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Influence of Material Properties on the Durability of Automotive Hydraulic Brake Discs: A Finite Element Analysis Approach

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ABSTRACT

The brake system in automobiles is critical for ensuring both safety and operational efficiency, enabling the vehicle to reduce speed or come to a complete stop when required. Among the components of the brake system, the brake disc plays a pivotal role, undergoing regular operation and being subjected to considerable mechanical stresses, thermal fluctuations, and wear. As such, ensuring the durability of the brake disc is paramount for the overall performance and safety of the vehicle. This study investigates the influence of different materials on the durability of automotive hydraulic brake discs by evaluating stress, deformation, heat generation, and safety factors. A 3D model of the brake disc was developed using SolidWorks, and the finite element method (FEM) was employed to analyze the system's response under operational conditions using ANSYS. The results indicate that the gray cast iron material demonstrates the most favorable performance, exhibiting a deformation of 0.03987 mm, a maximum stress of 57.457 MPa, a heat generation of 67.363°C, and a safety factor of 3.1328. These findings suggest that gray cast iron is a viable material for manufacturing brake discs, offering a balance of mechanical strength, thermal management, and durability. This study provides a foundational understanding of material properties for the design and mass production of automotive brake discs, contributing to the development of safer and more efficient braking systems.

1. INTRODUCTION

The structure of the hydraulic disc brake system on a car consists of two main parts: the control mechanism and the disc brake assembly. The control mechanism uses hydraulics to create pressure to control the disc brake assembly [1]. When the braking system operates, the pressure from the master cylinder leads to the slave cylinder, and the brake disc generates a large amount of heat due to the pressure exerted by the piston of the slave cylinder caused by the friction between the brake disc and the brake pad. During the braking process, the temperature of the brake pads and discs can reach up to 900°C [2]. The phenomenon of brake discs overheating during braking can lead to various types of plastic deformation, causing the brake discs to vibrate, resulting in deformation and creating cracks due to the continuous process of heat absorption and dissipation [3]. Therefore, it is necessary to have a solution to improve the quality of brake discs to improve braking efficiency and increase the reliability of the braking system under working conditions. This can limit risks, ensuring safety for people and property.

Until now, there have been many studies related to the temperature analysis of braking systems. Belhocine and Bouchetara [4] discussed the thermal analysis and heat dissipation of the braking system using the FEM and ANSYS 11 software for analysis. The results obtained show that the FG 25 AL cast iron has a higher temperature than the other two types of cast iron, FG 20 and FG 15, under the same simulation conditions. On the other hand, the importance of radial vents in significantly reducing the amount of heat generated during the braking process can be observed, thereby laying the groundwork for further studies on stress, displacement, and so on.

In addition to the above studies, Ahmed et al. [5] used Autodesk Inventor 2019 software to design different 3D-shaped brake discs for Bajaj Pulsar, and used ANSYS to analyze the factors affecting the brake disc, such as weight, stress, temperature and deformation, to determine the optimal structure to increase the quality of the brake disc before putting it into use. Moreover, Chaturvedi et al. [6] studied the temperature analysis of three types of materials by modeling with AutoCAD and using ANSYS for simulation. The temperatures of three types of materials, namely, AL356, SS420, and gray cast iron, were analyzed. The results showed that aluminum has the highest thermal conductivity, making it the most effective heat dissipation material among the types studied. Along with that, Pain et al. [7] redesigned the brake model and used SolidWorks software for the design and ANSYS for thermal and stress simulation of the brake disc.

Furthermore, several studies have used different simulation software to build 3D models of brake discs and applied the FEM to analyze the stress and deformation of the discs corresponding to different materials using ANSYS [8-10]. Yildiz and Duzgun [11] presented different shapes of brake discs with ventilation holes and cross grooves to compare with solid brake discs in terms of stress while applying the braking force differently along the brake pads. The research results showed that the stress on the brake disc with ventilation holes was reduced.

Research on brake discs is still of great interest and attention to the world in order to improve their efficiency and durability. Currently, brake disc materials are also very diverse, but it is necessary to consider their safety factor before putting them into production. Therefore, the study focuses on analyzing stress, deformation, heat generation and safety factor corresponding to different types of materials using ANSYS through the 3D model of the brake disc built with SolidWorks.

2. CALCULATION AND MODEL BUILDING

For problems related to the durability of parts, mathematical methods can be used to solve them. However, this is useful for simple parts, when they are simulated in the form of mathematical equations. For complex parts, it is necessary to use the FEM based on simulation software. The component needs to be evaluated for different materials. The procedure is illustrated in Figure 1.

