Thermal and Mechanical Analyses of Dry Clutch Disk made of Functionally Graded Material.

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Abstract

This paper presents an innovative utility of Functionally Graded Aluminum Matrix Composite (FGAMC) with Silicon Carbide as a friction material in clutches since having an acceptable friction coefficient and high wear resistance. FGAMC's properties were calculated using rule-of-mixture and power law, represented by layered geometry. FGAMC's behavior is examined considering statics, dynamics, thermal and wear. Analyses were done using Finite Element method, by ANSYS. Results are discussed by comparing FGAMC's clutch to Aluminum matrix composite with 20% of Silicon Carbide clutch and E-glass clutch. Clutches design based on the common size and working conditions of clutches in mid-size and heavy automobiles. Most analyses reveals FGAMC's clutch has higher strain than AMC's clutch with less deformation in thickness direction and less stresses. FGAMC's clutch has higher mass leading to lower first natural frequency but with low resulted deformations. Transient analyses showed 10 times fewer maximum deformations for FGAMC's clutch than AMC and E-glass with lower strains and higher stress but in much less area for FGAMC's clutch. Wear which indicates working life of a clutch, have been studied using Archard Wear Equation in ANSYS, FGAMC's clutch has 10 times lower wear with much less affected area compared to AMC and E-glass. Thermal analysis results of the three clutches are close to each other with 0.07 watts between FGAMC's and AMC's clutches, and 0.03 watts between FGAMC's and E-Glass's clutches.

2. Introduction

Clutch is used in automobiles with manual transmission systems, washing machines, and many rotating tools. The clutch is used to transmit power and motion. It transmits the rotation movement from a driving shaft, connected to a power source (combust engine or motor) to a driven shaft. In automobiles, clutches are designed to transmit the torque and motion from the flywheel connected to the engine, to the gearbox while maintaining the same velocity, but allowing connection and disconnection between those two parts without the need of stopping the power source (engine). It transmits the motion in automobiles by friction contact. The friction disc of the clutch will be pressurized by springs (mostly diaphragm springs) towards the flywheel, the friction lining will connect to the flywheel and start to rotate with the flywheel, transmitting the motion and torque. Therefore, frictional materials in clutches are being under focus in several research to develop new materials or studying the utility of existing ones to achieve the highest efficiency in transmission of power and motion, while maintaining long working life. The friction lining materials should have beside high friction coefficient, withstanding high temperatures and wear resistance other essential properties such, developing friction force between the lining surface and flywheel, the ability to hold and transmit the load, keeping between surfaces pressure 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 ones are E-glass epoxy with a competitively low cost. The type of glass fiber is E-class, which is famous for its high quality, it has high strength and even high chemical resistance, but the low modulus of elasticity and the high density considered as a disadvantage because they result in weight increase [2]. Aluminum matrix

composites (AMCs), especially Aluminum matrix composite enforced by silicon carbide, with high strength to weight ratio. AMCs reinforced by SiC have a lower coefficient of thermal expansion and higher elasticity modulus than the unenforced aluminum matrix alloy [2]. As the improvement in the reinforced cause of the SiC partials in the material resulting in higher hardness. Artificial Functionally graded materials (FGMs) are only imitating the ones found in nature, such as bones and Mollusk shells. Nevertheless, there are many types of functionally graded materials, 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, we can say 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 to be used in components used in multifunction and various 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. S. Dhanasekaran, S. Sunilraj, G. Ramya, and S. Ravishankar in their work [4], found that if aluminum matrix composites are processed by stir casting specifically will result in an arise in three properties tensile, yield strengths and hardness by 16%, 50% and 16% respectively when 20% of the volume is Silicone carbide for reinforcement. R. Gomes et al, found when the Aluminum matrix composite reinforced by 20% silicon carbide produced by functional graded material methods, specifically by centrifugal casting, the wear coefficient is increased to reach $(10^{-6} mm^3 / N * m)$, meaning higher wear resistance compared to the homogenous Aluminum matrix composite reinforced by 20% silicon carbide, and friction coefficient of 0.50 when examined against cast iron pin disk[5]. Other research went further studying the effects of the size and percentages of the Silicon Carbide effects just like I.M. El-Galy et al, resulting in many findings, one of them the hardness will increase when using smaller particles. The tensile strength will increase linearly with the increase of the silicon particles until reaching 10% [6]. Considering FGM, M. Siva Suryaa and G. 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 silicon carbide 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. In their work G. Shanthi and S. Praveen Kumar [8], they conducted a structural and thermal analysis using finite element represented in ANSYS for multi-clutch plate made of different material to decide which is the best of them, they found that SFBU material has the best characteristics as clutch friction material amount cork, copper, SF100 and SFBU. Ayush Srivastava et al, [9] 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. Jairo Aparecido Martins and Estaner Claro Romão [10] examined clutch discs with different

