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Friction Modeling of Composite Brake Pads with Ulin Wood Powder (*Eusideroxylon zwageri*)

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ABSTRACT

This study investigates the performance of composite brake pads made of Ulin (*Eusideroxylon zwageri*) sawdust using simulation modeling, focusing on the pressure distribution, frictional stress, and contact state in five brake pad designs (DS0 to DS4). The brake pad designs used U-shaped grooves to improve cooling efficiency and debris removal. The results show that DS1 and DS2 exhibit the most uniform pressure distribution, with maximum values of 0.045 MPa and 0.048 MPa, respectively. DS1 recorded the highest peak frictional stress at 2.53×10^{-8} MPa, while DS2 showed consistent stress stability, reducing the possibility of uneven wear. DS3 achieved a balanced performance, with a maximum pressure of 0.062 MPa and a stable frictional stress distribution. In contrast, DS4 showed the highest stress (0.072 MPa) and increased "sliding" contact area, indicating reduced braking efficiency and potential for faster wear. Contact condition analysis showed predominantly "sticky" conditions on DS1, DS2, and DS3, which contributed to effective braking performance, while DS4 exhibited significant "sliding" conditions, which reduced friction efficiency. These findings confirm the potential of Ulin sawdust as an environmentally friendly brake lining material, with DS1 and DS2 emerging as the most suitable designs to achieve optimal braking performance and long life.

Keywords: *brake pads, composite, Eusideroxylon zwageri, frictional stress, pressure distribution, simulation, ulin wood*

I. Introduction

Brake pads are an important component in the vehicle braking system, which functions to convert kinetic energy into heat energy through friction [1]. Brake lining in its mechanism, in direct contact with the rotating disk brake rotor so that it can slow down the speed of the vehicle until it stops safely and in a timely manner. To find alternative environmentally friendly materials for brake linings, Ulin wood powder (*Eusideroxylon zwageri*) is one potential option. Ulin wood has strong physical and mechanical properties and is resistant to wear, which makes it suitable for application in composite brake linings. Currently, brake linings are generally made from metal or mineral powders, which harm the environment, both in terms of production and post-use waste. By utilizing Ulin sawdust as a base material for brake linings, this research seeks to reduce the carbon footprint while supporting sustainability.

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E. zwageri, also known as Borneo ironwood, is highly valued for its strength and water resistance, making it ideal for heavy-duty applications like bridges and ships. However, its popularity has led to significant exploitation, with much of the demand met through illegal logging, especially in regions like Kalimantan and Sumatra. This overharvesting has caused population decline and habitat degradation, posing challenges for conservation due to the limited genetic diversity in wild populations. Sustainable forestry efforts are underway to mitigate demand and support biodiversity conservation [2]. In this context, using *E. zwageri* for sustainable products, such as eco-friendly brake pads, offers a valuable economic alternative that reduces deforestation pressures. Its strength, density, and durability make it a promising candidate for composite materials, providing ecological and economic benefits by generating controlled revenue sources while lessening reliance on illegal logging [3]. Ironwood (*E.zwageri*), known for its strength and resistance to extreme environmental conditions [4]. Ulin wood's hard and durable nature is expected to improve brake lining performance, especially in terms of a stable coefficient of friction and resistance to wear [5]. Powdered ironwood, with its superior mechanical properties, has the potential to be a filler material in the polymer matrix that makes up composite brake pads. Development of environmentally friendly type brake pads using agro-industrial waste and sawdust has been carried out [6], [7]. Wear performance of brake pads with several developments using agro-industrial waste juxtaposed with commercial brake pads, showing that sawdust is an underutilized waste to be a feasible material for making environmentally friendly brake pads [8], [9].

Research with modeling simulation methods has been widely carried out in the automotive industry [10]-[13], however, on the other side, friction modeling of composite brake linings that use ironwood powder as a filler material is important to observe, where *there* is interaction between the ironwood powder material and the brake disc during the braking process. Research by Akar [14] showed that the simulation results were linear with the actual values. In addition, it can be seen that the wear distribution in the simulation occurs in the center of the brake lining in only one model, which requires some variation in the shape of the brake pad. Design modeling with several brake pad shape variations, providing important insights into frictional behavior, thereby facilitating the development of more efficient designs [15].

