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ECO-DESIGN And MECHNICAL STRENGTH ANALYSES Of A BRAKE PAD

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Abstract—**Brake pads are a crucial component of any vehicle's braking system. It is important to consider both eco-design and mechanical strength analyses when developing brake pad materials to ensure they are environmental-friendly and safe to use. When developing brake pad material, it must satisfy certain criteria, among which are supporting high temperature, pressure, tensile stresses, decreased wear rate, and in addition to that its environmental sustainability by using eco-friendly materials. Four types of brake pad materials are analyzed. The eco-design analysis revealed that one material was the most environmentally friendly compared to the others. From a mechanical strength perspective, one material with better performance was selected. By combining the two analyses, one material was identified that meets both environmental and mechanical requirements. These findings can be used to guide future research and development in brake pad design, with the goal of reducing the environmental impact and improving the safety of brake pads for all users.**

Index Terms: **Eco-design, LCA, CAD sustainability, mechanical strength, brake pads.**

I. INTRODUCTION

The concern of designing environmentally sustainable products is becoming a necessity by the day. Engineers are willing to guide their products to be more environmentally benign using systematic procedure. Motivated by this fact, in this paper, the analysis is concerned with the investigation of different materials utilized for making brake pads. The assessment is generally employed throughout the lifecycle of products, from raw material extraction to final disposal.

Eco-design can be defined as a product assessed to reduce the environmental impacts in its life cycle stages by incorporating environmental requirements into design activities [1]. Life cycle assessment (LCA) is a common used tool for eco-design. A few research in eco-design has been achieved considering life cycle assessment and mechanical analysis for products. Russo and Rizzi [2] have developed an eco-design approach based on integrating computer aided design (CAD) sustainability, functional modeling and LCA to support designers through the environmentally sustainable redesign of products. In the research a simulation tool based SolidWorks module was used to optimize strength and minimize impacts. While the use of LCA has been focused on assessing products for environmental performance [3], many researchers have recognized that LCA can be used as an optimization tool to combine life cycle issues into design practice and optimization processes [4,5]. Taha et al. [6] used a CAD model of a product with some design scenarios to analyze the energy consumption of the machining process for the manufacturing phase. This paper aims to promote the applicability of the eco-design scheme by selecting brake pads as a case example of eco-design application, and conducting a systematic procedure for mechanical analysis. In particular, the research objectives are set as follows:

- develop a systematic procedure for environmental impact assessment of brake pads using LCA and SolidWorks sustainability package
- perform a mechanical strength analysis of the brake pads using the finite element package ANSYS and find out selected materials performance from the mechanical strength perspective
- combine both analyses to identify the pad material that meets both environmental and mechanical requirements

II. OVERVIEW OF THE BRAKE PADS

The brake rotor is an important system in automobile vehicles. The system consists of several components, the brake pad is one of the main components of the system, in which the function of the brake system is based on, as shown in Figure 1. The mechanism of this system begins when the brake pedal is pressed, at this time the master cylinder sends fluid under pressure to the brake caliper, which carries the brake pads, and the caliper begins to press the brake pad against the rotor brakes, which causes friction. This action occurs during normal use of the brakes, and over time the brake pads wear out and become thinner. Once the thickness of the brake pad reaches less than 3 mm, the car driving becomes unsafe. Therefore, once this is noticed, the brake pad should be

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replaced [7]. These parts are exposed to damage and wear faster as a result of driving in crowded cities and the selection of the used material might be not appropriate. Since years ago, several materials have been used to meet the sustainability requirements, such as: good corrosion strength, good thermal conductivity, low weight, long durability, steady friction, and low wear rate. Furthermore, it becomes essential to develop efficient products in terms of environmental performance.

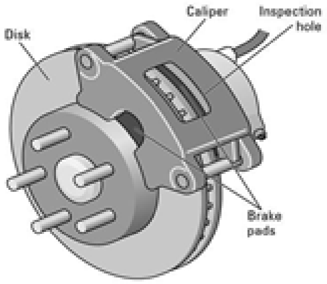

Figure 1. The brake rotor assembly [8]

III. DEVELOPMENT OF A CAD MODEL FOR THE BRAKE PADS

Using SolidWorks software, the brake pads components can be modeled and disassembled to conduct the analysis and assessment to the components. The brake pad consists of two parts: part 1 which is the base part composed of a steel backing plate, and part 2 bound to its surface that is in contact with the brake disc. Part 2 is the focus of assessment of this research. The brake pad is shown in Figure 2. The brake pad used in this paper is considered made of four types of materials; Aluminum Bronze alloy, Carbon fiber, Ceramic porcelain, and E-glass fiber. These materials were chosen as they are the most commonly used in the manufacturing of brake pads [9, 10, 11, 12].