materials and geometries statically and dynamically. Cast Iron as reference material while aluminum is under study materials. The difference between geometries is having rips (Disc with rips) or flat discs. They found that aluminum showed better results in static analysis but in dynamics a premature failure due to fatigue occurred, knowing the fatigue is the evaluation criteria of their work. The difference in geometries had no big effect regarding overcoming stresses. Considering only free vibration analysis N. A. Barve and M. S. Kirkire [11], conducted a design and analysis of single-plate clutch with finite element method using Pro-e software and ANSYS comparing it to giving model to result, the two models are approximately having the same natural frequencies. B. Sreevani and M. Murali Mohan [12], 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 ending up that e-glass plate clutch is better considering the lower weight and acceptable high strength. The same results have been proofed by Seyoum Kebede and Hailemariam Nigus Hailu [13] 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 linings, Aluminum alloy 6061, Gray Cast Iron, and E-glass epoxy. The last material achieved lower weight, the lowest deformation for its working condition, and acceptable wear resistance. Anosh 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 then longer life of the part can be obtained.

In this research work, different friction materials E-glass epoxy, Aluminum Matrix composite (20% Sic) reinforced, and Functionally graded Aluminum matrix composite (with Silicon carbide) are analyzed as a friction lining of single clutch plate working in usual automobiles conditions regarding Static, Dynamic, Wear, and theoretical Thermal behaviors using finite element method by ANSYS software. To give a comparison result of the possibility of using FGAMCs in friction clutches.

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.

3. Functional Graded Aluminum Matrix Composite (Fgamac) 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:

$$\beta_{fgm} = V_{material1} * \beta_{material1} + V_{material2} * \beta_{material2}$$

1

Where β is material property and V volume proportion in the mixture.

$$V_{material1} + V_{material2} = 1$$

2

Considering the change in properties is in single direction, in location (x) [9]:

$$\beta_{fgm} = \beta_{fgm}(x)$$

3

Solving using law of power:

$$\beta_{fgm}(x) = \left[1 - V_{material2}(x)\right] * \beta_{material1} + V_{material2}(x) * \beta_{material2}$$

4

Where, $V_{material2}(x)$ is the volume proportion:

$$V_{material2}(x) = \left(\frac{x}{L}\right)^{\kappa}$$

5

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

$$\beta_{fgm}(x) = \left[1 - \left(\frac{x}{L}\right)^{\kappa}\right] * \beta_{material1} + \left(\frac{x}{L}\right)^{\kappa} * \beta_{material2}$$

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), where table (1) shows the two materials forming the FGM properties, this method applied here shown in table (2), for step equal to .25 mm in the thickness direction for total thickness 8 mm 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. The average properties are shown in figure (2).

Table (1) showing the two materials' properties.