Accordingly, through a modeling approach, various parameters such as pressure distribution, friction behavior, and surface contact can be analyzed in depth. The results of this modeling will provide important insights into developing more efficient and environmentally friendly brake linings while offering a sustainable alternative to the traditional materials used today.

II. Material and Methods

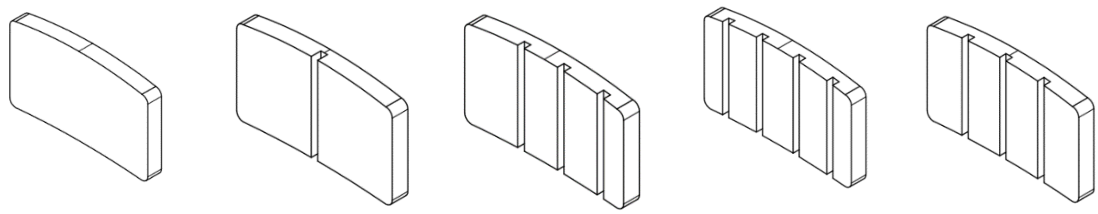
The geometric 3D model of the braking system was designed using Autodesk Inventor 2019 which was converted to igs format, and then friction simulation was carried out using ANSYS Version R19 2021. The mechanical characteristics, dimensions, and brake pad/bag material (ironwood powder) selected in the analysis are presented in Table 1. In Table 2, the independent variables expressed as DS0, DS1, DS2, DS3, and DS4 are brake lining specimen designs with variations in the U-shaped groove pattern. Each design has a different number and position of grooves. The selection of U-shaped grooves in the brake lining design was driven by the need for effective cooling and efficient debris removal during braking. U-shaped channels offer a larger and more open bottom, which facilitates better airflow across the brake lining surface, thereby improving the cooling process. The wider channel profile also provides space for particles generated from friction (such as dust) to settle, preventing buildup on the braking surface and allowing continuous heat dissipation. This configuration improves overall brake performance and longevity by maintaining lower surface temperatures during operation [16].

Table 1. Engineering data properties of brake pad mixture materials [17]-[19]

Property	Disc	Pad
Dimension	Ø in : 81,5 Ø out : 160	Lenght: 55 mm Hight: 43 mm Thickness: 5 mm
Density (kg/m^3)	7.850	1.200
Young Modulus [MPa]	20,000	20.4
Poisson's ratio	0.3	0.045

Table 2. Design brake pad

Design of specimen				
DS 0	DS 1	DS 2	DS 3	DS 4



The 3D method meshes a total of 19748 nodes and 10369 elements. Data analysis using the contact body and contact target applied friction to the model in the contact of brake pads and brake discs, and all element size 5 mm. The friction coefficient used for modeling is 0.35 [7].

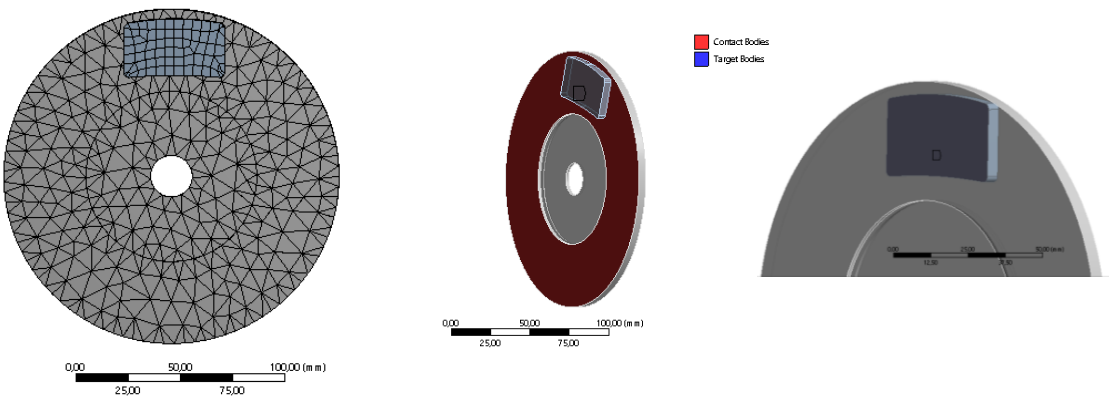


Fig. 1. Model meshing (left) and contact modeling and brake pad body target (right)

In the simulation modeling, the material characteristics were presented, and the braking treatment parameters were simulated with an initial wheel speed of 75 km/h (110 rad/s) within 5 seconds. A braking force of 49 N.mm was applied to the brake pad. Figure 1 illustrates the mesh modeling as well as the contact and target bodies of the brake disc and brake pad.