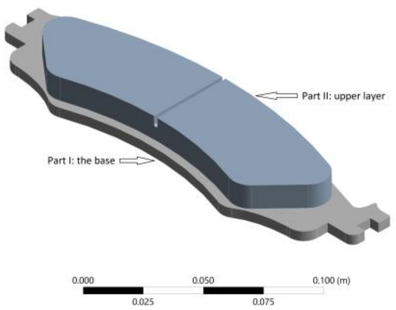

Figure 2. Brake pad model.

IV. ENVIRONMENTAL IMPACT ASSESSMENT USING DIFFERENT MATERIALS

In the brake pad, the original material of part II is aluminum bronze. In the assessment, aluminum bronze as an original material is compared with another three materials, carbon fiber, ceramic porcelain and E-glass fiber to select the best material for environment. The comparisons are presented to three different cases. The three assessed materials are compared in terms of carbon footprint CO2, total energy consumed, air acidification SO2 and water eutrophication PO4. The considered life cycle of the assessment are material, manufacturing, transportation and end of life.

A. *Case 1: Carbon Fiber*

Carbon fiber is regarded one of the most common composite materials used in the engineering applications as a promising material for environment. The results of the assessment after using carbon fiber compared to aluminum bronze are shown in Figure 33. The results show that carbon fiber as non-metallic material achieved relative reductions in carbon emissions, air acidification and water eutrophication. It shows that relative improvements were realized as the carbon emissions was reduced to 21%, and the air acidification significantly was improved to 87%. In addition, water eutrophication reduced by 38 %. Whereas, the total energy consumption was increased by 32%.

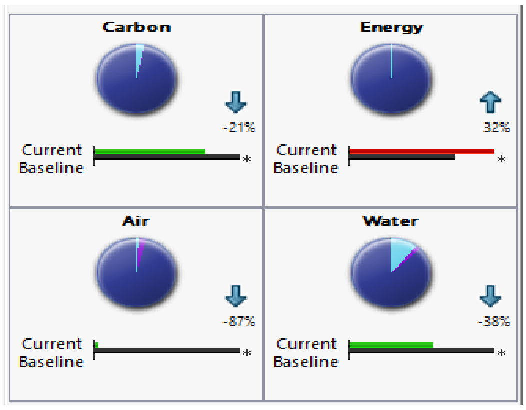

Figure 3. Environmental impacts of carbon fiber compared to aluminum bronze.

B. *Case 2: Ceramic Porcelain*

It is demonstrated in industry that ceramic porcelain is one of the most environmentally friendly options. Figure 44 shows the environmental impact assessment of the ceramic porcelain. It achieved a significant reduction in the overall environmental impacts compared to the aluminum bronze, where the four indicators show high improvements. The air acidification was improved by 98%, total energy consumed improved by 96%, carbon emissions went down to 94%, and water eutrophication reduced to 88%.

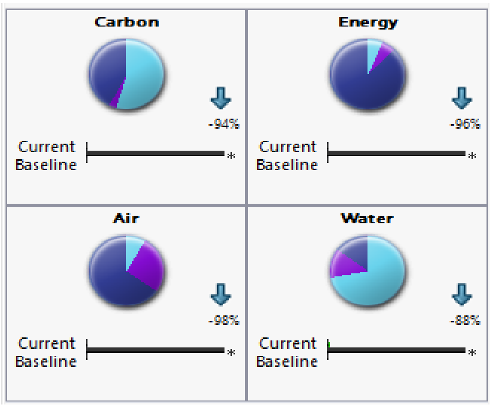

Figure 4. Environmental impacts of ceramic porcelain compared to aluminum bronze.

C. Case 3: E-Glass Fiber

E-glass fiber is a good choice for environmental impacts reductions, in particular, for energy reduction. The results show that E-glass fiber overall reached fewer environmental impacts compared to the original material (aluminum bronze). The improvement was a 59% reduction in carbon footprint, a 61% improvement in total energy consumption, a 79% drop in air acidification, and a 45% decline in water eutrophication. The results are summarized in Figure 55.

