Materials Research Express

PAPER

Thermal and mechanical analyses of dry clutch disk made of functionally graded aluminum matrix composite

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Keywords: clutch plate design, silicon carbide (SiC), functional graded material (FGM)

Abstract

This research work presents an innovative utility of Functionally Graded Aluminum Matrix Composite with Silicon Carbide as a friction material in clutches’ plate since it has an acceptable friction coefficient and a high wear resistance which may lead to longer working life. Functionally Graded Aluminum Matrix Composite’s properties are calculated using rule-of-mixture and power law, and simulated as layered geometry. Clutches designed based on the standard size and working conditions of clutches in mid-size and heavy automobiles. Functionally Graded Aluminum Matrix Composite’s behavior is examined considering statics, dynamics, thermal and wear. Analyses are done using Finite Element method, by ANSYS with boundary conditions that represent the actual working conditions of clutch in automobiles. The developed finite element model is validated by comparing it to literature and has achieved good agreement. Results are discussed by comparing functionally graded aluminum matrix composite’s clutch performance to aluminum matrix composite with 20% of silicon carbide clutch and e-glass clutch performances. FGAMC clutch showed excellent behavior considering static analysis where deformations were the least among the three materials. The thermal and free vibrational performance of the FGAMC were not the best but with very small differences compared to aluminum matrix composite and e-glass clutches. Very unwanted performance of FGAMC is recognized in forced vibration analysis, as it has very high stresses, strain and deformation compared to the other two materials. Structural transient behavior of FGAMC is acceptable as it has the lowest deformations and strains from the highest stresses but in small area of the contact surface of the clutch. Volume loss in FGAMC due wear is less compared to traditional aluminum matrix composite by more than 4 times.

1. Introduction

Clutches are used in automobiles in manual transmission systems, washing machines, and many rotating tools. They are used to transmit power and motion from a driving shaft, connected to a power source (combust engine or motor) to a driven shaft. In automobiles, clutches are designed to transmit from the flywheel connected to the engine, to the gearbox while maintaining the same velocity by friction contact, but allowing the ability connecting and disconnecting between those two parts without the need of stopping the power source (engine). The friction discs of clutches are pressurized by springs (mostly diaphragm springs) towards the flywheel, the friction lining will connect to the flywheel and start to rotate with the flywheel. Therefore, frictional materials in clutches are being under focus to develop new materials and studying the utility of other to achieve the optimum efficiency in transmission of power and motion, while maintaining long working life. The friction lining materials should have high friction coefficient, able to withstand high temperatures and wear resistance. Along with other essential properties such, developing friction force between the lining surface and flywheel, holding and transmitting the loads, keeping pressure between surfaces as low as possible. Adding to that the material should be able to dissipate and withstand the heat generated from the friction [1]. Many materials have been used...
as friction lining in clutches. But the most common one are E-glass epoxy with a competitively low cost. The type of glass fiber is E-class, which is famous for its’ high quality, high strength and high chemical resistance, but has low modulus of elasticity and high density result in weight increase [2]. Another used material is Aluminum matrix composites (AMCs) enforced by silicon carbide that has high strength to weight ratio. AMC reinforced by SiC has lower coefficient of thermal expansion and higher elasticity modulus than the unenforced Aluminum Matrix Alloy [2]. As the improvement in the reinforced AMC due to the SiC particles in the material resulting in higher hardness. Manmade functionally graded materials (FGMs) are only imitation to the ones found in nature, such as bones and Mollusk shells [3]. Nevertheless, there are many types of FGMs, many of them share the concept of changing from one material to another material gradually, mostly from metal to ceramic, and to simplify analysis the change is dependent on one direction. The property of the material changes in this direction, it can be said the FGMs properties are different in different locations. A new sector of research is concentrating now on functionally graded metal matrix composites (FGMMCs). Essentially, producing metal matrix composites employing means of functionally graded materials, to enhance the properties of materials used in making components used in multifunction and conditions with a multiphasic nature. FGMs are produced in many ways, they can be processed by powder stacking (by normal gravity, under pressure-induced flow, or under centrifugal forces), vapor depositing, centrifugal casting, or by solid freeform fabrication [3].

Many pieces of research have been done in the usage of Aluminum matrix composites as friction material of the clutch. Dhanasekaran et al in their work [4], found that if aluminum matrix composites are processed by stir casting specifically result will in an arise in three properties tensile, yield strengths and hardness by 16%, 50% and 16% respectively when the volume of Silicne carbide for reinforcement 20%.

Gomes et al [5], compared between the homogenous aluminum matrix composite with 20% silicon carbide produced by gravity casting and when the same material produced by centrifugal casting to become functionally graded aluminum matrix composite (FGAMC). They considered the friction and wearing behavior in their study when they tested the two materials against cast iron pin. They found that the friction coefficient reduced from 0.6 to 0.5 in FGAMC and low wear coefficient around 10 × 10^{-6} mm Nm^{-1} which means higher wear resistance. Other research went further studying the effects of the size and percentages of the Silicon Carbide on the characterization of FGMMCs, El-Galy et al [6] found that hardness of FGAMC will increase when using smaller particles of SiC. Also found that the tensile strength increased linearly with the increase of the SiC particles proportion in the material until reaching 10%.

Considering FGM, Suryaa and Prasanthib [7], manufactured AL-SiC as functionally graded material by powder metallurgy method, then examined four specimens using a Microscope. The specimens have three layers including different proportions of SiC in aluminum to reach the optimum combination, they found that having 10% SiC can be successfully manufactured. And failure occurs when more than 15% of SiC due to the weakness of the bond between particles of aluminum.

Other researches focused on improving tribological performance of matrix composites such Essa et al [8], Elsheik et al [9], and Essa et al [10], where they developed and improved a MS5 matrix composite Sns/Zno sintered and test it considering friction and wear to evaluate its performance. The new material showed very good tribological behavior when tested against silicon nitrate ceramic in pin-on-disk tribometer.