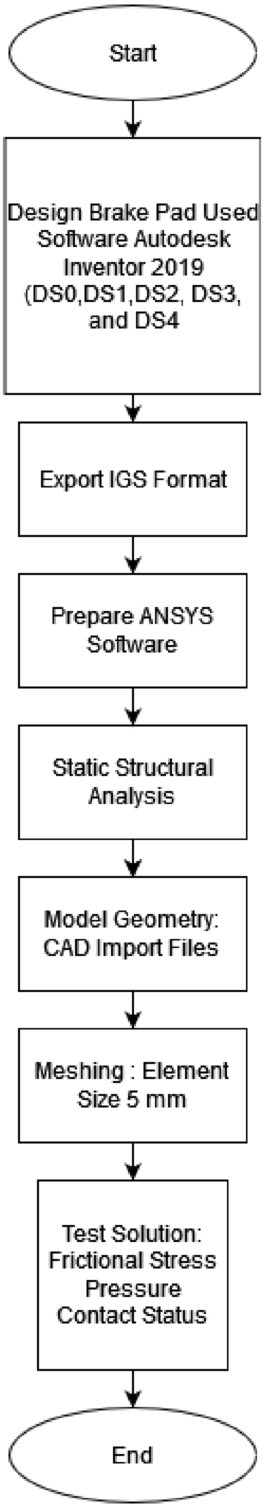


Fig. 2. Flow chart methodology

III. Results and Discussions

The results of this study provide an in-depth analysis of the friction behavior, pressure distribution, and contact state of ulin (*E.zwageri*) wood powder-based composite brake linings. Through simulations using ANSYS software, several brake lining designs (DS0 to DS4) were evaluated under standard conditions. Analysis showed that the DS1 and DS2 designs performed better overall, with a more even distribution of frictional stress and pressure, potentially resulting in more uniform wear and longer service life. Although DS 3 also showed stable characteristics in some areas, the DS1 and DS2 designs showed consistently superior performance, while DS4 had significant drawbacks with increased localized stresses and larger areas of "sliding". These results support the development of more efficient and sustainable eco-friendly brake lining materials.

1. *Frictional Stress Distribution*

In braking mechanisms, contact between the brake pad and the drum rotor creates friction, which serves as the primary mechanism for slowing down the vehicle. The graph in Figure 3 displays the dynamic characteristics of frictional stress on the brake pad during the loading process. The observed decrease in stress in most of the initial data indicates a transition to a steady-state condition, where the brake pad material adapts to the applied load.

