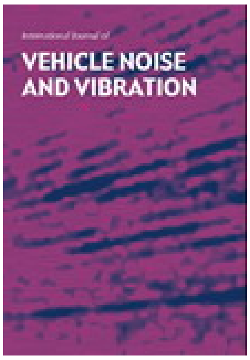

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Numerical analysis of single dry clutch using functional graded aluminium matrix composite reinforced with silicon carbide

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Abstract: Functionally graded aluminium matrix composite (FGAMC) with silicon carbide is used as a friction material in clutches since this material has acceptable friction coefficient and high wear resistance. The functionally graded material (FGM) is represented as layered solid parts, each layer with different properties, the properties are calculated using rule-of-mixture and power-law of Voight. The FGAMC clutch is compared with two material e-glass and aluminium matrix composite with 20% silicon carbide particles, the FGAMC also has silicon carbide as the second material. Analysis reveals an increase in strain for the FGAMC over the traditional aluminium matrix composite (AMC). Adding to that a significant decrease in deformation at thickness direction and for stresses, in most analysis, it was the least. The drawbacks of the material is a rise in the mass resulting in low natural frequency, but the deformation is low. The results combined with FE simulation are used to predict the properties grading function.

Keywords: functionally graded material; aluminium matrix composite; deformations; stresses; strain.

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Biographical notes: Saeed Asiri's research activities are on the vibration control of mechanical systems. He and his advisor, Professor A. Baz, have innovated a new class of support struts called periodic struts as an isolator of mechanical vibrations. He presented the innovative use of unique characteristics of periodic struts in many critical applications where the control of the wave propagation and the force transmission both in the spectral and spatial domains is essential to stopping/confining the propagation of undesirable disturbances. He got in 2010 a patent from KACST titled: Differential Agitator and a patent from US Patents titled: Smart Boat for Swimming Pool Maintenance and Water Safety. He currently teaches vibrations and control courses for undergraduate and graduate students. In addition, he published lately many papers on vibration analysis and modal analysis of functionally graded materials using FEM.

1 Introduction

A few decades ago iron and steel were most prevailing materials in auto industry, but present work is on eco-friendly and control of unnecessary weight. Aluminium matrix composite is most suitable material to resolve such type of problems. Metal matrix composites (MMC) materials have advantages over cast iron because of superb properties like lower density, better resistance to corrosion, lower thermal expansion, higher thermal conductivity (Dagwa and Adama, 2018). Clutch is one of the most important mechanical parts in the equipment such as automobiles with manual transmission systems, washing machines, and many rotating tools. Clutches are used to transmit the rotation movement from a driving shaft, connected to a power source (combust engine or motor) to a driven shaft (Clutch Catalogue, 2021). In automobiles, the clutch is designed to transmit the torque and motion from the flywheel connected to the engine, to the gearbox while maintaining the same velocity, but the main idea of it is to allow connection and disconnection between those two parts without the need of stopping the power source (i.e., the engine). It is well known that it can be an efficient way to isolate the vibrations and noise of engine since it is a transmission path of structure-born vibrations which is very important issue in automotive engineering and industry as presented by Qatu et al. (2009) and Qatu (2012). However, the main function of the clutches is to transmit the motion in automobiles by friction contact, as the friction disc of the clutch will be pressurised by a spring (mostly diaphragm spring) towards the flywheel, the friction lining will connect to the flywheel and start to rotate with the flywheel, transmitting the motion and torque. Therefore, friction materials in clutches have been under focus in many research projects to develop new materials or studying use 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 also high friction coefficient, withstanding high temperatures and wear resistance other essential properties, such as 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 (Hassan and Alrashdan, 2009).

Nowadays, an attractive area of research is to introduce advanced meta-matrix micro- and nanocomposite (MMCs) which can improve their reliability, efficiency, and light weight. Not only high specific strength but also specific stiffness, low thermal expansion and coefficient of friction. Many materials have been used as friction lining in clutches (Toros and Altinel, 2016; DevSrivyas and Charoo, 2019; Kashyzadeh and Asfarjani, 2016; Bian and Wu, 2015; Miyamoto et al., 1999; El-Galy et al., 2017; Gomes et al., 2003). The most common ones are E glass epoxy with a competitively low cost (El-Tayeb and Gadelrab, 1996). The type of glass fibre is E-glass which is famous for its high quality, high strength and even high chemical resistance, but the low modulus of elasticity and the high density are considered as a disadvantage because they result in weight increase. AMCs have excellent combination of properties like light weight, and high performance that's why AMCs are used in automobile, aerospace defence and many other fields (Mack et al., 2012). Aluminium matrix composites (AMCs), especially AMC enforced by silicon carbide, with high strength to weight ratio, (in this study Al+20% SiC will be used). AMCs reinforced by SiC have a lower coefficient of thermal expansion and higher elasticity modulus than the unreinforced aluminium matrix alloy (Natarajan et al., 2006). As the improvement in the reinforced case of the SiC particles in the material resulting in higher hardness. Effect of SiC content on wearing behaviour of aluminium alloy. By changing the SiC particles in 10%, 15%, and 25% and sliding speed of 0.25, 1.72, 3.35 and 5.23 m/s for same sliding distance of 5000m. So result showed that SiC content increases the wear rate and temperature decrease (Rao and Das, 2011). Artificial functionally graded materials are only imitating the ones found in nature, such as bones and mollusc shells. Mollusc shell, for instance, is made of one material calcium carbonate ($CaCO_3$), and it is not considered as a structural material, but to withstand external stresses and hydraulic pressure (under deep water) the shells by combining different microstructure formed a graded structure that achieves uniform strength, and has flexible deformation ability in microstructures boundaries by making these areas softer (Dhanasekaran et al., 2016). Nevertheless, there are many types of functionally graded materials, all of them share the changing of materials from metal to ceramic mostly, and to simplify analysis the change is dependent on one direction. The property of the material changes in this direction, we can say the FGM properties are different in different locations. This character is the reason to develop FGM materials.

