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Exploring Multi-scale Thermal Behaviour in Pin-on-Disc Systems for Organic, Metallic, Ceramic, and Polymer Composites

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ABSTRACT

This paper presents a multi-scale strategy for the thermal simulation of frictional systems, such as brakes, considering the microscale properties of the polymer composites. A finite element model is supposed to model the system components at the macro scale. At the microscale, the thermal properties are evaluated to identify the effective thermal properties of the polymer composites. As regards wear, Archard's law is used with a wear rate coefficient depending on temperature. The micro-scale properties of the polymer composites are integrated into the macro-scale model using the COMSOL computational package. In the conducted study, it is determined that the contact temperature for organic disk brake pad material reaches the highest value at 727 K, followed by ceramic material pad at 691 K, and semi-metallic material at 689 K. Focusing on epoxy and epoxy-fiber composites, it is observed that the Kevlar-epoxy composite exhibits temperature performance characteristics comparable to those of the semi-metallic and ceramic materials, registering a contact temperature of 693 K. In contrast, both epoxy and epoxy-carbon fiber composites display significantly higher temperatures, with values of 1254 K and 944 K, respectively. Consequently, these findings suggest that Kevlar epoxy shows promise in serving as a future brake pad material for the automotive industry. The multi-scale study on different materials focusing on the use of computational results for replacing the traditional brake pad material with advanced composites is the novelty of the study.

1. Introduction

Observing the thermal behavior of pin-on-disc systems on different scales is one of the most significant areas in materials science. It also covers calculations and measurements of the type of bonding that occurs in materials, as well as the mechanical behavior of complex produced goods under harsh circumstances [1]. Companies worldwide are moving from providing raw materials such as metals, polymers, and ceramics to providing completed goods such as systems and components to industries like aerospace, energy, healthcare, and others that depend on creatively combining novel materials [2–4]. This also helps researchers to understand how various materials interact under heat stimuli. The versatile nature of pin-on-disc tribometers makes them suitable for studying the wear and frictional properties of different materials that are used in various sectors of the economy [5,6]. Organic substances, which have C-H bonds in their structure, play an important role in many engineering fields due to their low weight, flexibility, and adjustable features [7,8]. Pin-on-disc measurement setups are utilized to investigate thermal behavior at different scales for organic materials to understand their response to varying heat conditions [9,10]. These properties must be optimized given that automotive components like brakes require enhanced performance from organics due to high

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levels of friction and wear within this industry sector [11–14].

Indeed, metallic substances are extensively employed in high-stress applications due to their great electrical conductivities and mechanical strengths [10]. By studying the multi-level thermal performance of metallic materials in pin-on-disc systems that provide fundamental insights into thermally stable heat dissipation mechanisms, the thermal behavior of cermet can be explained. Such knowledge is essential for a sector like aerospace and manufacturing as far as ensuring the life span and dependability of their components are concerned [15,16].

When one considers the hardness that ceramics possess as well as their ability to resist high temperatures, they are often used under extreme conditions. It is, therefore, crucial to study the multi-scale thermal behavior of ceramics in pin-on-disc systems to understand how they perform in cutting, grinding, or sliding wear. For instance, in the cutting tool industry, such information is vital because it helps determine tool efficiency and durability based on how resistant ceramic blades are to changes in temperature.

The thermal properties of these polymer composites are very unique and this makes such materials suitable for various applications [17,18]. The study of the multi-scale thermal behavior of polymer composites in pin-on-disc systems will be instrumental in optimizing their performance as bearing materials and sliding components in machinery [19,20]. This understanding facilitates the development of materials resistant to various environmental conditions.

The investigation of organic, metallic, ceramic, and polymer composites' multi-scale thermal behavior in pin-on-disc systems is an all-rounded activity with wide-ranging implications in material sciences and engineering [21–23]. In so doing, this research seeks to unlock complexities surrounding how these substances behave under different thermal stimuli at diverse scales intending to contribute towards the creation of advanced materials that would be used across the entire range of industry while still eliciting enhanced functionality and dependability. The study explores four different classes of materials, namely organic, metallic, ceramic, and polymer composites, concerning their thermal behavior. This will give a basis for designing and improving advanced materials in many engineering applications.

2. Materials, Geometry, and Mesh

This study conducted a computational analysis of the disk brake pad thermal analysis considering the pad of common brake pad material, specifically organic, semi-metallic, ceramic, polymer, and polymer composites, The polymer is epoxy and composites are Kevlar-epoxy composites, and carbon fiber-epoxy composites. The material's properties, organic, metallic, ceramic, epoxy, Kevlar-epoxy, and carbon fiber-epoxy are respectively in Table 1, were studied using various mesh sizes (Table 2), including coarser, normal, and finer mesh sizes, and different air temperatures, such as 360 K and 153 K, which are the highest and lowest temperature ever recorded [24,25].

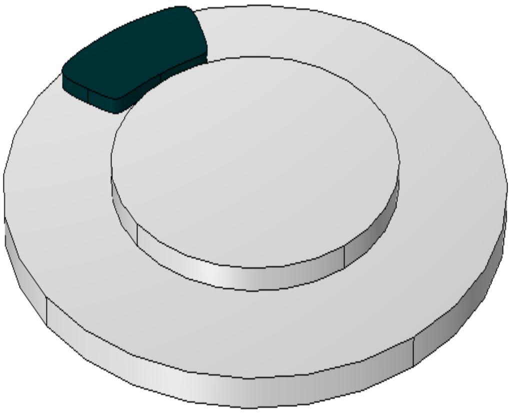

Figure 1. Pad and disk used for the computational work

In Figure 1., The geometric arrangement is conducive to effective simulation. The arrangement involves placing the brake pad statically, to focus solely on the interaction between the pad and the disk.

The disk is positioned as the primary component, serving as the foundational element for the analysis. It is typically oriented horizontally, mimicking its position within the braking system. The pad is then placed parallel to the disk surface, ensuring direct contact between the two components. This arrangement facilitates the examination of heat distribution at Contact, and Isothermal contours between the pad and the disk.

Careful consideration is given to the alignment and orientation of the pad relative to the disk to simulate real-world conditions accurately. Factors such as contact area, atmospheric temperature, and material properties are crucial parameters in this setup. By isolating the pad from the caliper hub, the analysis can focus specifically on the dynamics between the pad and the disk, providing valuable insights into braking performance and efficiency.

The disk is given material properties of steel AISI 52100 Alloy Steel. Chemical composition of AISI 52100 alloy steel content 96.5%–97.32% of Iron (Fe), 1.30%-1.60% of Chromium (Cr), 0.980%-1.10% of Carbon (C), 0.250%-0.450% of Manganese (Mn), 0.150%-.300% of Silicon (S), ≤ 0.0250% of Sulphur (S) and ≤ 0.0250% of Phosphorous (P) [26,27].

Table 1. Properties of organic brake pad material [28], semi-metallic brake pad material [27], ceramic brake pad material [26], epoxy polymer brake pad material, kevlar/epoxy brake pad material, and carbon fiber/epoxy brake pad material.

Properties/Symbols (Units)	Organic [28]	Semi-metallic [27]	Ceramic [26]	Epoxy polymer	Kevlar/epoxy composite	Carbon fiber/epoxy composite
Density/δ (kg/m^3)	2320	7750	2320	4700	1263.58	1150
Thermal conductivity/k (W/m-K)	2.51	44.4	2.51	35	12.805	0.22
Specific heat in constant pressure/ Cp (J/kg-K)	1233.8	505	1233.8	478.9	1440	1000

Table 2. Element size parameters according to mesh size

Mesh types	Maximum element size	Minimum element size	Element growth rate	Curvature factor	Mesh types
Normal	0.028 m	0.00504 m	1.5	0.6	Normal
Coarser	0.0532 m	0.0112 m	1.7	0.8	Coarser
Finer	0.0154 m	0.00112 m	1.4	0.4	Finer