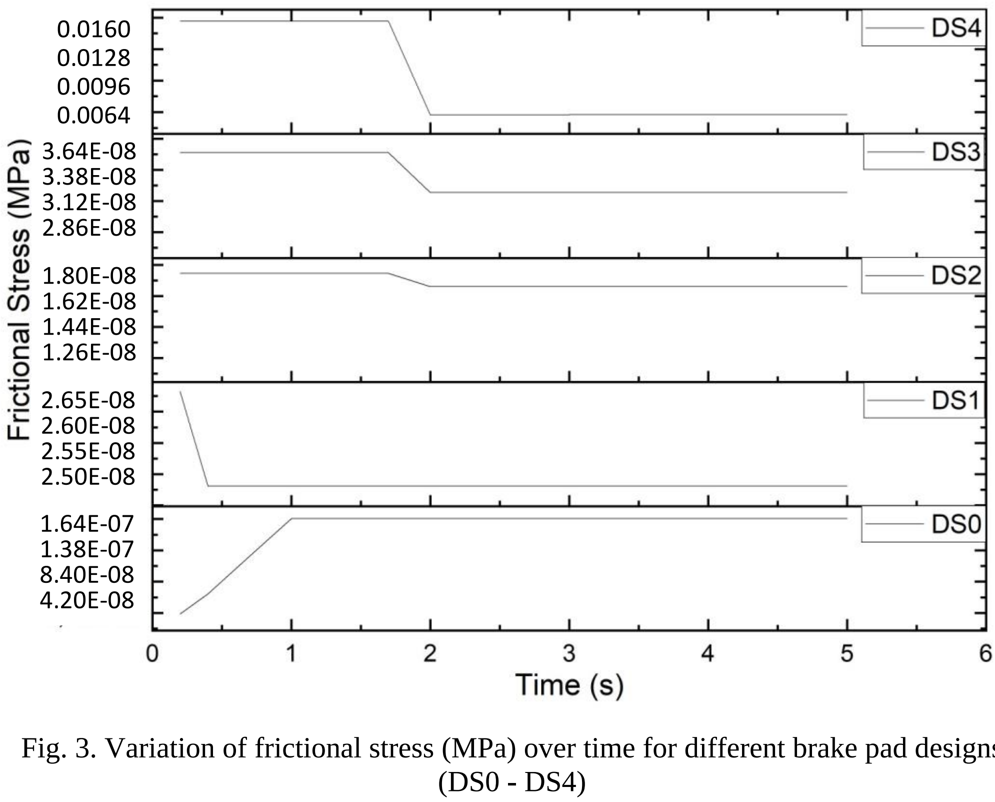


Fig. 3. Variation of frictional stress (MPa) over time for different brake pad designs (DS0 - DS4)

In Model DS0, the frictional stress starts at a higher value of approximately 1.68×10^{-7} MPa, followed by a stabilization with slight fluctuations. This may indicate an initial phase of deformation or stabilization before the main loading begins. In Model DS1, the frictional stress increases rapidly, reaching a peak of around 2.53×10^{-8} MPa, and then stabilizes after a slight decrease. This suggests the primary loading phase, where the contact stress begins to form, followed by a stabilization of stress on the contact surface. The DS2 design model shows that the initial stress increases sharply but then decreases significantly before stabilizing at a value of 1.67×10^{-8} MPa. Similarly, in the DS3 model, the frictional stress rises to around 3.53×10^{-8} MPa. This indicates strong initial frictional contact that then declines as the contact phase allows for changes in surface friction conditions on the brake pad surface layer.

The DS4 design model shows the highest frictional stress, starting at approximately 1.56×10^{-2} MPa. This model illustrates a scenario in which the brake pad experiences high stress initially, likely due to maximum contact, which is then followed by wear. However, the rapid decrease may indicate a reduction in effectiveness due to heating, wear, or a drop in the friction coefficient after the initial peak stress.

The overall analysis of the graph in Figure 3 aligns with findings in the literature, showing that frictional stress on the brake pad experiences an initial increase, followed by stabilization or a decrease in frictional stress depending on factors such as material wear and pressure distribution on the contact surface of the model [20]. The decrease in frictional stress after the peak stress in some data points can be attributed to wear or pressure redistribution, a phenomenon commonly observed in studies of brake pad friction and wear [21].

Figure 4 shows the distribution of frictional stress on a brake pad, representing different conditions or scenarios with various maximum and minimum frictional stress values (in MPa). In the DS0 design, frictional stress is concentrated on the upper side and tends to decrease horizontally across the brake pad surface. This indicates an uneven distribution, with higher pressure in one corner of the brake pad. In the DS1 design, frictional stress is more evenly distributed compared to the DS0 scenario. The stress distribution is more stable, but the highest concentration remains in the central and upper-left areas, indicating that these regions experience higher pressure.

This distribution indicates a significant difference in the frictional force distribution between the two sides of the brake pad. In the DS2 design, there is a decrease in maximum frictional stress compared to previous scenarios. The stress distribution is more concentrated on the left side of the brake pad, with lower stress values in other areas, indicating an imbalance in pressure distribution.

In the DS3 scenario, frictional stress increases significantly in certain areas, particularly in the center. The stress distribution is fairly even across the entire brake pad surface, suggesting improved stability in pressure distribution compared to previous scenarios. Meanwhile, in the DS4 design, frictional stress rises dramatically, especially on the bottom and left side of the brake pad. The maximum value is considerably higher than in other scenarios, indicating a concentration of high stress in that area. However, there are still areas with zero stress on the right side, indicating an imbalance.

