SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

MASTERS OF MECHANICAL DESIGN ENGINEERING

MODELING, AND FEA OF MULTI-PLATE CLUTCHES BY VARYING CLUTCH MATERIALS FOR USE IN TCT SYSTEM OF GREEN, AND LIGHT VEHICLES

A THESIS SUBMITTED TO SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING FOR PARCIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF MASTERS OF SCIENCE IN MECHANICAL ENGINEERING

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By: SEYOUM KEBEDE

ID. GSR/1503/08

Advisor: Dr. DANIEL TILAHUN

Co. Advisor: Mr. NATHNAEL ABEBAW

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Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical and Industrial Engineering

This is to testify that the thesis prepared by Seyoum Kebede, entitled: *Modeling, and FEA of Multi-Plate Clutches By Varying Clutch Materials for use in TCT System of Green and Light Vehicles* submitted in partial fulfillment of the requirements for the degree of Master of Sciences (Mechanical and Industrial Engineering) complies with the regulation of the University and meets the accepted standards with to originality and quality.

Signed by the Examining Committee:

Internal Examiner ______________________Signature __________Date___________

External Examiner _____________________ Signature __________Date___________

Advisor Dr. Daniel Tilahun___ Signature________ Date__________

Co- Advisor Mr. Nathnael Abebaw Signature___________Date__________

____

School or center Chair Person

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ABSTRACT

Multi-plate Clutches (MPCs) are projected for transferring the greatest amount of torque with less heat generation. The main objective of this thesis is modeling and FEA of multi-plate clutches (MPCs) for selecting an optimum light weighted material for clutch plate for use in twin clutch transmission (TCT) system of green, and Light Weight Vehicles using ANSYS Work bench software. The candidate materials; Aluminum alloy 6061, E-Glass Epoxy UD, and Gray Cast Iron are selected based on their weight and strength, and the mathematical model has done for each materials using Euler Lagrange's Equation. The 3D solid model has done using SOLID WORK 2016. The deformation and stress analyses were considered for both static and dynamic analysis. The static analysis were developed using fixed support on an inactive face of a clutch in static; and dynamic analysis is done applying displacement boundary conditions on clutch plate, and 523 rpm rotational velocity on a plate rotating with shafts. By default, since the objective is to increase the torque transfer capacity of a clutch, the wear analysis were done by varying the coefficient of friction and intensity of pressure, and thermal analysis were also done considering a heat flux of $0.54W/m^2$ at limiting temperature of 150ºC for candidate materials. The total deformation, and maximum equivalent stresses were evaluated by varying the compressive pressure acted upon the clutch plate. Then comparison has been done in terms of total deformation and Equivalent stresses of each material, and the composite E-Glass Epoxy is found to be a better Clutch material with a lower deformation compared to the other selected materials for design of multi-plate clutches in TCT system.

Keywords: Clutch materials, Multi-plate clutch, TCT, FEA, and Modeling.

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NOMENCLATURE

A	Area of a friction plate
AAiT	Addis Ababa Institute of Technology
Al	Aluminum
Al-Si	Aluminum Silicon alloys
AMT	automated- manual transmission
ANSYS	system analysis software
APDL	ANSYS Parametric Design Language
ASME	American Society of Mechanical Engineers
AT	automatic transmission
C	Constant force of clutch plate
C_1	clutch plate number one
C_2	clutch plate number two
CVT	controlled variable transmission
D	Diameter clutch plate
DCT	dual clutch transmission
$D_i = D_1$	Inner Diameter of clutch plate
$D_o = D_2$	Outer Diameter of clutch plate
E	Elastic Modulus property of material
F	Applied Force on Pin Holder Top Face
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Model/ Method
f_f	Frictional force
h	Heat transfer coefficient of the material
H	Hardness of Tasted Material
H	Hardness Property of Material
I_1	moment of inertia of clutch plate one
I_2	moment of inertia of clutch plate two
k	Thermal conductivity of the material
K	Wear Coefficient
L	Length
M	Moment
Mc	moment of a clutch plate

MPCs	multi – plate clutches
MT	manual transmission
n	Number of friction surfaces
N	Speed in RPM
n_1	number of clutch plates on driven shaft
n_2	number of clutch plates on driving shaft
NVH	noise and vibration health
P	Applied Pressure
P_{max}	engine maximum power
q	Heat energy generated in watts
q_f	heat flux in
R	Effective mean radius of a clutch
r_i	Inner Radius Of clutch plate
r_o	outer radius of clutch plate
RPM	revolution per minutes
Si	Silicon
SW16	Solid work 16
T	Thickness
TCT	twin clutch transmission
$T_{e.max}$	Engine Maximum Torque
t_s	Slip time in seconds
v	Poison’s Ratio
W	Clamping force on clutch plate
Y	Yield strength
B	Clutch safety factor
P	Density of pin materials
Ω	Rotational Velocity
ω_1	angular velocity of clutch plate one
ω_2	angular velocity of clutch plate two
ω_r	Rotational speed
Fe	Engine frequency
Ne	Engine rpm range
n	Order of frequency
μ	Coefficient Of Friction

2D	two dimensional models
3D	three dimensional models

CHAPTER ONE

INTRODUCTION

1.1 Background

The important component of any automotive machine is the friction clutch. Clutch is a mechanism for transmitting rotation which can be engaged and disengaged. It is a link between engine and transmission system which conducts power in the form of torque from engine to the gear assembly. Multi-plate Clutches (MPCs) are projected for transferring the greatest amount of torque with less heat generation [3]. In today's world, with natural resources such as oil and gas, petrol and diesel prices have been sky rocketing. Therefore, it is becoming increasingly important for automobile manufacturers to make cars that deliver good fuel economy. Powertrain engineering and in particular transmission systems and their components, are facing very difficult and diverse challenges nowadays compared to the decades before. These challenges are triggered mainly by international legislation, which is tightening the regulations on emissions and fuel consumption all around the globe. In Europe the carbon dioxide emissions have been reduced by 10% from 1995 to 2003 [10]. Those effects can be reduced by improving the components in transmission system such as clutch.

Clutch is one part of the transmission system, and Twin clutch transmissions (TCT) have emerged as a viable alternative to conventional planetary automatics and continuously variable transmissions with the development of precise control strategies. TCT can be considered as two lay shaft transmissions in one. Odd gears are connected to one shaft while the even gears are connected to the other, and the developed multi plate clutches would be used on those shafts as to transmit power.

Eventhough there are different components of transmission systems, a TCT system is the most efficient and to be employed in vehicles to achieve better vehicle fuel economy and comfort [5]. Normally, a manual clutch transmission system is not been the preferred choice; due to recently developed Automatic TCT [1]. Evidences show that racing cars and most electric vehicles, and Honda cars and motorcycles have been available with automatic transmission systems [1].

Particularly, researchers shows that TCT which combines the advantages of manual transmission and automatic transmission features the convenience and comfort of automatic transmission and the fuel economy even better than manual transmission in any ordinary, and electric vehicles. This also is influenced by types of clutches used single or multi-plate and/or wet or dry. But, wet multi-plate clutches can improve torque transferring capacity and power transfer efficiency even in their smaller size [5].

Our institution; Addis Ababa Institute of Technology (AAiT), School of Mechanical and Industrial Engineering (SMIE) aim to develop a more robust light weight and Green Vehicle. The Light Weight and Green Vehicle to be developed in our institution is claimed to be excellent and competitive in every situation. So, different system designs are to be held on each component parts.

Nowadays the diffusion of the TCT is limited to the high class vehicles because their costs are higher with respect to the AMT or MT. On the other hand, market forecasts say that in the next years the vehicles equipped with TCT will attain more than 10% of the market shares [6]. So, developing MPCs from available and low cost materials would be essential.

Due to its advantages, MPCs has become a hotspot topic that attracts extensive development interests in the automotive industry in recent years [5]. In this paper, mostly modeling and FEA of MPCs has been held for a light weight and green vehicles. Special emphasis has been laid on selection of better lining material and detailed model of MPCs.

1.2 Statement of the Problem

Addis Ababa Institute of Technology, School of Mechanical and Industrial Engineering is to develop a light weight and Green vehicle which is robust, environmentally friendly, and supporting the advancement of green area protocol.

The existing commercial clutch plate (Disc) material (i.e. Gray Cast Iron) weight which is 4.5-6 kg is a major issue in design of MPCs. But, the green vehicle to be developed would have to have lighter weight and lighter component parts.

Therefore, to overcome those problems this paper was proposed and done to investigate a better lining material and design of appropriate MPCs, for use in TCT system for a Green, and light weight vehicles.

1.3 Objectives of the study

1.3.1 General Objective

The main objective of this thesis is modeling and FEA for Total Deformation, von-misses stress, Von-misses Strain, and wear of clutch disc materials (i.e. Aluminum Alloy, E-Glass Epoxy UD, and Gray Cast Iron) for use in TCT system of Green and light vehicles, and validate the results using FEM/ANSYS work bench.

1.3.2 Specific Objectives

The specific objectives of the study are to:

- ✓ Identifying the better lining material, properties and their composition.
- ✓ Select Modeling type, modeling, and analysis of MPCs.
- ✓ Identifying the wear, stresses, and total deformation, of sample materials in their maximum pressure conditions.
- ✓ Comparing for basic similarity and difference of selected materials and state the cause of difference.
- ✓ Validating and Conclusion the results.

1.4 Methodology of Research

Some basic procedures that will be followed in order to fulfill the objectives of the thesis are stated below:

- ✓ Identifying the material types considering cost, availability, and their weight.
- ✓ Calculation of stresses, and maximum pressures using Euler-Lagrange equations.
- ✓ Developing 3D model of MPCs using Solid work 16 software.
- ✓ Exporting the model of MPCs from solid work 16 to ANSYS 16 work bench for FEA.
- ✓ Static and dynamic analysis of MPCs using ANSYS work bench at different operating condition.
- ✓ Determining the wear, maximum deformation and equivalent stresses for each material using FEA
- ✓ Showing the relation of deformation and resistance property of each material using figures and tables.
- ✓ Comparing and discussion of results for selection of better lining materials.

All the above procedures have been conducted with application of a specified conditions and constraints that helps to get the suitable and reliable result.

1.5 Significance of the Research

This research paper outcome would have a great role for the further analysis and design for manufacturing of MPCs. The advantage of this thesis mostly relay on the material analysis in point of strength and identifying a better lining material for clutch plate. For newly developing of Green, and light weight vehicles, this thesis provide new point of view and knowledge in clutching system of green vehicles. In the future this paper adds more knowledge on analysis of wear rate and deformation of friction plates using related software in simplified and effective way. This paper indicates the easy way of analyzing MPCs deformation using different operating conditions (i.e. pressures and loads).

1.6 Organization of the Paper

This paper is organized in to five main chapters. The first chapter discusses the introduction of the MPCs and a TCT system and the study. On this chapter background, objectives, statement of problem, limitations, and methodology is identified. On the second chapter two is the review of literature that includes journals, articles and publications that related to the thesis paper work. Additionally on this chapter some literature work is also seen that related to field of study to strength the paper. On chapter Three the model and failure analysis for selected materials is discussed. The requirement for analysis of structural mechanics or deformation using related software also studied on chapter Three. On fourth chapter the final result and discussion is performed. The result is obtained from the structural analysis using related software. The software provides a basic solution that helps to determine the required answers for the study based on the results the discussion follows. On the final chapter, Based on the result of analysis conclusion, and recommendation is stated; additionally the possible future work on the field of the study is included.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Multi-plate clutches in TCT system

Most people are aware that in today's time, motor vehicles come with two basic types of clutches. These are namely; Wet and Dry types which carry out power transmission based on vehicle speed. There is a new type of transmission system that has become increasingly popular over the last decade, called the TCT and, semi-automatic transmission. The TCT falls somewhere in between manuals and automatics, offering the best of both worlds. So, different researchers have done analysis on this. To improve the TCT system they have done analysis on those clutch types for better performance. They have used various approaches and means to attain their main intention in designing MPCs.