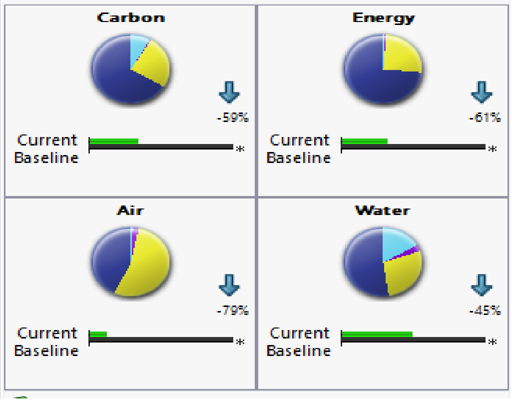

Figure 5. Environmental impacts of E-Glass fiber compared to aluminum bronze.

V. COMPARISON OF LIFE CYCLE ASSESSMENT

Table 1 summarizes the results of the assessment that are obtained by the SolidWorks sustainability software. The compared materials are suggested to be used as a component of part II (upper layer) of the brake pad. The results show a significant variance of environmental impacts between the original material and the new recommended materials. According to the results of the assessment, it is clear that ceramic porcelain is the safest material for the environment, which achieved an important improvement for the all environmental measures. For example, the carbon footprint CO2 improved to be 0.201 kg instead of 3.6 kg, energy consumption is reduced to 1.3 MJ, air acidification SO2 is reduced to 7.9E-4 kg, and water eutrophication PO4 is improved to 1.5E-4 kg. Likewise, E-glass fiber realized the second top in terms of the appropriately to the environment.

Table 1. Environmental assessment results of different materials.

Environmental impacts	Aluminum bronze	Ceramic porcelain	Carbon fiber	E-glass fiber
Carbon Footprint CO_2	3.6 kg	0.201 kg	2.8 kg	1.5 kg
Total Energy Consumed	37 MJ	1.3 MJ	49MJ	14 MJ
Air Acidification SO_2	0.045 kg	7.9E-4 kg	5.7E-3 kg	9.6E-3
Water Eutrophication PO_4	1.3E-3 kg	1.5E-4 kg	8.0E-4 kg	7.1E-4 kg

VI. MSCHANICAL STRENGTH ANALYSIS

The four materials proposed as environmental-friendly and considered in the analysis are as shown in Table 1. The mechanical parameters of these materials are given in Table 2. The brake pad is mounted on a bed made of structural steel, and is the one utilized in Ford Explorer 2010 model, chosen as a study case. It is important to mention that the yield strength of ceramic porcelain is difficult to measure. Ceramics tend to fracture before entering the plastic deformation region because they are brittle materials. Thus, its yield strength value is somewhat approximate and correctly represents its compression strength rather than tensile strength.

Table 2. The mechanical properties of the four used brake pad materials.

Material	Density kg/m3	Young's modulus Pa	Poisson's ratio	Tensile yield strength Pa	Tensile ultimate strength Pa
Structural steel	7800	2.0E11	0.28	1.72339E8	5.13613E8
Aluminum bronze	7400	1.1E11	0.3	2.75742E8	5.51485E8
Carbon fiber	1780	2.9E11	0.2	2.5E9	3.5E9
Ceramic porcelain	2300	2.2059E11	0.22	2.9E7	1.7234E8
E-Glass fiber	2440	7.6E10	0.2	3.4E9	4.3E9

The modeling is performed using Finite Element Analysis (FEA) in ANSYS simulation platform. The purpose of the simulation is to study the behavior of the brake pad made of these different materials when subjected to a shear pressure caused by the braking system. A shear pressure of 1000 MPa is applied to the upper surface of the brake pad in the positive x-direction, to simulate the braking force, see Figure . There is no nominal shear stress that can be utilized as a load in brake pads analysis, as the value depends on several factor such as type of brake system, specific application, and operational conditions. However, in general, the nominal shear stress typically ranges from tens of MPa to hundreds MPa [13]. The value chosen is considered the worst-case scenario.

The thickness of the brake pad used in the analysis is 12mm, which is the average thickness usually manufactured. The pad bed is considered totally fixed at its bottom surface. The FEA model, of the brake pad with the pad bed that it sits on, using brick element called SOLID187, and the mesh consists of 22944 elements and 52792 nodes, as shown in Figure 6.