A new sector of research is concentrating now on the functionally graded metal matrix composites (FGMMCs). Essentially, producing metal matrix composites by 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. FGM are produced by many ways. They can be processed by powder stacking (by normal gravity, under pressure-induced flow, or under centrifugal forces), vapour depositing, centrifugal casting, or by solid freeform fabrication (El-Galy et al., 2017). Many pieces of research have been done in the usage of AMCs as friction material of the clutch. It has been found that A356 aluminium alloy when reinforced by SiC and Al_2O_3 particles and produced by stir casting, the tensile, hardness, and yield strength compared to alloy. An increase of 16% in tensile when 20% of SiC reinforced and the yield increased 50%. 10% of Al_2O_3 increased the tensile by 19% and the yield is nearly the same as of 20% SiC reinforced (50%). Some researchers studied the effects of different percentages and sizes of SiC particles, also investigated the effects of the different conditions in processing, their criteria of instigation were tensile, hardness, and wear rate. They found that the SiC particles in the outer part of the cast tubes reach their maximum and then gradually decreased towards the inner diameter. Large particles and high rotation speed increase the concentration of reinforced particles in the outer part. Hardness measurement revealing on FGM outer zone has the highest hardness in all tests, compared to the inner zone. The smallest particles have the highest hardness in all tests. The increase of SiC weight results in a rise of hardness in the outer zone and tensile strength rises too. With up than 10% SiC the tensile strength increase linearly. It has been shown recently that mechanical properties of surface and bulk can be attained when processing aluminium matrix composite reinforced by 20% SiC particles processed as functionally graded material, by centrifugal casting. The outcome of this process resulted in a material which was examined to evaluate its wear and friction properties by sliding it on a cast iron pin disk. Comparing to the homogenous aluminium matrix composite, the new material has a lower friction coefficient [from .60 for the homogenous AMC to .50 for the functionally graded aluminium matrix composite (FGAMC)]. Also a lower wear coefficient for the functionally graded matrix composite (10^{-6} $mm^3N^{-1}M^{-1}$) meaning higher wear resistance. Friction and wear properties of aluminium matrix composites are based on the effect of the reinforced particles works as load-bearing elements in addition to the formation of protective attached iron-rich tribolayers, refilled by the characterisation of worn surfaces.

Here we compare wearing behaviour of (Al MMC) with conventional grey cast iron under identical conditions. The Al MMC was fabricated by A356 aluminium alloy and 25% silicon carbide, both have been tested at various sliding velocities, loads and sliding distance. Al MMC has a 25% greater friction coefficient than cast iron. Effect of aluminium oxide and silicate oxide in the presence of 8% pumice is an increment of 11 08%–28.39% on hardness and tensile strength (Dagwa and Adama, 2018). In this research work different friction materials (E-glass epoxy, AMC (20% SiC reinforced and functionally graded aluminium matric composite (with SiC) are tested as a friction lining of single clutch plate working in normal automobiles conditions to give a comparison result of the possibility of using FGAMCs in friction clutches.

2 Designing the friction plate

There are many aspects to be considered while designing the plate including but not limited to the clutch moving parts, to have minimum inertia load, should have low weight as possible. Clutch must not be in need of external force to maintain the connection of the friction surface. Adding to that a capability of dissipating heat from contacted surfaces.

There are two cases to be considered in the design, either uniform pressure or uniform axial wear. In this research work, the latter will be considered, as it is the actual condition that the plate works at for the longest time of plate life. The uniform pressure is found only for a very small time when the plate is new and changes to uniform axial wear after wear starts in the lining.

T	transmitted torque
F_a	force axially acting on the friction surface
p	axial pressure holding surfaces in contract
Ri, Ro	the inner and outer radius
R	the main radius of the fractioning face
μ_L	friction coefficient of the lining material.

Consider the clutch plate as a ring. In uniform wear the design is done based on the following equations:

Force axially acting on the friction surface (F_a):

$$F_a = Pressure * Area$$
$$F = p * \pi * \left[R_o^2 - R_i^2 \right]$$

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

$$T = n * \mu_L * F * R$$
$$R = (R_o + Ri)/2$$

and

$$n = number\ of\ acting\ surfaces \begin{pmatrix} 2\ surfaces\ in\ most\ single-clutch\ plates, \\ and\ is\ considered\ in\ this\ case \end{pmatrix}$$

2.1 Design specifications

Many medium weight and heavy vehicles and equipment have clutch plates with outer diameters of 300mm. Therefore, the outer diameter in this study will be taken as 300 mm, while the inner diameter will be fixed at 150 mm. 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 1,250 r.p.m, as initial speed. And the engine output power is assumed 110 kW. The torque will be:

$$T = \frac{60*110*10^3}{2*\pi*1250} = 840.34N-m = 840.34*10^3 N-mm.$$

To calculate the needed pressure on the clutch plate for the different materials

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

$$R = (R_o + Ri)/2 = 112.5mm$$

$$F_a = pressure*Area$$

$$F_a = p*\pi\left[R_o^2 - R_i^2\right]$$

Then:

$$F_a = \frac{T}{n*\mu_L*R}$$

$$p = T/(n*\mu_L*Area*R)$$

For E-glass epoxy, the pressure should be the friction coefficient taken on normal load 50N, it ranges from 0.42 to 0.5. The latter will be considered in this study:

$$\mu_L = .5$$

$$\therefore F_a = 7470N$$

$$\therefore p = .141N/mm^2$$

For aluminium matrix composites 20% SiC reinforced:

$$\mu_L = .6$$

$$\therefore F_a = 6224.7N$$

$$\therefore p = .117N/mm^2$$

For the functionally graded aluminium matrix composite:

$$\mu_L = .54[\textit{as the average of the total material}]$$

$$\therefore F_a = 6916.4$$

$$\therefore p = .131 N/mm^2$$

It can be seen that the new material has average working pressure more than the traditional AMC by 10.7% and lower than e-glass by 20.5%.

3 Modelling

3.1 E-glass epoxy and AMC 20% sic reinforced

The clutch plate is designed and represented by 3D geometry with SolidWorks software contains three parts. Two friction lining sides and a structural support disc. With 4 mm as lining thickness for each side (8.5 mm in total thickness). Figure 1 shows the 3D model of the clutch plate. To carry the analysis on the clutch plate, firstly the analysis method used is the finite element method, which is a numerical method that relies on dividing the structure into small elements connected by nodes and analyses those elements and then reassembles them to give a reaction of the complete structure based on the reactions of each element in the nodes. To perform this analysis by this method ANSYS 2020R2 is used.

Figure 1 The developed 3D Model in SolidWorks (see online version for colours)

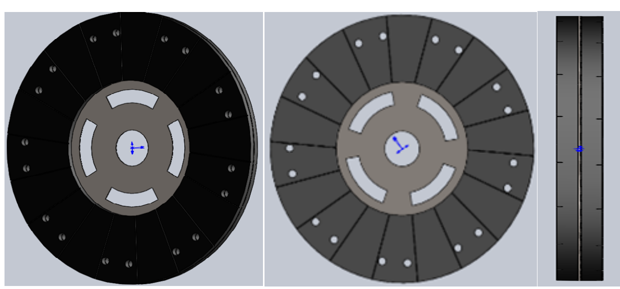
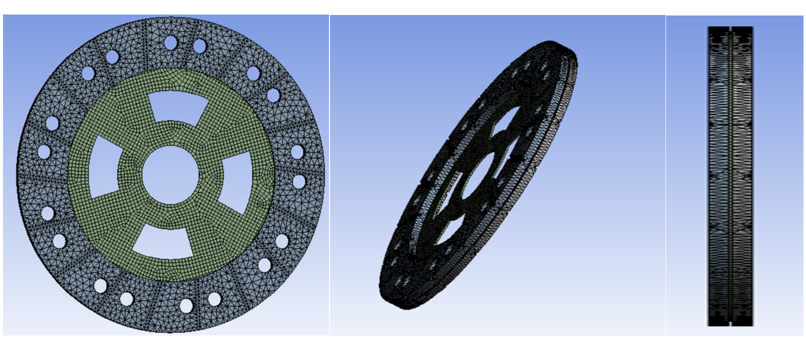


Figure 2 Meshed clutch plate for E-glass epoxy and Al-SiC (see online version for colours)



The representation geometry is imported from the SolidWorks to the ANSYS. In all models, elements sizes are settled at 2 mm for each. Achieve 122171 elements connected by 322237 nodes for the e-glass epoxy and aluminium matrix composite 20% SiC reinforced. Figure 2 shows the clutch plate meshed in ANSYS.