Material 1	
Aluminum alloy Properties	Value
Density (Kg/m3)	2770
Thermal Expansion (1/c)	2.30E-05
Young Modulus (Pa)	7.10E+10
Poisson's Ratio	0.33
Bulk Modulus (Pa)	6.96E+10
Shear Modulus (Pa)	2.67E+10
Tensile yield strength (Pa)	2.80E+08
Compression yield Strength (Pa)	2.80E+08
Specific Heat (J/kg.c)	923.5
Hardness (Vickers) (Pa)	7.99E+8
Friction Coefficient against Steel [15, 16]	0.47
Fracture Toughness (Pa/m ^{0.5})	2.85E+07
Conductivity (W/m•°K)	160
Material 2	
Sic Silicon Carbide, SiC Ceramic Properties	Value
Density (kg/m3)	3100
Thermal Expansion (1/c)	4.00E-05
Young Modulus (Pa)	4.10E+11
Poisson's Ratio	0.14
Bulk Modulus (Pa)	2.20E+11
Shear Modulus (Pa)	4.15E+10
Tensile yield strength (Pa)	9.33E+08
Compression yield Strength (Pa)	3.90E+09
Specific Heat (j/kg.c)	750
Hardness (Vickers) (Pa)	2.7459E+10
Friction Coefficient against Steel [15, 16]	0.6
Fracture Toughness (Pa/m ^{0.5})	6.70E+7

Material 1	
Conductivity (W/m•°K)	120

For the other two materials no need for a special method in modeling only assigning the materials and properties for the clutch plate and their properties are shown in table (2).

Table (2) showing the two materials' properties AMC and E-glass.

Aluminum Matrix Composite [20]		
Property	Value	Unit
Density	2.74E+03	kg/m ³
Young modulus	9.86E+01	GPa
Tensile strength	359	MPa
Poisson Ratio	3.11E-01	
Yield strength	3.03E+02	MPa
Elongation	4.00E-01	%
Hardness [17, 18]	480	MPa
Thermal Expansion (20 °C)	20.7*10 ⁻⁶	°C ⁻¹
Thermal Conductivity	144	W/(m*K)
Friction Coefficient	0.6	
Wear Coefficient(K)	0.0000488	
E-Glass UD		
Property	Value	Unit
Density	2.00E+03	kg/m ³
Young Modulus (X, Y, Z)	45,10,10	GPa
Tensile strength (X, Y, Z)	1.01E+08	MPa
Poisson's Ratio (XY, YZ, XZ)	0.3,0.4,0.3	
Yield Strength	900-1000	MPa
Elongation	3.3 - 4	%
Hardness [19]	3000	MPa
Thermal Expansion (20 °C)	1.1*10 ⁻⁶	°C ⁻¹
Thermal Conductivity [19]	1.35	W/(m*K)
Friction Coefficient	0.5	
Wear Coefficient(K)	-	-

4. Clutch Plate Designing

Considering clutch designing methods, only uniform axial wear is used to determine the properties of the clutch plate [1], for the three different materials. Considering the dimension of common clutch plates used in medium and heavy automobiles [20] and the working condition at the starting of engines, as follows. A lot of medium-weight and heavy vehicles and equipment have clutch plates with outer diameters of 300mm[20]. Therefore, the outer diameter in this study will be taken as 300mm, while the inner diameter will be fixed at 150mm. Frictional material thickness is taken as 4 mm for each side as most commercial clutches. To find the pressure needed on the clutch plate, most vehicles the engines run at 1250r. p. m, as initial speed. And the engine output power is assumed 110KW. Considering the clutch plate as a ring. In uniform wear the design is done based on the following equations [1]:

Force axially acting on the friction surface (F_a):

$$F_a = Pressure * Area$$

7

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

8

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

$$T = n * \mu_L * F * R$$

9

$$R = (R_o + R_i) / 2$$

10

And

$n \equiv$ number of acting surfaces (2 surfaces in most single-clutch plates and is considered in this case).

$T \equiv$ transmitted torque $F_a \equiv$ Force axially acting on the friction surface

$p \equiv$ axial pressure holding surfaces in contact

$R_i, R_o \equiv$ the inner and outerradius.

$R \equiv$ the main radius of the frictioning face

$\mu_L \equiv$ friction coefficient of the lining material

Considering Friction Coefficients of the three materials FGAMC, AMC and E-Glass, .54 (taking the average), 0.60, and 0.50 respectively from material properties tables. The outcomes of the calculation

applying at equations (10), (9), and (8) are showed in the below table.