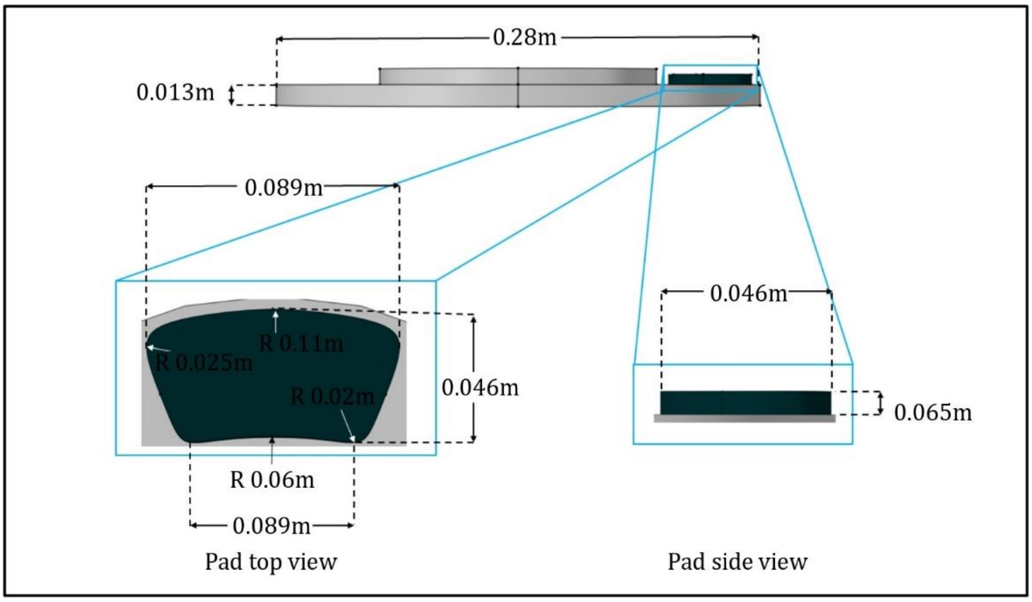

Figure 2. Dimensions of pad and disk used for the computational work [29].

3. Computational Methodology

The thermal properties of composites were evaluated using the Mori-Tanaka first-order technique. The theory can be referred to from our previous published work [23]. The process of implementing the provided data involved several steps as shown in Figure 3. One key assumption is that the thermal properties of the polymer composites remain constant throughout the simulation, potentially oversimplifying real-world variations due to temperature fluctuations. Additionally, the wear rate coefficient used in Archard's law is assumed to depend solely on temperature, without accounting for other factors such as pressure or sliding velocity, which can also impact wear behavior.

Incorporating the microscale characteristics into the macro-scale model of the system improves the accuracy of thermal simulations for brake systems by telling us more about the ways materials behave at small scales. These detailed data can predict how materials may respond to varying levels of heat and wear in the actual real world. With this information, the simulations can more accurately simulate real performance, which means engineers can use this to pick the right materials for brakes being built to withstand high heat and last longer. This method makes models more accurate and credible, which in turn will enable safer and more efficient brakes.

Firstly, the geometries of the pad and disk were created using the COMSOL Multi-physics software. The geometries were designed according to the specifications provided in the BIS standards [29] as per research requirements shown in Figure 2. Once the geometries were created, they were assembled into a single component called a Pad and disk. This involved aligning the geometries and making sure they were positioned correctly about one another.

After the component was created, contact types were applied. This allowed the software to simulate the interaction between the pad and disk. Next, materials were defined for both the pad and disk. The material properties were specified in the cited literature following the research requirements as in Table 1. To enable accurate analysis, meshes were created for the component. The meshes were designed to provide sufficient detail to capture the behavior of the pad and disk during operation.

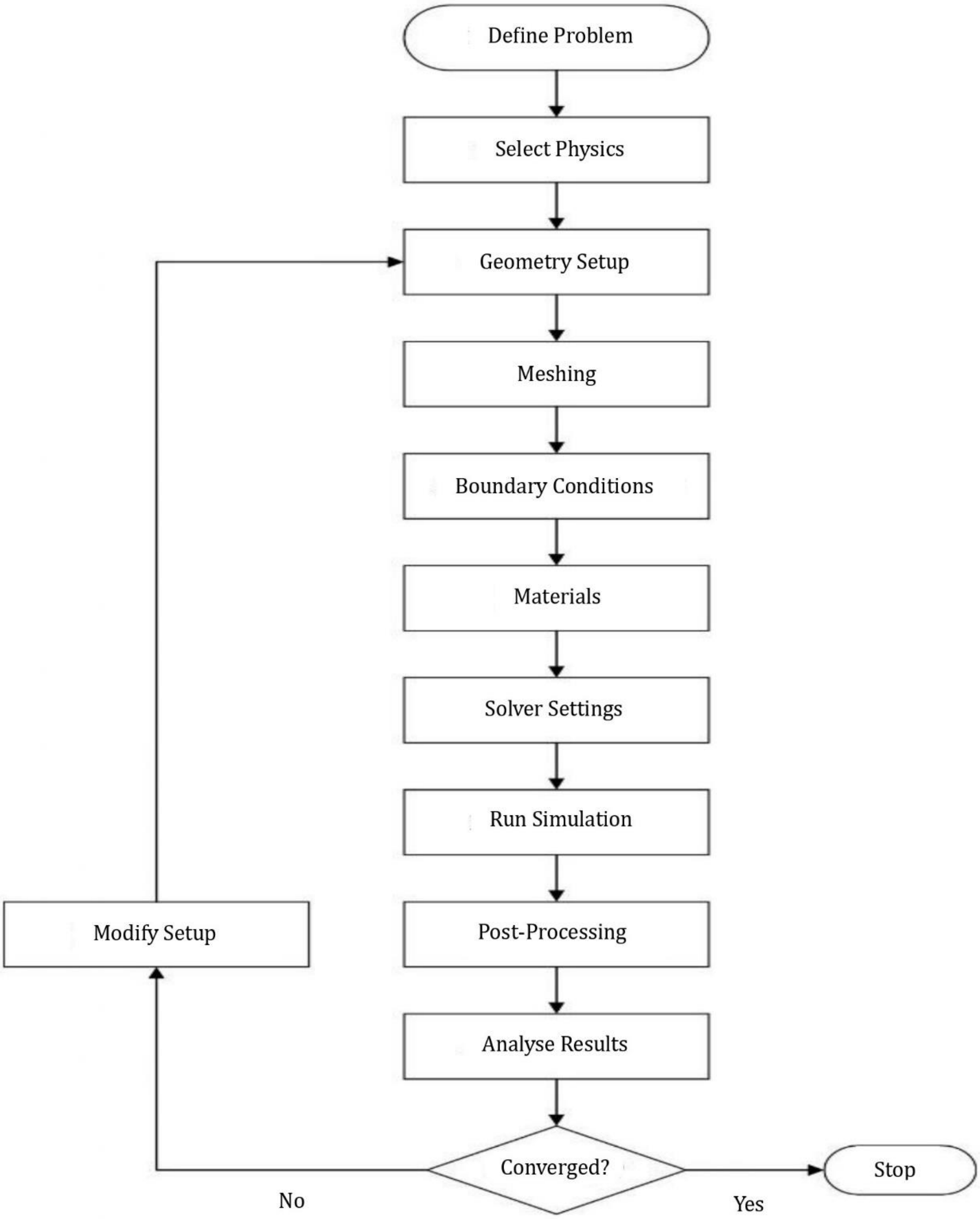

Figure 3. Computational methodology for pin-on-disc FEA.

After the meshes were created, thermal conditions were applied to both the pad and disk. This involved specifying the air temperature and constraints that the component would be subjected to during operation as mentioned in Table 3. Once the breaking is simulated, by friction heat is generated. These thermal changes were designed to simulate the thermal characteristics that the component would experience during use.

Finally, the results were obtained through post-processing within the COMSOL Multi-physics software. This involved analyzing the contact temperature and isothermal contour data generated by the simulation directly to determine the performance characteristics of the Pad and disk component under the specified operating conditions i.e. air temperature (360 K and 153 K as per the standards used in the study).

3.1. Results and Discussions

The computational results obtained from the pad and disk thermal analysis were categorized based on the contact temperature and von Mises stress. These results were evaluated for different mesh sizes and air temperatures, as outlined previously.

3.2. Contact Temperature

All values presented denote the maximum contact temperature observed across different materials and are expressed in units of Kelvin (K). Figures 4 to 9 illustrate the contact temperature of the pad at finer mesh and maximum air temperature. Table 3 represents the computed results of maximum contact temperature for different mesh and different air temperatures for organic, semi-metallic, ceramic, epoxy, Kevlar-epoxy composites, and carbon fiber-epoxy composites.