3.2 Functionally graded AMC

FGM mechanical properties change in a certain direction. Normally one solid part may not be sufficient to represent and modelling them. There are several methods to predict the behaviour of FGMs and to model, the simplest one, and used here, is the linear rule of mixture method (Voight estimate) for two materials.

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

where β is the property of the material and V is the volume fracture of the material in the new FGM.

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

To determine the properties of the new FGM It is assumed that its properties change with respect to only one direction. Therefore, we can consider the property is a function in location (x):

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

And this function can be solved with power-low assumptions based on Voight model to get:

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

where $V_{material2}(x)$ refers to the volume fraction of the material 2 and is changing in power form:

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

where L is the length of graded direction, and κ is the given graded parameter (it is assumed that $\kappa = 1$ *which means the change linearly*), substituting the previous two equations to get:

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

And this is the equation used in modelling the FGAMC.

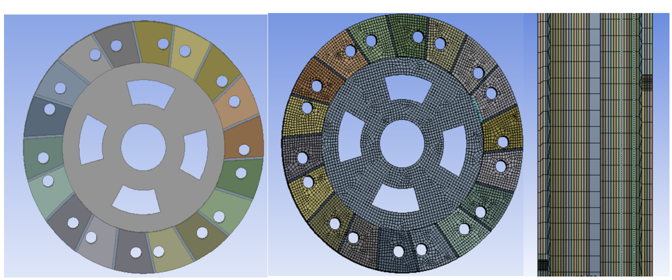
The FGAMC considered is changing in the thickness direction. One of the methods of modelling FGMs is representing them as small layers forming together one complete part, each layer with different proportions of the materials forming the FGMs. To get accurate results, each side of the friction lining was divided into 16 layers, by step thickness .25 mm, and the two materials used to produce the FGAMC properties are in Table 1.

By applying the above method, the new material has different properties in the different 16 layers, Table 3 shows the properties in the 16 layers. In SolidWorks to represent the new material, the 3D model was established with 16 parts to form each side and with the structural support disc. The 3D model is imported to ANYSYS to carry out analyses. It is also meshed with a 2 mm element in size. Also, here the model has three parts, one for the support disc and two for the two-side friction material including 32 solid bodies, 16 layers for each. The number of elements is 649564 attached in 2401471 nodes. Figure 3 shows the model of the new material and after meshed.

Table 1 Showing the two materials' properties

Material 1			*Material 2*	
Aluminium alloy properties			*SiC silicon carbide, SiC ceramic properties*	
Density	2770	kg/m³	3100	kg/m³
Thermal expansion	2.30E-05	1/c	4.00E-05	1/c
young modulus	7.10E+10	pa	4.10E+11	Pa
Poisson's ratio	0.33	-	0.14	-
Bulk Modulus	6.96E+10	pa	2.20E+11	Pa
Shear Modulus	2.67E+-10	pa	4.15E+10	Pa
Tensile yield strength	2.80E+08	pa	9.33E+08	Pa
Compression yield strength	2.80E+08	pa	3.90E+09	Pa
Specific heat	923.5	j/kgc	750	J/kg•°K
Hardness (Vickers)	799000000	pa	27458620000	Pa
Friction coefficient against steel	.47		.6	
Fracture toughness	28500000	Pa/m$^{0.5}$	67000000	Pa/m$^{0.5}$
Conductivity	160	W/m•°K	120	W/m•°K

Figure 3 Meshed clutch plate for FGAMCs with a gradual change in the thickness direction (see online version for colours)



4 Vibration analyses

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.

4.1 Free vibration analyses

The three models are studied under free vibration conditions with fixed support implemented in the centre of the clutch plate. Results are shown below.

Figure 4 Deformations at different frequencies for the 3 models (see online version for colours)

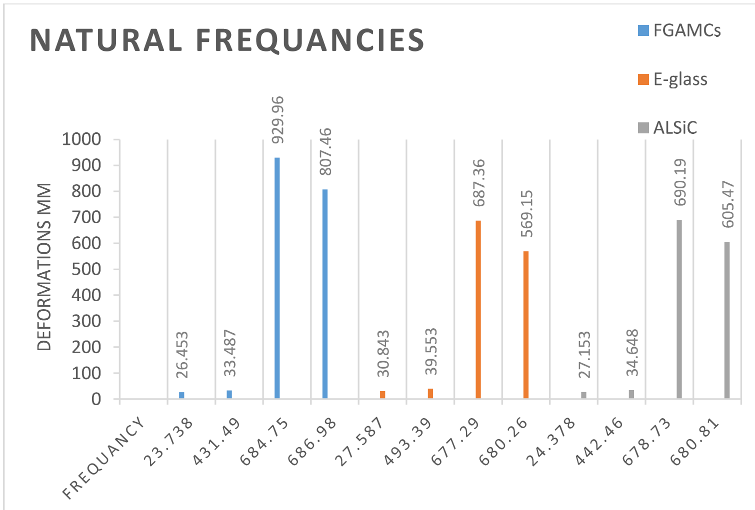
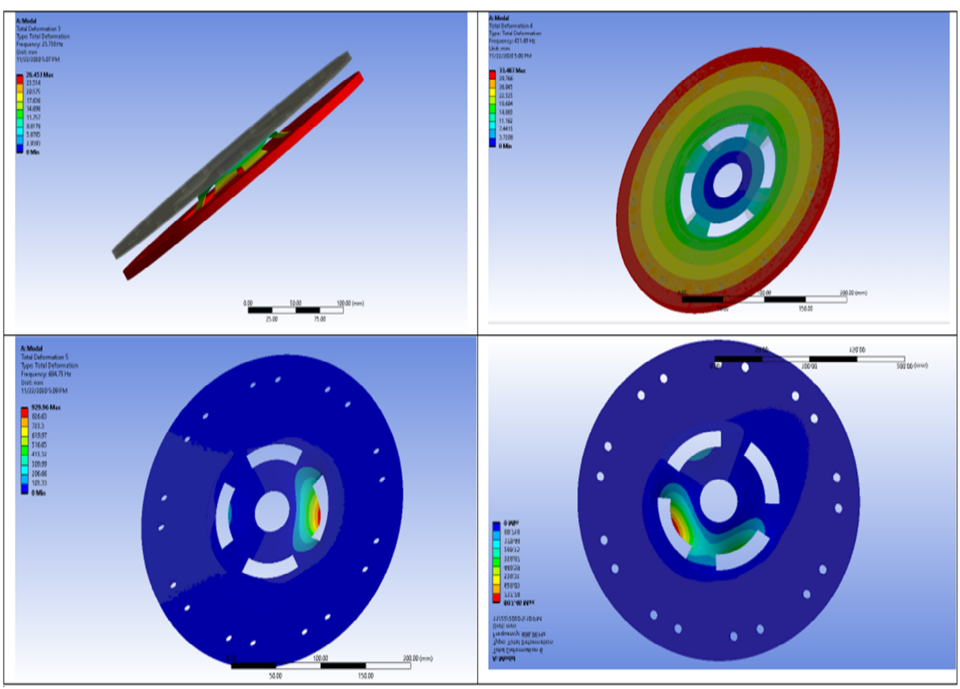