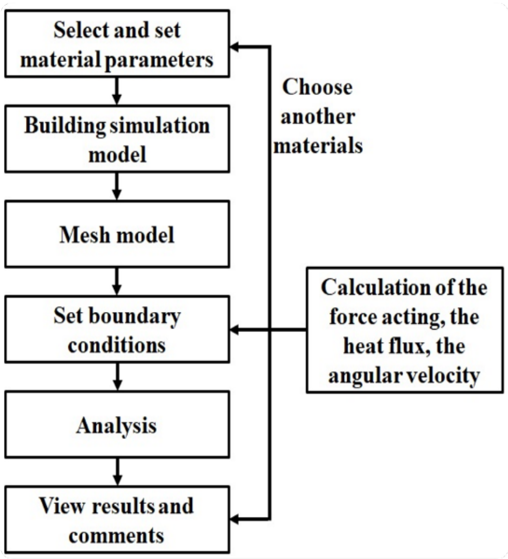


Figure 1. FEM application process

Before conducting FEA, a model of that part must be built. Based on the structural parameters of the disc brake of a passenger car and the simulation of the size similar to the research results [12], SolidWorks was applied to build a 3D model of the disc brake, as shown in Figure 2.

According to the operating principle of the hydraulic disc brake system, when the car starts to brake, the oil pressure is transmitted from the control mechanism to the disc brake assembly and the disc brake piston pushes the brake pad to press tightly against the brake disc. When the braking pressure is large enough, it can cause the disc brake caliper assembly to move in the opposite direction to the brake piston, and the remaining brake pad presses tightly against the brake disc to help the braking process occur.

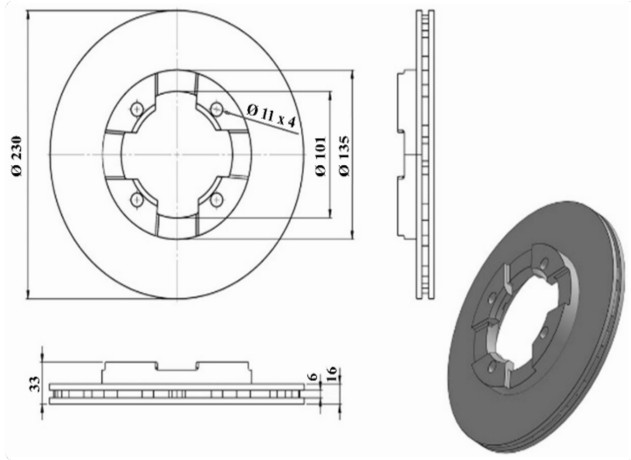


Figure 2. Car brake disc model

Therefore, it is necessary to determine the braking force acting on the brake disc. First, the coordinates of the car's center of gravity [13] were determined according to the following Eq. (1):

$$a = L * 43\%, b = L - a, h_g = H * 37\% \tag{1}$$

The force acting on the brake disc [14, 15] was calculated, as shown in Eq. (2):

$$F_A = \frac{m_V g * (b + z_T * h_g)}{L}, \\ \varphi_A = \frac{z_T + 0.07}{0.85}, F_w = \frac{\varphi_A * F_A}{2} \tag{2}$$

After calculating the required braking force for a wheel, the materials commonly used to manufacture brake discs, such as aluminum alloy, gray cast iron, stainless steel, aluminum-copper alloys [16-23], were chosen. The parameters are presented in Table 1.

Table 1. Material properties

Material	AA	GCI	SS	ACA
Density (kg/m^3)	2700	7200	7610	2840
Thermal conductivity (W/mC)	171	52	15.1	121
Friction coefficient	0.23	0.28	0.57	0.29
Specific heat capacity (J/kgC)	897	490	480	963
Tensile yield strength (MPa)	480	180	380	485
Poisson's ratio	0.33	0.27	0.31	0.33
Elastic stress (GPa)	69.7	720	195	71

Note: AA indicates aluminum alloy, GCI indicates gray cast iron, SS indicates stainless steel, and ACA indicates aluminum-copper alloys.

When the brake pads rub against the brake disc, heat can be generated. The temperature is too high and can affect the braking efficiency. Therefore, so it is necessary to determine this value to choose the appropriate manufacturing material. Then the heat flux (HF) [17] corresponding to each material was calculated by Eq. (3):

$$A_d = \pi * \left(R_1^2 - R_2^2\right),$$

$$Q = m_{db} \times c_P \times \Delta T, HF = \frac{Q}{t.A_d} \quad (3)$$

Moreover, the angular velocity [24] of the wheel with tire parameters 165/70 R13 was calculated as:

$$r_W = \lambda * \left(W * S_C + d * 25.4 / 2\right), \omega_T = \frac{V}{r_W} \quad (4)$$

The basic parameters of the car are described in Table 2.