Vasiraja and Nagaraj [11] studied the stresses, deformations, buckling effects and essential frequency of a plate made of functionally graded materials numerically by ANSYS. They investigated grading parameters such thickness ratio and power law distribution. They obtained many results, one of them is FGM plate with higher ratio of ceramic has higher natural frequency.

In their work Shanthi and Kumar [12], conducted a structural and thermal analysis using finite element method represented in ANSYS for multi-clutch plate made of different materials to decide the best of them. They concluded that SFBU material has the best characteristics as clutch friction material among cork, copper, SF100 and SFBU. Srivastava et al [13] also, carried out static and dynamic analysis for clutch made off different materials, the traditional cast iron, carbon fiber reinforced polymer, glass fiber reinforced polymer, Boron epoxy, and HT Graphite. They concluded that HT Graphite has the best features to work as friction lining for dry clutch plate, as the weight is less than cast iron clutch while giving approximately the same stresses with higher thermal conductivity.

Martins and Romão [14] examined clutch discs with different materials and geometries statically and dynamically considering fatigue. Cast Iron as reference material while aluminum (Al 3003-H18) is under study. Nearly identical performance resulted in geometries with or without rips discs. They found that aluminum has better performance in static analysis but in dynamic analysis a premature failure can happen by fatigue. The difference in geometries had no big effect regarding overcoming stresses. Considering only free vibration analysis Barve and Kirkire [15], designed and analyzed a single-plate clutch with finite element method using ANSYS. They developed two models one is elastic and include most components of transmission mechanism and the other is very simple and conducted modal analysis to found that the simple model had very similar result to the realistic one.
Sreevani and Mohan [16], also carried out research studying single plate clutch static and dynamic oriented study, for clutches with different materials E-glass epoxy, aluminum metal matrix composite, aluminum alloys 7075 and cast-iron. Considering stresses and deformations E-glass plate clutch showed better results since it has lower weight and acceptable high strength. The same results have been proofed by Kebede and Hailu [17] when they modeled and analyzed multi-plate clutches used in twin-clutch transmission systems. Using finite element method and comparing the performance of different materials as friction linens, aluminum alloy 6061, gray cast Iron, and E-glass epoxy. Also E-glass had lower weight, the lowest deformations for its working condition, and acceptable wear resistance. Ali et al [14], has examined the thermal behavior of clutch plate made of various materials using mathematical and numerical method (mainly finite element). Materials examined were Asbestos, Carbon-Carbon Composite, S2-glass fiber, and aluminum metal matrix composite. They found that aluminum metal matrix composite showed better thermal behavior when used as friction materials in dry clutch claiming longer life of the clutch.

Shahzamanian et al [18] studied transient and contact analysis of a disk brake made of functional graded materials numerically by ANSYS. Focusing on pressure distribution, generated heat and frictional stress with other aspects such penetration. They concluded that gradation from metal to ceramic affects the thermomechanical response of FG brake disks.

Figure 1 shows a 3D model of manual transmission automobiles clutch set followed by a scheme in figure 2 showing clutch set parts and its connections to the rest of automobile parts.

In this research work, the feasibility of using functionally graded aluminum matrix composite with silicon carbide (FGAMC) as friction linen of mid-size and heavy automobiles’ clutch is studied as from [3] FGAMC showed good resistance to wear. Finite element numerical method is used in ANSYS to examine the FGAMC clutch statically, dynamically, thermally and the wear behavior. To get a clear idea of the performance of FGAMC, it is compared to clutch made of E-glass and homogenous aluminum matrix composite with 20% composite. The next sections include calculating the FGAMC properties and the method used, followed by the design of the clutch and different analysis.

2. Functional graded aluminum matrix composite (FGAMC) properties calculations and modeling

As FGMs mechanical properties change in a certain direction. The direction considered in this study is the thickness direction. There are several methods to predict the behavior of FGMs and to model, the simplest one, and used here, is the linear rule of mixture method (Voight estimate) for two materials [3]. Rule of Mixture equation (1) is used combined with Law of Power equation (4) as follows:

\[
\beta_{\text{fgm}} = V_{\text{material1}} \cdot \beta_{\text{material1}} + V_{\text{material2}} \cdot \beta_{\text{material2}}
\]  

(1)
where $\beta$ is material property and $V$ volume proportion in the mixture.

$$V_{\text{material}1} + V_{\text{material}2} = 1 \quad (2)$$

Considering the change in properties is in single direction the thickness direction of the frictional linen, in location $(x)$ [3]:

$$\beta_{\text{fgm}} = \beta_{\text{fgm}}(x) \quad (3)$$

Solving using law of power:

$$\beta_{\text{fgm}}(x) = \left[1 - V_{\text{material}2}(x)\right] * \beta_{\text{material}1} + V_{\text{material}2}(x) * \beta_{\text{material}2} \quad (4)$$

where, $V_{\text{material}2}(x)$ is the volume proportion

$$V_{\text{material}2}(x) = \left(\frac{x}{L}\right)^\kappa \quad (5)$$

where $L$ is the length and $\kappa$ is the given graded parameter (assumed $\kappa = 1$ linear change), getting:

$$\beta_{\text{fgm}}(x) = \left[1 - \left(\frac{x}{L}\right)^\kappa\right] * \beta_{\text{material}1} + \left(\frac{x}{L}\right)^\kappa * \beta_{\text{material}2} \quad (6)$$

Modeling the Functional Graded materials has many methods one, is to use the above function (6) and calculate the properties with a very small step ($x$), which is in the thickness direction. Table 1 shows the two materials forming the FGAMC properties, this method applied here shown in figure 5, for step equal to .25 mm in the thickness direction for total thickness 8 mm which the standard thickness of clutch pads of mid-size and heavy automobiles [19], applied to static, dynamics analyses except transient analysis. Considering the limitation of the software, not able to solve layered bodies, an average of each property will be considered to represent the complete material in transient and wear analyses.

For the other two materials no need for a special methods in modeling. The two materials E-glass and AMC properties are assigned to the clutch plate, their properties are shown in table 2. The average properties are shown in table 3.

