical models (Voigt, Reuss, Hashin–Shtrikman, Mori–Tanaka). The results for HP samples fell between the Hashin–Shtrikman bounds, while those for SPS samples were within the Voigt–Reuss range. For FGMs, the best agreement with experimental data was obtained using the Reuss model, which describes the effective conductivity of layered systems. Finite element method (FEM) simulations based on micro-XCT images confirmed good agreement with the measurements (error < 6%), especially when the thermal boundary resistance at the Al/Al_2O_3 interface was included.

The final section of the chapter presents the analysis of thermal residual stresses (TRS) measured by neutron diffraction (ND). It was shown that the stresses in the AlSi12 matrix were tensile, while in the Al_2O_3 particles they were compressive, and their magnitude increased with the ceramic content. In FGM materials, these stresses were on average about 10% lower than in homogeneous composites, which was also confirmed by FEM simulations. The author concludes that the reduction of residual stresses is beneficial for improving strength and resistance to cracking.

In summary, this chapter presents consistent experimental and numerical results demonstrating that the HP method enables the fabrication of composites with superior density, microstructure, and thermal conductivity compared to SPS. The analytical and numerical models accurately reproduce the experimental data, and the graded structure (FGM) effectively reduces thermal stresses.

Chapter 5 presents the results of studies on the physical, thermal, and mechanical properties of AlSi12/SiC composites and functionally graded materials (FGMs), in a manner analogous to the previous chapter devoted to the AlSi12/Al_2O_3 system.

At the beginning of the chapter, the density and porosity of the samples are discussed. Composites fabricated by the HP method achieved very high relative densities – above 99.5% for larger samples (33 mm) and about 98% for smaller ones (20 mm). Samples produced by the SPS method reached a density of about 95%, which the author attributes to the lower sintering temperature (547 °C) and the very high heating rate (70 °C/min), both of which hindered full densification of the AlSi12-SiC mixture.

In the section devoted to microstructural analysis (SEM, micro-XCT), a homogeneous distribution of SiC particles in the aluminum matrix was observed, with clearly visible interfacial bonding. In the FGMs, continuous transitions between layers with different ceramic content were confirmed, indicating good metallurgical integrity.

Phase analysis (XRD, TEM) revealed the presence of Al, Si, SiC, and a thin Al_2O_3 layer (~20 nm) at the Al–SiC grain boundaries. The presence of this oxide layer was identified as a factor responsible for reducing the composite's thermal conductivity.

The next part of the chapter presents the results of thermal conductivity (λ) measurements in the temperature range of 25-500 °C. It was experimentally demonstrated that with increasing

SiC content from 10% to 30%, thermal conductivity decreased, even though SiC itself has higher conductivity than AlSi12. The author explains this phenomenon by the presence of porosity and the thin Al_2O_3 layers acting as thermal barriers. For the three-layer FGMs, thermal conductivity values were similar to those of homogeneous samples, indicating good continuity of heat flow along the gradient direction.

The analytical analysis (Reuss model) showed good agreement with experimental results for both HP and SPS samples, confirming that the Reuss approach can effectively estimate the thermal conductivity of FGMs.

In the numerical modeling (FEM), the author compared simulation results obtained with and without considering the interfacial thermal resistance (ITR) caused by the presence of Al_2O_3. Models that did not include ITR produced an incorrect trend – an apparent increase in conductivity with higher SiC content – while models incorporating ITR showed very good agreement with the experimental data.

Subsequently, the results of residual stress (TRS) measurements obtained using neutron diffraction (ND) are presented. Tensile stresses were recorded in the AlSi12 matrix, while compressive stresses occurred in the SiC particles. Increasing the SiC content led to higher stress values, whereas in FGMs, the stresses were approximately 10% lower than in homogeneous composites, which is beneficial for crack resistance. Numerical FEM simulations based on micro-XCT models reproduced the stress distributions obtained from neutron diffraction measurements with high accuracy.

At the end of the chapter, the results of thermal expansion coefficient (CTE) measurements are presented for both longitudinal and transverse directions. The CTE value decreased with increasing SiC content, and the FGMs exhibited slight anisotropy – the transverse CTE was slightly higher than the longitudinal one.

In summary, this chapter provides a comprehensive set of results for the AlSi12/SiC system, confirming the good quality of the microstructure and the consistency between experimental and numerical data. The key role of the thin Al_2O_3 oxide layer in reducing thermal conductivity is identified, and it is confirmed that the graded structure (FGM) effectively reduces thermal stresses. The results indicate that composites fabricated by the HP method have better thermal and structural properties than those produced by SPS.

In *Chapter 6*, the author presents the results of tribological tests of AlSi12/Al_2O_3 and AlSi12/SiC composites, treated as a supplementary stage to the analysis of materials intended for brake system components. The author emphasizes that the wear tests were of a preliminary character, intended only to provide an initial assessment of the materials' wear resistance. The tests were carried out using a linear abrasion test with the Taber Linear Abraser device and a ceramic pin of H–10 Calibrade type.