Figure 5 Modal shapes of first 4 natural frequencies (see online version for colours)

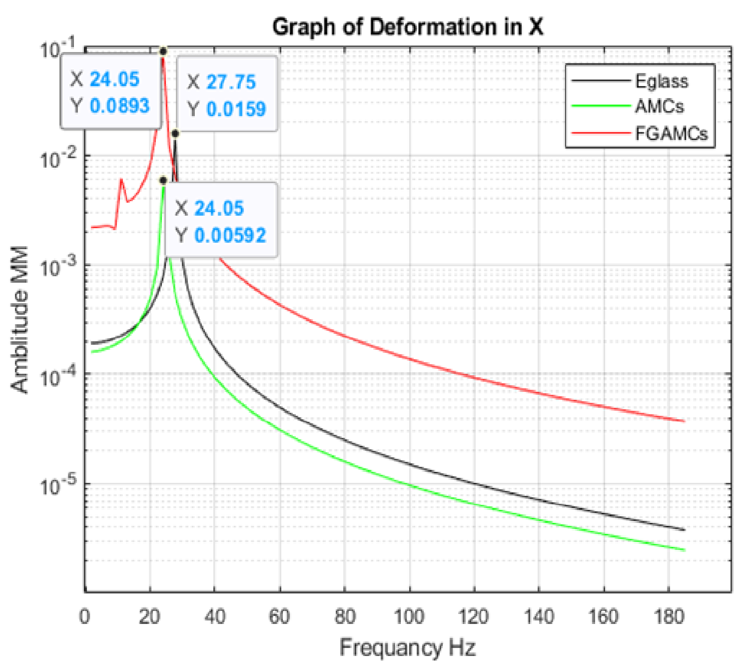


From the three tables, it can be seen that the FGAMC has lower first natural frequency than the others, but for the important natural frequency range, where the deformation is in the Y direction, the FGAMC has lower natural frequency, 23.74 Hz, with a deformation less in magnitude than the AMC by 2.6%, while the AMC is 27.153 mm at 24.38. E-glass has 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 4 shows the deformation at different natural frequencies. Figure 5 shows the modal shapes which are identical to the three models in appearance.

5 Forced vibration 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, .141N/mm^2 for clutch made of E-glass, .117N/mm^2 for aluminium matrix composites with 20% SiC particles, and lastly .131N/mm^2 for the functionally graded aluminium 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.pm. to 11,000 r.pm) as it is the common vibration range developed by automobiles and other equipment engines.

Figure 6 Deformation in X direction (see online version for colours)



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.

Figure 7 Normal elastic strain in X direction (see online version for colours)

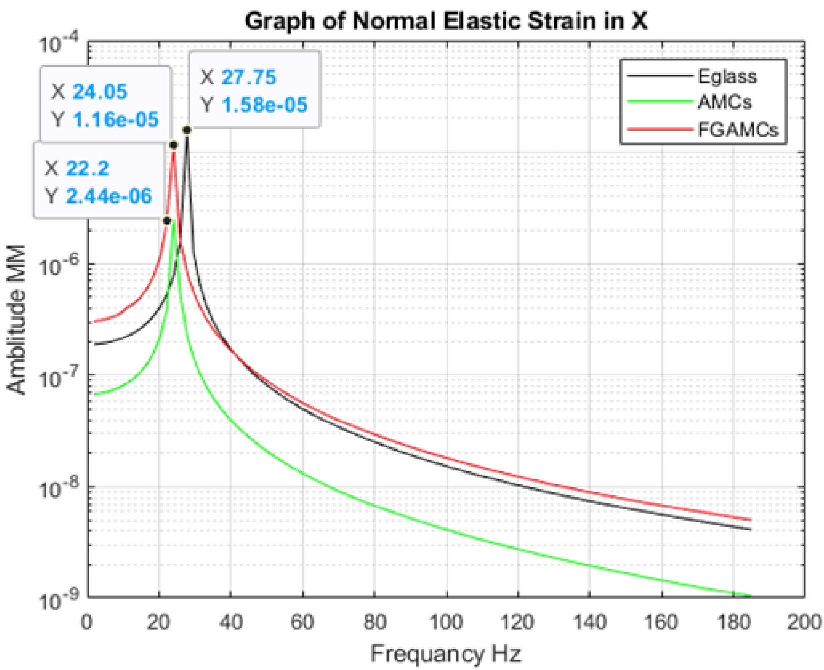


Figure 8 Normal stress in X direction (see online version for colours)

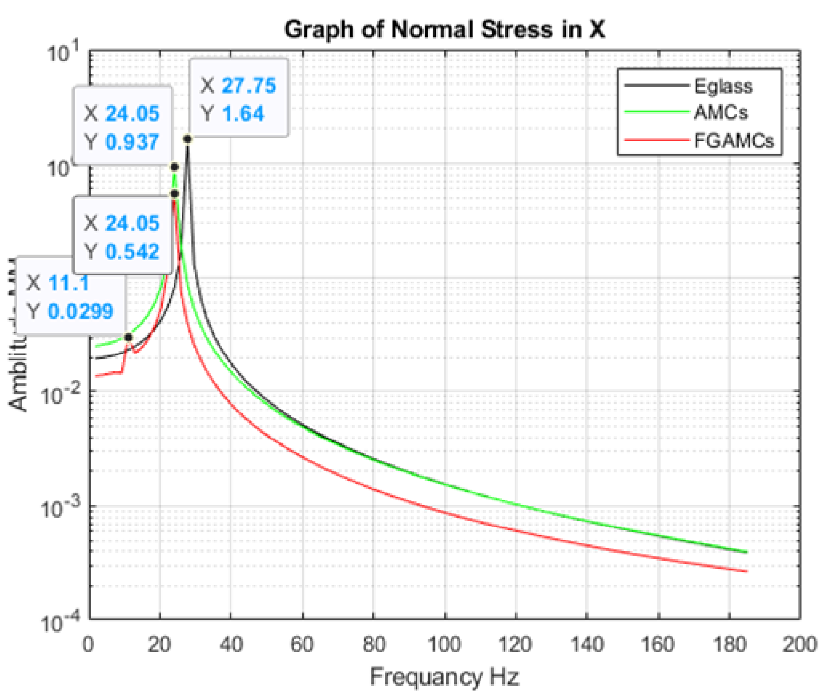


Figure 9 Deformation in Y direction (see online version for colours)