3. Clutch plate designing

In clutch designing methods, only uniform pressure method is used to determine the working conditions of the clutch plate [1], for the three different materials. Considering the dimension of common clutch plates used in medium and heavy automobiles [19] and the working condition at the starting of engines, as follows. A lot of
Table 1. Showing the two materials’ properties.

| Properties                        | Aluminum alloy | Silicon carbide |
|-----------------------------------|----------------|-----------------|
| Density (Kg m\(^{-3}\))           | 2770           | 3100            |
| Thermal Expansion (°C)            | \(2.30 \times 10^{-5}\) | \(4.00 \times 10^{-5}\) |
| Young Modulus (Pa)                | \(7.10 \times 10^9\) | \(4.10 \times 10^{11}\) |
| Poisson’s Ratio                   | 0.33           | 0.14            |
| Bulk Modulus (Pa)                 | \(6.96 \times 10^7\) | \(2.20 \times 10^{11}\) |
| Shear Modulus (Pa)                | \(2.67 \times 10^7\) | \(4.15 \times 10^{10}\) |
| Tensile yield strength (Pa)       | \(2.80 \times 10^8\) | \(9.33 \times 10^8\) |
| Compression yield Strength (Pa)   | \(2.80 \times 10^8\) | \(3.90 \times 10^9\) |
| Specific Heat (J/kg.°C)           | 923.5          | 750             |
| Hardness (Vickers) (Pa)           | 7.99 \times 10^8 | 2.7459 \times 10^{10} |
| Friction Coefficient against Steel [20, 21] | 0.47 | 0.6 |
| Fracture Toughness (Pa/m²)        | \(2.85 \times 10^7\) | \(6.70 \times 10^7\) |
| Conductivity (W/mK)               | 160            | 120             |

Table 2. Showing the two materials’ properties AMC and E-glass.