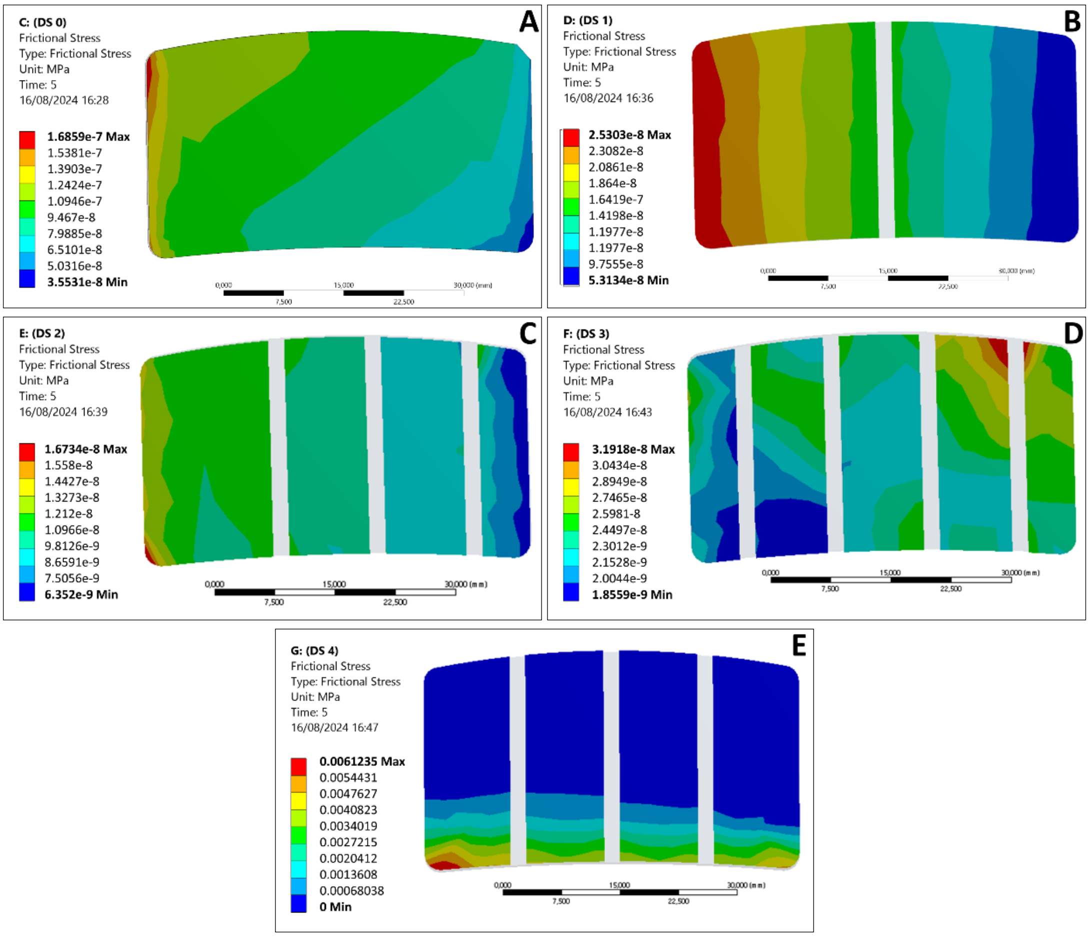


Fig. 4. Frictional Stress Distribution Design Brake Pad, A: DS0, B: DS1, C:DS2, D:DS3, E:DS4

2. *Contact pressure distribution*

In Figure 5, the high contact pressure in DS4 (around 0.072 MPa) could lead to localized wear in that area, as explained by [22], this suggests that under certain operational conditions, the brake pad associated with DS4 experiences excessive pressure, which may trigger overheating or uneven wear. The stable and low contact pressure in model DS0 indicates that this area might be less engaged in effective braking, potentially resulting in minimal wear or even an inactive zone. The lower and more stable contact pressure in models DS1 and DS2 may indicate areas of reduced wear, which is consistent with expectations. A more even pressure distribution contributes to a longer service life [23]. The initial increase followed by a rapid decrease in contact pressure seen in model DS3 illustrates how the composite material adapts to the applied load, resulting in a quick wear-in period and contact stabilization.