Table (3) the working pressure and axial force in each clutch plate.

Material	Working Pressure (N/mm ²)	Axial Force (N)
Functionally Graded Aluminum Matrix Composite	0.131	6916.4
Aluminum Matrix Composites	0.117	6224.7
E-glass Epoxy	0.141	7470

5. 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. for the AMC is lower by 5.7% than the FGAMC plate. The clutch plate was studied against the pressure when the flywheel is revolving with 1250R. P. M. and the pressure is assigned for each material as in the design part. The graphs show the different deformations of all the plates with different assigned materials. FGAMC has the lowest deformations except in Z direction, where AMC is the lowest. In total deformation, FGAMC is lower by 45% and 44% from AMC and E-glass, respectively. In X-direction, FGAMC is lower by 38% than AMC and even lower by 86.7% from the E-glass. In Y-direction it is the same scenario lower by 38.4% and 93% from AMC and E-glass. In Z-direction, AMC is the lowest, nearly 95% from the FGAMC. E-glass is higher than FGAMC with 97.5%. Results presented in figure (4).

The second bar chart figure (5) shows the equivalent stresses maximum and minimum on each model, and the FGAMCs plate is having the lowest value of stress. For the maximum stresses, it is nearly half of the traditional AMC (50% less than AMC). While it is 95 times E-glass.

For strain, the FGAMCs clutch has the highest strain among the three models. The FGAMC is higher in strain than AMC by 17.6% while its higher than the E-glass with 11.6%. Figure (6) illustrates the results.

Table (4) below shows the deformation in the 3 directions X, Y, and Z respectively followed by the stress and strain in the FGAMC plate.

Table (4) Shows the deformations, strain, stress of the FGAMC Model.

6. Dynamic Analysis

The dynamic analysis will include vibration analysis (Modal and Harmonic) and Transient analysis.

6.1. Vibration Analyses:

6.1.1 Free Vibration (Modal) Analysis:

The 3 models are studied under free vibration conditions with fixed support implemented in the center of the clutch plate, which is applied also in forced harmonic and static analyses. Results are shown below in figure (7) and mode shapes in figure (8).

Figure (7) Deformations at different frequencies for the 3 Models.

The FGAMC has a lower first natural frequency than the others, but for the important natural frequency range, where the deformation is in the Y Direction, the FGAMC has a lower natural frequency, 23.74 Hz, with a deformation less in magnitude than the AMC by 2.6%, while the AMC is 27.153mm at 24.38. E-glass is having the highest first natural frequency with the highest deformation by 13.6% than FGAMC at 27.59 Hz. The same thing happens in the second natural frequency. Figure (7) shows the first 4 modal shapes which are identical to the three models in appearance.

Figure (8) Modal Shapes of First 4 Natural Frequencies.

6.1.2 Forced Vibration (Harmonic) Analysis:

The analysis is conducted under the condition of the clutch plate is under working pressure for each material type, which calculated in the Design step, $.141 N/mm^2$ for Clutch made of E-glass, $.117 N/mm^2$ for Aluminum matrix composites with 20% Silicon Carbide particles, and lastly $.131 N/mm^2$ for the functionally Graded Aluminum matrix composite with Silicon Carbide. The graphs below show the result of the analysis while the range of frequencies is from 0 to 180 Hz (equivalent to 0 r.p.m. to 11000 r.p.m) as it is the common vibration range developed by automobiles. In X direction the deformation of the FGAMC is the highest by 93.4 and 82.2 % than AMC and E-glass at peaks, respectively. While in the same direction the strain is higher than the AMC by 79% and less than E-glass plates with 60% at peaks. In terms of stresses in X-direction the FGAMC is the lowest, it is from AMC and E-glass by 72.9% and 202.6% respectively. Figures (9-11) reveal deformation, strain, and stresses at X-direction.

Figure (9) Deformation in X Direction

Figure (10) Normal Elastic Strain in X Direction.

Figure (11) Normal Stress in X Direction.