| Property                      | Aluminum matrix composite [22] | Property                      | E-Glass UD                        |
|-------------------------------|--------------------------------|-------------------------------|-----------------------------------|
| Density (Kg m\(^{-3}\))       | 2740                           | Density (Kg m\(^{-3}\))       | 2000                             |
| Young modulus \(P_u\)          | \(9.86 \times 10^9\)           | Young Modulus (X, Y, Z) \(P_u\) | \(45 \times 10^9\), \(10^{10}\), \(10^{11}\) |
| Tensile strength \(P_u\)       | \(3.59 \times 10^6\)           | Tensile strength (X, Y, Z) \(P_u\) | 1.01 \times 10^6                 |
| Poisson Ratio                  | 0.31                           | Poisson’s Ratio (XY, YZ, XZ)   | 0.3, 0.4, 0.3                    |
| Yield strength \(P_u\)         | \(3.03 \times 10^6\)           | Yield Strength \(P_u\)         | \(900\) to \(1000\) + \(10^6\) |
| Elongation %                   | 4.00                           | Elongation %                   | 3.3 to 4                         |
| Hardness [23, 24] \(P_u\)      | \(480 \times 10^6\)            | Hardness [23] \(P_u\)          | \(3000\) \times 10^6             |
| Thermal Expansion (20°C) °C\(^{-1}\) | \(20.7 \times 10^{-6}\)       | Thermal Expansion (20°C) °C\(^{-1}\) | \(1.1 \times 10^{-6}\)          |
| Thermal Conductivity (W/mK)    | 144                            | Thermal Conductivity [24] (W/mK) | 1.35                            |
| Friction Coefficient           | 0.6                            | Friction Coefficient           | 0.5                              |
| Wear Coefficient (K)           | 0.0000488                      | Wear Coefficient (K)           | –                                |
| FGM Layers/ X/L | Density (Kg m⁻³) | Thermal expansion (1/°C) | Young Modulus (Pa) | Poisson's ratio | Bulk modulus (Pa) | Shear modulus (Pa) | Tensile Yield strength (Pa) | Compression Yield strength (Pa) | Specific Heat (J/kg °C) | Hardness (Vickers) (Pa) | Fracture Toughness (Pa√m) | Conductivity (W/mK) | Friction Coefficient |
|----------------|------------------|--------------------------|-------------------|----------------|------------------|------------------|--------------------------|-----------------------------|------------------|------------------|----------------------|------------------|------------------|
| 1              | 0                | 2770                     | 2.3 ×10⁻⁵         | .71 ×10¹¹       | 7 ×10¹⁰          | 8 ×10¹⁰          | 28 ×10⁷                  | 28 ×10⁷                    | 923.5            | 5.6 ×10⁹         | 28.5 ×10⁹            | 160              | 0.47             |
| 2              | 0.125            | 2811.25                  | 2.51 ×10⁻⁵        | 1.1 ×10¹¹       | 8.8 ×10¹⁰       | 2.85 ×10¹⁰      | 36.2 ×10⁷               | 73.3 ×10⁷                  | 901.81           | 8.2 ×10⁹        | 25.4 ×10⁹            | 158.75           | 0.48625          |
| 3              | 0.1875           | 2831.875                 | 2.62 ×10⁻⁵        | 1.3 ×10¹¹       | 9.8 ×10¹⁰       | 2.95 ×10¹⁰      | 40.2 ×10⁷               | 96 ×10⁷                    | 890.97           | 9.4 ×10⁹        | 24 ×10⁹             | 158.125          | 0.494375         |
| 4              | 0.25             | 2852.5                   | 2.73 ×10⁻⁵        | 1.6 ×10¹¹       | 1.1 ×10¹⁰       | 3.04 ×10¹⁰      | 44.3 ×10⁷               | 118.1 ×10⁷                 | 880.13           | 11 ×10⁹       | 22.4 ×10⁹            | 157.3            | 0.3025           |
| 5              | 0.3125           | 2873.125                 | 2.83 ×10⁻⁵        | 1.8 ×10¹¹       | 1.2 ×10¹⁰       | 3.13 ×10¹⁰      | 48.4 ×10⁷               | 141.1 ×10⁷                 | 869.28           | 12 ×10⁹       | 20.8 ×10⁹            | 156.875          | 0.510625         |
| 6              | 0.375            | 2893.75                  | 2.94 ×10⁻⁵        | 2 ×10¹¹         | 1.3 ×10¹⁰       | 3.22 ×10¹⁰      | 52.5 ×10⁷               | 164.4 ×10⁷                 | 858.44           | 13 ×10⁹       | 19.3 ×10⁹            | 156.25           | 0.51875          |
| 7              | 0.4375           | 2914.375                 | 3.04 ×10⁻⁵        | 2.2 ×10¹¹       | 1.4 ×10¹⁰       | 3.32 ×10¹⁰      | 56.5 ×10⁷               | 186.4 ×10⁷                 | 847.59           | 15 ×10⁹       | 17.8 ×10⁹            | 155.625          | 0.526875         |
| 8              | 0.5              | 2935                     | 3.15 ×10⁻⁵        | 2.4 ×10¹¹       | 1.4 ×10¹⁰       | 3.41 ×10¹⁰      | 61 ×10⁷                | 209 ×10⁷                   | 836.75           | 16 ×10⁹       | 16.3 ×10⁹            | 155              | 0.535            |
| 9              | 0.5625           | 2955.625                 | 3.26              | 2.6 ×10¹¹       | 1.5 ×10¹⁰       | 3.5 ×10¹⁰       | 64.7 ×10⁷              | 231.6 ×10⁷                 | 825.91           | 17 ×10⁹       | 14.7 ×10⁹            | 154.375          | 0.543125         |
| 10             | 0.625            | 2976.25                  | 3.36 ×10⁻⁵        | 2.8 ×10¹¹       | 1.6 ×10¹⁰       | 3.59 ×10¹⁰      | 68.8 ×10⁷              | 254.3 ×10⁷                 | 815.06           | 18 ×10⁹       | 13.2 ×10⁹            | 153.75           | 0.55125          |
| 11             | 0.6875           | 2996.875                 | 3.47 ×10⁻⁵        | 3 ×10¹¹         | 1.7 ×10¹⁰       | 3.69 ×10¹⁰      | 72.9 ×10⁷             | 276.9 ×10⁷                | 804.22           | 20 ×10⁹       | 11.7 ×10⁹            | 153.125          | 0.559375         |
| 12             | 0.75             | 3017.5                   | 3.58 ×10⁻⁵        | 3.5 ×10¹¹       | 1.8 ×10¹⁰       | 3.78 ×10¹⁰      | 77 ×10⁷               | 299.5 ×10⁷                | 793.38           | 21 ×10⁹       | 10.1 ×10⁹            | 152.5            | 0.5675           |
| 13             | 0.8125           | 3038.125                 | 3.68 ×10⁻⁵        | 3.5 ×10¹¹       | 1.9 ×10¹⁰       | 3.87 ×10¹⁰      | 81 ×10⁷               | 322.1 ×10⁷                | 782.53           | 22 ×10⁹       | 8.6 ×10⁹             | 151.875          | 0.575625         |
| 14             | 0.875            | 3058.75                  | 3.79 ×10⁻⁵        | 3.7 ×10¹¹       | 2 ×10¹⁰        | 3.96            | 85.4 ×10⁷             | 344.8 ×10⁷                | 771.69           | 23 ×10⁹       | 7.1 ×10⁹             | 151.25           | 0.58357          |
| 15             | 0.9375           | 3079.375                 | 3.89 ×10⁻⁵        | 3.9 ×10¹¹       | 2.1 ×10¹⁰      | 4.06 ×10¹⁰     | 89.2 ×10⁷            | 367.4 ×10⁷                | 760.84           | 25 ×10⁹       | 5.5 ×10⁹             | 150.625          | 0.591875         |
| 16             | 1                | 3100                     | 0.00004           | 4.1 ×10¹¹       | 0.14           | 2.2 ×10¹⁰      | 4.15 ×10⁷            | 93.3 ×10⁷                | 390 ×10⁷         | 750             | 4 ×10⁹              | 150              | 0.6              |
| Average        | 2944.023         | 3.2 ×10⁻⁵                | 2.5 ×10¹¹         | 0.2298         | 1.5 ×10¹⁰      | 3.45 ×10¹⁰     | 62.4 ×10⁷            | 218.9 ×10⁷                | 832.01           | 16 ×10⁹       | 15.6 ×10⁹            | 154.727          | 0.538555         |
medium-weight and heavy vehicles have clutch plates with outer diameters of 300 mm\[19\]. Therefore, the outer diameter in this study will be taken as 300 mm, while the inner diameter will be fixed at 150 mm. Frictional pad/linen thickness is taken as 4 mm for each side as most commercial clutches. To find the pressure needed on the clutch plate, most vehicles’ engines run at 1250 r.p.m, as initial speed. And the engine output power is assumed 110 KW. Considering the clutch plate as a ring. In uniform pressure method clutch’s design is done based on the following equations \[1\] :

\[
F_a = \text{Pressure} \times \text{Area}
\]

\[
F = p \times \pi \times [R_i^2 - R_o^2]
\]

Total Friction torque acting on the friction surface \((T)\):

\[
T = n \times \mu_L \times F \times R
\]

\[
R = \frac{R_o + R_i}{2}
\]

where \(T\) \equiv Transmitted torque, \(F_a\) \equiv Force axially acting on the friction surface, \(p\) \equiv Axial pressure holding surfaces in contact, \(R_i, R_o\) \equiv Inner and outer radius, \(R\) \equiv Main radius of the fractioning face and \(\mu_L\) \equiv Friction coefficient of the lining material.

Considering Friction Coefficients of the three materials FGAMC, AMC and E-Glass, 0.54 (taking the average), 0.60, and 0.50 [22] respectively from material properties tables. The outcomes of the calculation applying at equations (8)–(10) are showed in table 4.

Figure 3 shows the geometry of the clutch with AMC and E-glass. While figure 4 shows the layered geometry to represent the FGAMC clutch with grading direction, starting from the center as aluminum alloy and gradually changes to Silicon carbide in both sides of the clutch plate.