Areas with high contact pressure tend to exhibit higher wear rates. Studies note that composite materials with a more even pressure distribution will have a longer lifespan and better performance stability. Figure 6 shows the modeling of friction on the contact surface of the brake pad. High pressure concentration occurs in certain areas, which may lead to faster wear at these points. This is evident in DS0 and DS4, where high-pressure concentration could result in accelerated wear, while in DS1 and DS3, the pressure variation is more stable compared to DS0 and DS4, though some areas still experience higher pressure.

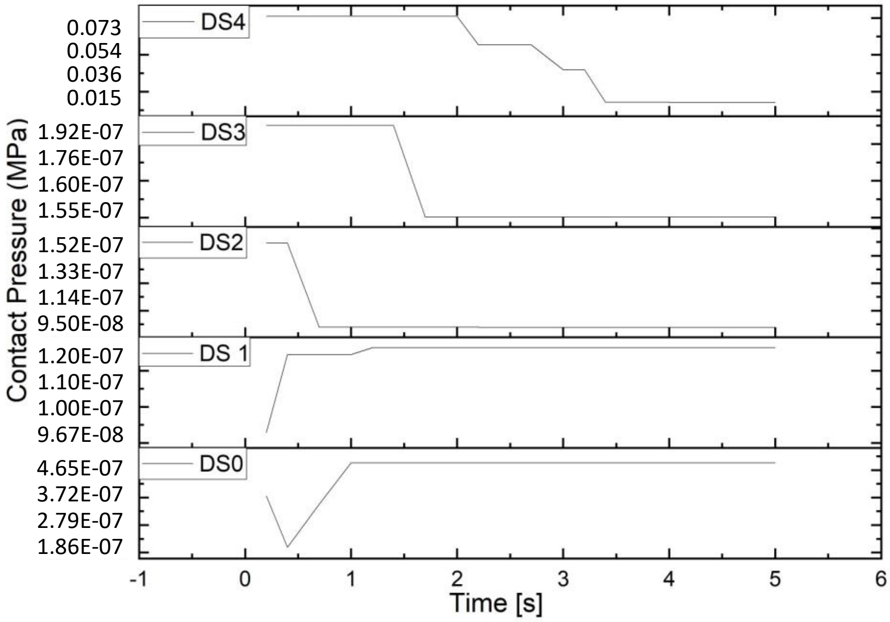


Fig. 5. Variation of contact pressure (MPa) over time for different brake pad designs (DS0 - DS4)