A TCT system essentially comprises of two manual gearboxes operating independently contained within housing. To be able to understand how it works, it would essential to first review how a traditional manual gearbox works. Whilst driving a standard manual car, when the driver wants to shift from one gear to the next, he or she first depresses the clutch pedal. This operates a clutch, which disconnects the engine from the gearbox and interrupts power flow to the transmission.

2.2 papers reviewed

In a vehicle with a 6-speed TCT, however, the clutches operate independently. One clutch controls the odd gears (first, third, fifth and reverse), while the other controls the even gears (second, fourth and sixth). Using this arrangement, gears can be changed at lightning fast speeds, without interrupting the power delivery from the engine to the transmission [3].

In this paper literature has been critically involving various studies carried out by various researchers related to the design, load, shifting and dynamic analysis of clutches as a transmission system. The conventional existing types of transmission systems are continuously being investigated by many researchers during the past year under different condition in order to reduce the failure or increase their efficiency either by modifying the power strain systems and component transmission geometry [4].

Automatic Transmissions aren't widely used, especially in the European market. But recent automotive market forecasts predict that there will be a decline of the Manual Transmissions (MTs) in favor of the AMTs and TCTs. TCTs will gain market share continuously over the next few years although it depends on several circumstances based on the automakers' and transmission manufacturers' strategies. As shown in table 1, at the moment, however, Europe is the fastest growing market for TCTs. There is also significant interest at the moment in North America. And we know that there are some programmes already released on (2009) [6]. Since the recent market forecasts predict the growth both for the AMTs and TCTs, the manufactures are investing huge resource to improve the performances of this kind of transmissions and, at the same time, to reduce their cost. In this light, the work developed in this thesis aims to give useful information both to the clutches designers and to the control algorithms designer in order to improve the performances of clutches for use in the AMTs and TCTs.

Table 1: West European Light Vehicle Production by Transmission Type.

Type	Year		
	2002	2008	2014
AMT	1.0%	4.3%	5.5%
Automatic	13.5%	16.1%	13.5%
CVT	0.5%	1.8%	1.3%

TCT	0.0%	2.6%	11.4%
Manual	86.5%	75.2%	68.3%
Grand Total	100%	100%	100%

(Source: CSM Worldwide, retrived from C. Worldwide. (2009). Source for Automotive Market Forecasting and Automotive Market Foresight, [Online]. Available: www.csmauto.com) (visited on 01/08/2017).

Their paper gives an input for identifying types of clutches to be used and why wet MPCs in TCT system is more preferable in this work. The main advantage of a TCT is that the shifts can be achieved without sensible torque gap with the help of clutches. In fact, with this system is possible to apply the engine torque to one clutch just as the engine torque is being disconnected from the other clutch.

It is as smooth as the most sophisticated automatic, but more economical than a conventional automatic; it is as easy to drive as a standard auto, faster and more responsive than manual gearbox on high performance cars. Another important advantage of the TCT is the reduction of fuel consumptions. In fact, by eliminating the torque gap the efficiency of the system is improved.

2.2.1 Common Clutch types

The types of clutches can be classified depending on different methods of operation. So, this design paper is done based on the methods stated: [7, 9]

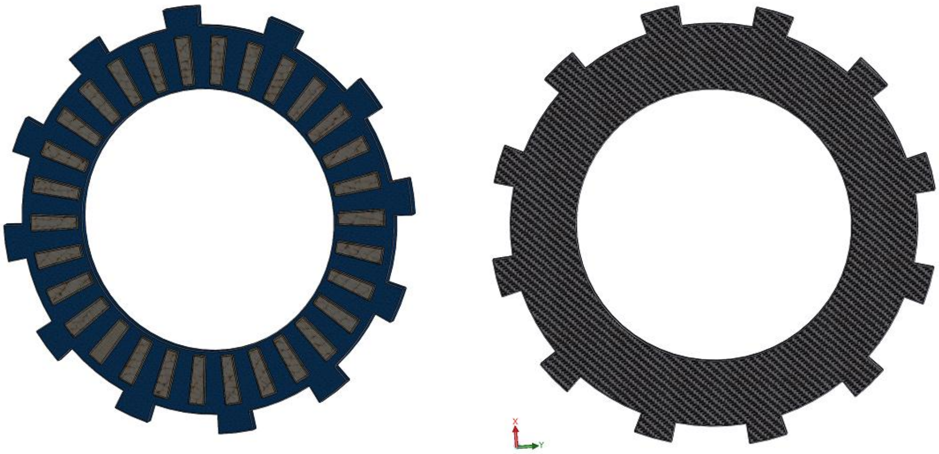
The method of transmitting torque: automatic.

- ✓ The method of control: automatic.
- ✓ The method of creating force on pressure plate: Spring clutches.
- ✓ The shape of friction surfaces: Disc.
- ✓ The number of driven plate: Multi-plate clutch (mainly used in automatic transmission)

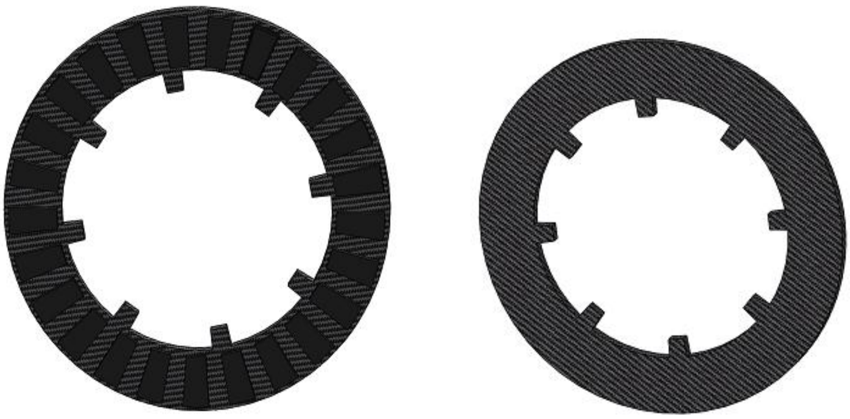
2.2.2 Why multi-plate clutch

While designing MPCs for use in a system with combined AT and AMT which is TCT system, consider the method of operation which depends on the number of driven plate. A twin clutch transmission is quite similar to the conventional automatic, the main difference being the double clutch structure compared to the single automatic clutch used in automatics. Automatics make the use of a torque converter to transfer engine torque from the engine to the transmission; TCTs on the other hand don't require torque converters. TCTs present in the market today use single plate clutches to fulfill the same purpose. A "wet" clutch is a type of clutch whose components are bathed in lubricating fluid, with the purpose of reducing friction and limiting the production of heat energy.

Manual transmissions are generally equipped with dry clutches and some TCT manufacturers are using these too, however, all production vehicles today which are equipped with TCTs use the wet version. [11]



a) Active and rear faces of external spline multi-plate clutch



b) Active and rear faces for internal spline multi-plate clutch

Figure 1: 2D Basic multi-plate wet clutch design [solid work design]

Fundamentally, there are two types of clutching used in TCT depending on materials properties, i.e. wet and dry clutch. Wet clutches require a large amount of lubricating oil to operate, the oil needs to be evenly spread on the clutch plates to allow the energy generated during shifting to be dissipated [8].

Wet clutches hold certain benefits over their dry counterparts, such as low wear and high torque output. The wet MPCs used in the Bugatti Veyron's TCT, for instance, is designed to cope with torques as high as 1,250 Nm, but at the cost of a lower efficiency.

A Wet type MPCs, is more preferable, and has been developed to meet the very high torque capacity and to have more efficiency.

Compression of Wet, and Dry type clutches with their advantages and disadvantages has been done [14]. So, this helps to analyze and identify which clutching type will be more preferable for light duty vehicles.

2.2.3 Characteristics of Wet clutches

Good Characteristics of Clutches [9], [13] and [15]

- ✓ High torque capacity
- ✓ Low weight, easy packaging
- ✓ No noise or vibrations (Good NVH characteristics)
- ✓ Long life
- ✓ High energy density
- ✓ Low drag Torque to reduce fuel cost

From comparison a wet clutch is more preferable for this design, since they are more efficient because of the reduced volume of oil being pumped though the transmission system. This is because of the torque capacity of the green vehicle are designed to be higher.

2.3 Materials

The friction material is very similar to the material used in brake shoes and pads and contained asbestos in the past. Also, clutches found in heavy duty applications such as trucks and competition cars use ceramic clutches that have a greatly increased friction coefficient, however these have a "grabby" action and are unsuitable for road cars [12].

Structural analysis for clutch plate has done using the properties of three materials which are used for liner (i.e. carbon-carbon composites, Kevlar, Ceramic composites) [16]. In this cited paper comparison is done for above materials to validate better lining material for clutch plate, and also validates and made analysis on other materials used for clutching system. This helps to identify appropriate materials to be used for clutch design.

2.4 Methods

2.4.1 Force, Pressure, and Torque Analysis

Researchers have done and wrote more on methods used for designing and modeling of twin clutch. Most related papers are discussed below.

The design and modeling of twin clutch transmission system depends on the operating system [13]. It is in principle impossible to skip a gear (e.g. a direct shift from 4th to 2nd gear) without first disengaging the appropriate clutch. They give special emphasis on a detailed model of the hydraulic actuation of clutches and synchronizers.

Moreover, the researchers have done analysis of synchronizers to balance the gear shifting that takes place in the system. Gear shifting takes place in odd number gearbox transmission systems. But, it is better if we use a 6-speed gearbox than 5-speed or 7-speed gearbox systems [3].