Table 2. Specifications of car

Symbols	Value	Symbols	Value
m_V	1345	m_{db}	1.66
V	100	ΔT	20
L	2.3	t	2
H	1.4	W	165
z_T	0.61	λ	0.92
ϕ_A	0.8	S_C	70
g	9.81	d	13
$D_{1,2}$	230;135		

The above presentation determines the force acting on the wheel, HF on the brake disc and angular velocity of tire.

3. SIMULATION RESULTS

In this section, the FEM was used in this study to analyze the deformation, stress, heat generated and safety factor corresponding to each type of material. There are many different ways to solve problems using this method. If the research object is simple, it is possible to use functions to represent the models. However, the case of the object to be analyzed in study is quite complicated. To determine the change of each point on the brake disc, it is necessary to separate it into small areas for analysis. This step is called meshing the model, which was conducted by ANSYS, as shown in Figure 3.

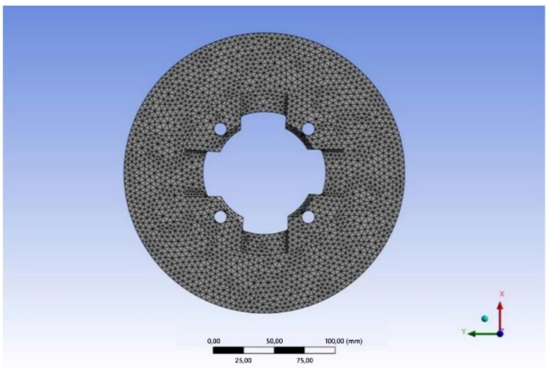


Figure 3. Brake disc meshing model

Figure 4 below shows the model input parameters, also known as boundary conditions. These values were calculated from the above equations and are presented in Table 3.

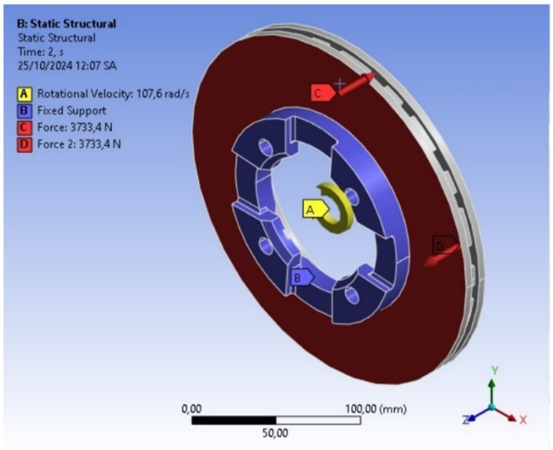
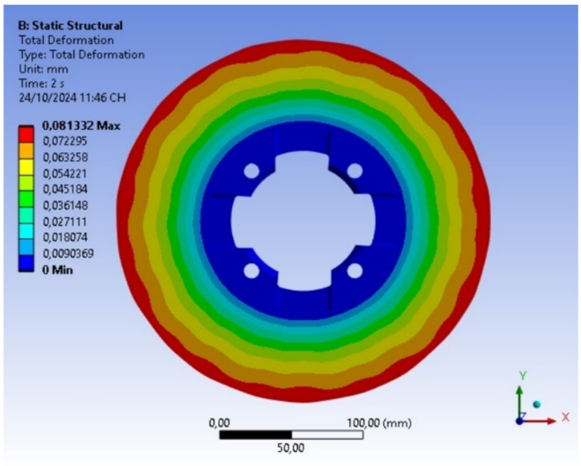


Figure 4. Model input parameters

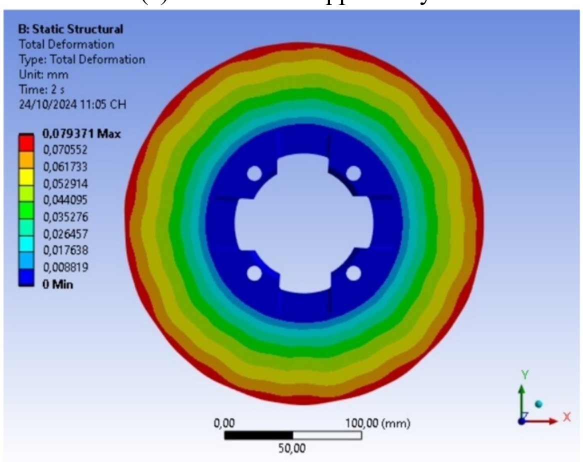
Table 3. Input parameter values

Symbols	Value	Symbols	Value
F_W	3733.41	HF_{SS}	292578.88
HF_{AA}	546756.78	HF_{ACA}	586986.37
HF_{GCI}	298674.27	ω_T	107.602