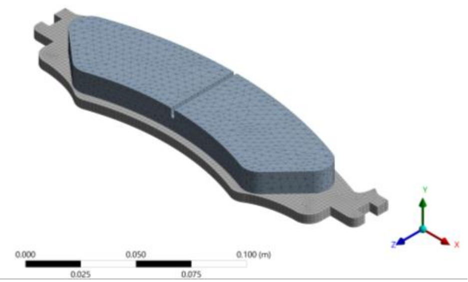

Figure 6. Finite elements mesh of the brake pad system.

The results obtained from the structural static analysis, performed using each type of the mentioned pad materials, are demonstrated in what follows. All analysis is performed considering room temperature environment. The static behavior of the pad is definitely highly sensitive to its temperature, but the purpose of this investigation is to compare the static behavior of different materials regardless of temperature change.

A. Aluminum bronze pads

The resulting deformations and equivalent von Mises stresses are shown in the figures below. Higher deformations and stresses are observed at the tips of the pad, see Figure 77. A maximum deformation of 5.98e-7 m is observed, with a maximum stress of ~7.6x106 Pa. The shear stresses are also calculated and a maximum value is observed to be ~3.5x106 Pa at the first tip of the pad structure.

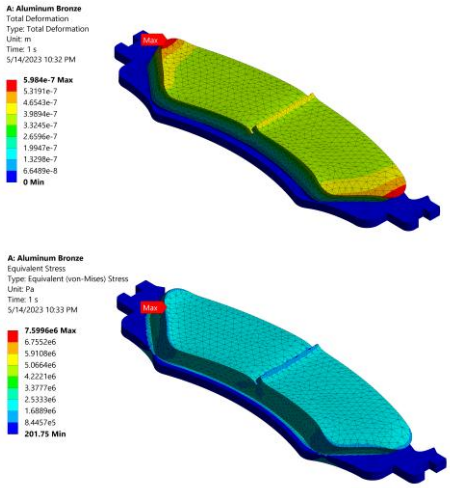

Figure 7. Deformation and von Mises stress in the Aluminum Bronze pad.

B. Carbon fiber pads

Figure 8 shows the deformations and equivalent stresses. The maximum deformation, localized at the tip, is equal to 2.76e-7 m, which is about one half of the Aluminum Bronze case, and with higher equivalent stresses at the same location, of 9.04x106 Pa, and a maximum shear stress of 4.23x106 Pa at the same area on the pad.

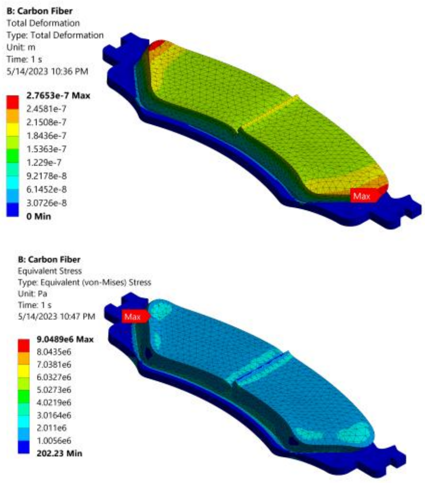

Figure 8. Deformation and von Mises stress in the Carbon fiber pad.

C. Ceramic porcelain pads

Figure 99 shows the deformations and equivalent stresses in this case. The maximum deformation and maximum stress are found equal to 3.38e-7 m and 8.61x106 Pa, respectively, which are somehow not very different from the Carbon Fiber case.

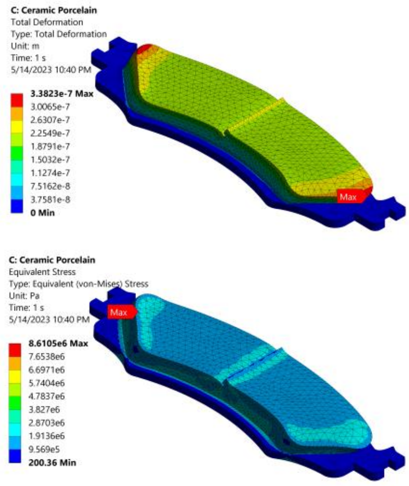

Figure 9. Deformation and von Mises stress in the Ceramic porcelain pad.

D. E-Glass fiber pads

Figure 10 shows the deformations and equivalent stresses. The maximum deformation and maximum stress are found equal to 8.2e-7 m and 5.13x106 Pa, respectively. The deformation behavior is somewhat between the Carbon Fiber and the Aluminum Bronze materials.