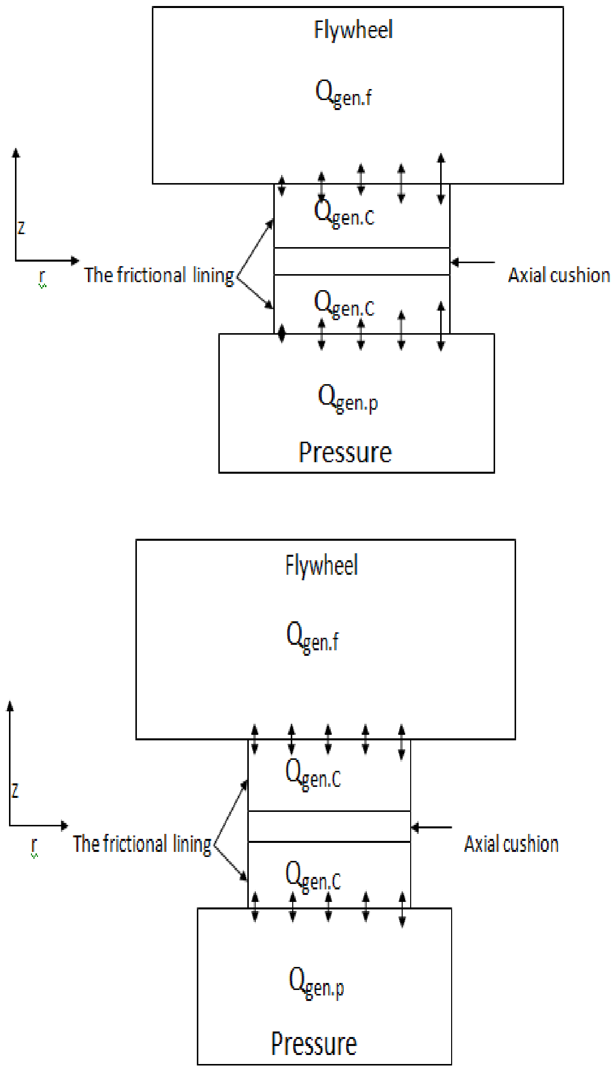
There is a power loss to be considered while designing a clutches in manual transmission system since there is a power loss due to torque convertor. A TCT due to its double clutch structure, doesn't need a torque converter, the result is improved fuel efficiency (most automatics lose their power and efficiency in the torque converter). For transmissions with torque converters the torque ratio can be met with a mechanical ratio spread which is smaller, because in the initial launch phase the torque converter provides additional torque amplification [17]. Actually, this would give an input for design and dynamic analysis especially on Torque transfer analysis.

2.4.2 Stress Analysis

Finite element analysis of grooved friction plate of Diaphragm spring Clutch can be used to show the effects of material structure on stresses. This can be used to study of temperature distribution and thermal stresses during single engagement [14]. The main objective of my thesis is to obtain a minimum safe stress value and temperature distribution of friction plate by using analytical and numerical calculation.

Finite elements analyses of the thermal and shear stresses in clutches can also be stated using FEMs. The calculations were performed using the axisymmetric and fully three-dimensional computational models [2].

The friction clutch design is strongly dependent upon the frictional heat generated between contact surfaces during the slipping at beginning of engagement [15]. Because of that the frictional heat generated firstly will reduce the performance of clutch system and then will lead to premature failure in some cases. They had used Finite element method to investigate an effect of thermal load type on the temperature field of the clutch system and Two-dimensional axisymmetric model was used to study the temperature distribution for the clutch system (pressure plate, clutch disc and flywheel) during heating phase (slipping period) and in the cooling phase (full engagement period) as shown on figure 3. Depending on basic friction clutch design they had applied two types of thermal loads; load type A (uniform pressure) and load type B (uniform wear). Repeated engagements made at regular interval were considered in this work. ANSYS13 has been used to perform the numerical calculation in their paper.



(a) (b)

Figure 2: The Contact model for clutch system a) Uniform pressure/ load A. b) Uniform wear/ load B.

In this paper the transient thermal analysis of a dry friction clutch system during 10 repeated engagements based on the uniform pressure and uniform wear theories was performed. Two dimensional axisymmetric models were built to obtain the numerical simulation for friction clutch elements during the slipping. The temperature will increase rapidly when the number of engagements increase and in some cases the temperature exceeds the maximum limit of temperature, this situation lead to friction clutch failure before the expected lifetime, therefore the study of the temperature field of contact surfaces during repeated engagements operation is necessary to give an indication about the maximum temperature during the engagements.

The Lagrangian, Galerkin's and Rayleigh-Ritz equation are preferable in mathematical calculation and simulation analysis of TCT system. Mathematic calculation and simulation have done in order to study the thermal behaviour of a two-speed dual clutch transmission. In order to demonstrate the effectiveness of the model, they have done simulations based on the presented theoretical analysis and developed powertrain model using different vehicle test driving cycles.

Thermal behaviour study can contribute to the design of MPCs prototypes and calculating its reliability avoiding unnecessary failures [15]. It could help accelerating products development speed and save funds.

They also put a future work especially on investigation of the proposed model. This helps to study and made analysis on clutching and other related component parts thermal behaviour in transmission system.

The Model-Based Design with MATLAB/Simulink can be shown, and enable all automakers and suppliers to achieve optimization results once reserved for a few large automakers with the resources to develop large internal simulation models and optimization programs [19]. By using a system model that incorporates the engine, transmission, axle ratio, driver, and vehicle, engineers can precisely match powertrain components and optimize hardware variables, such as transmission ratios, and calibration parameters, such as shift schedules, simultaneously.

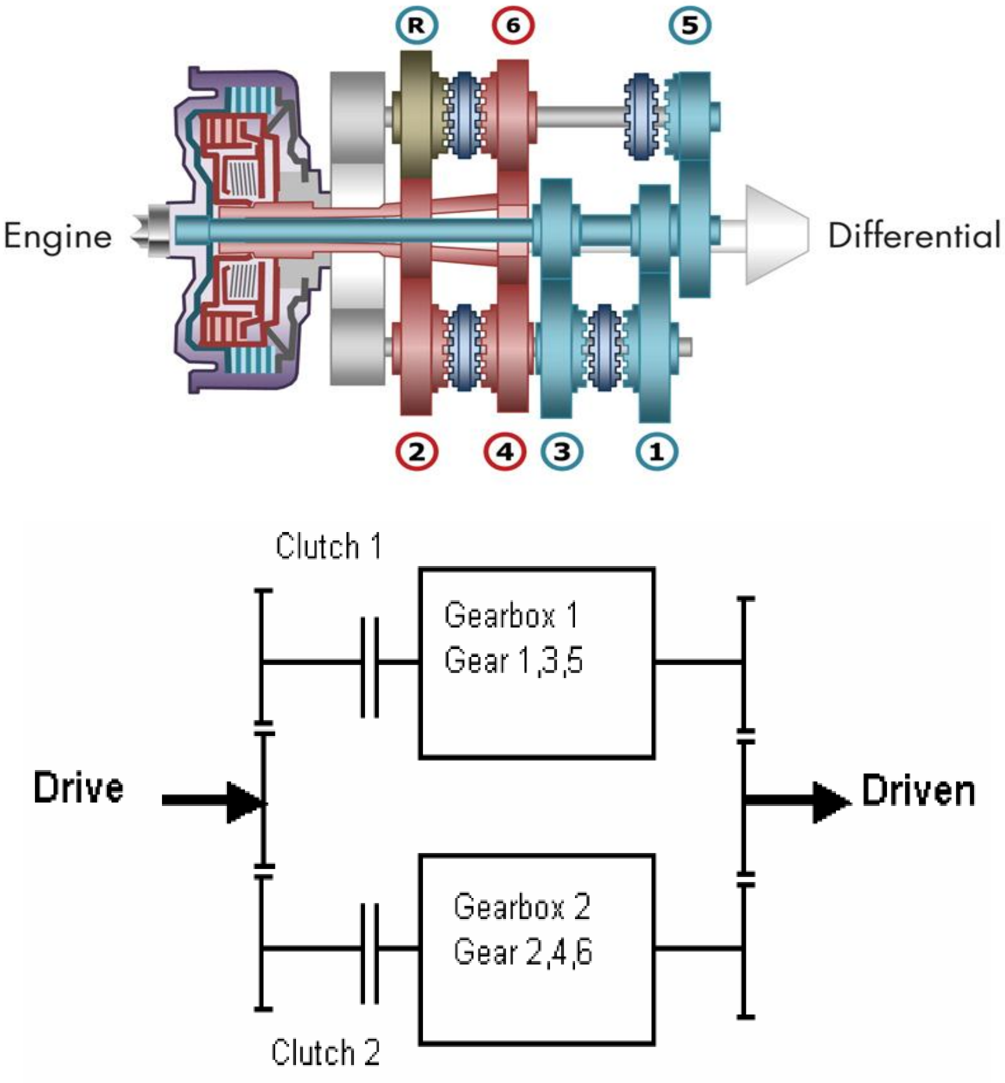


Figure.3: a Twin Clutch Transmission [3].

A dual clutch transmission is a new kind of semi-automatic transmission system which utilizes a double clutch structure, comprising of two independent clutches, one each for the odd and even gear sets. The dual clutch transmission is based largely on a conventional manual gearbox, it can be described as two separate manual gearboxes sharing the same housing, each consisting of a gear set (odd or even) and a respective clutch. However, unlike the manual transmission; the two clutches in a DCT are linked to two input shafts, the shift and clutch actuation is controlled by the transmission control module also known as the mechatronics module, and there is no physical clutch pedal for a driver.

In most modern cars equipped with a DCT, the driver can initiate the gear change either manually using a paddle shift or buttons, or by keeping the shift-stick in the fully automatic 'D' or 'S' modes. [8]

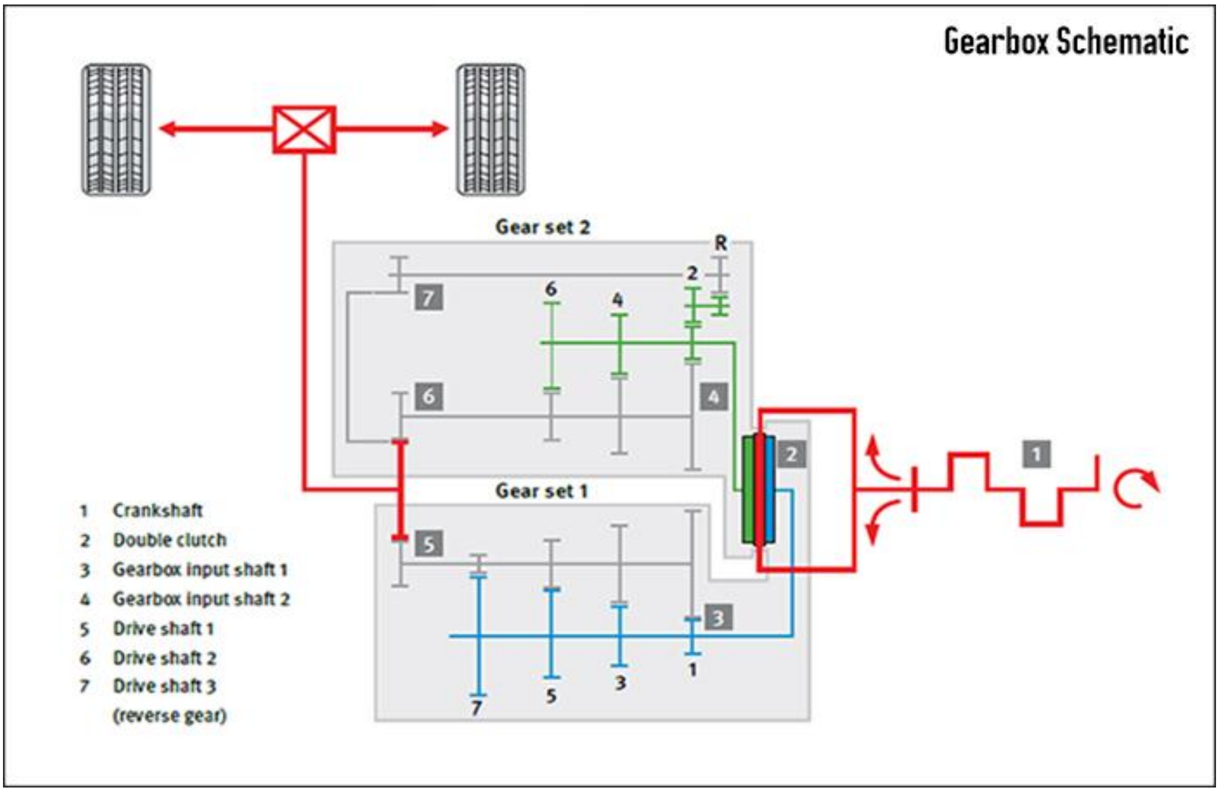


Figure 4: a Gear box Twin Clutch Transmission lining stricture [8].