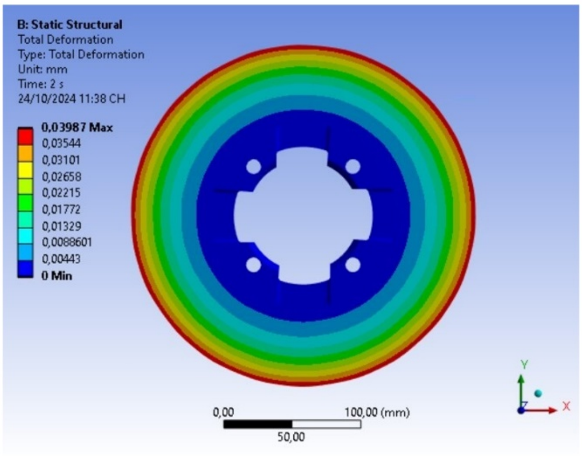
After meshing and setting the boundary conditions, simulation was finally conducted to collect data related to the process of selecting materials for manufacturing the brake disc. The simulation results of deformation, stress, the generated heat and safety factor are shown in Figures 5-8.



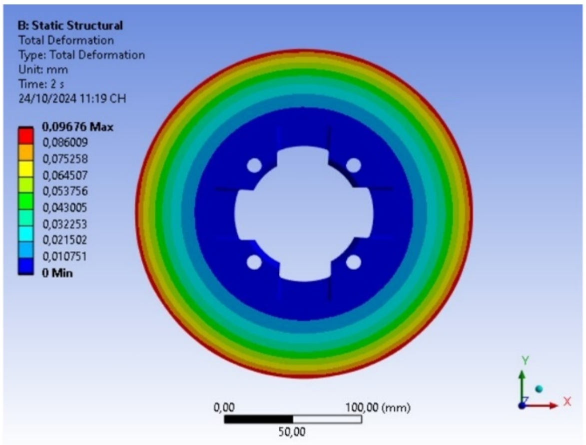
(a) Aluminum-copper alloys



(b) Aluminum alloy



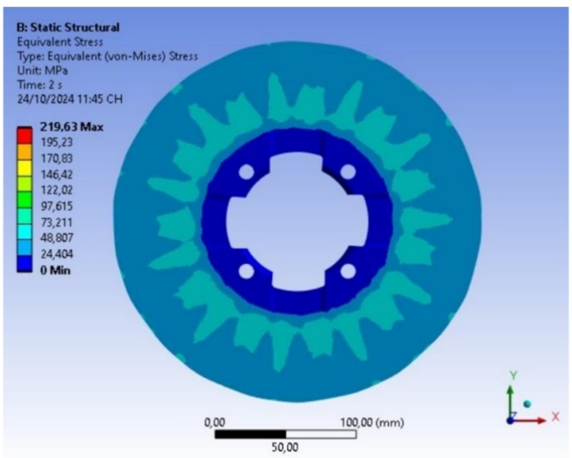
(c) Gray cast iron



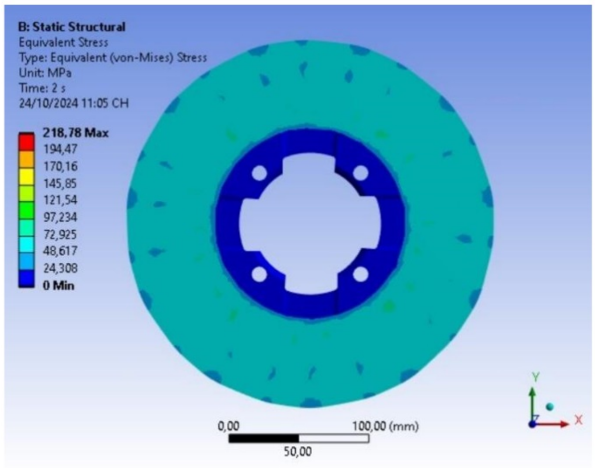
(d) Stainless steel

Figure 5. Simulation results of brake disc deformation

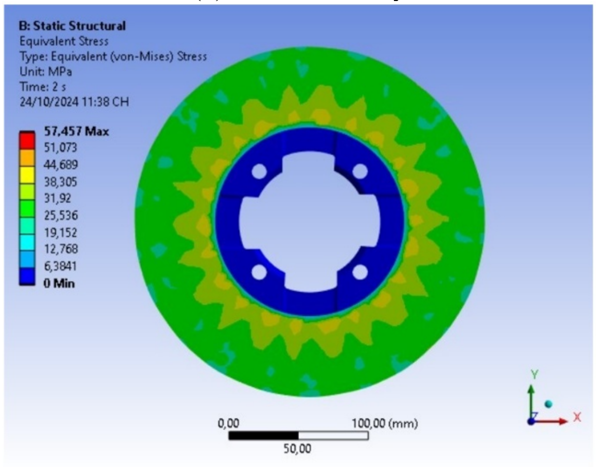
The analysis in Figure 5 shows that the deformation increases gradually from the center to the outer edge of the brake disc. The red position on the brake disc is the largest position, the blue position has the smallest value. Besides, the gray cast iron material used to make the brake disc has the smallest value of 0.03987 mm, and the largest is the stainless steel material of 0.09676 mm. The stress simulation results of the brake disc in Figure 6 display that the aluminum-copper alloy brake disc has the highest stress of 219.63 MPa, and the gray cast iron brake disc has the lowest stress of 57.457 MPa. The most concentrated stress is around the wheel hub, the further away the stress decreases.