In Y-direction the deformation of the FGAMC clutch plate is the highest, 91.5% higher than AMC and 96.5% than E-glass. Regarding strain, is between the AMC and E-glass plates. But for stresses, FGAMC is having the highest stresses and AMC is the lowest by 60.7% lower than FGAMC and E-glass is lower by 29%. Findings are shown in figures (12-14).

Figure (12) Deformation in Y Direction

Figure (13) Normal Elastic Strain in Y Direction.

Figure (14) Normal Stresses in Y Direction.

In Z-direction, which is the direction of applied pressure, FGAMC has nearly identical curves to the AMC in deformation and strain, but for stress, the FGAMC is the lowest. As AMC and E-glass stresses equals approximately 2 times and 3 times respectively the stress of FGAMC. Figures (15-17) represent findings.

Figure (15) Deformation in Z Direction.

Figure (16) Normal Elastic Strain in Z Direction.

Figure (17) Normal Stresses in Z Direction.

6.1.3 Structural Transient Analysis:

The transient analyses were done with boundary conditions as following, rotation from the middle with $.13rad/s$ equivalent to the $1.250r.p.m.$ as $.1\%$ of the actual rotation velocity and changing the assigned material and changing the working pressure taking also 0.1% of the working pressures 1.17×10^{-4} for 1.41×10^{-4} for and lastly $1.31 \times 10^{-4} N/mm^2$ for 2.5 seconds. This reduction in value minimizes computing time and not exceeding software capabilities. These reductions are also applied in wear analysis. Flywheel material is Structural Steel.

A. E-Glass:

E-glass analysis showed an equivalent strain range from $4.1E - 11 mm/mm$ as minimum strain on the plate and a maximum of $3.5E - 7 mm/mm$. While having equivalent stresses from $2.8E - 3 Mpa$ to $1.5E - 4 Mpa$ 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 $2.15E - 5 mm$ to $6.4E - 14 mm$. And the frictional stresses have a maximum value at middle $1.3E - 4 Mpa$ of the plate decreasing slowly at outer diameter direction and rapidly at inner diameter direction. Table (5) contain graphics and figures of E-glass transient analysis.

Table (5) Transient analysis of E-glass.

B. Aluminum Matrix Composite

The transient analysis of the AMC clutch as shown in table (6) gives a range of $6.5E - 8 mm/mm$ to $3.12E - 9 mm/mm$ for equivalent strains and having maximum stresses at the inner diameter also with $6.5E - 3 Mpa$ and lowest stresses $1.5E - 4 Mpa$ at outer diameter area. The deformations at the same locations of E-glass but with maximum value $1.025E - 5 mm$ to $4.02E - 14 mm$. The Frictional stresses are identical to the E-glass but with an area having the maximum value larger.

Table (6) Transient analysis of AMC.

C. Functionally Graded Material:

FGAMC analysis reveals that the equivalent strains are $4.4E - 8mm/mm$ maximum and $3.2E - 9mm/mm$. Equivalent stresses range from $1.1E - 2Mpa$ to $3.6E - 4Mpa$ at inner and outer diameters, respectively. The deformations are higher at outer diameter with $9.1E - 6mm$ and lower at inner one $6.4E - 14mm$. With frictional stresses, the maximum is affecting only on the outer diameter tip area with $2.5E - 4Mpa$. Analysis results are demonstrated in table (7).

Table (7) Transient analysis of FGAMC.

The graph in figure (18) shows the strains of the three clutches compared together. The FGAMC having the lowest equivalent strains.

Figure (18) shows the differences in Strains.

The bar graph in figure (19) compares the equivalent stresses in the different clutch plates, the E-glass is the lowest then AMC, and lastly the FGAMC.

Figure (19) shows the differences in Stresses.

The deformations of the clutch plates with respect to each other, are demonstrated with the above graph figure (20), the FGAMC is the lowest.

Figure (20) shows the differences in Deformations.