Composites containing different amounts of the ceramic phase (30 and 40 vol.%) were tested, along with grey cast iron taken from a commercial Brembo brake disc, which served as the reference material. The results showed that composites with 30% ceramic content exhibited lower wear than those containing 40%. Among all tested materials, the AlSi12–30%SiC composite demonstrated the best wear resistance. However, all tested composites showed a significantly higher mass loss compared to grey cast iron, which exhibited the lowest wear rate.

The higher material loss in samples containing 40% ceramic phase was explained by the author as resulting from greater porosity and surface roughness, both of which facilitate particle detachment during friction. It was also observed that an excessive amount of reinforcing particles makes it difficult to densify the matrix during sintering, further reducing wear resistance.

Based on the obtained results, it was concluded that the optimal ceramic content in AlSi12-based composites is around 30%, while further increasing the reinforcement fraction leads to a deterioration of tribological properties. SiC proved to be a more effective reinforcement than Al_2O_3.

In the final part of the chapter, the author notes that the Taber Linear Abraser test does not fully reproduce the real operating conditions of a brake disc – both due to the limited contact area and the absence of an actual friction counterpart. Therefore, further tests are recommended using real brake pad materials and under conditions closer to actual service operation.

Chapter 7 presents a comparison of both types of composites in terms of their potential application as brake disc materials. The author focuses mainly on three key aspects: density, thermal conductivity, and residual stresses (TRS), complemented by a comparison of basic mechanical properties.

At the beginning of the chapter, the relative and actual densities of the AlSi12/Al_2O_3 and AlSi12/SiC composites fabricated by HP and SPS methods are compared. Composites reinforced with Al_2O_3 exhibit higher densities than those with SiC, and HP samples are denser than those obtained by SPS. All materials had a density below 3 g/cm^3, which is approximately half the density of typical grey cast iron (GCI, ~7 g/cm^3).

In the following section, mechanical properties such as hardness, bending strength, and fracture toughness are presented. Both composite systems showed an increase in hardness and strength with higher ceramic content, but the AlSi12/Al_2O_3 composites achieved better strength results than AlSi12/SiC. The author explains this by the closer match of thermal expansion coefficients (CTE) between Al_2O_3 and the AlSi12 matrix, which reduces thermal stresses and the risk of microcracking. Additionally, the finer and more spherical Al_2O_3 particles (5 μm compared to 10 μm for SiC) promoted a more uniform distribution and better stress transfer within the matrix.

Next, the thermal properties are discussed. The three-layer FGMs (both AlSi12/Al_2O_3 and AlSi12/SiC) exhibited a thermal conductivity of approximately 140 W/mK, more than twice that of grey cast iron. Although SiC has a higher intrinsic conductivity than Al_2O_3, the actual conductivity of AlSi12/SiC composites was slightly lower, which was attributed to the formation of thin Al_2O_3 layers around SiC particles, acting as barriers to heat transfer.

The final part of the chapter analyzes residual stresses (TRS) determined by neutron diffraction (ND). In both composite types, compressive stresses occurred in the ceramic phase and tensile stresses in the metallic matrix. Increasing the ceramic content (from 10% to 30%) led to higher stress values, with significantly higher stresses observed in AlSi12/SiC composites than in AlSi12/Al_2O_3 ones. This was explained by the larger difference in CTE values and the particle geometry (40 μm SiC vs. 10 μm Al_2O_3). The use of a graded structure (FGM) reduced TRS by about 10% compared to homogeneous samples. It was shown that at 30% ceramic content, the stresses in the AlSi12 matrix were up to 40% lower in AlSi12/Al_2O_3 composites than in AlSi12/SiC counterparts. This indicates that AlSi12/Al_2O_3 composites have better resistance to thermal loads and a lower risk of thermal cracking. The author also points out that, despite their higher thermal conductivity and lower residual stresses, both composite systems exhibited lower tribological resistance than grey cast iron. However, it is emphasized that the Taber Linear Abraser test does not fully reflect actual operating conditions, and that final evaluation requires testing under realistic braking conditions.

In summary, this chapter serves as a logical synthesis of the entire dissertation, comparing the two composite systems in terms of their potential for brake disc applications. The author demonstrates that both AlSi12/Al_2O_3 and AlSi12/SiC composites feature very low density and high thermal conductivity compared to grey cast iron. However, the Al_2O_3-reinforced composites show more favorable residual stress distribution, higher strength, and slightly better thermal stability. Although the tribological performance does not yet match that of cast iron, the author highlights the potential of these composites as a lightweight alternative for brake discs, requiring further optimization of wear resistance.

The final, *chapter 8* contains a summary of the results, the most important conclusions, and proposals for future research directions.

The dissertation concludes with an extensive bibliography, comprising all scientific sources used throughout the study.

2. Evaluation of the dissertation

The dissertation concerns the development and evaluation of metal-ceramic composites AlSi12/Al_2O_3 and AlSi12/SiC, including functionally graded materials (FGMs), as potential lightweight materials for brake discs. The author carried out a comprehensive study encompassing the analysis of microstructure, thermal conductivity, residual stresses, mechanical properties, and tribological wear, using both experimental methods and numerical simulations.