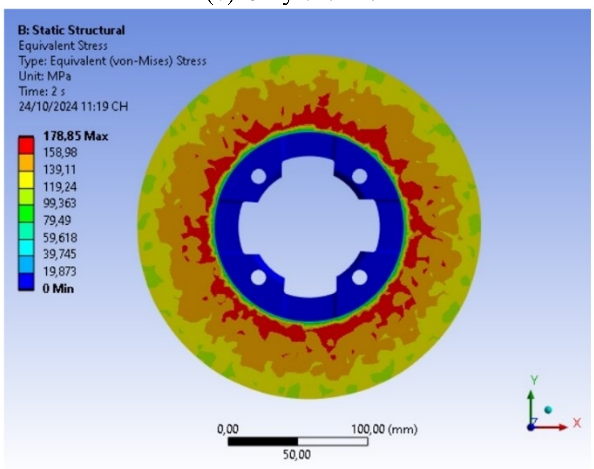
(a) Aluminum-copper alloys



(b) Aluminum alloy



(c) Gray cast iron

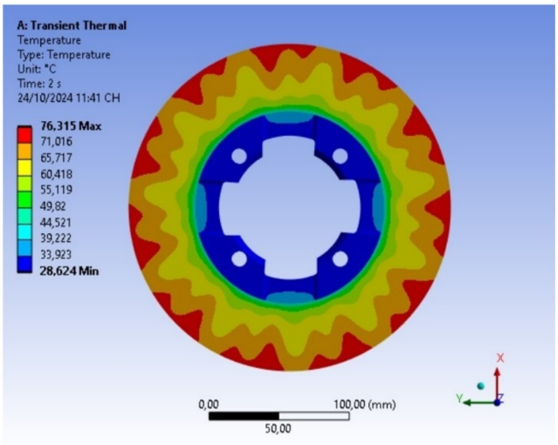


(d) Stainless steel

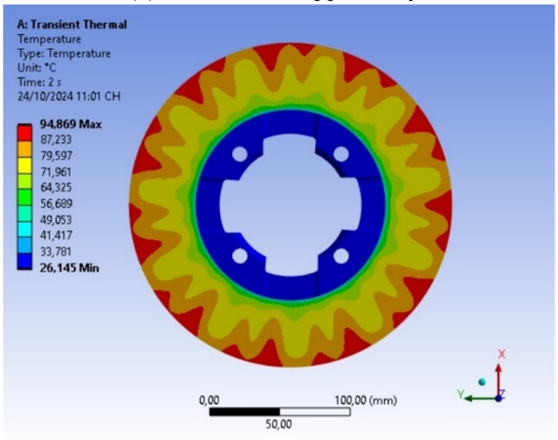
Figure 6. Simulation results of brake disc stress

The stress simulation results of the brake disc in Figure 6 display that the aluminum-copper alloy brake disc has the highest stress of 219.63 MPa, and the gray cast iron brake disc has the lowest stress of 57.457 MPa. The most concentrated stress is around the wheel hub, the further away the stress decreases.

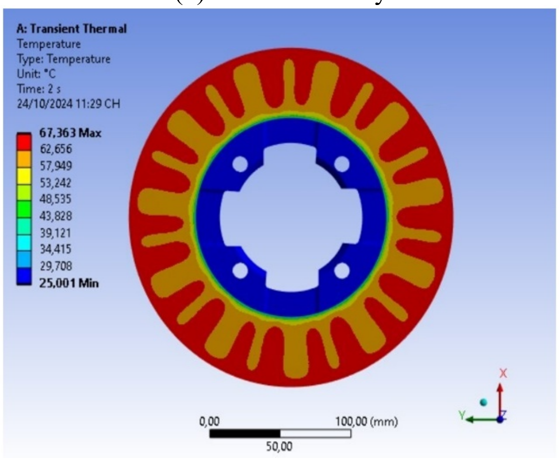
The heat generated on the brake disc after friction with the brake pad is indicated in Figure 7. The heat generated increases gradually from the center of the disc to the outer diameter of the disc. The highest temperature is 94.869°C for the aluminum alloy brake disc, the lowest is 67.363°C for the gray cast iron brake disc.