Table 3. Contact temperature of materials for different mesh sizes and air temperatures.

Mesh type	Air temperature (K)	Organic	Ceramic	Semi-metallic	Epoxy	Kevlar-epoxy	Carbon fiber - epoxy
Normal	360	714	670	671	1230	673	924
	153	506	441	464	1010	466	713
Coarser	360	689	643	644	1210	728	904
	153	480	414	437	1120	437	691
Finer	360	727	691	689	1250	693	944
	153	524	484	483	1030	486	733

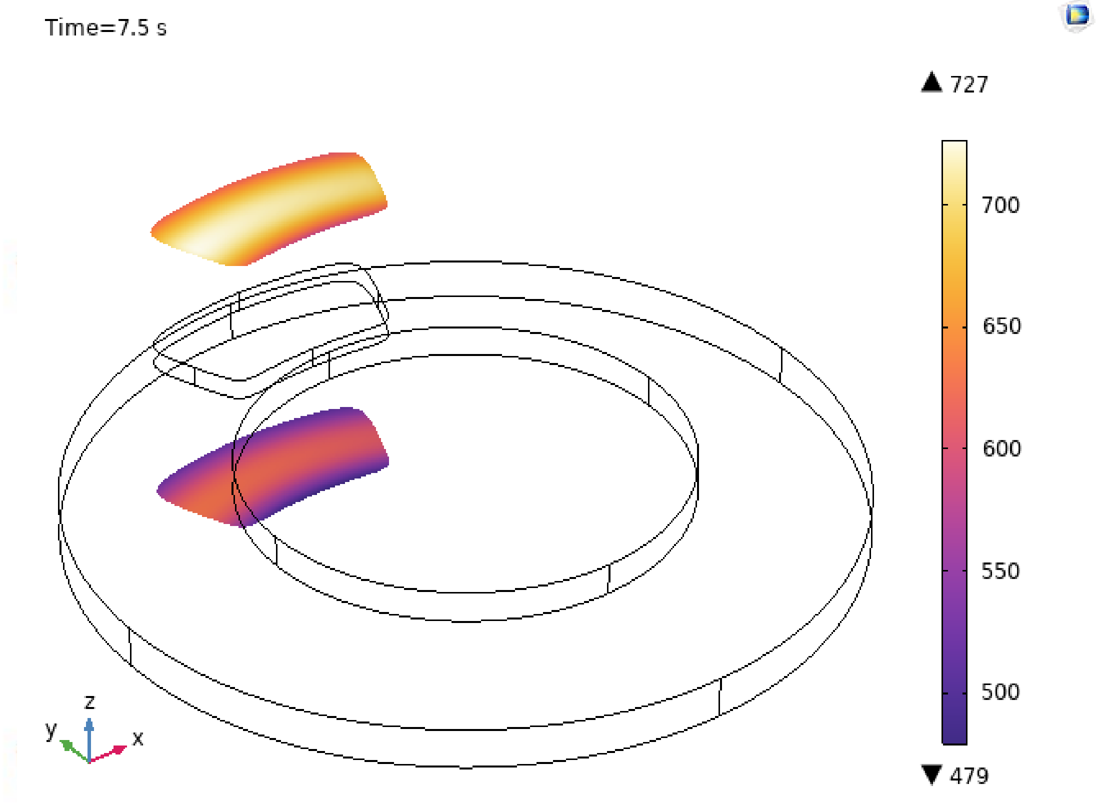

Figure 4. Contact temperatures of organic pad material

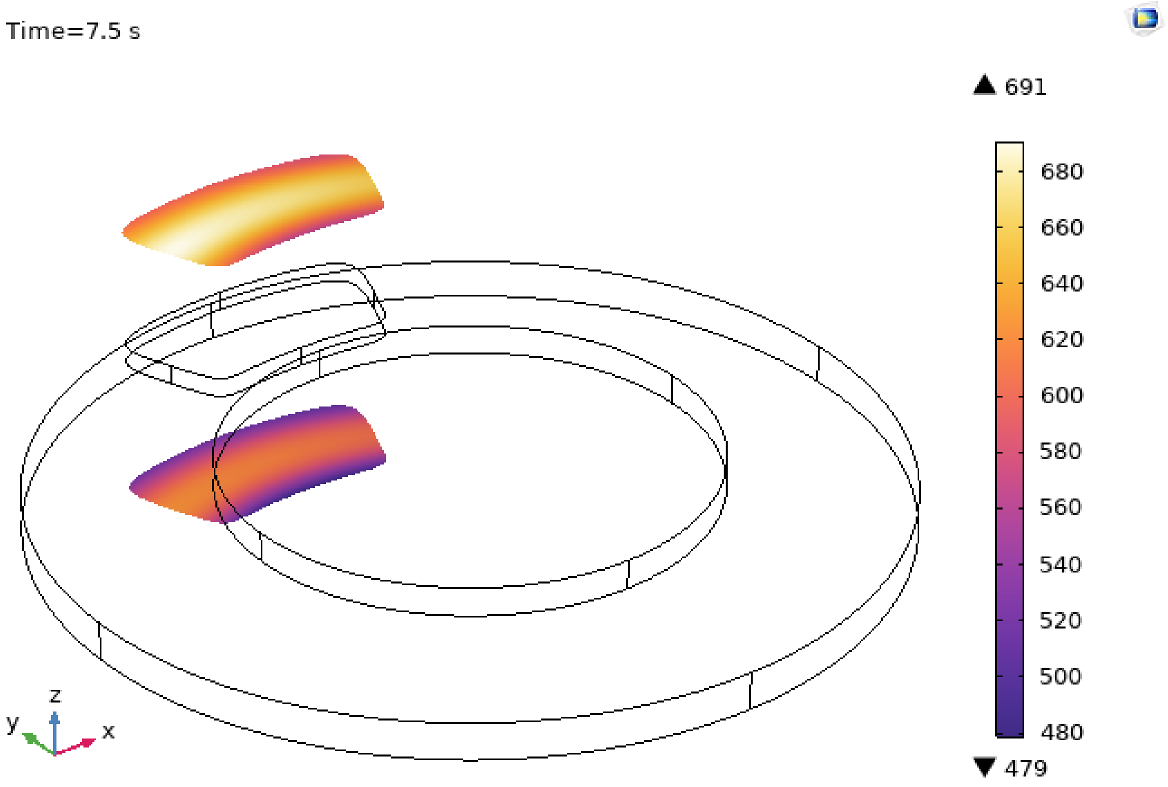

Figure 5. Contact temperatures of ceramic pad material

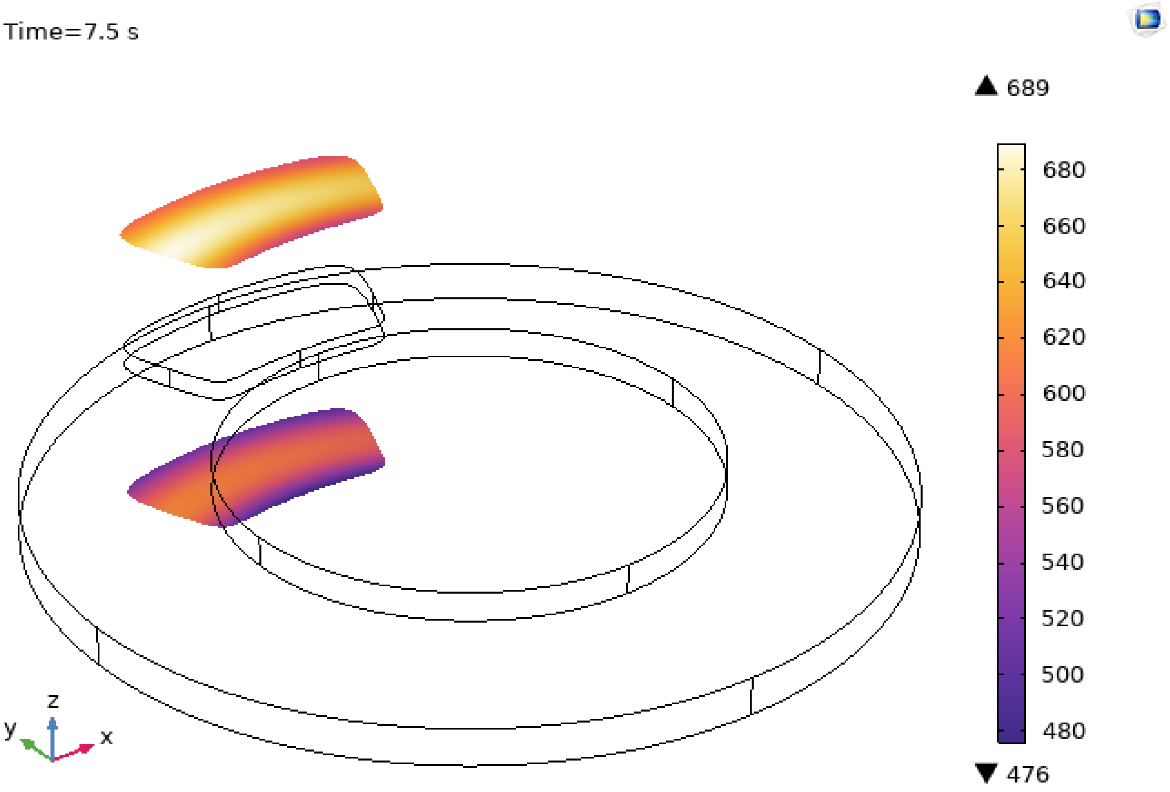

Figure 6. Contact temperatures of semi-metallic pad material

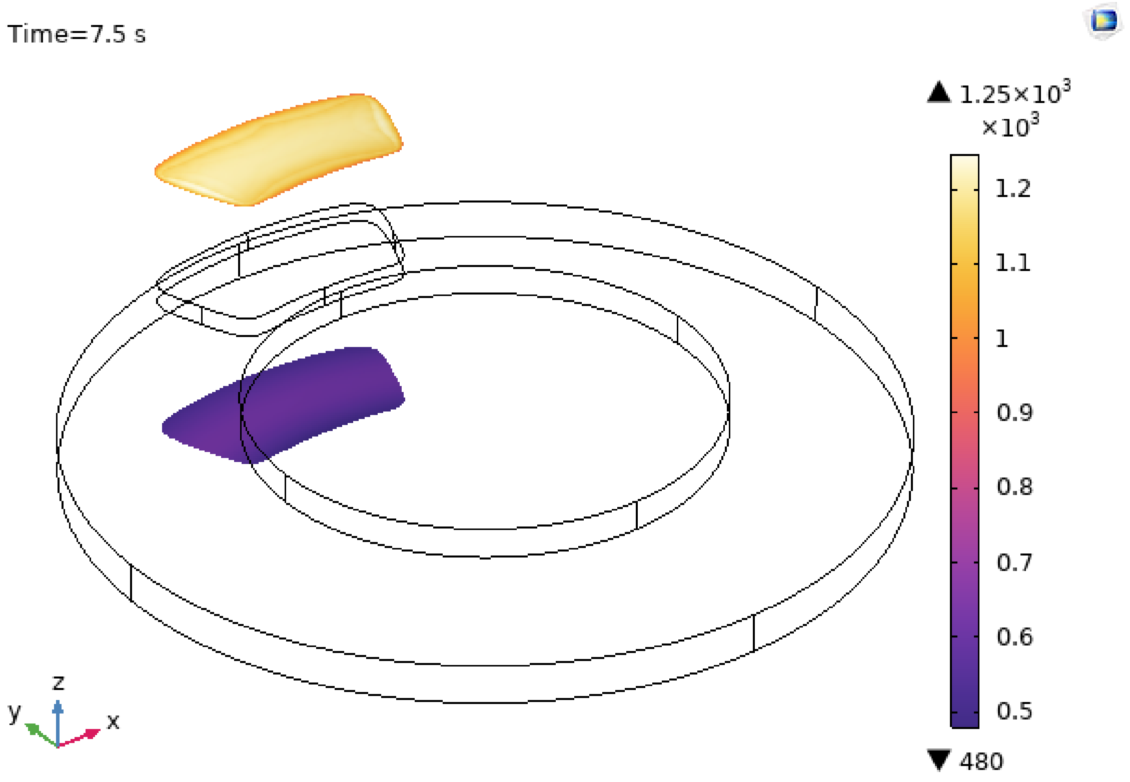

Figure 7. Contact temperatures of epoxy pad material

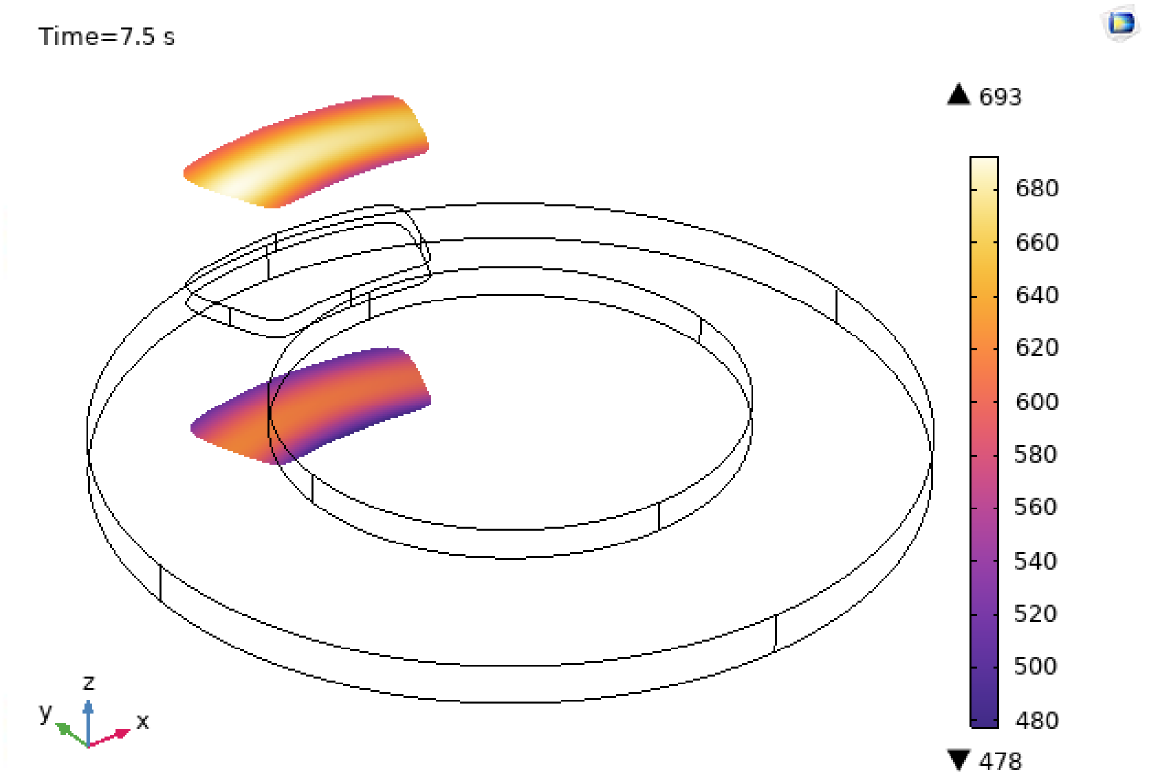

Figure 8. Contact temperatures of kevlar-epoxy pad material

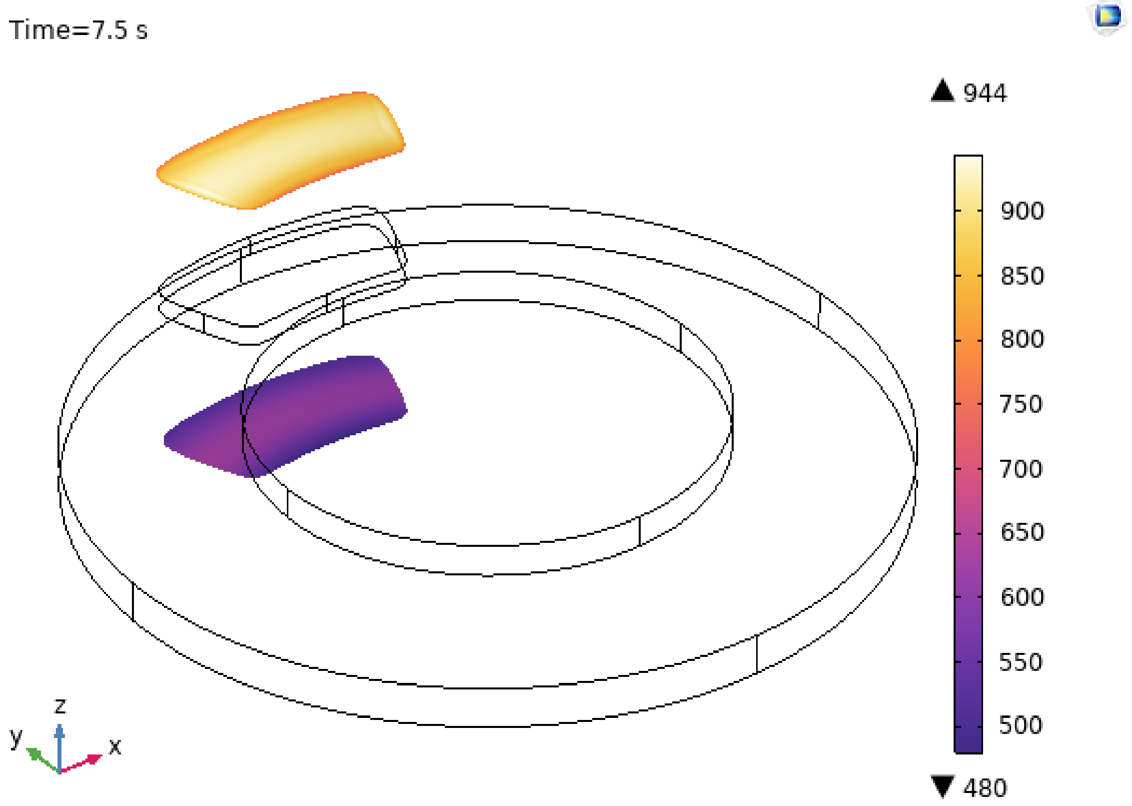

Figure 9. Contact temperatures of carbon fiber – epoxy pad material

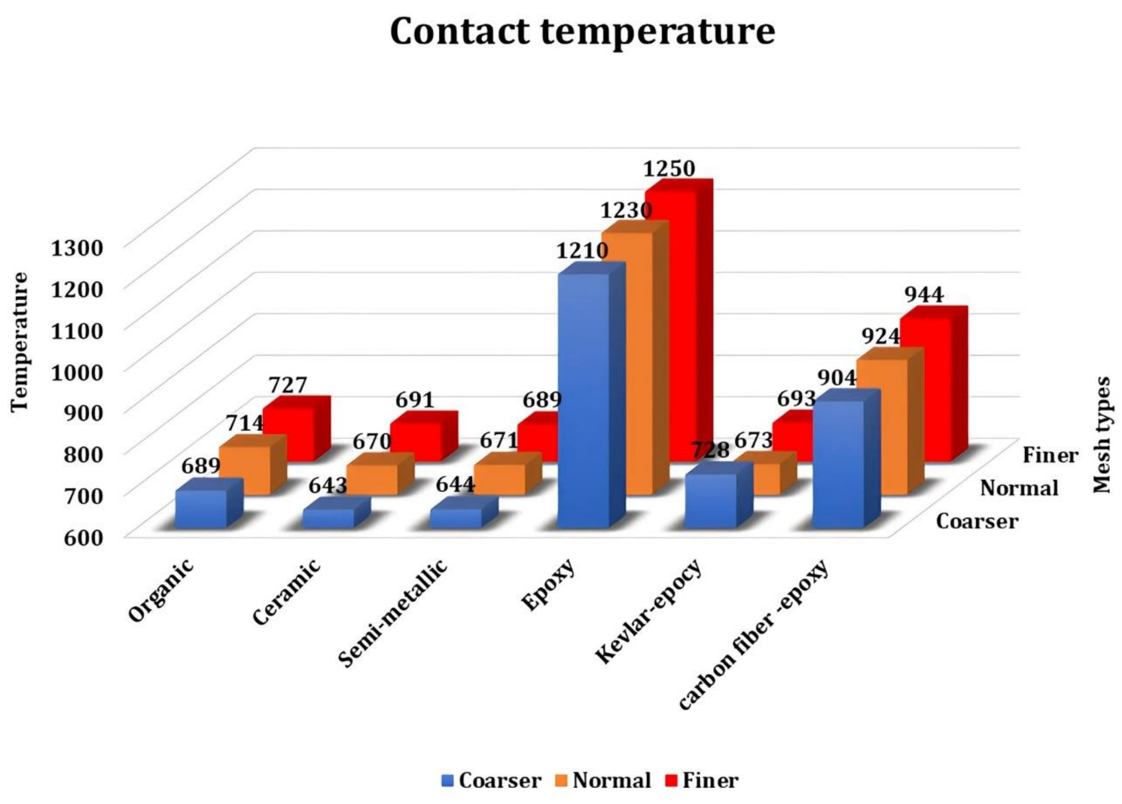

Figure 10. Contact temperature of materials for different mesh sizes and air temperatures.

The finding that Kevlar-epoxy composite exhibits temperature performance characteristics comparable to traditional brake pad materials like semi-metallic and ceramic, but significantly lower temperatures