The results demonstrated that both types of composites exhibit high thermal conductivity (up to 140 W/mK) and low density (approximately 3 g/cm^3), with AlSi12/Al_2O_3 showing better thermal stability and lower residual stresses than AlSi12/SiC. The introduction of a graded structure further reduced stress concentration and improved the structural integrity of the materials.

Although these composites do not yet match grey cast iron in terms of wear resistance, they represent a promising lightweight alternative, requiring further optimization of sintering parameters and tribological testing conditions.

3. Comments and questions

After analyzing the manuscript, the following remarks and questions have arisen. The broader discussion or clarification could contribute to a fuller understanding of the context of the conducted research and to a more comprehensive assessment of the significance of the obtained results.

1. The dissertation generally follows the SI system, but not consistently. It would be advisable to unify all units, as this would undoubtedly facilitate the comparison of results and make the work more transparent.
2. The author employed two different sintering processes, Hot Pressing (HP) and Spark Plasma Sintering (SPS), to compare their effects on the properties of the composites. Were the parameters of those processes (temperature, pressure, and sintering time) selected to ensure a comparable degree of densification and similar microstructure of the materials?
3. On what basis was a block of 50×50×50 μm^3 assumed to be a representative volume element (RVE) of the composite microstructure, and was it verified that that volume

contains a sufficient number of ceramic particles and pores to represent the real material accurately – particularly in the case of functionally graded materials (FGMs)?

4. Do differences in the geometry and size of samples, as well as in the direction of measurements, affect the possibility of directly comparing the results obtained using different experimental methods?
5. On what basis was the temperature range of 25–300 °C (for $AlSi12/Al_2O_3$) selected, given that materials of this type used in brake system components may operate at temperatures exceeding 500 °C?
6. The applied wear test of the pin–on–flat type (Taber Linear Abraser) constitutes an appropriate and useful preliminary method for comparing the wear resistance of materials of different compositions and manufacturing methods (HP, SPS). It enables the evaluation of basic tribological properties under controlled laboratory conditions. However, it does not fully reflect the real working conditions of a brake disc, where variable sliding speeds, high temperatures, and interaction with the brake pad material occur. What further research should be taken to assess the applicability of these materials for brake disc production?
7. The dissertation does not provide the number of finite elements used, nor details concerning the mesh density in the FEM analysis. The author indicates the types of elements used (cubic and tetrahedral) and their influence on microstructure representation, but it would be valuable to include information on mesh size and density to better assess the accuracy of numerical results.
8. Was a finite element mesh convergence study performed to determine whether the obtained results are independent of the number and size of finite elements?
9. Is the assumption of isotropic material properties in the FEM models justified, given that the measured CTE values indicate a certain degree of anisotropy in the FGM structures?
10. The author notes the presence of pores and nanopores in the samples, but their influence on thermal conductivity is discussed only qualitatively. No quantitative relationship between porosity and the decrease in thermal conductivity was presented, which makes it difficult to clearly determine whether the differences between HP and SPS samples result primarily from the microstructure or from porosity itself.
11. What could explain the differences in thermal conductivity values observed in Fig. 4.7 between the tested samples at low temperatures, and why do these differences decrease gradually with temperature increasing?

12. It is worth considering why, in Fig. 4.15b, the discrepancies between experimental and numerical results (for SPS samples) are significantly greater, whereas for HP samples (Fig. 4.15a) much better agreement was achieved.
13. In the FEM thermal conductivity analysis, the interfacial thermal resistance (ITR) was included, which improved agreement with experimental results. However, the specific value of ITR was not provided, nor was it stated whether this value changes with temperature or was validated for different SiC fractions. Was the ITR model calibrated individually for each material, or was a single "universal" value applied?
14. What could be the reason for the significantly larger drop in thermal conductivity at 25 °C for HP samples – between sample A and samples B and C – as shown in Table 5.3?
15. Is it possible to improve the properties of composites containing 30–40% ceramic particles by modifying the sintering process parameters (e.g., increasing temperature, pressure, or dwell time) to reduce porosity and thus enhance tribological resistance?
16. What changes and adjustments in process parameters, production time, machinery, and energy requirements would be necessary to enable the laboratory-fabricated materials to be scaled up and implemented in industrial brake disc production?

The above remarks and questions are of an informative and discussion-oriented nature and do not affect the overall positive evaluation of the presented doctoral dissertation.

The doctoral thesis by Mr. Anil Antony Sequeira has been prepared carefully and in accordance with the standards required for works of this type. The author has demonstrated independence and creativity in addressing the research problems undertaken.

4. Conclusion

The doctoral dissertation entitled *Thermal properties and thermal residual stresses in graded Al–matrix composites reinforced with Al_2O_3 and SiC particles: experiments and numerical simulations*, by M.Sc. Eng. Anil Antony Sequeira, meets the requirements set forth in the Act of 20 July 2018 Law on Higher Education and Science (Dz. U. 2021 poz. 478 z późn. zm.). This work makes a significant contribution to the development of materials engineering. Therefore **I recommend the dissertation to be accepted for public defense,** as the basis for the author's application **for the degree of Doctor of Engineering and Technical Sciences in the discipline of Materials Engineering.**