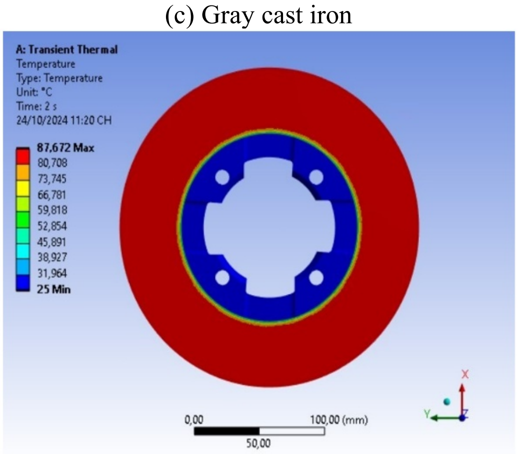
(a) Aluminum-copper alloys



(b) Aluminum alloy

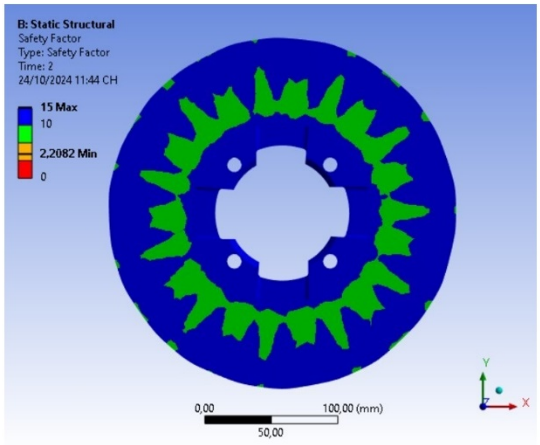


(c) Gray cast iron

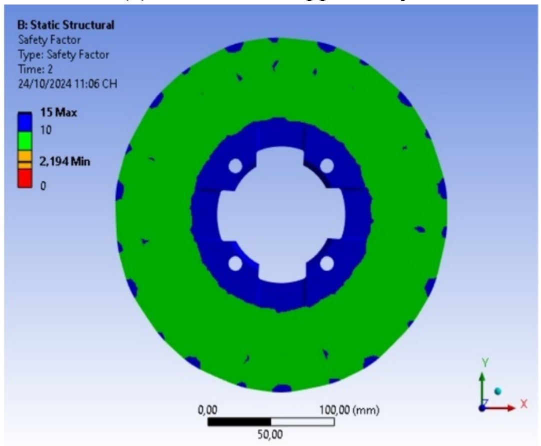


(d) Stainless steel

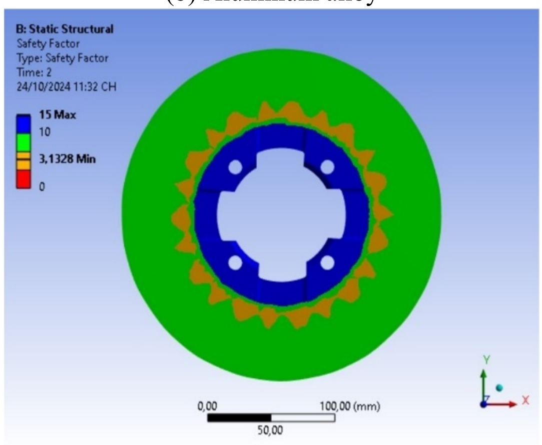
Figure 7. Simulation results of heat generation of brake disc



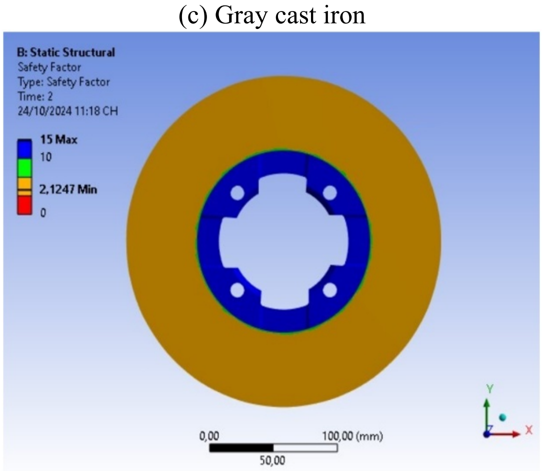
(a) Aluminum-copper alloys



(b) Aluminum alloy



(c) Gray cast iron



(d) Stainless steel

Figure 8. Simulation results of safety factor of brake disc

The final factor to consider is the safety factor, as defined in Figure 8. The meaning of safety factor is the ability of a system or component to carry a load greater than the expected load. The gray cast iron brake discs have the highest safety factor of 3.1328, and the stainless steel brake discs have the lowest safety factor of 2.1247.

After analyzing the simulation factors, the resulting values of four types of materials used for brake discs, namely, aluminum alloy, gray cast iron, stainless steel, and aluminum-copper alloys, are listed in Table 4.