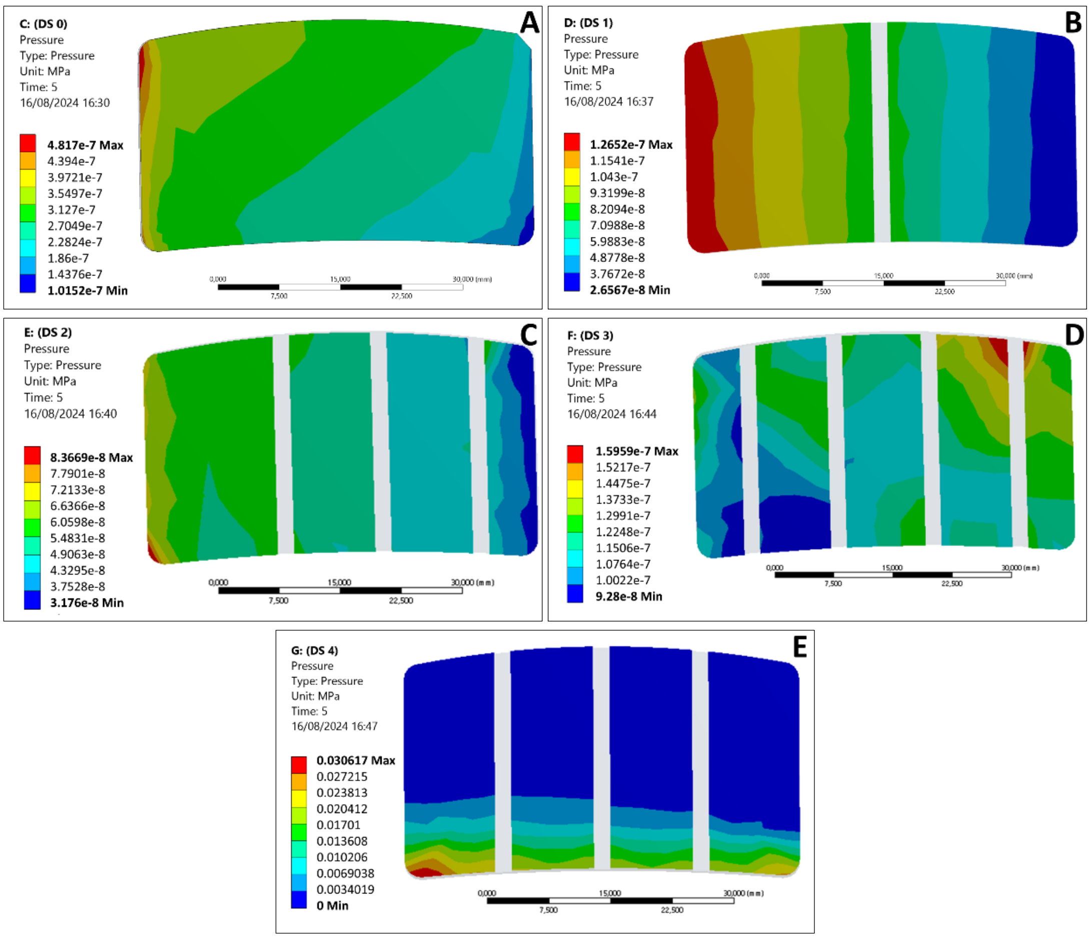


Fig. 6. Contact pressure distribution design brake pad: A. DS0; B. DS1; C. DS2; D. DS3; E. DS4

Based on this modeling, it suggests that non-abrasive wear may occur in low-pressure areas, whereas abrasive wear could develop in high-pressure areas (red zones), which, overall, reduces braking performance. A more even pressure distribution, as shown in DS 2, tends to provide a more uniform braking force distribution. In DS2, there is no noticeable pressure concentration as seen in DS0 or DS4. This model indicates that the braking force distribution is more evenly spread across the entire contact surface during braking.

3. *Contact Status*

Contact conditions of the brake lining surfaces in several scenarios (DS0 to DS4), with different parameters such as “Over Constrained”, “Far”, “Near”, “Sliding” and “Sticking”. Each color in the figure represents a specific condition of the interaction between the brake lining surfaces. Figure 5 shows some of the friction area surface contact conditions of various brake lining modeling. In Design DS0, DS1, most of the brake lining surface area is in the “Sticking” condition, where there is no relative motion between the brake lining surface and the rotor, meaning that the brake lining has tight contact with the rotor. DS2, and DS3 show a “Sliding” condition (orange color), which indicates that there is relative movement in these areas. There are no areas showing an “Over Constrained”.