Frictional stresses of FGAMC compared to the two other clutches are the highest, while the AMC and E-glass are identical. The above tables, figures, and graphs show the performance of the different clutches. The FGAMC considering strain is the best as it achieves the lowest equivalent strain by nearly 10 times from E-glass and two times from AMC. In addition, the deformation in the clutch plate of FGAMC is also less than the others by 10 times. And 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. But the affected area in FGAMC clutch equals 30% of the affected AMC clutch and 15% of the E-glass clutch. The only drawback of the FGAMC material is in the equivalent stress as it is doubled from the AMC and E-glass and approximately distributed along all the area of the clutch. Figure (21) gives the comparison between the three clutches.

Figure (21) shows the differences in Frictional Stresses.

7. Wear Analysis

Wear analysis is done 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, which should be obtained from experimental work, but to keep the simplicity of the analysis the two terms are assumed equal unit (1). The analyses were done in two cases: first symmetric analyses (the wear in the flywheel and the clutch plate both) and Second Asymmetric (wear in 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 formulation:

$$\dot{W} = \frac{K}{H} * P^m * v_{rel}^n$$

11

Where, K is wear coefficient of the material, H is material hardness, P is the contact pressure, m is the exponent of pressure. While v_{rel} is relative sliding velocity 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 steel, as the flywheel is made of steel commonly. Same boundary conditions are used in the transient analysis used here to reduce computational costs.

A. Aluminum Matrix Composite (AMC):

The wear analysis modeled in Ansys for AMC clutch shows (represented in table (8)) that the total wear in both the flywheel and the clutch plate is reaching a maximum value of $4.1E-8mm^3$ with steady wear at the flywheel and graded wear at the clutch starts from the middle to the outer diameter increasingly.

The wear at only the clutch has the maximum value at outer diameter too of $3.5E-8mm^3$.

Table (8) Wear analysis of AMC.

B. Functionally Graded Material (FGAMC):

Wear of the FGAMC clutch with the flywheel is reaching a maximum value of $7.7E-8mm^3$ but it is clear that the maximum wear is happening in the tip area of the clutch. The wear analysis of the clutch only resulted in maximum wear of $0.37E-8mm^3$ only on the outer diameter area. Table (9) shows analysis results.

Table (9) Wear analysis of FGAMC.

The analyses show after compared with each other as in the above graph (Figure 22) the FGAMC's clutch is having approximately 10 time less wear in asymmetric analysis (Clutch plate and Flywheel Together) and causes 18 times less wear on the flywheel than the AMC's clutch. Adding to that the affected area by wear with FGAMC's clutch is nearly half of the one belonging to AMC's clutch.

Figure (22) illustrate the differences in wear between FGAMC and AMC.

8. Theoretical Thermal Analysis

The heat generated in each clutch is calculated using the mentioned working condition in the design phase in the following equations:

$$Q_g = \mu * \omega * P$$

12

$$Q_f = Q_g / A$$

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 (10) below.

Table (10) shows results of thermal analysis.

Material	E-glass	AMC	FGAMC
Friction Coefficient	0.5	0.6	0.54
Working Pressure N/mm^2	0.141	0.117	0.131
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)	1.74E-04	1.74E-04	1.75E-04

The FGAMC material will generate the highest heat among the three materials but the difference between them is very small and can be considered identical.

9. Results And Discussions

The functionally graded aluminum matrix composite clutch plate has 5.7% and 26% more mass, with 200 g and 500 g more mass than AMC and the E-glass, respectively. In Static analysis, FGAMC is having the lowest total deformations by more than 40% than the other two. For static stresses, FGAMC is having 50% less than AMC and 95% less than E-glass with $2.60e - 6 N/m^2$ maximum and $2.375e - 08 N/m^2$. Considering strain, FGAMC has the highest value by more than 11% from other materials. The first natural frequency for the FGAMC is 24.4 nearly the same as AMC and lower than the E-glass frequency by 3 Hz but with the lowest deformation of the three models less by 2.6% from AMC and 13.6% from E-glass. In harmonic analysis, the working pressure of the FGAMC is $(.131 N/mm^2)$ which is between the working pressure of the AMC $(.117 N/mm^2)$ and E-glass $(.141 N/mm^2)$. The total deformations in X and Y for