Table 4. Values of simulation results

Material	AA	GCI	SS	ACA
Deformation (mm)	0.079371	0.03987	0.09676	0.081332
Stress (Mpa)	218.78	57.457	178.85	219.63
Temperature (°C)	94.869	67.363	87.672	76.315
Safety factor	2.194	3.1328	2.1247	2.2082

Note: AA indicates aluminum alloy, GCI indicates gray cast iron, SS indicates stainless steel, and ACA indicates aluminum-copper alloys.

For the brake system on the car, the top priority is braking efficiency and long-term use, in which the brake disc plays a very important role. Several factors must be ensured, including low wear and low heat generation, so that its surface does not become hard and burn to reduce braking efficiency. Therefore, based on the values of Table 4, among all analyzed materials, this study recommends choosing the gray cast iron material to manufacture the brake disc because it has a low deformation of 0.03987 mm and a low heat generation of 67.363°C. In addition, the high safety factor of gray cast iron is 3.1328 to ensure stable operation of the brake disc even though its stress is lower than other materials. However, this does not affect braking efficiency because stress only represents the internal force value inside the brake disc when it is deformed by braking force. Therefore, the greater the stress, the greater the deformation and vice versa. Similar to the results of several studies [25, 26], the suggestion about the selection method in the study is appropriate.

4. CONCLUSIONS

The main objective of this study is to determine the type of material used to manufacture disc brakes to ensure efficiency and long-term use of the brake system. Four types of materials, namely, aluminum alloy, gray cast iron, stainless steel, and aluminum-copper alloy, were used in this study to manufacture brake discs. The study used SolidWorks to build a 3D model of the brake disc, and then applied ANSYS to analyze the durability of the disc through stress, heat dissipation and deformation values. In addition, the study also determined the safety factor to increase the accuracy and manufacturing cost when selecting materials. This study used four factors to draw the final conclusion that gray cast iron is recommended for manufacturing brake discs on cars because this material ensures the necessary durability and reduces manufacturing costs compared to other materials. This result contributes to future research related to brake discs or can improve in terms of design. In addition, it also helps factories to create new ideas about the use of manufacturing materials in the automotive industry.

REFERENCES

[1] Barik, N., Khadari, S.A.R. (2021). Analysis of disc brake. IOP Conference Series: Materials Science and Engineering, 1123: 012004. https://doi.org/10.1088/1757-899X/1123/1/012004

[2] García-León, R.A., Flórez-Solano, E., Rodriguez-Castilla, M. (2019). Thermo-mechanical assessment in three auto-ventilated disc. Journal of Physics: Conference Series, 1257: 012019. https://doi.org/10.1088/1742-6596/1257/1/012019

[3] Deshpande, S., Kamat, A., Dalvi, R., Deshpande, Y. (2017). Review on thermal cracking phenomenon in brake disc. International Journal of Engineering Research & Technology, 6(6): 233-236.

[4] Belhocine, A., Bouchetara, M. (2011). Study of the thermal behaviour of dry contacts in the brake discs «application of software Ansys v11.0». Mechanics, 17(3): 271-278. https://doi.org/10.5755/j01.mech.17.3.502

[5] Ahmed, A.A., Kumar, V.A., Gokul, S., Vijay, P., Parthasarathy, C. (2020). Design and analysis of disc brake rotor using different profiles. International Journal of Engineering Applied Sciences and Technology, 4(9): 286-293. https://doi.org/10.33564/ijeast.2020.v04i09.037

[6] Chaturvedi, K., Pandey, K., Siddiqui, M.A., Burarak, K., Prabu, S.S. (2023). Comparative study on thermal analysis of disc brake using ANSYS simulation. AIP Conference Proceedings, 2869: 040015. https://doi.org/10.1063/5.0168487

[7] Pain, P., Chakraborty, A., Dewan, D. (2020). Development of braking system in automobiles. International Research Journal of Engineering and Technology, 7(3): 2250-2258.

[8] Reddy, V.C., Reddy, M.G., Gowd, G.H. (2013). Modeling and analysis of FSAE car disc brake using FEM. International Journal of Emerging Technology and Advanced Engineering, 3(9): 383-389.

[9] Balu, L.C., Rajendra, R. (2023). Analysis of disc brake with composite materials. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.07.288

[10] Sainath, A., Dehadray, P.M., Bharath, P., Rao, L.B. (2021). The thermal and stress analysis of disc brake. IOP Conference Series Materials Science and Engineering, 1128: 012015. https://doi.org/10.1088/1757-899X/1128/1/012015

[11] Yildiz, Y., Duzgun, M. (2010). Stress analysis of ventilated brake discs using the finite element method. International Journal of Automotive Technology, 11: 133-138. https://doi.org/10.1007/s12239-010-0018-0

[12] Sayeed Ahmed, G.M., Algarni, S. (2018). Design, development and fe thermal analysis of a radially grooved brake disc developed through direct metal laser sintering. Materials, 11(7): 1211. https://doi.org/10.3390/ma11071211

[13] Lee, M.S., Kim, S.S. (2010). A experimental study on the measurement and estimation of vehicle center of gravity. Transactions of the Korean Society of Automotive Engineers, 18(5): 91-99.