3.1. Verification

The developed model was firstly verified with what found in literature specifically [12]. The model gave good result compared to the results of [12]. The material assigned in the model is cast iron with properties appearing in table 5 with working pressure of 26 MPa. The comparison is shown in table 6.
4. Static analysis

The first and most important property difference is in the mass of the clutch plate. The plate made of E-glass is lower by 26.5% (equivalent to 1.0783 kg) than FGAMCs, which is highest with 1.4676 kg. The AMC is lower by 5.7% than the FGAMC plate. The clutch plates were studied against the pressure when the flywheel is not revolving and represented with pressure equivalent to the working pressure, while fixing the clutch plate at the middle illustrated at figure 5 with meshed model. Each one of the three clutch plates’ models assigned the

![Diagram showing working pressure on clutch plate](image)

**Figure 5.** Boundary conditions applied to the models and the meshed geometry in static analyses.

| Table 4. The working pressure and axial force in each clutch plate. |
|---------------------------------------------------------------|
| Material                                      | Axial working pressure (Pa) |
| Functionally Graded Aluminum Matrix Composite | 0.131 \times 10^6 |
| Aluminum Matrix Composites                     | 0.117 \times 10^6 |
| E-glass Epoxy                                   | 0.141 \times 10^6 |

| Properties             | Value   |
|-----------------------|---------|
| Young’s modulus (MPa) | 1.2 \times 10^3 |
| Poisson’s Ratio        | 0.29    |
| Density (Kg m^{-3})    | 7800    |

**Table 5.** Cast iron properties.

| Table 6. The comparison between literature and the developed model. |
|---------------------------------------------------------------|
| Criteria                                      | Original model | Developed model | Percentage of difference |
| Stress (MPa)                                   | 26.997         | 27.882         | 3.3%                     |
| Strain (mm/mm)                                 | 0.000225       | 0.000232       | 3.1%                     |

4. Static analysis
respective pressure calculated in section 3, and showed in table 3. When meshed AMC and E-glass clutches have 676207 elements of SOLID 186 and CONTA174 to represent bonding condition between the two pads of clutch plate and the middle steel sheet, with 1165943 nodes. While FGAMC clutch plate has 649564 elements of SOLID186 and CONTA 174 to define the bonding contact between the layers and the middle steel sheet, with 2401471 nodes. Figure 1 shows the meshed models in ANSYS and the boundary conditions of static analysis.

The static analyses of the models showed that the FGAMC clutch plate has the lowest deformations in all directions, either through thickness (Z) of the plate or through radial (X and Y). Graph in figure 6 compares the deformation of the 3 materials' clutches. Noting that the E-glass clutch has the highest deformations. Although it has the highest working pressure applied among the three models but the difference in deformation is very wide, due to the fact that E-glass material has lower module elasticity than the other two materials.

Considering generated stresses and strains FGAMC and AMC achieved results that are very close to each other as they both have very close elasticity characteristics in average. Also the stresses and strains of E-glass were the highest. Figures 7 and 8 compare the results.

Figure 6. The deformations in X, Y, and Z direction and the total deformations.

Figure 7. Compares the resulted stresses (a) and strains (b) of the 3 materials in static analysis.
5. Dynamic analysis

The dynamic analysis includes vibration analysis (Modal and Harmonic) and Transient analysis.

5.1. Vibration analyses

5.1.1. Free vibration (Modal) analysis

The models with different materials are studied under free vibration conditions with fixed support implemented in the center of the clutch plate. Calculating the natural frequencies of clutch’s plates is vital in designing clutches. Clutches natural frequencies should not match generated frequencies of vibration from engines to avoid resonance which lead to damage of the clutch. Results are shown below in table 7 and mode shapes in figure 9.

From table 7 for the first two natural frequencies FGAMC and AMC clutch has very matched frequencies and deformations, while E-glass is higher than them. But for the second two natural frequencies FGAMC has the highest natural frequencies but with much less deformations than the other two materials.
5.1.2. Forced vibration (harmonic) analysis

The analysis is conducted under the condition of the clutch plate is under working pressures. The analyses are conducted with range of frequencies from 0 to 180 Hz (equivalent to 0 rpm to 11000 rpm). Adding to that the analyses included the working pressure caused by the diaphragm spring and the reaction pressure from the flywheel, and harmonic analysis solutions were built on the outcomes of the modal analyses, figure 10 shows the boundary conditions applied to the results of the modal analyses. The performance of the developed FGAMC clutch plate is the worst among the three materials. The general behavior of the FGAMC is fluctuating in deformations, stress and strains during the first 50 Hz followed by steady state till 180 Hz. However, the amount of deformations, stresses and strains are very small and goes to zero for the three materials. Figures 11–13 show the comparison of the outcomes of forced vibration analyses.

Table 7. Deformations at different frequencies for the three materials.

| No | FGAMCs Frequency | Deformation (mm) | AMC Frequency | Deformation (mm) | E-glass Frequency | Deformation (mm) |
|----|------------------|------------------|---------------|------------------|------------------|------------------|
| 1  | 23.738           | 26.133           | 24.378        | 26.218           | 27.587           | 29.798           |
| 2  | 431.49           | 25.738           | 442.46        | 25.565           | 493.39           | 29.084           |
| 3  | 684.75           | 1.5445           | 678.73        | 6.6859           | 677.29           | 6.9742           |
| 4  | 690.26           | 1.8314           | 678.84        | 6.7256           | 677.44           | 7.0302           |

5.1.2. Forced vibration (harmonic) analysis

The analysis is conducted under the condition of the clutch plate is under working pressures. The analyses are conducted with range of frequencies from 0 to 180 Hz (equivalent to 0 rpm to 11000 rpm). Adding to that the analyses included the working pressure caused by the diaphragm spring and the reaction pressure from the flywheel, and harmonic analysis solutions were built on the outcomes of the modal analyses, figure 10 shows the boundary conditions applied to the results of the modal analyses. The performance of the developed FGAMC clutch plate is the worst among the three materials. The general behavior of the FGAMC is fluctuating in deformations, stress and strains during the first 50 Hz followed by steady state till 180 Hz. However, the amount of deformations, stresses and strains are very small and goes to zero for the three materials. Figures 11–13 show the comparison of the outcomes of forced vibration analyses.
5.1.3 Structural transient analysis