FGAMC are the highest but in Z are the lowest, which is the direction of applied pressure. Stresses in Z and X are the lowest for FGAMC in Y are the highest but not too far from the other two materials. In terms of strain, the FGAMC keeps values in the middle between AMC and the E-glass, as higher than AMC. The Structural Transient analyses showed that the behavior of FGAMC's clutch considering Strain is having 10 times lower strain than the E-glass while having nearly half of AMC strain. Regarding deformation the FGAMC's clutch is the lowest deformed clutch among the three, the E-glass clutch deformed twice times more than the FGAMC and AMC had higher deformation than the FGAMC. Taking stress into account, FGAMC's clutch achieved the highest equivalent stress what is about 4 times of E-glass, and less than double of AMC equivalent stresses. For Frictional Stresses, the AMC and E-glass clutches have the same amount of frictional stress and the FGAMC is doubling them, But with affected area by the frictional stress equivalent to 30% and 15% of the affected, areas of AMC and E-glass clutches, respectively. The wear analysis in the symmetric case, considering wear in both clutch plate and flywheel, shows that the wear in FGAMC's clutch is 4 times less than what resulted from AMC and the affected area in clutch plate and flywheel for FGAMC is equal to half the area affected with AMC. The asymmetric case, wear in clutch only, the FGAMC clutch had 9 times and half less wear than the AMC with also half area affected by the wear. Theoretical thermal analysis shows the heat generated in the 3 clutches are very close to each other with differences of 0.03 between E-glass and FGAMC and only 0.07 Between FGAMC and AMC.

10. Conclusions And Recommendations

As the result shows using FGAMC as a frictional lining in clutches has many benefits. In thickness direction deformations is less than the other two materials. Also, there is an increase in the weight comparing to AMC, but lower total deformations are achieved. The strain of the functionally graded aluminum matrix composite increased and in certain situations it is near to E-glass material, giving it higher strength than its successor AMC. Stresses in most of the tests of the FGAMC is the lowest in term of magnitude. From the transient analysis, the performance of the FGAMC is very good and exceeds the other two materials in most of the analysis criteria because it has less deformation, less affected area with frictional stress, and less strain. Meaning the FGAMC material has a very good ability to be used as a frictional lining of an automobile clutch. The wear performance of FGAMC compared to the AMC is better and 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. Thermal analysis reveals that the three clutches are producing approximately identical heat and heat flux. Which is an additional positive side of using FGAMC as frictional material. 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 the model can be studied when the change in the material properties happens in the radial direction. Finally, the utility of FGAMC material can be implanted innovatively to be used as braking pads.

11. Declarations

11.1 Availability of data and materials:

The Materials and data are available.

11.2 Competing interests:

No competing interests.

11.3 Funding:

Not applicable.

11.4 Authors' contributions:

First author Ibrahim Ali, the analysis work. Second Autor Saeed Asiri supervising and monitoring.

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Tables

Tables 4-9 are available in the Supplemental Files section

Figures

Figure 1

3D Model for a clutch set (Pressure Plate, Clutch Plate, and Flywheel). [Made by SolidWorks].

Figure 2

Clutch set (clutch plate, flywheel, and pressure plate). [1]