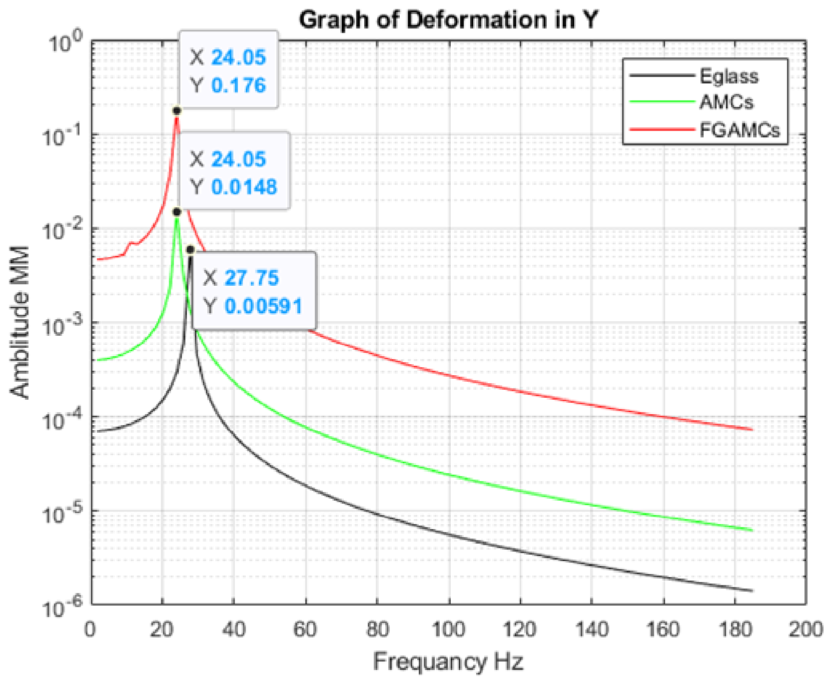


Figure 10 Normal elastic strain in Y direction (see online version for colours)

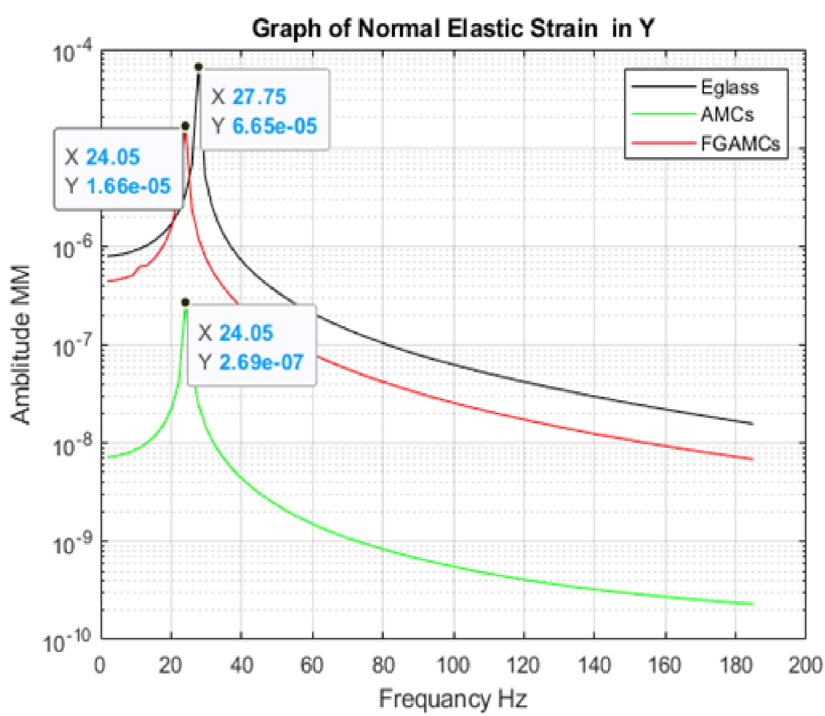


Figure 11 Normal stresses in Y direction (see online version for colours)

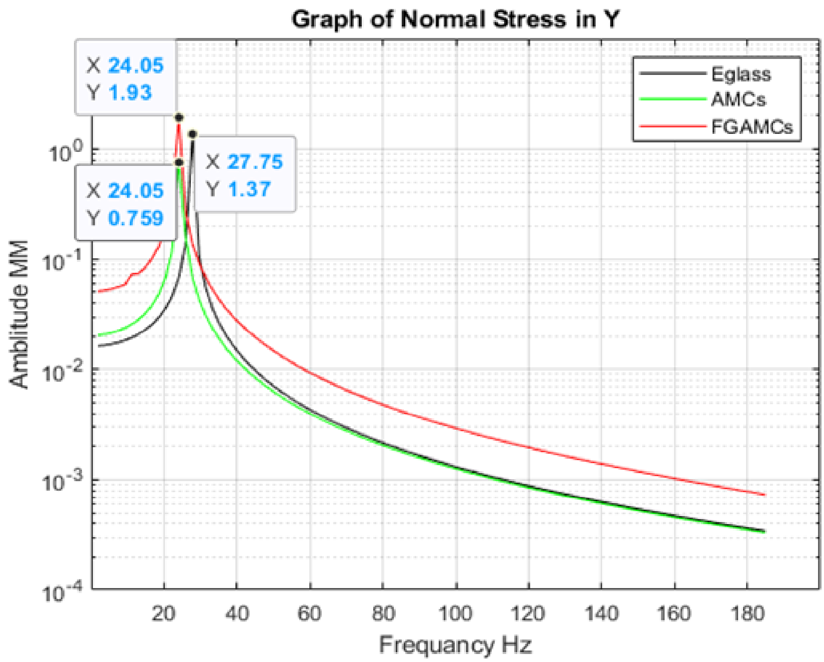


Figure 12 Deformation in Z direction (see online version for colours)