compared to other epoxy-based composites, has several important implications. Firstly, it suggests that Kevlar epoxy could be a superior alternative for brake pads, offering both high performance and better thermal management. This can lead to improved braking efficiency, reduced risk of overheating, and enhanced safety. Secondly, the lower temperatures observed in Kevlar-epoxy composites indicate greater thermal stability and less thermal degradation, potentially increasing the lifespan of the brake pads. Lastly, this finding opens up possibilities for using Kevlar-epoxy in other high-temperature applications, providing a material that balances the benefits of organic composites with the robustness of traditional materials. This could drive innovation in automotive and other industries where thermal performance is critical.

The analysis was conducted for a finer mesh size, which provides greater resolution and accuracy in solving the governing partial differential equations in the allocated cell compared to a coarser or normal mesh size. By increasing the number of smaller cells within the mesh, the computational model can more accurately represent the physical behavior of the material under different air temperatures. This is particularly important in contact temperatures, where minor modifications in the material's surface can have a significant impact on contact temperatures.

3.3. Isothermal Contours

All values presented in Table 4 denote the maximum isothermal contours observed across different materials and are expressed in kelvin (K). Figures 11 and 16 illustrate the isothermal contours generated in the pad of organic, semi-metallic, ceramic, epoxy, Kevlar-epoxy composites, and carbon fiber-epoxy composites, respectively, for finer mesh and maximum air temperatures.

The findings of this study open several future research directions and applications in automotive engineering. These include developing new composite materials that enhance the thermal and wear resistance properties, optimizing brake system designs for improved performance and efficiency, and conducting long-term durability studies to ensure reliability. Advanced simulation models could be developed to better predict real-world performance, and the potential for Kevlar-epoxy composites to be used in other industries like aerospace and industrial machinery could be explored. Additionally, evaluating the environmental impact and conducting cost-benefit analyses will be crucial for promoting sustainable and economically viable material choices in automotive applications.

Table 4. Isothermal contours of materials for different mesh sizes and air temperatures.