Fgm\Layers	X/L	Density	Thermal Expansion	Young Modulus	Poisson Ratio	Bulk Modulus	Shear Modulus	Tensile Yield Strength	Compressive Yield Strength	Specific Heat	Hardness (Vickers)	Fracture Toughness	Conductivity	Friction Coefficient
1	0	2770	0.000023	7.1E+10	0.33	7E+10	2.67E+10	2.80E+08	2.80E+08	923.5	5.6E+08	2.85E+07	160	0.47
2	0.125	2811.25	2.51E-05	1.1E+11	0.30625	8.8E+10	2.85E+10	3.62E+08	7.33E+08	901.81	8.2E+08	2.54E+07	158.75	0.48625
3	0.1875	2831.875	2.62E-05	1.3E+11	0.29438	9.8E+10	2.95E+10	4.02E+08	9.59E+08	890.97	9.4E+08	2.39E+07	158.125	0.494375
4	0.25	2852.5	2.73E-05	1.6E+11	0.2825	1.1E+11	3.04E+10	4.43E+08	1.19E+09	880.13	1.1E+09	2.24E+07	157.5	0.5025
5	0.3125	2873.125	2.83E-05	1.8E+11	0.27063	1.2E+11	3.13E+10	4.84E+08	1.41E+09	869.28	1.2E+09	2.08E+07	156.875	0.510625
6	0.375	2893.75	2.94E-05	2E+11	0.25875	1.3E+11	3.22E+10	5.25E+08	1.64E+09	858.44	1.3E+09	1.93E+07	156.25	0.51875
7	0.4375	2914.375	3.04E-05	2.2E+11	0.24688	1.4E+11	3.32E+10	5.65E+08	1.86E+09	847.59	1.5E+09	1.78E+07	155.625	0.526875
8	0.5	2935	3.15E-05	2.4E+11	0.235	1.4E+11	3.41E+10	6.06E+08	2.09E+09	836.75	1.6E+09	1.63E+07	155	0.535
9	0.5625	2955.625	3.26E-05	2.6E+11	0.22313	1.5E+11	3.5E+10	6.47E+08	2.32E+09	825.91	1.7E+09	1.47E+07	154.375	0.543125
10	0.625	2976.25	3.36E-05	2.8E+11	0.21125	1.6E+11	3.59E+10	6.88E+08	2.54E+09	815.06	1.8E+09	1.32E+07	153.75	0.55125
11	0.6875	2996.875	3.47E-05	3E+11	0.19938	1.7E+11	3.69E+10	7.29E+08	2.77E+09	804.22	2E+09	1.17E+07	153.125	0.559375
12	0.75	3017.5	3.58E-05	3.3E+11	0.1875	1.8E+11	3.78E+10	7.69E+08	3.00E+09	793.38	2.1E+09	1.01E+07	152.5	0.5675
13	0.8125	3038.125	3.68E-05	3.5E+11	0.17563	1.9E+11	3.87E+10	8.10E+08	3.22E+09	782.53	2.2E+09	8.59E+06	151.875	0.575625
14	0.875	3058.75	3.79E-05	3.7E+11	0.16375	2E+11	3.96E+10	8.51E+08	3.45E+09	771.69	2.3E+09	7.06E+06	151.25	0.58375
15	0.9375	3079.375	3.89E-05	3.9E+11	0.15188	2.1E+11	4.06E+10	8.92E+08	3.67E+09	760.84	2.5E+09	5.53E+06	150.625	0.591875
16	1	3100	0.00004	4.1E+11	0.14	2.2E+11	4.15E+10	9.33E+08	3.90E+09	750	2.6E+09	4.00E+06	150	0.6
Average		2944.023	3.2E-05	2.5E+11	0.2298	1.5E+11	3.45E+10	6.24E+08	2.19E+09	832.01	1.6E+09	1.56E+07	154.727	0.538555

Figure 3

Shows the Properties at each layer and their average.

Figure 4

shows deformations under static analysis

Figure 5

shows stresses under static analysis

Figure 6

shows strains under static analysis.

Figure 7

Deformations at different frequencies for the 3 Models.

Modal Shapes of First 4 Natural Frequencies.

Figure 9

Deformation in X Direction

Figure 10

Normal Elastic Strain in X Direction.

Figure 11

Normal Stress in X Direction.

Figure 12

Deformation in Y Direction

Figure 13

Normal Elastic Strain in Y Direction.

Figure 14

Normal Stresses in Y Direction.

Figure 15

Deformation in Z Direction.

Figure 16

Normal Elastic Strain in Z Direction.

Figure 17

Normal Stresses in Z Direction.

Figure 18

shows the differences in Strains.

Figure 19

shows the differences in Stresses.

Figure 20

shows the differences in Deformations.

Figure 21

shows the differences in Frictional Stresses.

Figure 22

illustrate the differences in wear between FGAMC and AMC.

Supplementary Files

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- [Tables49.docx](#)