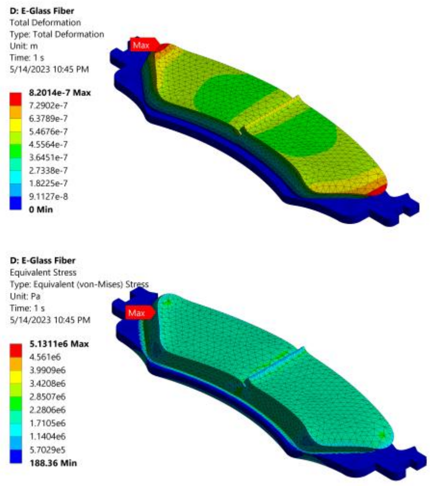

Figure 10. Deformation and von Mises stress in the E-Glass fiber pad.

Comparing the results for all these types of pads and their mechanical behavior, Table 3 summarizes the outcome. The Factor of Safety (FoS) is also calculated, which is an indication of the ratio of the strength of the used material to the maximum stress in the analyzed product made of that material. It is an indication of how safe the used material is in terms of stress behavior, so the higher the value the better is the design. The maximum possible FoS in ANSYS is 15.

Table 3. Comparison of the static behavior in all types of analyzed pads.

Property	Aluminum Bronze	Carbon Fiber	Ceramic Porcelain	E-Glass Fiber
Total Deformation, m (Max)	5.9840E-07	2.7653E-07	3.3823E-07	8.2014E-07
Equivalent (von Mises) Stress, Pa (Max)	7.5996E06	9.0498E06	8.6105E06	5.1311E06
Shear Stress, Pa (Max)	3.5025E06	4.2337E06	3.9794E06	2.3741E06
Equivalent total Strain, m/m (Max)	6.9542E-05	3.1332E-05	3.9217E-05	6.8243E-05
Factor of Safety (Min)	15	15	3.2347	15

Theoretically, the higher the stress value, the higher the friction rate, and thus the higher the braking ability, not considering other factors such as the temperature rise. The more effective stress type in this case is the shear stress, as friction forces act on the direction parallel to the pad surface. The deformation distribution is also an important factor in the analysis. In addition to this analysis, a wear analysis would be recommended, which highly depends on the type of material used. Brake pads with high friction rate is always an advantage, but pads should also have resistance to degradation, especially at brusque braking cases [14]. If a more thorough analysis is desired, then a squeal analysis is needed to study the level of noise the brake pads produce. Different materials produce different squeal levels.

When the obtained results are examined, from the mechanical point of view, ceramic porcelain seems to be the worst choice among these four materials if the FoS is taken as an indicator. Nevertheless, this factor is based on the yield strength of ceramic porcelain and this is usually difficult to measure due to its very low plastic deformation susceptibility. On the other hand, Carbon fiber is the choice, as it has the highest shear stress, which means a high friction rate, and has the lowest deformation of 2.7653E-7 m.

VII. CONCLUSIONS

This study highlights the integration of eco-design and mechanical strength analysis as an important approach for developing environmentally friendly and mechanically safe brake pads. Four types of brake pad materials are analyzed in this study to satisfy certain criteria, including high temperature, pressure, tensile stresses, and decreased wear rate, while also incorporating eco-friendly materials. These four materials are commonly used in the manufacturing of brake pads. The results of the eco-design analysis showed that ceramic porcelain is the safest material for the environment.

However, it should be noted that ceramic porcelain might not be selected with regard to its mechanical strength properties, specifically its relatively low factor of safety. Nevertheless, the yield strength of ceramic porcelain is usually difficult to measure due to its very low susceptibility to plastic deformation. Thus, ceramic porcelain could be chosen, given its yield strength is accurately measured and is high enough to enhance its mechanical strength. On the other hand, ceramic porcelain has a relatively high shear stress of 3.9794E6 Pa, which means a high friction rate, and a relatively low deformation of 3.3823E-7 m. Our scientific outcome suggests that, when considering off-the-shelf options, ceramic porcelain emerges as a preferred choice for the manufacturing of brake pads, provided that its mechanical properties are thoroughly verified.

Overall, the findings presented in this paper can serve as a guide for further research in the area of brake pad design, particularly for more in-depth investigations into the mechanical properties of ceramic porcelain. With further research, it may be possible to develop even more effective and sustainable brake pad materials to ensure safer and more environmentally-friendly driving experiences.

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