Mesh type	Air temperature (K)	Organic	Ceramic	Semi-metallic	Epoxy	Kevlar-epoxy	Carbon fiber -epoxy
Normal	360	702.06	696	698	1170	700	894
	153	495	486	492	959	495	684
Coarser	360	680	666	670	1160	749	876
	153	472	456	464	1160	472	662
Finer	360	709	713	712	1200	714	913
	153	505	508	507	983	509	703

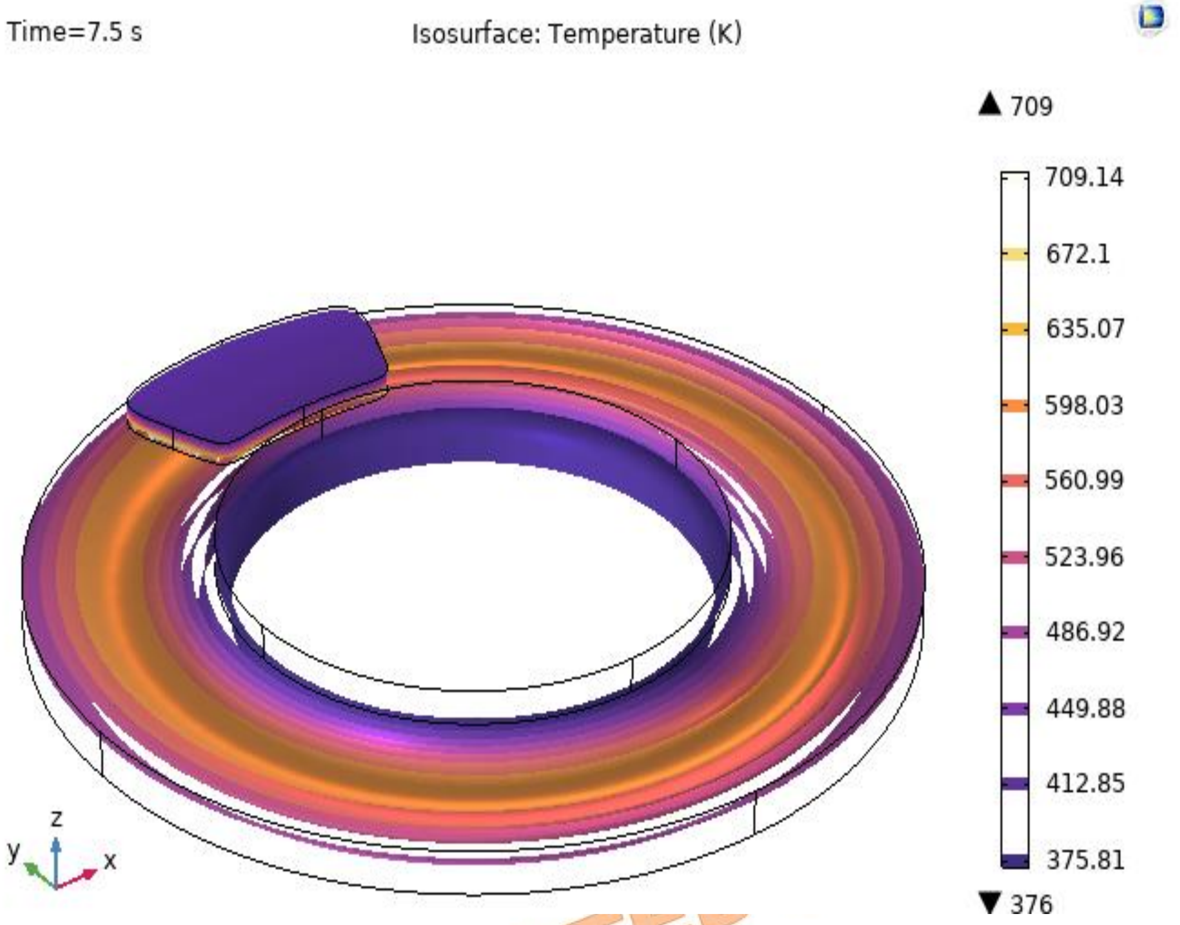

Figure 11. Isothermal contours of organic pad material

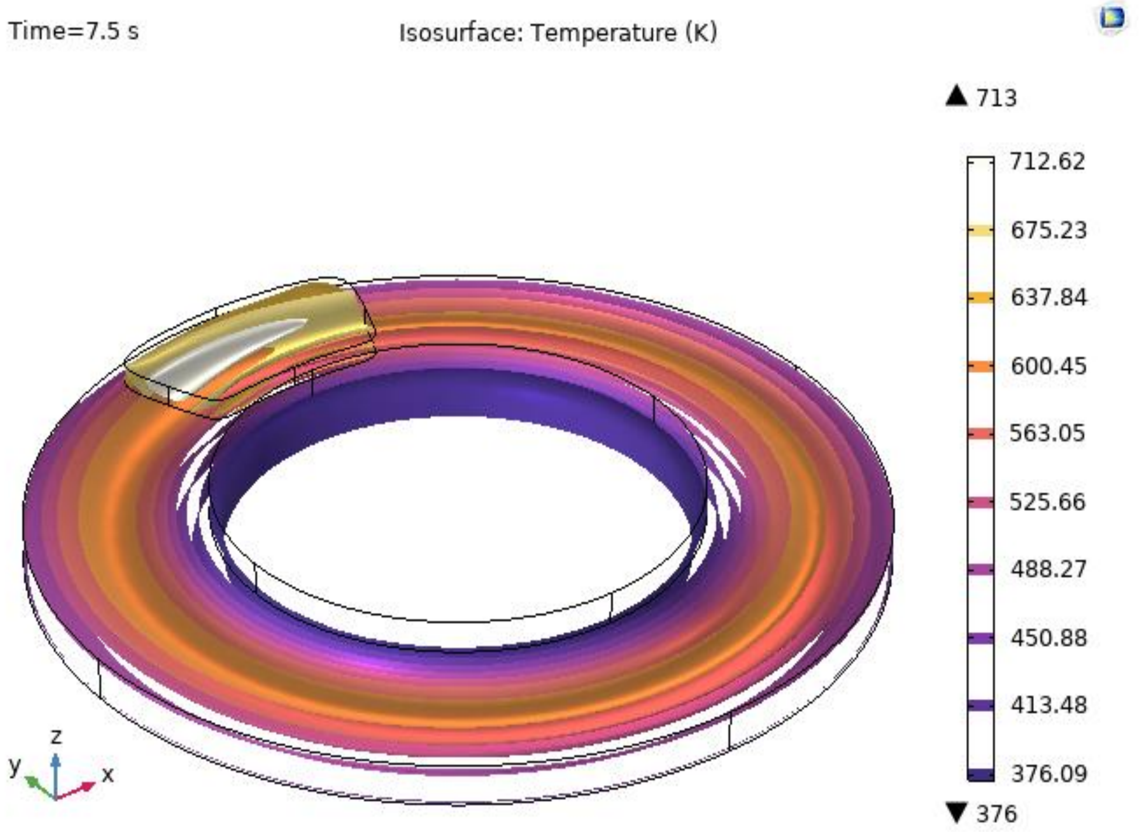

Figure 12. Isothermal contours of ceramic pad material

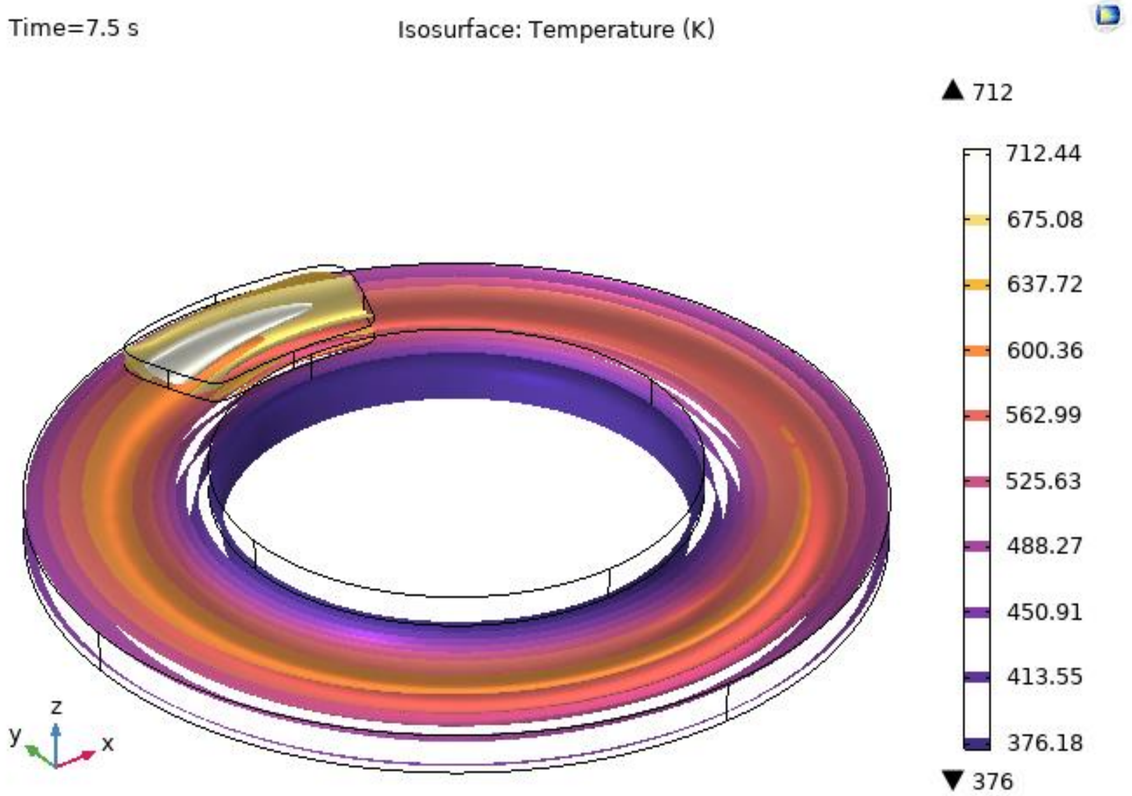

Figure 13. Isothermal contours of semi-metallic pad material

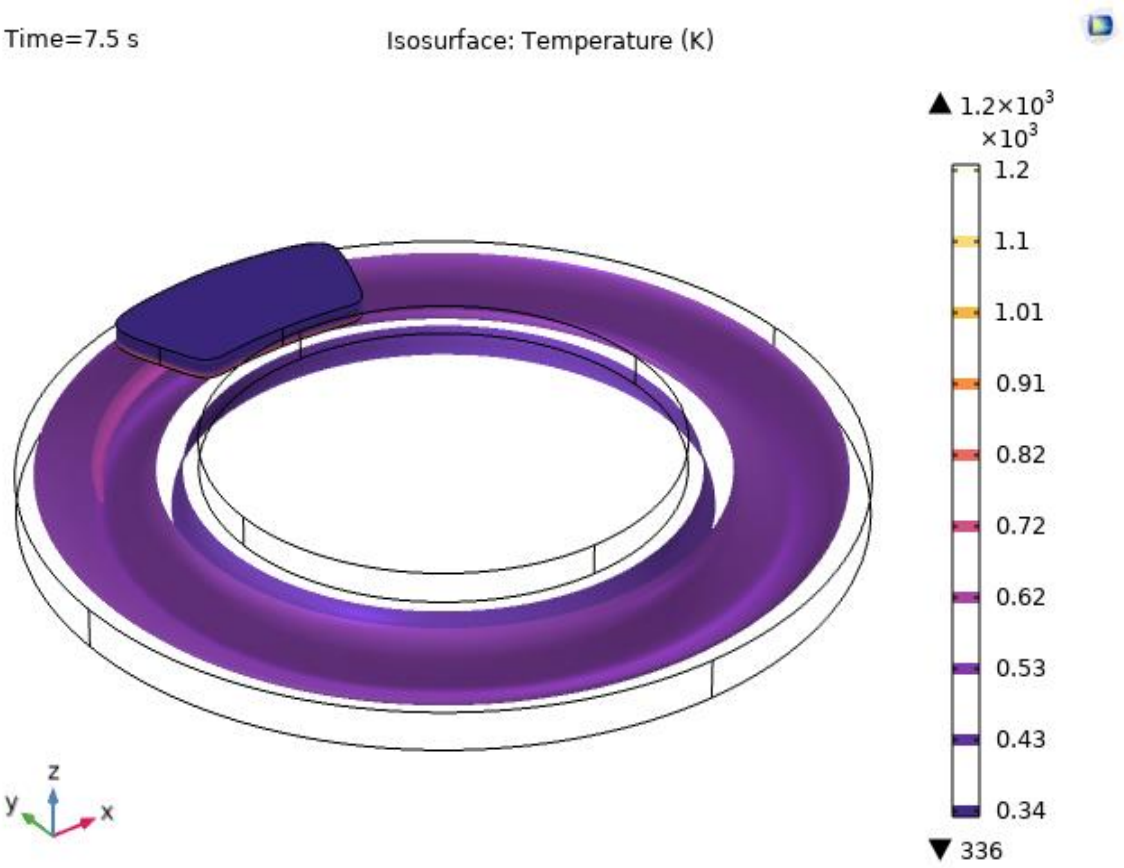

Figure 14. Isothermal contours of epoxy pad material

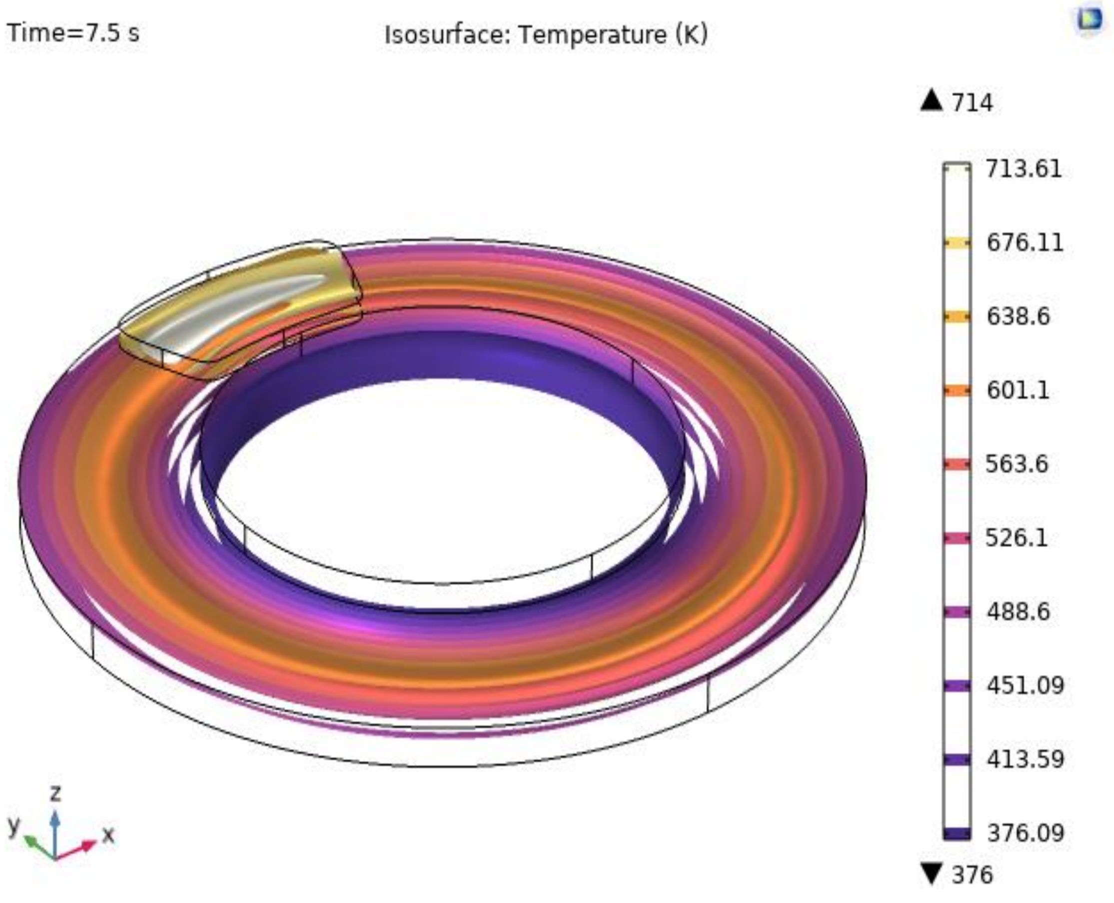

Figure 15. Isothermal contours of kevlar-epoxy pad material

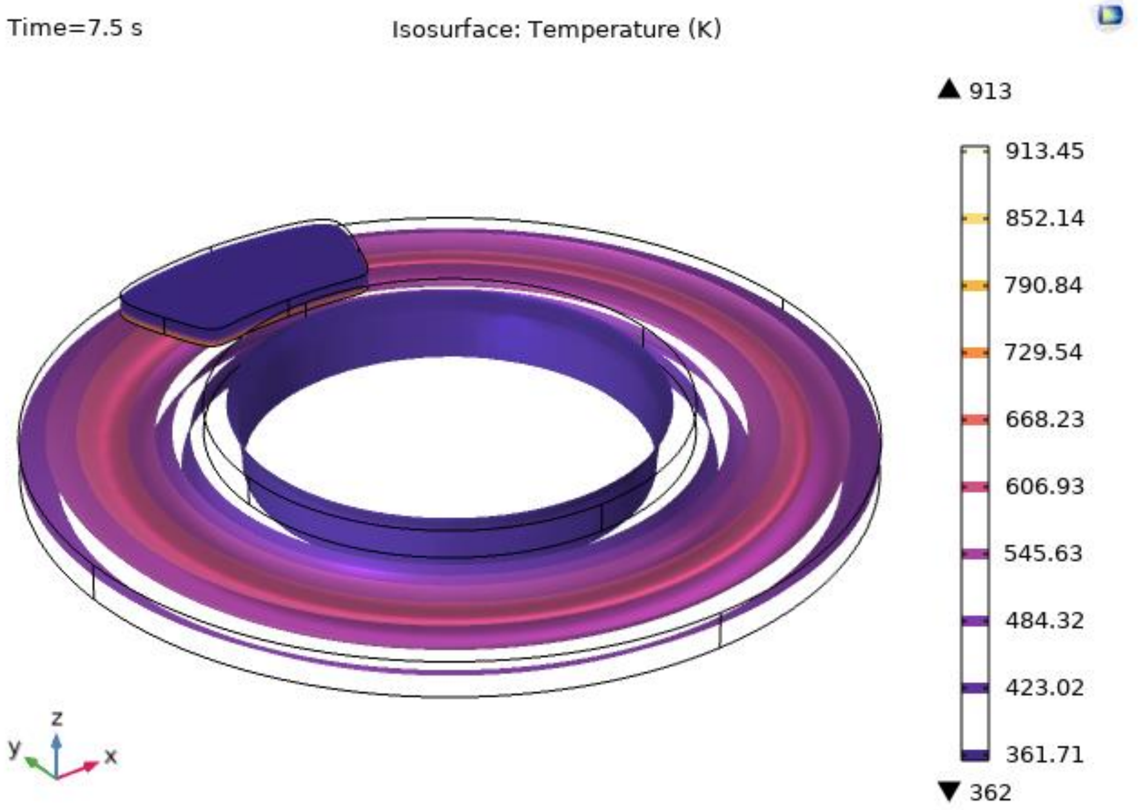

Figure 16. Isothermal contours of carbon fiber – epoxy pad material

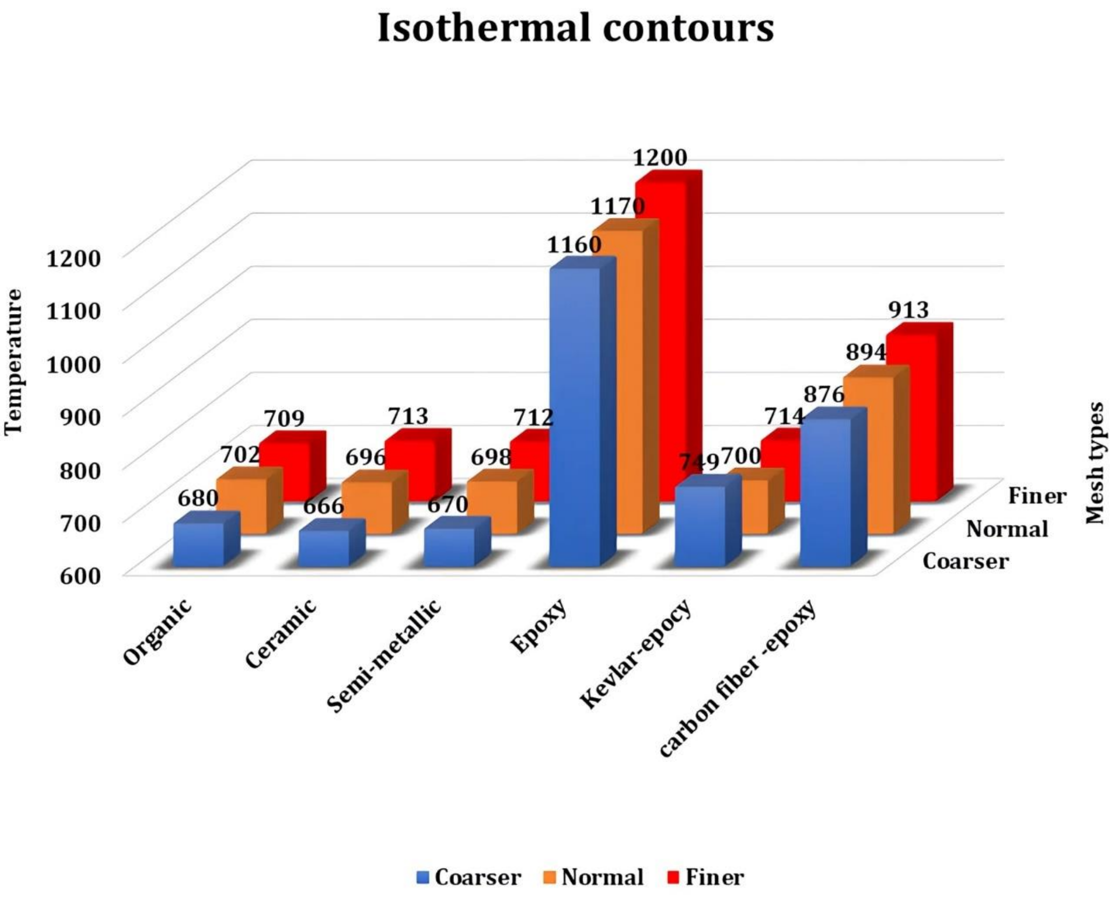

Figure 17. Isothermal contours of materials for different mesh sizes and air temperatures.

The analysis was conducted for a finer mesh size, which provides greater resolution and accuracy in solving the governing partial differential equations in the allocated cell compared to a coarser or normal mesh size. By increasing the number of smaller cells within the mesh, the computational model can more accurately represent the physical behavior of the material under different conditions. This is particularly important in isothermal contours testing, where even small changes in the material's properties can significantly impact heat generation.