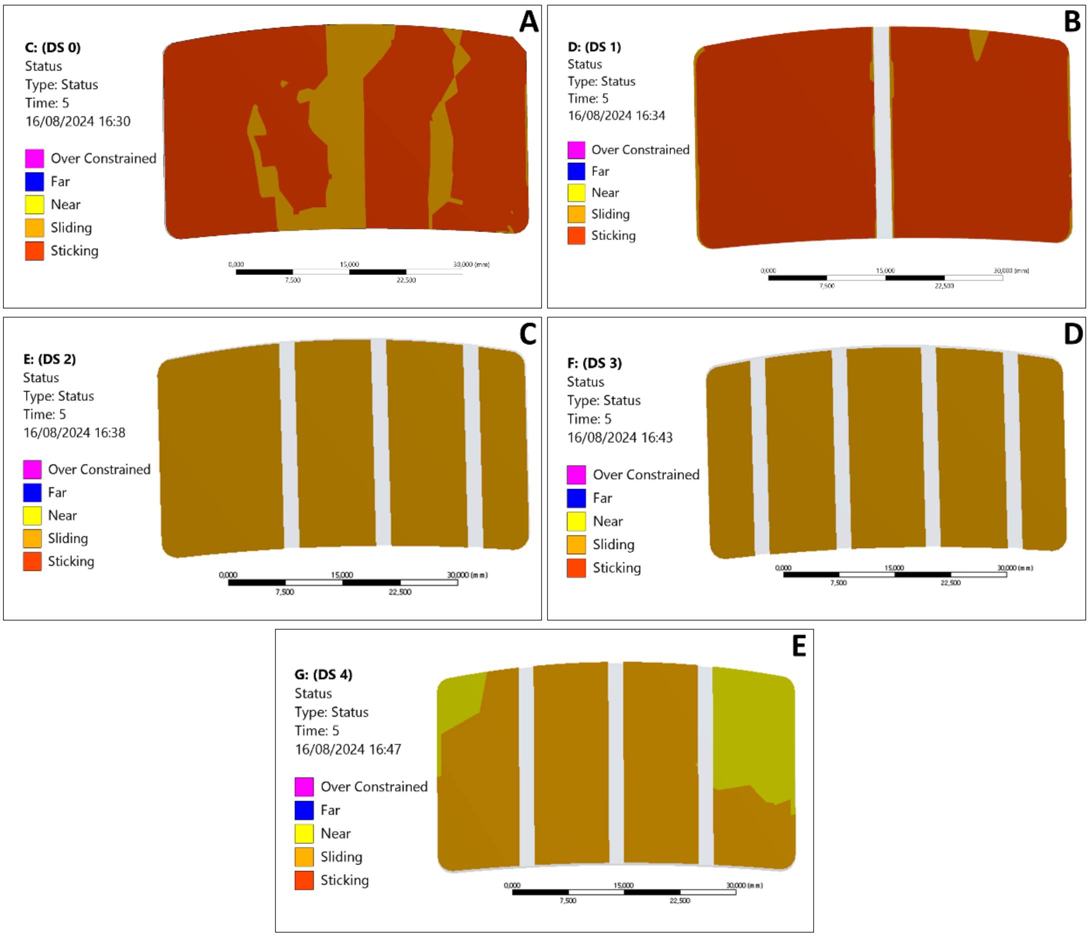


Fig. 7. Contact status design brake pad: A. DS0; B. DS1; C. DS2; D. DS3; E. DS4

This results in very high friction in some areas, which can lead to rapid and uneven brake lining wear. The predominant sticky condition in both conditions also indicates the risk of excessive heat buildup in those contact areas, indicating good, tight contact between the brake lining and rotor, which is ideal for effective braking. Unlike the other scenarios, the DS4 design has some brake pad surfaces that exhibit a “Near” condition (yellow color), indicating significant relative movement between the brake pad and rotor. The “Sticking” area is smaller and limited to the center and left side of the brake pad. This indicates that in the DS4 scenario, the brake pad may experience lower friction with the rotor, which could lead to a decrease in braking effectiveness. This uneven pressure distribution, if sustained over a long period of time, could lead to excessive wear, as well as the possibility of generating excessive heat. This excessive heat can lead to brake fade, which is a decrease in brake capability due to accumulated heat, reducing braking effectiveness.

In general, the contact distribution of the brake pad surfaces varied depending on the scenario, with the predominant “Sticky” condition in most scenarios indicating good braking performance, while in DS4, a fairly predominant “Near” condition indicated a possible decrease in braking effectiveness.

IV. Conclusions

Modeling braking from variations in brake lining geometry can be studied with the results that have been carried out using modeling software simulation. It can be concluded that DS3 displays the most optimal scenario with relatively balanced pressure distribution, frictional stress, and contact state. Brake pads in this scenario tend to have good braking performance with even pressure distribution and stable frictional stress, resulting in even wear potential. DS4 shows an anomaly with a significant increase in maximum pressure and an increase in the area with a “Sliding” condition. This indicates that despite the increase in local pressure, the brake pad may be performing less optimally due to the increase in relative motion which reduces friction efficiency. Uneven pressure and areas of high frictional stress at DS0, DS2, and DS4 may cause uneven wear and shorten the life of the brake pad. A more even distribution of frictional stress and pressure at DS 3 has the potential to extend brake pad life due to more consistent wear. It is recommended to conduct further testing on scenarios that exhibit contact and pressure imbalances (such as DS4) to understand the true impact on braking performance and wear performance.

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