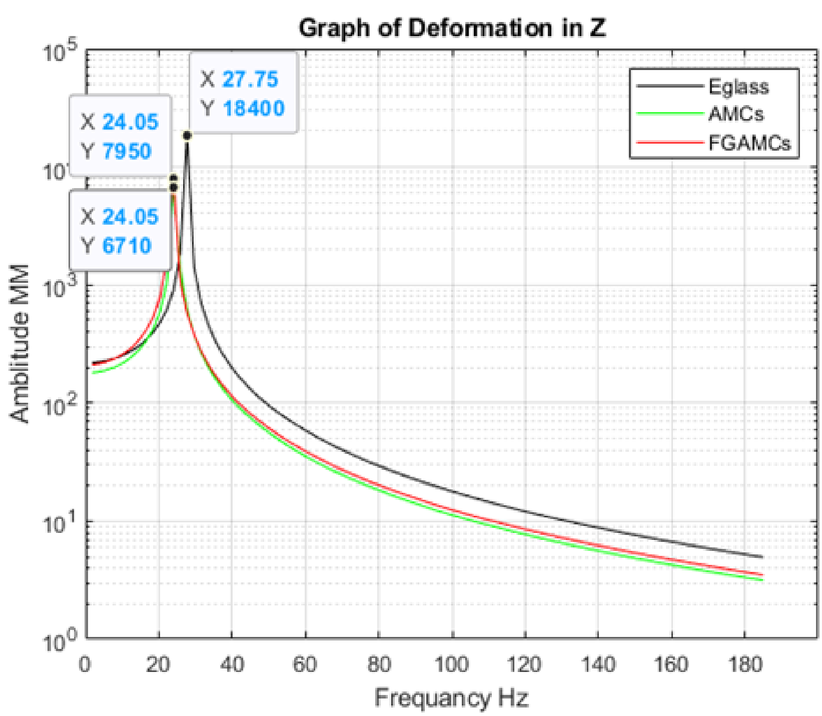


Figure 13 Normal elastic strain in Z direction (see online version for colours)

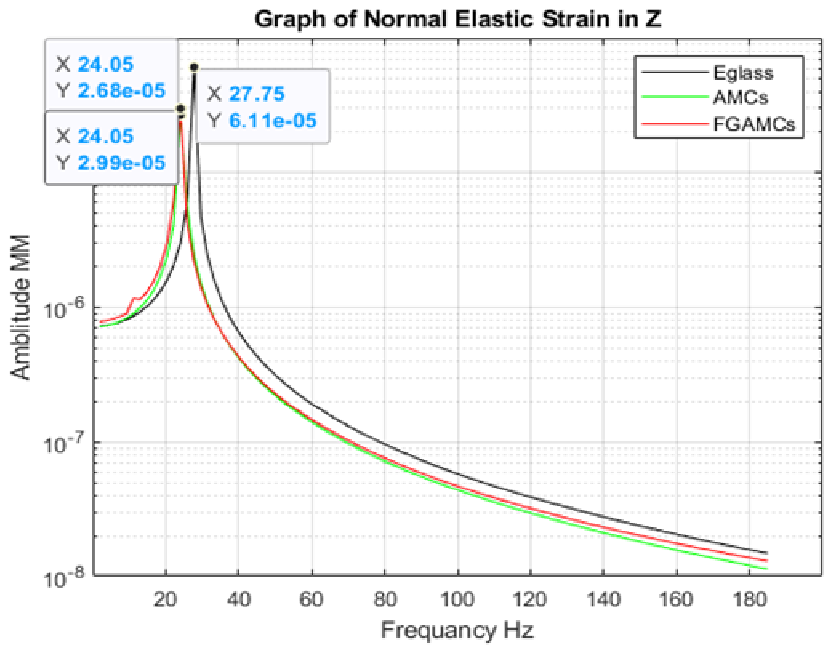
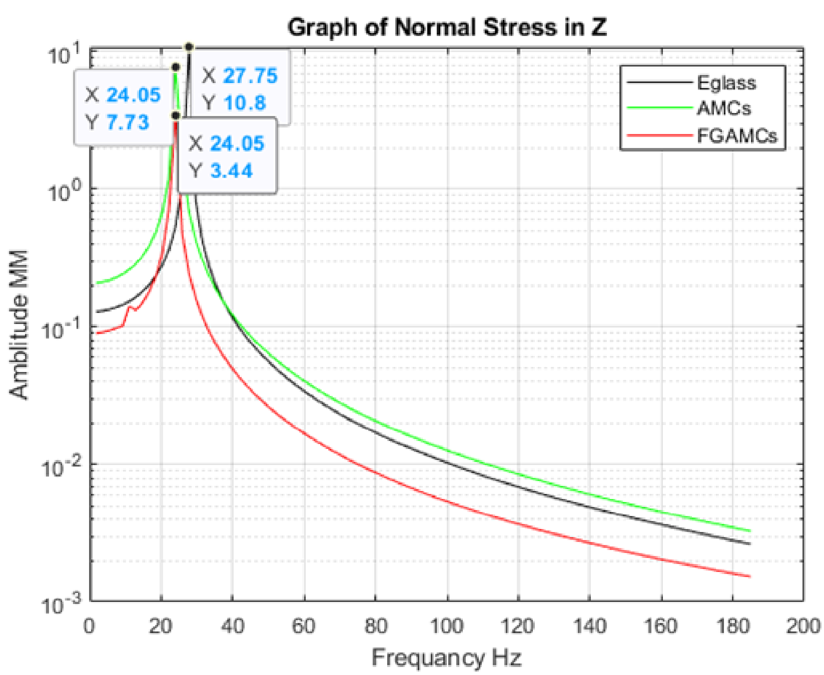


Figure 14 Normal stresses in Z direction (see online version for colours)



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%.

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. AMC and E-glass stresses equal approximately two and three times respectively the stress of FGAMC.

6 Static analysis

The clutch plate was studied against the pressure when the flywheel is revolving with 1250 r.p.m. and the pressure is assigned for each material as in the design part. The graphs show the different deformations of all of the plates with different assigned material.

Figure 15 Deformations under static analysis (see online version for colours)

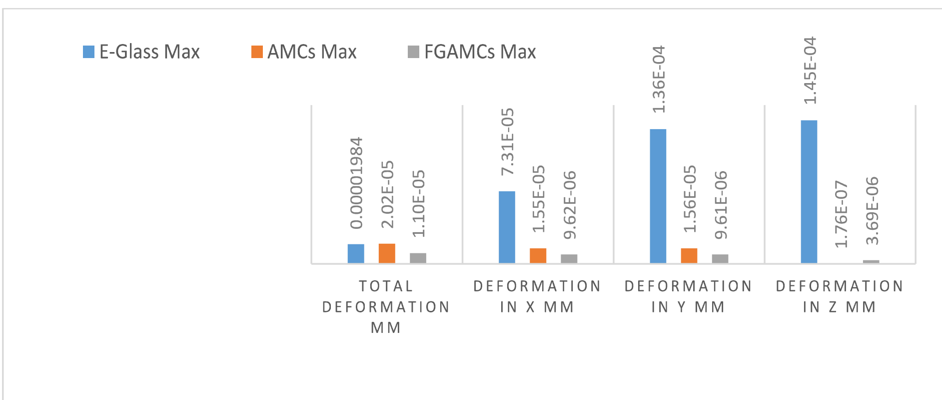


Figure 15 shows deformations under static analysis. The first bar chart shows the total deformation and the deformation at X, Y, and Z directions respectively. FGAMC has the lowest deformations except in Z direction, where AMC is the lowest. In total deformation FGAMC is lower by 45% and 44% than AMC 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%.