The selection of mesh sizes (coarser, normal, and finer) and air temperatures (360 K and 153 K) significantly impact the accuracy and relevance of thermal analysis results in frictional systems. Coarser meshes reduce computational time but may overlook detailed thermal gradients, while finer meshes capture intricate details with higher accuracy at the cost of increased computational resources. Normal meshes strike a balance between these extremes. Analyzing at 360 K simulates high-temperature conditions typical of heavy braking, revealing material behavior under thermal stress, while 153 K represents low-temperature scenarios, important for understanding performance in different environmental conditions. These choices ensure that the simulations are comprehensive and applicable to real-world automotive engineering challenges.

Discrepancies or variations observed in the results across different materials, mesh sizes, and air temperatures can be attributed to several underlying factors. For instance, the significant temperature differences among the materials, such as the high contact temperatures for epoxy and epoxy-carbon fiber composites compared to Kevlar-epoxy, reflect their varying thermal conductivities and heat dissipation capabilities. The choice of mesh size in simulations also impacts the results' accuracy: finer meshes generally provide more precise temperature distributions and stress analyses due to higher resolution, whereas coarser meshes may overlook critical localized phenomena, leading to less accurate results. Additionally, the variations in air temperatures (360 K and 153 K) used in the analysis influence the cooling efficiency and thermal gradients within the braking systems. Higher ambient temperatures might reduce the cooling rate, resulting in higher contact temperatures, whereas lower ambient temperatures can enhance heat dissipation, thus lowering contact temperatures. These variations highlight the need to consider multiple factors, including material properties, simulation resolution, and environmental conditions, to achieve a comprehensive understanding and accurate modeling of thermal behavior in braking systems.

4. Conclusions

The study identifies Kevlar-epoxy composite as a superior alternative to traditional brake pad materials, offering enhanced thermal and mechanical properties. Kevlar-epoxy composite exhibits contact temperatures of 693 K, closely matching the performance of traditional materials like semi-metallic (689 K) and ceramic (691 K) brake pads. Kevlar's high thermal stability (specific heat capacity of 1440 J/(kg K) and low thermal conductivity of 12.805 W/(mK)) minimizes heat transfer to the caliper and brake fluid, reducing brake fade and maintaining consistent performance. The epoxy matrix in Kevlar-epoxy composites enhances adhesion and evenly disperses heat, mitigating hot spots and preventing thermal degradation. Kevlar's exceptional strength-to-weight ratio and durability under extreme heat and pressure conditions prolong pad lifespan and enhance overall braking efficiency, positioning it as a promising material for future brake pad applications.

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