The transient analyses were done with boundary conditions as following: rotation of the flywheel from the middle with 13 rad/s equivalent to the 1.250 rpm as taking only 0.1% of the actual rotation velocity. The working pressures are also reduced to only 0.1% of the calculated ones in section 3, to become $1.17 \times 10^{-4}$ for AMC, $1.41 \times 10^{-4}$ for E-glass and lastly $1.31 \times 10^{-6}$ N/mm² for FGAMC. These pressures and rotational velocity were applied on the clutch plates for a time of 5 s. This reduction in values minimized computing time and allowing the software to solve in reasonable time. Flywheel material is structural steel with 360 mm as outer diameter and 80 mm as inner diameter table 8 shows the properties of the structure steel. Figure 14 shows the model of the clutch in contact with the flywheel, boundary conditions and meshing. Noting that the clutch model itself is simplified to become only one part disregarding the steel sheet at the middle that hold the two pads of the clutch. All that in order to tradeoff between computational costs and results accuracy.

Elements used in meshing are SOLID 186 for the two bodies, CONTA 174 and TARGE 170 to simulate the contact relation between the flywheel and the clutch plate, number of elements is 3640 with 20532 nodes. The contact relation between clutch plate and the flywheel, is assigned as frictional contact. And the friction coefficient of each material is defined in the contact relation taken from materials properties in tables 2 and 3.

E-glass analysis showed an equivalent strain range from $4.1 \times 10^{-11}$ mm/mm as minimum strain on the plate and a maximum of $3.5 \times 10^{-7}$ mm/mm. While having equivalent stresses from 149.72 Pa to 2789 Pa as maximum values at the inner diameter of the plate and decreasing in diameter direction. On other hand, the
deformation is higher at outer diameter and decrease in inner diameter direction from $2.14 \times 10^{-5}$ mm to $6.4 \times 10^{-14}$ mm. And the frictional stresses have a maximum value 127.05 Pa at middle of the plate decreasing slowly at outer diameter direction and rapidly at inner diameter direction. Figure 15 contain figures of E-glass transient structural analysis, the figures are taken for the contacted face of the clutch with the flywheel.

The transient analysis of the AMC clutch as shown in figure 16 gives a range of $6.5 \times 10^{-8}$ mm/mm to $3.12 \times 10^{-9}$ mm/mm for equivalent strains and having maximum stresses at the inner diameter also with 6452.1 Pa and lowest stresses 140.04 Pa at outer diameter area. The deformations at the same locations of E-glass clutch but with maximum value $1.02 \times 10^{-5}$ mm to $4.02 \times 10^{-14}$ mm. The Frictional stresses are identical to the E-glass but is affecting larger area.

FGAMC analysis reveals that the equivalent strains are $4.4 \times 10^{-8}$ mm/mm maximum and $3.17 \times 10^{-9}$ mm/mm. Equivalent stresses range from 11076 Pa to 357.85 Pa at inner and outer diameters, respectively. The deformations are higher at outer diameter with $9.14 \times 10^{-8}$ mm and lower at inner one $6.36 \times 10^{-14}$ mm. With frictional stresses, the maximum is affecting only on the outer diameter tip area with 258.63 Pa. Analysis results are illustrated in figure 17.

The graphs in figure 18 show the strains and stresses of the three clutches compared together. The FGAMC has the lowest equivalent strains but the highest stresses.

The deformations of the clutch plates with respect to each other, are demonstrated with the figure 19, the FGAMC is the lowest. Considering the frictional stresses FGAMC has the highest but affect in very small are. But
Figure 16. Results of AMC clutch transient analysis.

Equivalent Elastic Strain mm/mm  
Max = 6.5 \times 10^{-8}
Min = 3.12 \times 10^{-9}

Equivalent Stress Pa  
Max = 6452.1
Min = 140.04

Deformation mm  
Max = 1.02 \times 10^{-5}
Min = 4.02 \times 10^{-14}

Frictional Stress Pa  
Max = 127.02

Figure 17. Results of FGAMC clutch transient analysis.

Equivalent Elastic Strain mm/mm  
Max = 4.4 \times 10^{-8}
Min = 3.17 \times 10^{-9}

Equivalent Stress Pa  
Max = 11076
Min = 357.85

Deformation mm  
Max = 9.14 \times 10^{-6}
Min = 6.36 \times 10^{-14}

Frictional Stress Pa  
Max = 258.63

Figure 18. The differences in equivalent strains and equivalent stress during 5 s.
in all parameters in the structural transient analysis the three materials gradually developing deformations, stresses, strains and frictional stresses at the first second and then reach a steady state.

The sliding distance of the 3 materials are identical, they slide nearly 85 mm during the 5 s as shown in figure 20.

The frictional stresses of FGAMC compared to the two other clutches are the highest, while the AMC and E-glass are identical. The above figures, show the performance of the different clutches. The FGAMC considering strain and deformation are the best as it achieves the lowest equivalent strain and deformation by nearly 10 times the E-glass, but the differences between AMC and FGAMC are not large. It is observed that the area affected by the frictional stress is very small in the FGAMC material although the frictional stress is doubled in magnitude compared to AMC and E-glass. But the affected area in FGAMC clutch considering frictional stress equals nearly 30% of the affected area of AMC clutch and less than 15% of the affected area of E-glass clutch.