Figure 5 below shows the arrangement for a typical five-speed dual clutch transmission, the transmission model created in this project will be very similar to this. We can see that clutch 1 which is labeled in green controls the green gears (2nd and 4th) and the clutch 2 controls the red gears (1st, 3rd and 5th). This arrangement ensures constant and uninterrupted power delivery to the wheels and lightning quick gear shifts. The same is not possible via a manual transmission, because manual gearboxes use a single input shaft and a single clutch for all odd and even gears. [8]

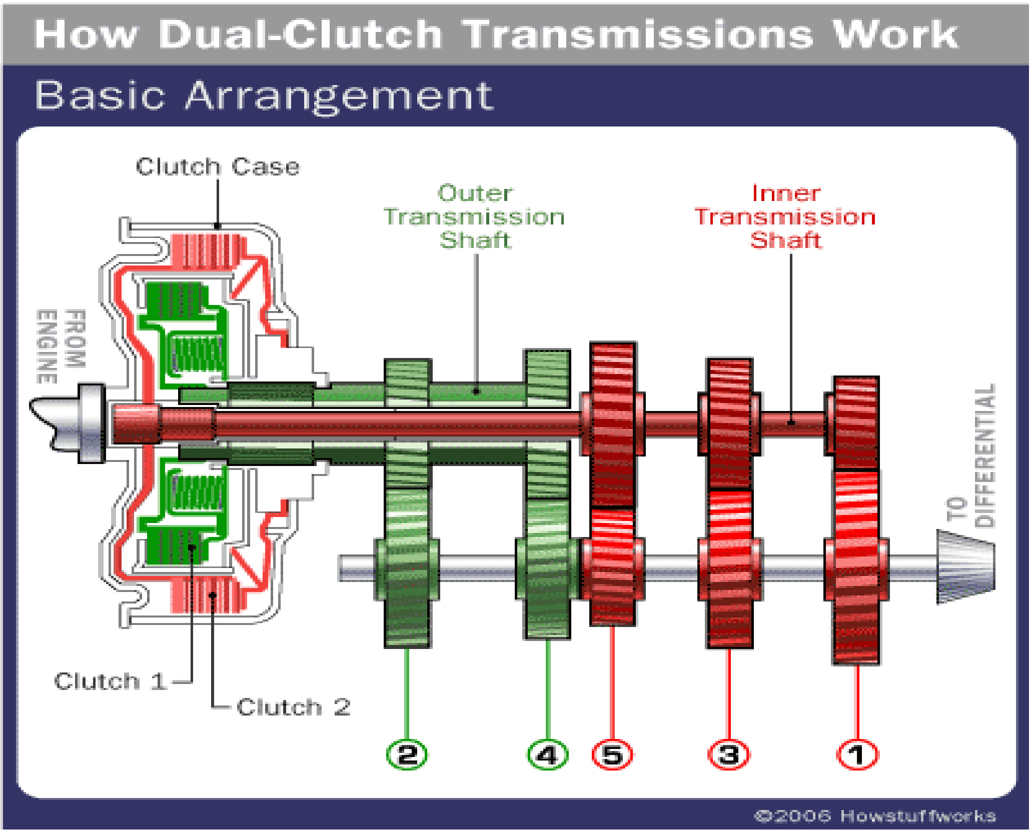


Figure 5: basic Twin Clutch Transmission arrangement [8].

2.5 Multi-plate clutches

A dual clutch transmission is quite similar to the conventional automatic, the main difference being the double clutch structure compared to the single automatic clutch used in automatics. Automatics make the use of a torque converter to transfer engine torque from the engine to the transmission; DCTs on the other hand don't require torque converters. DCTs present in the market today use wet multi-plate clutches to fulfill the same purpose. A "wet" clutch is a type of clutch whose components are bathed in lubricating fluid, with the purpose of reducing friction and limiting the production of heat energy. Manual transmissions are generally equipped with dry clutches and some DCT manufacturers are using these too, however, all production vehicles today which are equipped with DCTs use the wet version. [8]

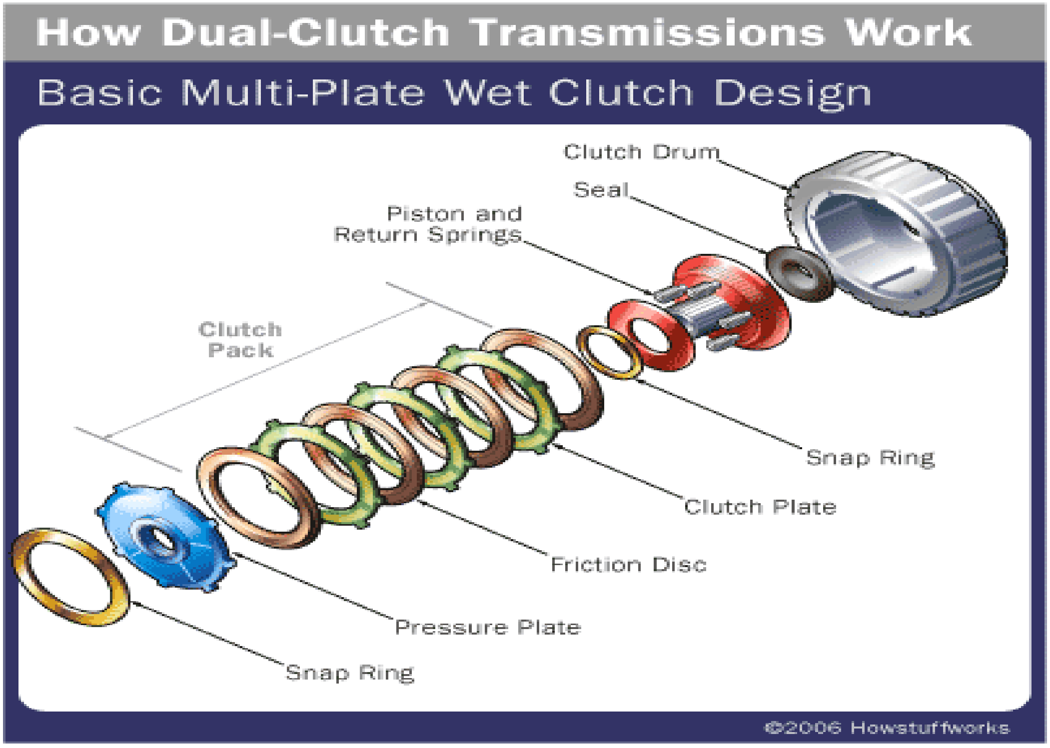


Figure 6: Basic multi-plate wet clutch design [8].

These wet multi-plate clutches are similar, in terms of principle of operation to torque converters, in that they also use hydraulic pressure to drive the gears. As seen in Figure 6, the lubricating fluid does it works inside the clutch piston. When the clutch is engaged, hydraulic pressure inside the piston forces a set of coil springs apart, this in turn pushes a series of stacked clutch plates and friction discs against a fixed pressure plate. The friction discs shown in Figure 5 have got teeth on the inside; these teeth are shaped and sized in such a way that they can mesh with splines on the clutch drum. This clutch drum is connected to the gear-set which will receive the transfer force. The wet multi-plate clutches in Audi's DCTs comprise of both a small coil spring and a large diaphragm spring. To disengage the clutch, fluid pressure inside the piston is reduced. This allows the piston springs to relax, which eases pressure on the clutch pack and pressure plate. These wet clutches engage and disengage based purely on fluid pressure which is controlled by the transmission control module (TCM) or the mechatronics module as VW like to call it. [8]

Figure 7 below shows the basic wet clutch design, when clutch 1 is engaged, clutch 2 is disengaged:

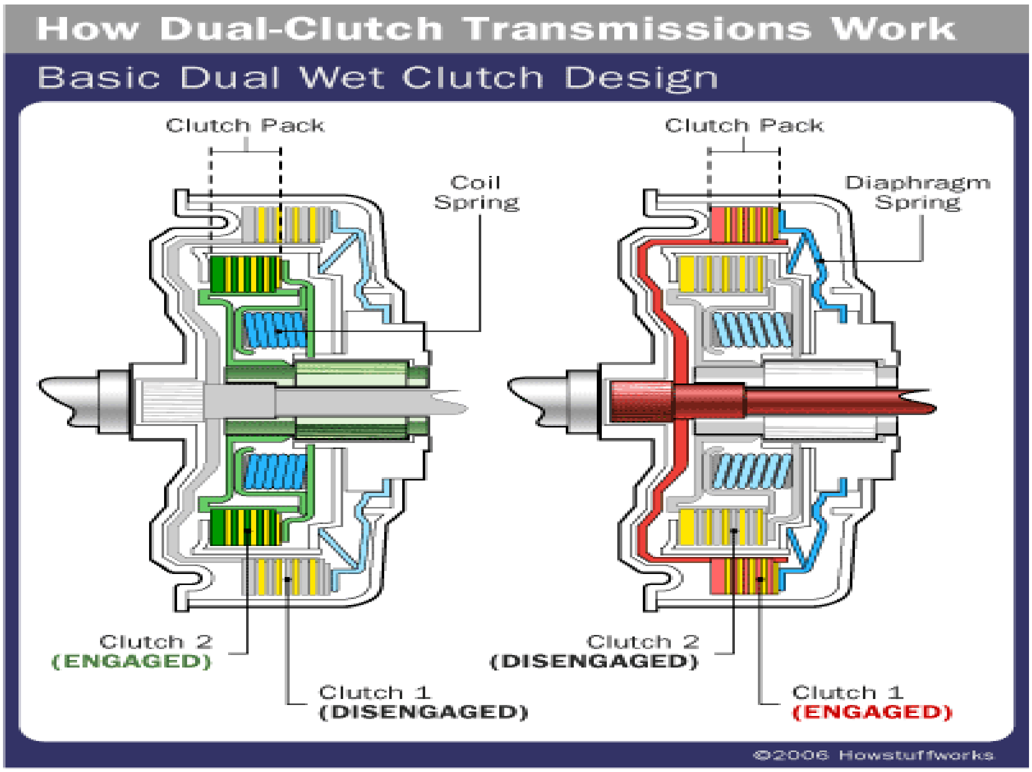


Figure 7: Basic multi-plate wet clutch design [8]

The main advantage that wet multi-plate clutches hold over single-plate dry clutches is that they can produce higher torque outputs and show a better resistance to wear. The bathing fluid used such as the DSG oil used by VW helps to reduce friction, and in turn dissipates the heat energy generated. The only real issue with wet multi-plate clutches is lower efficiency as compared to their dry counterparts; there is on-going research and development with regards to this. [9]

Generally all researchers have done their analysis on design for performance improvement of transmission system for better use. They have contributed a lot for easy way of design and applicability. But, they didn't have done more on modeling of clutches in transmission system of electric vehicles, and ways of replacement of MPCs in TCT system for light duty vehicles. This motivates to model MPCs for use in TCT system of green and light weight vehicle in this thesis.