Figure 16 shows stresses under static analysis. The second bar chart shows the equivalent stresses maximum and minimum on each model, and the FGAMC plate has the lowest value of stress. For the maximum stresses it is nearly the half of the traditional AMC (50% less than AMC). While it is 95 times that of e-glass.

Figure 16 Stresses under static analysis (see online version for colours)

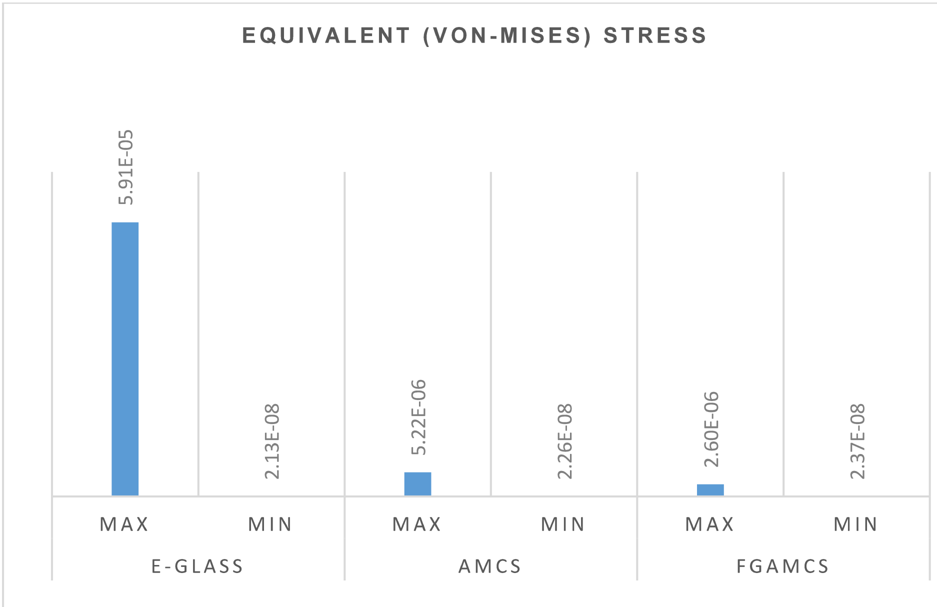
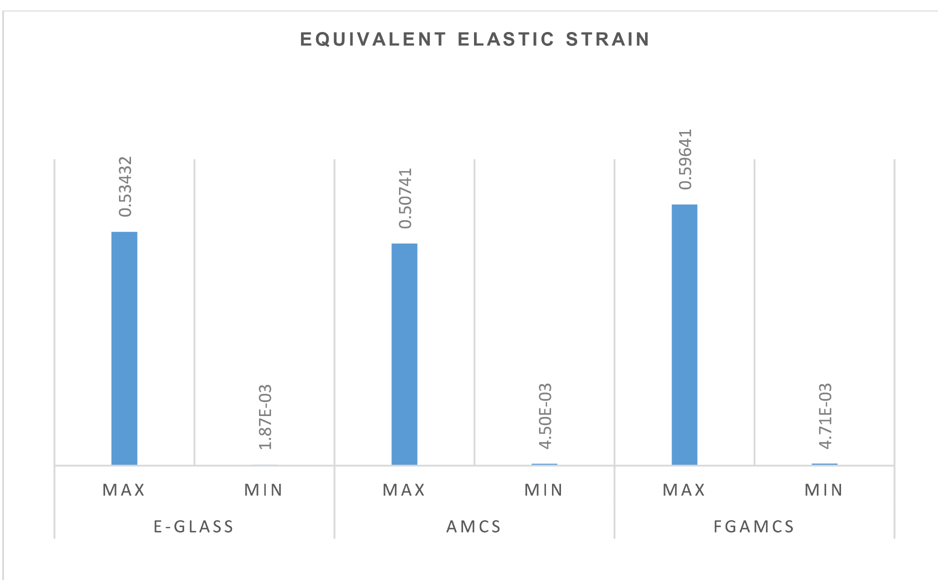


Figure 17 shows strains under static analysis.

Figure 17 Equivalent elastic strains under static analysis (see online version for colours)



For strain, the FGAMCs clutch has the highest strain among the three models. The FGAMC is higher in strain than the AMC by 17.6% and higher than the e-glass by 11.6%.

Table 2 The deformations, strain, and stress of the FGAMC model (see online version for colours)