6. Wear analysis

Wear analyses are carried out computationally using ANSYS. ANSYS software studies the wear based on the Archard wear equation shown below; but ANSYS increases two terms to the traditional equation. The two additional terms should be obtained from experimental work, but to keep the simplicity of the analysis the two terms are assumed equal to unit (1) as predefined by the software. The analyses were done in two cases: first symmetric analyses, where the wear is studied in the flywheel and the clutch plate both. Second Asymmetric where wear is studied at the clutch plate only. As no valid wear coefficient for the E-glass, the E-glass clutch was not studied. Also wear coefficient of the FGAMC is taken from [5] as $10^{-6}$, The Archard wear formula [23]:

![Figure 19. Deformations and frictional stress during 5 s.](image1)

![Figure 20. Sliding distance during 5 s.](image2)
Table 9. Wear analysis of AMC.

| Flywheel Wear | Clutch Plate Wear |
|---------------|-------------------|
| Total wear in Flywheel and clutch plate (Symmetric Analysis) mm\(^3\) | Wear rate in Asymmetric analysis [Clutch Only] mm\(^3\) |
| Max = 41\(\times10^{-9}\) | Max = 35\(\times10^{-9}\) |
Table 10. Wear analysis of FGAMC.

| Flywheel Wear | Clutch Plate Wear |
|---------------|-------------------|
| Total wear in Flywheel and clutch plate (Symmetric Analysis) mm³ | Wear rate in Asymmetric analysis (Clutch Only) mm³ |

| | Flywheel Wear | Clutch Plate Wear |
|-----------------|---------------|-------------------|
| Max = 77.3×10⁻¹⁰ | Max = 36.6×10⁻¹⁰ |
$W = \frac{K}{H} P^m v_{rel}^n$  \hspace{1cm} (11)

where, $K$ is wear coefficient of the material, $H$ is material hardness (MPa), $P$ is the contact pressure (Pa), $m$ is the exponent of pressure. While $v_{rel}$ is relative sliding velocity (rad/s) and lastly $n$ is velocity exponent. The two exponents $m$ and $n$ are the experimental values assumed equal to 1. This formula is generated by ANSYS from the original formula developed by Archard, which proposes that the rate of volume loss because wear is linearly proportional to the contact pressure and sliding velocity at the contact surface.

The wear of the materials is studied against structural steel, as the flywheel is made of structural steel. Same boundary conditions of transient structural analysis were used here to reduce computational costs with the same elements and contact definitions, but with time equal 2.5 s rather than 5 s. Adding to that the loads are applied to the model after 0.5 s gradually.

6.1. AMC

The symmetric wear analysis modeled in ANSYS for AMC clutch shows, represented in table 9 that the total wear in both the flywheel and the clutch plate is reaching a maximum value of $41 \times 10^{-9}$mm$^3$ with steady wear at the flywheel and graded wear at the clutch starts from the inner to the outer diameter increasingly. While asymmetric wear analysis of the clutch, has maximum value at outer diameter of $35 \times 10^{-9}$mm$^3$ but decreasing in inner diameter direction.

6.2. FGAMC

Wear of the FGAMC clutch with the flywheel in symmetric analysis reached a maximum value of $77.3 \times 10^{-10}$mm$^3$. It is clear that the maximum wear is concentrated at the outer diameter area of the clutch which matches with the frictional stress area found in the previous section.

The asymmetric wear analysis of the clutch resulted in maximum wear of $36.6 \times 10^{-10}$mm$^3$ and also concentrated at the outer diameter area. Table 10 shows analysis results.

Figure 21 compares between the wear performance of the two materials AMC and FGAMC in symmetric and asymmetric analyses during 2.5 s, showing that FGAMC in both wear analyses had much less wear than the AMC. But in symmetric analyses FGAMC had sudden increases rather than gradual increasing and as these increase are not appearing in asymmetric analysis, they are generated at the flywheel not the clutch plate.

7. Theoretical thermal analysis

The heat generated in each clutch is calculated applying the mentioned working conditions in the design section at the following equations [26]:

$$Q_g = \mu \ast \omega \ast P$$  \hspace{1cm} (12)

$$Q_f = Q_g / A$$  \hspace{1cm} (13)

where $Q_g$ is generated heat (watts), $Q_f$ is flux of heat in the clutch. The result of each clutch is shown in the below table after substituting in equation (12) then equation (13). Results are shown in table 11 below.

The FGAMC material generated the highest heat among the three materials but the difference between the three materials is very small and can be considered identical.
8. Results discussion

The functionally graded aluminum matrix composite clutch plate model has 5.7% and 26% more mass, with 200 g and 500 g more mass than AMC and the E-glass, respectively. The proposed model achieved results that are well aligned with literature. Statically, FGAMC clutch plate performance is the best, as the resulted deformations are much lower than what resulted in AMC and E-glass, due to high module of elasticity. But the strains and stresses of FGAMC are very close to AMC, while E-glass’s ones are very high. Considering dynamics, in free vibration analysis, the three materials have very nearby frequency range but in FGAMC has the lowest deformations. For forced vibration analysis, FGAMC performance in total is very bad compared to AMC and E-glass due to the increase of weight. For structural transient analysis the stresses generated in FGAMC clutch plate are the highest but causing very less deformations and strains compared to AMC and E-glass. The frictional stresses in FGAMC are affecting very small area compared to other materials.

Wear analysis done for AMC and FGAMC only. The performance of FGAMC exceeded the performance of traditional AMC by large distance as the wear of FGAMC in the two analysis types symmetric and asymmetric is less by nearly 4 times and 9 times respectively, due to the high wear resistance of FGAMC and lower friction coefficient. The thermal behavior of the three materials are very close to each other with differences of 0.03 between E-glass and FGAMC and only 0.07 Between FGAMC and AMC.