[14] Xu, J., Zhang, X. (2016). Optimization algorithm for vehicle braking force distribution of front and rear axles based on brake strength. In 2016 12th World Congress on Intelligent Control and Automation (WCICA), Guilin,

China, pp. 3353-3360. https://doi.org/10.1109/WCICA.2016.7578257
[15] Mathad, M., Kohli, A., Hombalmath, M., Kakol, B., et al. (2022). Non-linear structural and thermal analysis of automotive brake disc. Materials Today: Proceedings, 59: 1221-1224. https://doi.org/10.1016/j.matpr.2022.03.426
[16] Patil, K.K., Randive, V., Mulla, S., Parit, R., Mane, S., Kadam, S. (2020). Design and analysis of single plate clutch by mathematical modelling and simulation. International Journal, 8(3), 248-252.
[17] Najmi, H., Kumar, N., Himanshu, N., Singh, A., Singh, R., Kumar, S. (2021). Thermal analysis of brake disc of an automobile. IOP Conference Series Materials Science and Engineering, 1116(1): 012146. https://doi.org/10.1088/1757-899x/1116/1/012146
[18] Tawhare, G., Kulkarni, A. (2021). Static structural analysis of brake disc for FSAE vehicle. International Journal of Advance Research, Ideas and Innovations in Technology, 7(2): 607-612.
[19] Bhat, A., Pal, B., Dandotiya, D. (2021). Structural analysis of a Two-Wheeler disc brake. IOP Conference Series Materials Science and Engineering, 1013(1): 012024. https://doi.org/10.1088/1757-899x/1013/1/012024
[20] Chheda, A.D., Hattale, R. (2020). Selection of materials for manufacturing of disc brake rotor for a racing go-kart having single hydraulic disc brake system. In Proceedings of International Conference on Intelligent Manufacturing and Automation: ICIMA 2020, pp. 435-447. https://doi.org/10.1007/978-981-15-4485-9_45
[21] Ch, D., Kiran, U.C., Kumar, V.Y. (2017). Design, Analysis and manufacturing of disc brake rotor. International Journal of Engineering Research and Development, 13(11): 15-23.
[22] Shinde, H.S. (2017). Structural analysis of disc brake rotor for different materials. International Research Journal of Engineering and Technology, 4(7): 2129-2135.
[23] El-Sheikh, H., El-Gnemi, T. (2017). Analysis of the influence of EDM parameters on material removal rate and electrode wear ratio of AL-CU. Libyan Journal for Engineering Research, 1(1): 13-23. https://doi.org/10.37376/lyjer.v1i1.285
[24] Jazar, R.N. (2017). Vehicle Dynamics: Theory and Application, 3rd edition. Springer.
[25] Wibawa, L.A.N., Tuswan, T. (2023). Effect of cylinder length on the ratio of safety factor and weight of rocket motor tube using thin-walled cylinder. AIP Conference Proceedings, 2590: 020008 https://doi.org/10.1063/5.0106235
[26] Widyanto, S.A., Kurdi, O., Haryadi, G.D., Haryanto, I., Rokhim, M.I. (2019). Stress analysis of electric bus chassis using finite element method. Journal of Physics: Conference Series, 1321: 022014. https://doi.org/10.1088/1742-6596/1321/2/022014

NOMENCLATURE

m_V	Mass of vehicle, kg
V	Vehicle speed, km.h^{-1}
L	Wheelbase of vehicle, m
H	Height of vehicle, m
z_T	Brake strength
g	Acceleration of gravity, m.s^{-2}
$D_{1,2}$	Outer and inner diameter of brake disc, mm
m_{db}	Brake disc mass, kg
ΔT	The temperature difference, °C
t	Heat generation time, s
a, b	Length from center of gravity to front and rear axle, m
h_g	Gravity height of vehicle, m
F_A	Force on the vehicle axle, N
F_W	Force on the vehicle wheel, N
A_d	Contact area of brake disc, m^2
$R_{1,2}$	Outer and inner radius of brake disc, mm
Q	The generated heat, J
c_P	Specific heat capacity, J.kg^{-1}.°C^{-1}
HF	HF, W.m^{-2}
r_W	Tire working radius, m
W	Tire width, mm
S_C	Tire height/width Ratio
d	Rim diameter, inch

Greek symbols

ϕ_A	Adhesion coefficient
λ	Tire deformation coefficient
ω_T	Tire angular velocity, rad.s^{-1}