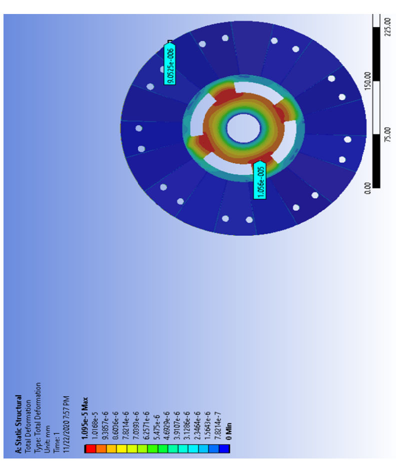
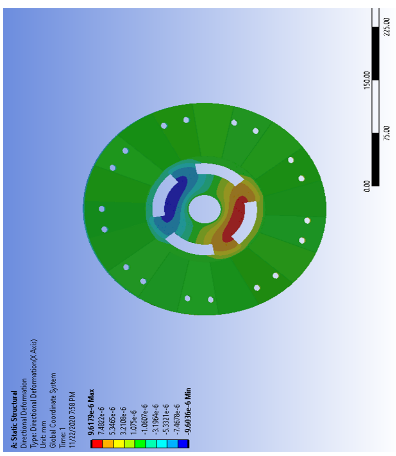
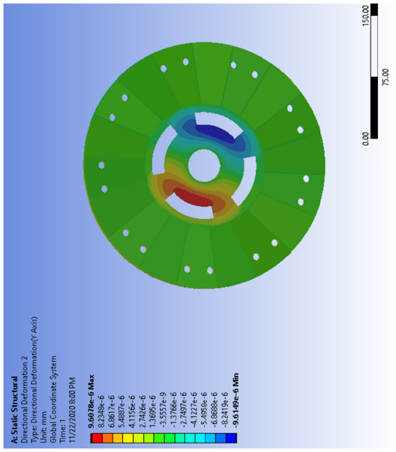
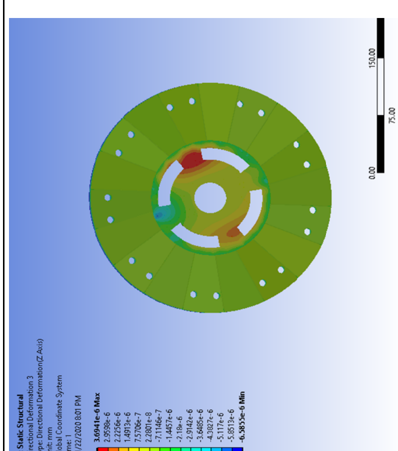
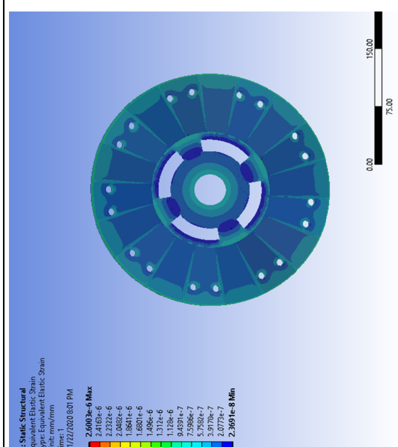
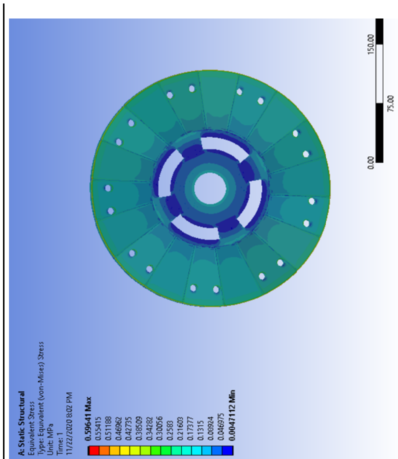
Total deformation	*Deformation in X*	*Deformation in Y*
		
Deformation in Z	*Equivalent (Von-Mises) stress*	*Equivalent elastic strain*
		

Table 3 The properties of the different layers

FGM\layers	*X/L*	*Density*	*Young modulus*	*Poisson's ratio*	*Bulk modulus*	*Shear modulus*	*Tensile yield strength*	*Compression yield strength*	*Hardness (Vickers)*	*Elongations*	*Friction coefficient*
0	0	2,770	7.1E+10	0.33	6.96E+10	2.67E+10	280,000,000	2.8E+08	1.18E+08	0.5	0.47
1	0.0625	2,790.625	9.2188E+10	0.31813	7.90E+10	2.76E+10	320,781,250	5.06E+08	1.83E+09	0.4688	0.478125
2	0.125	2,811.25	1.1338E+11	0.30625	8.84E+10	2.85E+10	361,562,500	7.33E+08	3.54E+09	0.4375	0.48625
3	0.1875	2,831.875	1.3456E+11	0.29438	9.78E+10	2.95E+10	402,343,750	9.59E+08	5.24E+09	0.4063	0.494375
4	0.25	2,852.5	1.5575E+11	0.2825	1.07E+11	3.04E+10	443,125,000	1.19E+09	6.95E+09	0.375	0.5025
5	0.3125	2,873.125	1.7694E+11	0.27063	1.17E+11	3.13E+10	483,906,250	1.41E+09	8.66E+09	0.3438	0.510625
6	0.375	2,893.75	1.9813E+11	0.25875	1.26E+11	3.22E+10	524,687,500	1.64E+09	1.04E+10	0.3125	0.51875
7	0.4375	2,914.375	2.1931E+11	0.24688	1.35E+11	3.32E+10	565,468,750	1.86E+09	1.21E+10	0.2813	0.526875
8	0.5	2,935	2.405E+11	0.235	1.45E+11	3.41E+10	606,250,000	2.09E+09	1.38E+10	0.25	0.535
9	0.5625	2,955.625	2.6169E+11	0.22313	1.54E+11	3.50E+10	647,031,250	2.32E+09	1.55E+10	0.2188	0.543125
10	0.625	2,976.25	2.8288E+11	0.21125	1.64E+11	3.59E+10	687,812,500	2.54E+09	1.72E+10	0.1875	0.55125
11	0.6875	2,996.875	3.0406E+11	0.19938	1.73E+11	3.69E+10	728,593,750	2.77E+09	1.89E+10	0.1563	0.559375
12	0.75	3,017.5	3.2525E+11	0.1875	1.82E+11	3.78E+10	769,375,000	3E+09	2.06E+10	0.125	0.5675
13	0.8125	3,038.125	3.4644E+11	0.17563	1.92E+11	3.87E+10	810,156,250	3.22E+09	2.23E+10	0.0938	0.575625
14	0.875	3,058.75	3.6763E+11	0.16375	2.01E+11	3.96E+10	850,937,500	3.45E+09	2.4E+10	0.0625	0.58375
15	0.9375	3,079.375	3.8881E+11	0.15188	2.11E+11	4.06E+10	891,718,750	3.67E+09	2.57E+10	0.0313	0.591875
16	1	3,100	4.1E+11	0.14	2.20E+11	4.15E+10	932,500,000	3.9E+09	2.75E+10	0	0.6

Table 2 shows the deformations, strain, and stress of the FGAMC model.

Table 3 shows the properties of the different layers.

7 Results

The functionally graded AMC has 5.7% and 26% more mass, with 200 g and 500 g more mass, than AMC and the e-glass respectively. 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 forced vibration analysis, the working pressure of the FGAMC is (.131N/mm^2) which is between the working pressure of the AMC (.117N/mm^2) and e-glass (.141N/mm^2). In forced vibration analysis, 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 and the 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. In static analysis, deformation and stress values FGAMC are the minimum ones, lower by more than 40% and from the strain point of view, it has the highest value by more than 11% from other materials.

8 Discussion and recommendations

The result shows using FGAMC as a frictional lining has benefits as in thickness direction deformation is less than the other two materials. Also, there is an increase in the weight comparing to AMC but lower deformations are achieved. The strain of the functionally graded AMC 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 are the lowest in term of magnitude, and with the anticipated higher wear resistance the developed clutch plate will have a longer lifetime. The future work of this study is to conduct dynamic analysis of the model and carry out optimum design research to mitigate the negative aspects concerning weight mostly. In addition, experimental studies can be done and compared to the theoretical results. Experimental tests can be done to examine the material wear behaviour. It will be an important part to study the thermal behaviour of the FGAMC clutch plate and compare it to the other materials. Finally, it is recommended to study the model when the change in the material happens in the radial direction.

Disclaimer

The author no financial and personal relationship with other people or organisations that could unprofessionally influence this work.

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