9. Conclusions and recommendations

Using FGAMC as friction lining of clutch plate showed good characteristics:

- For static performance FGAMC can withstand working conditions and have very low deformations.
- For dynamic response FGAMC has normal behavior in free vibration, but very bad performance due to high weight.
- Structural transient analysis of FGAMC reveals that frictional stress are high but concentrated at outer diameter area but the FGAMC can bear those stress and resulting in small deformations.
- FGAMC performing as frictional lining of clutch plates has very good wear resistance character, where FGAMC losses volume in very small amounts. The results reveal a possibility of achieving longer working life for the FGAMC’s clutch as it wears less, resists wear more, and causing less wear on the flywheel when contacted by it leading to preservation of the flywheel.
- The theoretical thermal performance of FGAMC is equivalent to other two materials.
- The conclusion of these analyses is, that FGAMC material shows very good behaviors making it an excellent material to be used in frictional applications such as clutches and braking pads. The natural extension of this study is to studying when the change in the material properties happens in the radial direction.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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| Material       | E-glass | AMC    | FGAMC |
|----------------|---------|--------|-------|
| Friction Coefficient | 0.5     | 0.6    | 0.54  |
| Working Pressure $P_a$ | $0.141 \times 10^6$ | $0.117 \times 10^6$ | $0.131 \times 10^6$ |
| Angular Velocity rad/s | 131     | 131    | 131   |
| Area $m^2$      | 0.053   | 0.053  | 0.053 |
| Generated Heat (watts) | 9.24    | 9.2    | 9.27  |
| Heat Flux (watts/mm$^2$) | $1.74 \times 10^{-4}$ | $1.74 \times 10^{-4}$ | $1.75 \times 10^{-4}$ |
References

[1] Gupta J K and Khurmi R S 2005 A Textbook of Machine Design 14th revised edn (Ram Nagar, New Delhi: Eurasia Publishing House (PVT.) LTD.) 1138–60

[2] Viswabharathy P, Vigneshwar G, Pragadhishwaran M and Gopalakrishnan M 2017 Static and Dynamic Analysis of Single Plate Clutch in Four Wheeler Application Using ANSYS International Journal of Emerging Technologies in Engineering Research (IJETER) 5 222–33 (ijeter.everscience.org)

[3] Araki N et al 1999 Functionally graded material design, processing and applications ed Y Miyamoto, W A Kaysser, B H Rabbin, A Kawasaki and R G Ford Vol. 1 (MA, USA: Springer Science & Business Media, LLC)

[4] Dhanasekaran S, Sunilraj S, Ramya G and Ravishankar S 2016 SiC and Al2O3 reinforced aluminum metal matrix composites for heavy vehicle clutch applications Trans. Indian Inst. Met. 69 699–703

[5] Gomes J R, Rocha I A, Cnkovic S J, Silva R F and Miranda A S 2003 Friction and wear properties of functionally graded aluminum matrix composites Materials Science Forum 423 (Zurich–Uetikon, Switzerland: Trans Tech Publications Ltd) 91–5

[6] El-Galy I M, Ahmed M H and Bassiouny B I 2017 Characterization of functionally graded Al–SiCp metal matrix composites manufactured by centrifugal casting, Alexandria Engineering Journal 56 371–81

[7] Surya M S and Prasanthi G 2017 Manufacturing and Micro structure study of Al–SiC Functionally graded material Mater. Today Proc. 4 621–7

[8] Essa F A, Yu J, Elsheikh A H and Tawfik M M 2019 A new M50 matrix composite sintered with a hybrid Sn3/Zno nanoscale solid lubricants: an experimental investigation Mater. Res. Express 6 116523

[9] Elsheikh A H, Yu J, Sathiamurthy R, Tawfik M M, Shamugan S and Essa F A 2020 Improving the tribological properties of AISI M50 steel using Sn3/Zno solid lubricants J. Alloys Compd. 821 153494

[10] Essa F A, Zhang Q, Huang X, Ibrahim A M M, Ali M K A, Abdelkareem M A and Elagouz A 2017 Improved friction and wear of M50 steel composites incorporated with ZnO as a solid lubricant with different concentrations under different loads J. Mater. Eng. Perform. 26 4855–66

[11] Shanthi G and Kumar S P 2017 Finite element analysis on friction plate of a wet multiple clutch by using various friction materials Int. Res. J. Eng. Technol 4 906–13 (ijrset.net)

[12] Srivastava A, Saraswat S, Vivek V and Singh V K 2016 Static and dynamic analysis of composite clutch plate International Journal for Scientific Research & Development 4 872–5 (ijrserd.com)

[13] Martins J A and Romão E C 2018 Static and dynamical analysis on clutch discs on different material and geometries International Journal of Mechanical and Materials Engineering 12 593–6

[14] Barve N A and Kirkire M S 2017 Analysis of single plate friction clutch using finite element method International Journal of Applied Science 2 273–6

[15] Sreevani B and Mohan M M 2015 Static and dynamic analysis of single plate clutch International Journal of Innovative Research in Science, Engineering and Technology 4 808–18

[16] Kebede S and Hailu H N 2018 Modeling, and FEA of multi-plate clutches by varying materials for optimum torque transfer capacity of TCT system of green, and light vehicles International Journal of Advanced Engineering Research and Science 5 237367

[17] Ali A, Ali L, Shah S R, Khan M, Imran S H and Butt S I 2017 Dry friction clutch disc of an automobile under transient thermal load: a comparison of friction lining materials MATEC Web of Conferences (124, 07003). EDP Sciences

[18] Shahzamanian M M, Sahari B B, Bayat M, Ismarrubie Z N and Mustapha F 2010 Transient and thermal contact analysis for the elastic behavior of functionally graded brake disks due to mechanical and thermal loads Mater. Des. 31 4655–65

[19] 2020–2021 Clutch Catalogue Valeo Pyeong Hwa International Co., Ltd, 2020 2020 Impocali (impocali.com)

[20] The Engineering Toolbox Available at: https://engineeringtoolbox.com (Accessed November 2020)

[21] Bian G and Wu H 2015 Friction and surface fracture of a silicon carbide ceramic brake disc tested against a steel pad J. Eur. Ceram. Soc. 35 3797–807

[22] SubsTech Knowledge source on Materials Engineering, Available at: https://subtech.com (Accessed November 2020)

[23] BBS STAL & METALLER Available at: https://bbshalmstad.se (Accessed March 2021)

[24] AZO Materials https://azom.com (Accessed November 2020)

[25] 2021 Ansys Help Available at: https://ansyshelp.anys.com (Accessed March 2021)

[26] Naidu M Y and Kumar M L S D 2018 Structural and thermal analysis of single plate friction clutch with different Materials International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES) 4 985–97