CHAPTER THREE

NUMERICAL ANALYSIS, AND MODELING OF MPCs

3.1 Clutch Material Selection Criteria

It is the friction pads or facings which actually transmit the power from the fly wheel to hub in the clutching systems and from there to the output shaft. There are grooves in active sides of the friction-disc facings. These grooves prevent the facings from sticking to the flywheel face and pressure plate when the clutch is disengaged. The grooves break any vacuum that might form and cause the facings to stick to the flywheel or pressure plate. The facings on many friction discs are made of cotton and asbestos fibers woven or molded together and impregnated with resins or other binding agents. In many friction discs, copper wires are woven or pressed into the facings to give them added strength. However, asbestos is being replaced with other materials in many clutches. Some friction discs have ceramic-metallic facings.

After gear shift & during the clutch reengagement the clutch disc allows the transmission of progressive torque through its Axial Stiffness. At that time wear or failure occurs in the friction plate. The different materials have different properties to resist wear and failure in the clutch plate. We use different materials but with suitable properties to obtain a better stress and functions of pressure plate. The commercial clutch disc materials should be modified and replaced by other materials which support the green area protocols. So, in this thesis materials are optimized as to be used in green and light weight vehicles.

The present work investigates the response of clutch plates to an external load and pressure and stresses. A Geometric model of clutch was designed in 3D by using solid work 2016 software and exported to Ansys16.0 work bench. The finite element program ANSYS is used to compute the stresses and the strain.

Different machine design and manufacturing companies have stated a lot on material properties used for clutches. The selection of correct clutch for the intended application is critical to good operation, including the characteristics.

Identifying what clutch to get is dependent on the characteristics of the vehicles (i.e. how much power does the vehicle make? how is it used? etc.) But, Materials using for MPCs for use in TCT system of Green and light weight vehicles should have to have the following common Properties;

- ✓ Clutch Materials must have high coefficient of friction.
- ✓ Materials must resist wear effects such as scoring, galling and ablation.
- ✓ Materials should resistant to the environment (moisture and dust).
- ✓ Material should possess good thermal properties, good thermal conductivity, high heat capacity, and with stand high temperature.
- ✓ Friction materials should have to be available locally and with lower cost.
- ✓ Material should withstand high contact pressure and stresses.
- ✓ Materials should be lighter in weight than the existing commercial clutch plate materials.
- ✓ Materials should have a long service life.

Depending on those properties stated above, some of the materials used for clutching are;

1 Aluminum Alloy (6061)

Aluminum-Silicon (Al-Si) alloys are most flexible materials, comprising 85% to 90% of the total aluminum shed parts produced for the automotive industry [4]. Depending on the Si focus in weight percent (wt. %), the Al-Si alloy systems drop into three major categories: hypoeutectic (<12% Si), hypereutectic (14-25% Si) and eutectic (12-13% Si).

However, most Al-Si alloys are not suitable for lowering temperature applications because tensile and fatigue strengths are not as high as preferred in the temperature range of 500 - 700 °F [7].

Advantages of Aluminum Matrix Composites Over iron, steel and other non-ferrous metals are as follows [7]:

- ✓ Higher elevated temperature strength
- ✓ Improved wear resistance
- ✓ Low density; high strength to weight ratio
- ✓ Improve damping capabilities
- ✓ Good corrosion resistance

2. Gray Cast Iron

Grey Cast Iron is made by re-melting pig iron. It is an alloy of Carbon and Iron. Small amounts of Silicon, Phosphorus, Manganese and Sulfur are also present in it. The reasons behind its popularity are: ability to make complex structures and low cost. In addition, the excellent properties of Grey Cast Iron have made it one of the most widely used alloys in vehicles braking and transmission system.

Properties of Gray Cast Iron are as follows [6]:

- ✓ Has **high compressive strength**
- ✓ **Resistance to deformation and to oxidation**
- ✓ High thermal conductivity
- ✓ High hardness

3. Composite materials

A Composite material (also called a composition material or shortened to composite, which is the common name) a material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different from the individual components. Many commercially produced composites use a polymer matrix material often called a resin solution. There are many different polymers available depending upon the starting raw ingredients.

4. E-Glass Epoxy material properties:

- ✓ Providing a lightweight, and Corrosion-resistant alternative to steel
- ✓ Higher Heat resistance strength, and Higher Impact strength
- ✓ Higher Inter laminar shear strength and Tensile strength

5. Ceramics

Ceramics are very high temperature materials usually found on multi-puck disks. The materials will accommodate 500hp+ with more abrupt engagement. The material will wear the flywheel surface faster, especially in traffic situations. The material is suitable for extreme clamping applications. The advantage of ceramics over aluminum alloy is that ceramic materials are used for high power vehicles and drag racing cars. But, because of their properties of wearing fly wheels the materials are not selected for design of MPCs for use in green vehicles

6. Silicon carbide [SiC]

Silicon and carbon with chemical formula SiC. Silicon carbide powder has been mass-produced since 1893 for use as a course. Grains of silicon carbide can be bonded together by sintering to form very hard ceramics that are widely used in applications requiring high staying power, such as car brakes, car clutches, grinding wheels, cutting tools and ceramic dishes in bulletproof vests. Single crystals of silicon carbide can be grown by the Lely method; they can be cut into trinkets known as artificial moissanite. Silicon carbide with high surface area can be produced from SiO2 contained in plant material. SiC particulates can be used as reinforcement, whiskers or fibers to improve the properties of the composite. When surrounded in metal matrix a composite SiC certainly improves the overall strength of the composite also it improves deterioration and wear resistance. Sic based composite has high hardness; it can also use in number of applications such as in cutting tools, jeweler, structural materials, electronic circuits, automobile parts, nuclear fuel particles, etc. [12]. Here, since SiC is a tool material, the cost of those materials are very high than expected for design of clutches. Due to this SiC is not selected for design of MPCs.

7. Kevlar 49

Kevlar is used in street-driven track cars up to 500hp. Due to the unforgiving nature of Kevlar, it is not recommended for street cars, and especially those that see frequent stop-and-go traffic which will cause surface glazing of the clutch.

Kevlar 49 materials properties

- ✓ Uses in a high temperature range, but can be ruined from overheating.
- ✓ Will not return to original characteristics if cooked.
- ✓ The material has a break in period of 500-1000 miles during which slippage may occur.

Eventhough Kevlar is a better friction materials, it is costly compared to the other. This makes the material not to be selected for design of clutches in green vehicles.

8. Organic

Organics facings were originally made with asbestos, but as health issues arose concerning the use of asbestos, it was phased out of industry. Facing were then made of fiber glass and brass as its main ingredients.

As stated on material selection guide line, we need to choose a material that is stiff, light, strong and cheap – we will therefore need to find information about the Young's modulus, density, strength and cost for lots of different materials.

Since there are number of materials to be used for modeling and design of friction plates; different criteria should be used for identifying best materials for clutching.

To specify and limit number of materials to be used for analysis; Material selection matrices is used for expected clutch disc materials and materials mostly used by different researchers.

Table2: comparison of better materials based on strength specification

Material types	Specific Strength	Yield Strength (Mpa)	Elastic Modulus(GPa)	Advantage value	Grading

E-Glass Epoxy	28.4	1270	28	15	5
Aluminum Alloy	4.8	275	69.7	10	4
ceramics	6.7	457	33	12	4
Gray Cast Iron	19.1	720	24.1	10	4
Silicon Carbide	57	1710	63	15	5
Kevlar 49	23.8	370	72	11	4
organics	17	270	28	10	4

1 = poor, 2 = fair, 3 = good, 4 = very good, 5 = excellent

Table shows that E-Glass Epoxy, Silicon Carbide, and Alloy Materials are better in resisting for yield while load is applying on them. But, it is clear that Silicon Carbide is a tool material which is very costly. So, it is not recommended for use of clutching.

Table 3: comparison of materials based on ability to resist corrosion.

Materials	Corrosion Resistance	Weighted value	Total	Grading
Aluminum Alloy	9	1.5	13.5	3
ceramics	23	1.5	34.5	4
Gray Cast Iron	7.13	1.5	10.7	3
Silicon Carbide	29	1.5	43.5	5
E-Glass Epoxy	12	1.5	18	4
Kevlar 49	8	1.5	12	3
organics	7.3	1.5	10.95	3

1 = poor, 2 = fair, 3 = good, 4 = very good, 5 = excellent

So from this table it is shown that Ceramics, Silicon Carbide, and Epoxy materials are better corrosion resistance materials than the other listed materials.

Table 4: Comparison based on their cost per Kilogram.

Materials	Mass (Kg)	Cost/Kg ($)	Grading
Aluminum Alloy	2.39	13.8	4
ceramics	2.88	38	2
Gray Cast Iron	3.4	40.7	2
Silicon Carbide	1.9	147.3	1
E-Glass Epoxy	1.8	29.2	3
Kevlar 49	2.92	56.7	2
organics	3.1	20.1	3

1 = very expensive, 2 = expensive, 3 = moderate price, 4 = inexpensive, 5 = very inexpensive

Table shows that Aluminum Alloy, E-Glass Epoxy and Organic materials have moderate price.

Table 5: comparison based on availability, service life, and manufacturability.

Materials	Local Availability	Services life	manufacturability	No. of +	No. of -
Aluminum Alloy	++	-+	++	5	1

ceramics	-+	-+	-+	3	3
Gray Cast Iron	-+	-+	-+	3	3
Silicon Carbide	--	++	--	2	4
E-Glass Epoxy	++	++	+-	5	1
Kevlar 49	--	-+	-+	2	4
organics	-+	--	+-	2	4

Table shows that using either of Aluminum Alloy, E-Glass Epoxy, Ceramics, and Gray Cast Iron materials is better for clutching.

Generally depending on those decision matrixes and on behalf of the literatures used E-Glass Epoxy, Aluminum Alloy, and Gray Cast Iron materials are selected for analysis of clutch disc.

From the above listed materials Aluminum Alloy, Gray Cast Iron and E-Glass Epoxy are better candidate materials for design of friction clutches. But, this is not the only way for selection. Beside, FEA should be done using ANSYS Work Bench depending on the properties of materials to identify which material is better.

The properties of the frictional lining are important factors in the design of the clutches. So, typical characteristics of some widely used friction linings are given in table 6.

Table 6: properties of candidate clutch lining materials.

Materials combination		Aluminum Alloy 6061	Gray Cast Iron	E-Glass Epoxy
Dynamic coefficient of friction	Dry	0.25 – 0.45	0.15 – 0.25	0.25 – 0.45
	Wet	0.06 – 0.09	0.03 – 0.06	0.06 – 0.09
Maximum pressure MPa		345 - 690	690 -720	345 -690
Maximum temperature ^{0}C		2104 -260	260	204 - 206

To identify this comparison is done using Aluminum alloy (6061), and Gray Cast Iron, and E-Glass Epoxy using ANSYS workbench and identify which one is better for use.

3.1.1 General properties of clutch Plate material

Table7: common Properties of selected clutch plate materials [18].

Materials combination	Aluminum Alloy 6061	Gray Cast Iron	E-Glass Epoxy
Young's Modulus (Mpa)	68900	120000	27600
Density(Kg/m^3)	2700	7200	1900

Poisson's ratio	0.33	0.29	0.34
Friction coefficient	0.23	0.28	0.48
Tensile strength (Mpa)	276	220	124

3.2 Geometrical analysis

3.2.1 Design Considerations

A clutch of good design must have adequate torque capacity, ability to withstand and dissipate heat and should have a long life. The clutch must have positive release, smooth engagement, low operating force and ease of repair. To permit easy engagement and to prevent excessive wear during the engagement period the facing should be flexible and the largest possible area should be in contact during engagement.

Design is started considering: a 6-speed TCTs, two wet type MPCs; one on internal, and one on external shaft, no gear shifting, and use of synchronizers, and use of lighter weight materials than existing.

3.2.2 Design statement

As shown on figure 3 and figure 4 the friction plates are splined on their inner and outer circumference and engage with corresponding splines on the flywheel or shafts. They are free to slide axially. The friction material thus, rotates with the flywheel and the engine shaft. The number of friction plates depends upon the torque to be transmitted. The driven shaft also supports discs on the splines which rotate with the driven shaft and can slide axially. If the actuating force on the pedal is removed, a spring presses the discs into contact with the friction rings and the torque is transmitted between the engine shaft and the driven shaft.

3.2.3 Methods of analysis

The method of analysis of a clutch plate is either a uniform pressure or a uniform wear. The torque that can be transmitted by a clutch is a function of its geometry and the magnitude of the actuating force applied as well the condition of contact prevailing between the members. The applied force can keep the members together with a uniform pressure all over its contact area and the consequent analysis is based on uniform pressure condition. Condition may no longer prevail. Hence the analysis here is based on uniform wear condition.

3.2.4 Specifications of multi-plate clutch

The composite clutch plate model is based on the clutches used in light duty and/or electric vehicles. The clutch plate model is based on a single plate clutch used in Lifan 620

(LF48/Q3) developed using Gray Cast Iron material. It is defined that for 1000Kg car and keeping everything else constant; on flat road at a speed of 25Km/hr requires 1.0KW power, and on 5^0 gradients climbing at a speed of 25Km/hr requires 6.9KW power. General specification of the vehicle is shown in table 8.

Table 8: Commercial Lifan sedan clutch specifications

Parameter	Value	Units
Geometry		
Outline dimension	L4550,W 1705,H 1495	mm
Max. power	85/115.6@5000rpm	KW/Hp
Weight of vehicle	1150	Kg
Vehicle weight with load	1555	Kg
Torque	137	Nm
Torque delivery Speed	4500	Rpm
speed	170	Km/Hr
Gross weight of clutch	4	Kg
Axial intensity of pressure	160	KN/m^2
Internal diameter of the clutches	140	mm
Outer diameter of the clutches	210	mm
Clutch thickness	10	mm
Size	1.6	Liters
Brake model	6speed	
Brake type	4wheel disk brake	
Seating capacity	5	person
Transmission	CVT	
Effective torque radius	130	mm
Number of friction surfaces	5	pcs
Friction		
Kinetic friction coefficient	0.3	-
Static friction coefficient	0.31	-

Clutch velocity tolerance	0.001	rad/s
Engagement threshold pressure	1	Pa

Source; instruction manual of Lifan Sedan (Lifan 620); Bushoftu Lifan vehicles assembling company, Eastern Industrial Zone)

The vehicle parameters in this paper are based on the Lifan 620 (LF48/Q3) Automobile, and the performance parameters are announced by Bushoftu Lifan Motors Assembling Company. The total vehicle parameter is shown in Table 4 above. In a multi-plate clutch, the number of frictional linings is increased which increases the capacity of the clutch to transmit torque.

A thesis design in this work is based and used the data tabulated below which have been selected from the standard clutch specifications of Japan, Germany, and America clutch manufacturing companies and some data's are taken from Bushoftu Automotive Industries (directly taken from Germany designers), Lifan motor vehicles assembling company, and Moenco car assembling company. Depending on those data the parameters of a clutch disk is specified and a model is done.

Table 9: Newly modeled clutch specifications

Symbol	Meaning	Value
$T_{e\ max}$	Engine maximum torque	135 N m at 5000 rpm
$P_{max.}$	Max. power	5KW at 5000rpm
β	Clutch safety factor	1.2-1.6
µof E-Glass Epoxy	Coefficient of friction	0.48
n	Number of friction surfaces	1
r_o	Clutch friction plate outer dia.	200mm
r_i	Clutch friction plate inner dia.	150mm
t	Thickness of clutch plates	8 mm

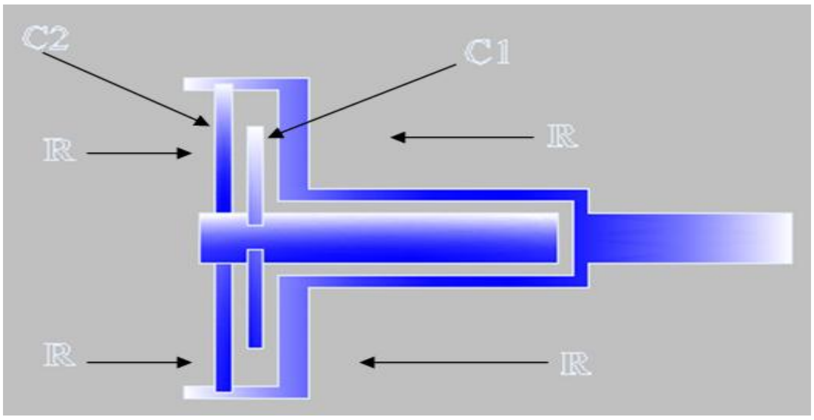


Figure 8: sectional view of set of multi-plate clutches (solid work model)

These are constructed with one plate attached to the inner shaft and the other plate to the outer case. On figure 8 there is a surface in contact due to clutch plates C_1 and C_2, and this allows a greater torque to be transmitted before slip occurs. Since there are two multi plate clutches the number of friction surface is (n + n – 1) which is 1; then the maximum torque increased n times. So, to deliver 5KW power, 135Nm torque, at a speed of 1000-5000rpm, using E-glass Epoxy UD material, design calculations include,

In vehicles, the power delivery of engine and speed can vary from 3.5 – 85 KW and 4500-5000 rpm respectively depending on engine transmission system. So, let's use the power delivery of the vehicle as 5KW and at a specified initial speed of 5000rpm. But the torque transferred by the clutch would be calculated for analysis of loads and maximum pressure with new specifications.

The number of friction surfaces used in Lifan 620, for torque transfer of 138Nm are 9 with number of friction surfaces on driving and driven shafts are 4 and 5 respectively, and have maximum output torque of 137Nm. Lifan 620 is used as a reference because of its weight and is being a light duty vehicle.

$$n = n_1 + n_2 - 1 \qquad \text{(eq.1)}$$

So, using twin multi-plate clutch is using the number of friction surfaces to be one.

Then, the total torque transfer would be;

$$T_t = \frac{P}{\frac{2\pi\omega}{60}} \qquad \text{(eq.2)}$$

Where T_t = a total torque transfer, P = a maximum power carried by a clutch, ω = speed in rpm

Then using eq.2 above;

$$T_t = \frac{5000}{\frac{2\pi * 5000}{60}} = \underline{10}\text{Nm}$$

Then, using the number of friction surfaces n=1, for Two MPCs:

$$T = T_t/n = 10/1 = \underline{10}\text{Nm} \qquad \text{(eq.3)}$$

Then using Clutch plate specifications for E-glass Epoxy UD material;

r_i and r_o are outer and inner radius of friction faces respectively

r_i =150mm and r_o = 200 mm,

n = no of pairs of contact surfaces.

Where n_1 and n_2 are number of disc on driving and driven shaft n_1= 1 and n_2= 1; n = 1 from eq. 1

R = mean radius of friction surfaces. $(r_i + r_o)/2$ = 175mm

μ = coefficient of friction for E-glass Epoxy UD = 0.48

Max.power (P) = 5KW, thickness t = 8mm

Torque (T) = 10 Nm (result from eq. 2); at speed N = 5000 rpm (for a double clutch plate).

3.2.5 Formulation and analysis of Loads and boundary conditions

Static Analysis is used to determine deformation, stresses. under static loading conditions. ANSYS can compute both linear and nonlinear static analyses. Nonlinearities can include plasticity, stress stiffening, large deflection, large strain, hyper elasticity, contact surfaces, and creep. And Dynamic Analysis - Used to determine the response of a structure to arbitrarily time-varying loads.

All nonlinearities mentioned under Static Analysis above are allowed and enough for doing this analysis. The clutches used here are a two wet type clutches, one on driving and the other on driven the shearing effects between the plate faces are negligible. So, to simplify the analysis and since the clutch plate face more effects of load than shearing, static modal analysis would be done to identify which material is a better lining material. So, to find the maximum pressure to be applied on clutch plate let's do the following.

Material used is Aluminum alloy with μ = 0.23, power (P) = 5KW, and torque capacity of 10 Nm at a speed of 5000rpm

D_1 =150 mm and D_2 = 200 mm; where D_1 and D_2 of friction faces

n = no of pairs of contact surfaces

Where n_1 and n_2 are no of disc on driving and driven shaft $n_1 = 1$ and $n_2 = 1$; n = 1

by considering uniform wear theory which states that, wear depends upon intensity of pressure P and velocity of rubbing which further depend on R, thus for uniform rate of wear PR = constant.

$$\text{For uniform wear } R = (D_1+D_2)/2 \qquad \text{(eq.4)}$$

Where R = mean diameter of friction material

$$R = (200+150)/2 = 175\text{mm} = 0.175\text{m}$$

$$\text{Torque } (T) = \mu\, W\, R\, n \qquad \text{(eq.5)}$$

Where, μ = coefficient of friction and W = clamping force in N

$$10 = 0.23 * W * 0.175 * 1$$

$$W = \underline{248}\ \text{N}$$

Now, from uniform wear theory,

$$W = 2\,\pi\,(P_{max} x\, D_1)\ x\ (D_2 - D_1) \qquad \text{(eq.6)}$$

Where, Pmax= maximum pressure between the contacting surfaces

$248 = 2\pi (P_{max} \times 0.15) \times (0.2 - 0.15)$

P_{max}= **0.0053MPa**

And for E-Glass Epoxy material (μ=0.48), power of 5KW, and 10 Nm at 5000rpm.

Clamping force for E-Glass Epoxy material using eq. 5 above;

$10 = 0.48 * W * 0.175 * 1$

W = 119 N

Value of maximum pressure for E-Glass Epoxy material using eq.6

$119 = 2\pi (P_{max} \times 0.15) \times (0.2 - 0.15)$

P_{max}= **0.00037MPa**

Similarly, for Material used is Gray Cast Iron with μ = 0.28, power (P) = 5KW, and torque capacity of 10 Nm at a speed of 5000rpm

The clamping force for Cast Iron material using eq. 5

$10 = 0.28 * W * 0.175 * 1$

W = 204 N

Value of maximum pressure for Cast Iron Using eq. 6

$204 = 2\pi (P_{max} \times 0.15) \times (0.2 - 0.15)$

P_{max}= **0.0043Mpa**

3.2.6 Dynamic Analysis

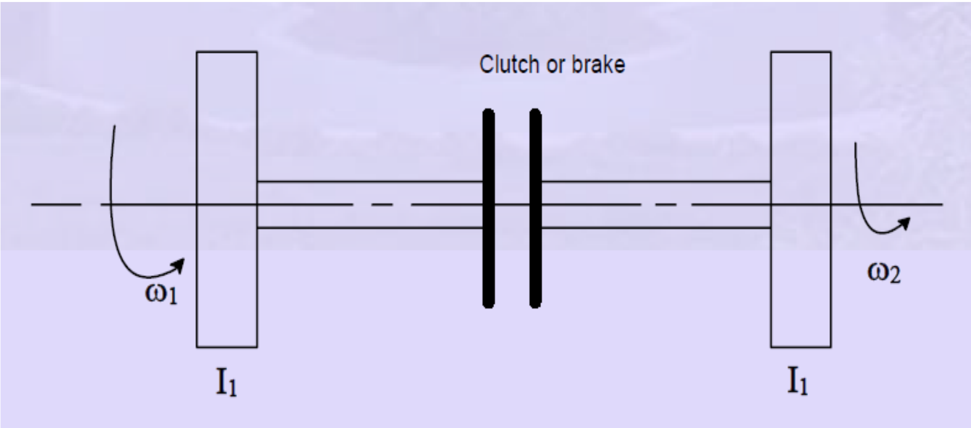


Figure 9: Dynamic Representation of Clutch or Brake

Consider a simple two- inertia system shown in Figure 9. Here, the coefficient of friction is assumed to be a constant, independent of speed. It is also assumed also that no external torques act on the system. The two clutches initially rotate at two different angular velocities ω_1 and ω_2.

Let the clutch be instantaneously applied at time t = 0 and the torque exerted by it on the two flywheels Mc = constant. This torque will act on the system only as long as these exists a difference in speeds between the two shafts Equations for speed, rate of heat dissipation etc., are therefore valid for time $0< t< t_0$, where t_0 is the time required to couple the two shafts.

The equations of motion for the two sides of the clutch are

$$I_1 (d\omega_1/dt) = -M_c \qquad \text{(eq.7)}$$

$$I_2(\omega_2/dt) = M_c \qquad \text{(eq.8)}$$

Where ω_1, and ω_2 are angular velocities of C_1 and C_2 respectively as shown on figures 11 and 12. Integrating equations and applying the conditions.

For the considered system, after calculating the I- section inertia we have $I_1 = 0.2kg.m^2$; $I_2 = 0.149kg.m^2$; $M_c = 50$ Nm. $\omega_1 = 1500rpm = 157.075rad/sec$. where I_1 and I_2 are inertia of clutch plate 1 and 2 respectively.

Assuming clutch is applied at the output speed $\omega_2 = 1000rpm = 104.7rad/sec$

The duration of engagement period or slip time of a clutch is,

$$t_s = \frac{I_1 I_2 (\omega_1 - \omega_2)}{M_c (I_1 + I_2)} \text{sec} \qquad \text{(eq.9)}$$

$$= \frac{0.2x0.149(157.075 - 104.7)}{50(0.2 + 0.149)} = 0.06\text{sec}$$

1 General Nomenclature

r_i – inner radius of clutch friction face

t_c – thickness of clutch plate

t_f – thickness of friction face

N – Speed of engine in rpm = 5000rpm

ω – angular velocity red/sec

P_{max} – maximum clamping pressure

2 Mathematical Calculations

The material considered for the friction pad is E-glass Epoxy UD. Uniform Wear Theory is considered for calculations, and accordingly, the intensity of the pressure is inversely proportional to the radius of friction plate.

$$R=R_i+R_o/2=87.5m \qquad \text{(eq.10)}$$

In general, the frictional torque acting on the clutch plate is given by eq. 1 as $P\times r=C$ $(constant)$

Since torque is 10Nm, Axial force on the clutch 114N,

$$W=2\pi\times C\times(R_o-R_i) \qquad \text{(eq.11)}$$

$$C = 0.7Nm$$

The maximum pressure occurs at the inner radius and the minimum pressure at the outer radius.

$P_{min} = C/Ro = 0.007\ Mpa$ (eq.12)

$P_{max} = C/Ri = 0.0093\ Mpa$ (eq.13)

Here, we consider the maximum pressure value obtained in the Finite Element Analysis of the clutch plate.

3.2.7 Thermal Analyses

1 Nomenclature

T – Temperature of the disc in Celsius

T_l – Limiting temperature of the material in Celsius = 150ºC

μ - Coefficient of friction of the material = 0.48

k – Thermal conductivity of the material in Watts per meter Kelvin

h – Heat transfer coefficient of the material.in Watts per sq. meters per Kelvin.

q – Heat energy generated in watts

q_f – heat flux in W/m^2

t – Slip time in seconds = 0.06sec

A – Area of a friction plate = 54950m^2

2 Mathematical Calculations

$\omega_r = 2\times\pi\times N/60$ (eq.14)

$= 2 \text{ x } \pi \text{ x } 5000/60 = 523\ rad/s$

$q = \mu\times W\times\omega_r$ (eq.15)

$= 0.5 \text{ x } 114 \text{ x } 523 = 0.03M\ W$

$q_f = q/A$ (eq.16)

$= 0.03/54950 = 0.54\ W/m^2$

3.2.8 Model Analysis

1 Nomenclature

F_e – Engine frequency

n – Order of frequency (1st order & 2nd order)

N_e – Engine rpm range (1500 rpm-5000 rpm)

2 Mathematical Calculations

$F_e = N_e/60\times n$ (eq.17)

$= 1500/60 \text{ x } 1 = 25$Htz

3.2.9 Wear analysis

A common and well known application for the clutch is in automotive vehicles where it is used to connect the engine and the gearbox. Here the clutch enables to crank and start the engine disengaging the transmission Disengage the transmission and change the gear to alter the torque on the wheel. Due to friction between mating part some part of friction material get wear out. So, let's discuss about the wear formation on selected candidate clutch materials.

i. Friction Facings

It is the friction facings which actually transmit the power from the fly wheel to hub in the clutch plate and from there to the output shaft. There are grooves in active sides of the friction-disc facings. These grooves prevent the facings from sticking to the flywheel face and pressure plate when the clutch is disengaged. The grooves break any vacuum that might form and cause the facings to stick to the flywheel or pressure plate. However, asbestos is being replaced with other materials in many clutches. Some friction discs have ceramic-metallic facings. Such discs are widely used in multiple plate clutches The minimize the wear problems, all the plates will be enclosed in a covered chamber and immersed in an oil medium Such clutches are called wet clutches.

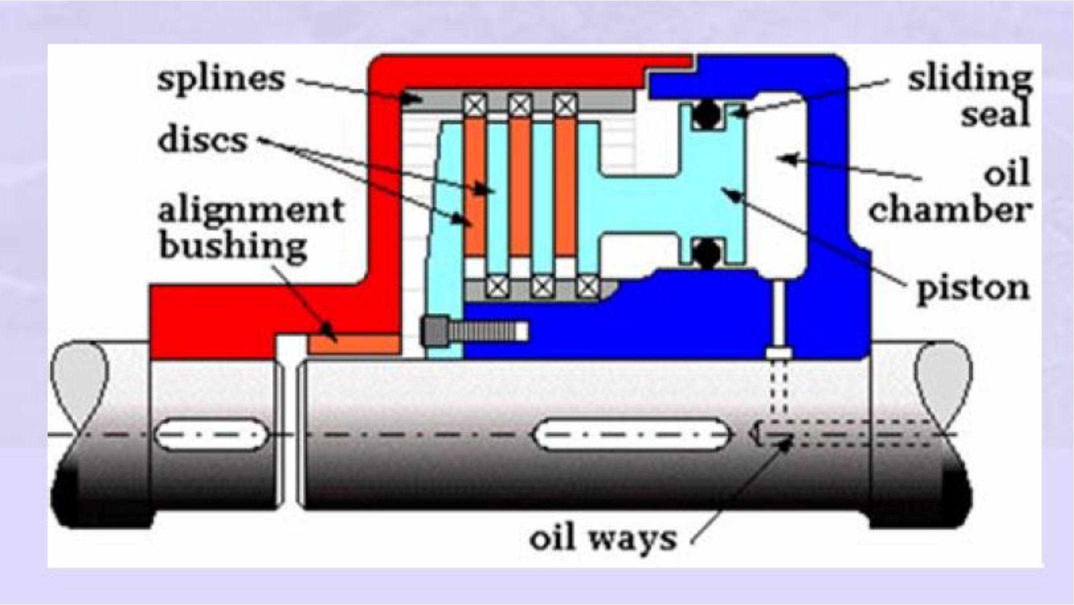


Figure 10: Multi-plate clutch facings

ii.Method of Analysis

There is number of method for analysis of wear and tear in clutch plate .The torque that can be transmitted by a clutch is a function of its geometry and the magnitude of the actuating force applied as well the condition of contact prevailing between the members. The applied force can keep the members together with a uniform pressure all over its contact area and the consequent analysis is based on uniform pressure condition. However as the time progresses some wear takes place between the contacting members and this may alter or vary the contact pressure appropriately and uniform pressure condition may no longer prevail. Hence the analysis here is based on uniform wear condition.

In this paper we aimed to solve the optimized result for the multi plate friction clutch using the uniform wear theory and obtained the optimum result of the inner radius and outer radius of the multi disc friction clutch.

The maximum torque which can be transmitted by the friction clutch for uniform pressure theory is given by

$$T_{max} = n\pi\mu p_a r(R^2 - r^2) \quad \text{(eq.18)}$$

Where Ro and Ri are external and internal radius respectively.

The objective function, F1 can be defined as

$$F_1 = \left(\frac{1}{T_{max}}\right) = \frac{1}{n\Pi\mu\rho_a r\left(R^2 - r^2\right)} \quad \text{(eq.19)}$$

$$F_d = F_1 + \left[\sum_{i=1}^{n}\left(\frac{\partial F_1}{\partial R_j}\right)^2 \sigma^2{}_{Rj}\right]^{\frac{1}{2}} \quad \text{(eq.20)}$$

If the constraint equation g_j is satisfied with a probability p_j if the normal variation for probability p_j is given then, the new constraint equation in deterministic form is given in equation. And finally problem reduces to minimize the objective function given by equation (18) satisfying constraint equation (19).

$$g_j = \Phi_j\left(\rho_j\right)\left[\sum_{i=1}^{n}\left(\frac{\partial g_j}{\partial R_j}\right)^2 \sigma^2{}_{Rj}\right]^{\frac{1}{2}} \quad \text{(eq.21)}$$

Now let’s consider the following figures

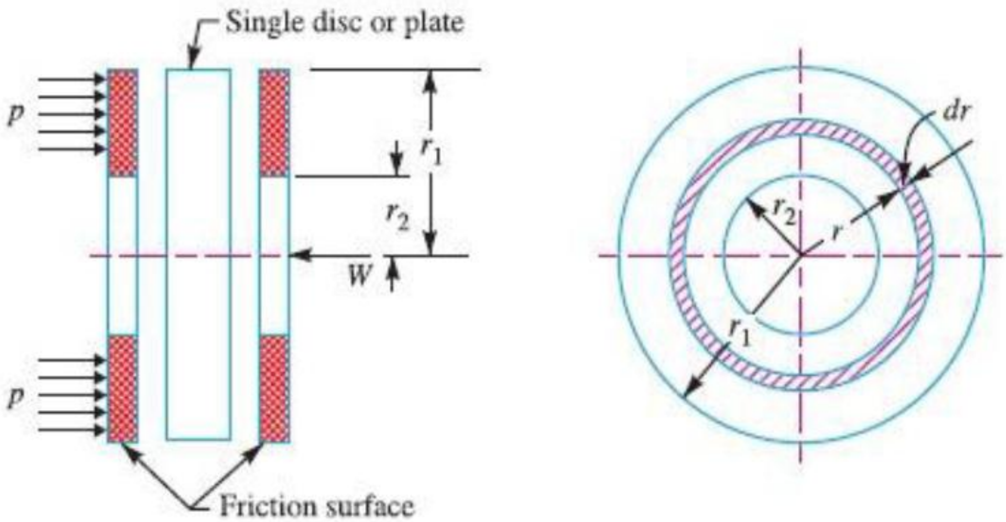


Figure 11: sectional view and geometry of clutch disc

To design the multi plate friction clutch for maximum torque transmitting capacity, given: [18]

μ= 0.48, n=1, $\rho = 0.35 N/mm^2 or 0.35 * 10^6 N/mm^2$

Solution:

On substituting the assumed data in equation 19;

$$F1 = \frac{1}{1*0.48*\pi*0.25*10^6*r(R^2-r^2)} = 7.8 * 10^{-7} / (R^2 r - r^3)$$

If the design parameters D and d are taken as random variables following normal distribution and the standard deviations are σ_D = 0.01D and σ_d = 0.01d respectively, then the new objective function in deterministic form, from equation 20 is:

$$F_d = \frac{7.8*10^{-7}}{(R^2 r - r^3)} + \frac{0.03*10^{-6} R^2 r}{(R^2 r - r^3)} + \frac{7.8*10^{-6}(R^2 r - r^3}{(R^2 r - r^3)^2}$$

$$= \frac{7.8*10^{-7}}{(R^2 r - r^3)}$$

On substituting assumed data in equation 21:

$$g_j = \frac{1.73r}{R} \quad \text{(eq.22)}$$

If the constraint equation is satisfied with a probability of 99.99%, then for Pj = 99.99% the normal variants from table is 5. Using equation (19) the constraint equation in deterministic form is:

$$g_j\, d = 1.733\, r/R - 0.087R \leq 1$$

Hence the problem reduces to minimize objective function given by equation (21) satisfying constraint equation (22). If the torsion is only considered as active constraint then the degree of difficulty will be zero. Applying signomial geometric programming the normality and orthogonally condition give.

3.2.10 Stress analysis

Assuming uniform pressure and considering an elemental area

$$dA = 2\Pi.r\, dr \quad \text{(eq.23)}$$

The normal force on this elemental area is

$$dN = 2.\pi.r.dr.p \quad \text{(eq.24)}$$

The frictional force dF on this area is therefore

$$dF = f.2.\pi.r.dr.p \qquad \text{(eq.25)}$$

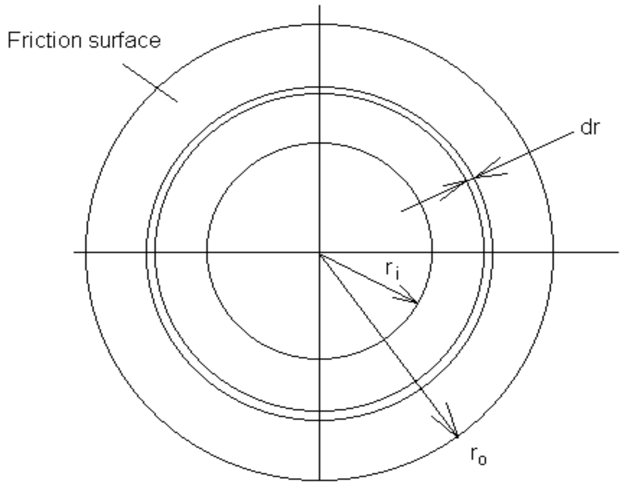


Figure 12: Multi-plate axial clutch

Now the torque that can be transmitted by this elemental are is equal to the frictional force times the moment arm about 8.2*10-5/0.001275

The axis that is the radius 'r' i.e.

$$T = dF.\ r = f.dN.\ r = f.p.A.r$$

$$= f.p.2.\pi.r.\ dr\ .r \qquad \text{(eq.26)}$$

The total torque that could be transmitted is obtained by integrating eq. 9 between the limits of inner radius r_i to the outer radius $r_{o.}$

$$T = \int_{ri}^{ro} 2\pi pf\, r^2 dr = \frac{2}{3}\pi pf\,(r_o^3 3 - r_i^3) \qquad \text{(eq.27)}$$

Integrating the normal force form eq.6 between the same limits we get the actuating force that need to be applied to transmit this torque.

$$F_a = \int_{r_i}^{r_o} 2\pi pr dr = \pi(r_o^2 - r_i^2)p \qquad \text{(eq.28)}$$

Equation 9 and 10 can be combined together to give equation for the torque,

$$T = fF_a \frac{2}{3}\frac{(r_o^3 - r_i^3)}{(r_o^2 - r_i^2)} \qquad \text{(eq.29)}$$

Here the maximum permissible stresses would be used for finding stresses. Where P_{max}= maximum permissible stress; inner radius of single plate clutch (R_i = 75mm); outer radius of single plate clutch (R_o= 100mm) the effective area of the clutch is Area = πr^2 = 54950 mm^2. Aluminum alloy 6061 with permissible stress of [$P_{max.}$ = 0.62 N/mm^2];

Pressure (p) = (P_{max}x r_i)/r_o

$$F_n = \int_{ri}^{r_o} pdA = \int_{r_i}^{r_0} ((P_{max.} * r_i)/r_o) * 2\pi r dr = 2\pi P_{max.} * r_i \int_{r_i}^{r_o} dr \quad \text{(eq.30)}$$

= [2π (0.32 x 75) x ri (ro-ri)]/ro

= [2π (0.62 x 75) x 75 (100 - 75)]/100

= 2826 N= 5475.375

Stress=F/A (eq.31)

= 5475.4/54950 = 0.1 N/mm^2

For Gray Cast Iron with permissible stress of [$P_{max.}$ = 0.69 N/mm^2]

Using eq. 6 for cast iron material

= [2π (0.69 x 75) x 75 (100 - 75)]/100

= 6093.6 N

And using eq. 26 the Stress value would be;

=0.11 N/mm2

E-Glass Epoxy Material with permissible stress of [$P_{max.}$ = 0.586N/mm^2]

Similarly using eq. 6 the normal force for an E-Glass Epoxy material would be

= [2π (0.586 x 75) x 75 (100 - 75)]/100 = 5175 N

And the Stress value is;

=0.09 N/mm^2

Generally we have seen that for a green, and light weight vehicle to be developed the clutch material should be a materials with lower weight than existing light duty commercial clutch plates and could resists the effects of stresses and loads. The existing clutch plates are those developed from Gray Cast Iron and sometimes those from asbestos free materials. But as shown in tables 2 above, E-Glass Epoxy material is more effective and efficient than Gray Cast Iron. The model of the clutch in this thesis is developed using E-Glass Epoxy material would have to resist the effects of force, torque and pressures as shown below.

Re arranging eq.3; the climbing force on a clutch would be:

w = 2T/n µR (eq.32)

= 2(10Nm)/ (0.48) (1) (0.0875) = <u>457N</u>

Torque capacity after initial wear,

T = 2/3µWD_mn (eq.33)

= 2/3*0.5*457*0.0875 =<u>13Nm</u>

Safety factor when T=10;

= 10/10 = $\underline{1}$

Using result from eq. 16; Safety factor after initial wear;

= 13/10 = $\underline{1.3}$

Reduction in a clamping force so that slippage occurs;

As the friction material of the disc wears the surface shows a slight expansion, reducing their clamping force.

New clamping force $(W_1) = W*\mu*T_t/T$

(eq.34)

$=457*0.5*10/13 = \underline{175.8N}$

Change in clamping force W_c would be $(W - W_1)$;

$W_c = 457- 175.8 = \underline{281.2N}$

Then, if we are calculating operating values for a number of pairs of contact surfaces:

Calculating operating force and operating average pressure by using uniform wear theory as follows.

Average operating pressure:

$F_o = (2*\pi*P_o*r_2)*(r_2-r_1)$

(eq.35)

$457= (1/2 \text{ x } \pi\times p_o\times 0.1) \times (0.1-0.075)$

$P_o = 0.1\underline{\text{ MPa}}$

Effective force acting at R_{radius}; will be,

$F_e = \mu W = 0.5(457) =$ **$\underline{228.5N}$**

(eq.3)

It is imperative to understand the factors that influence friction force because this device transmits torque via friction. Friction torque transmitted:

$T_f = F_e R$ (eq.37)

$= 228.5(0.0875) = \underline{20Nm}$

Since no of friction surfaces n = 1; the torque transmitted by clutch is

$T_c = nT_f = 1(20) = \underline{20Nm}$ (eq.38)

Then using eq. 13 the power transmitted by clutch is:

$P_c = T_c* \frac{2\pi N}{60} = 20* \frac{2\pi*5000}{60} = \underline{10KW}$

Since for a wet clutch allowable surface pressure varies from $0.05N/mm^2$ to $0.2N/mm^2$ for lining material; the normal force is (using the maximum of allowable surface pressure) [7]:

Using eq. 18 the normal force on a clutch is;

$F_n = 2\pi*0.3*75*(100-75) = 3532.5N$

Using eq. 11, the maximum input torque would be:

T = ½*0.5*457*0.0875 = 10Nm

Friction force: $F_f = n\mu F_n$ (eq.39)

= (1*0.5*3532.5) = 1766.25N

The efficiency designed multi plate clutch for use in TCT would be;

$$efficency = \frac{Outputpower}{imputpower} \quad \text{(eq.40)}$$

$$\eta = \frac{Po}{Pi} = 0.3/12 = 99.8\%$$

And in terms of torque transfer the efficiency would be:

$$efficency = \frac{Outputtorque}{imputtorque} \quad \text{(eq.41)}$$

$$\eta = \frac{To}{Ti} = 9.995/10 = 99.95\%$$

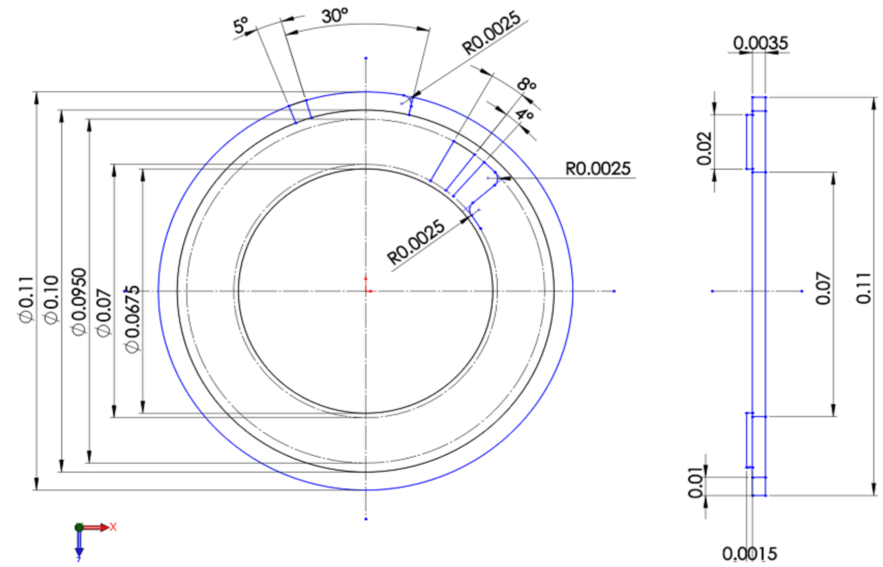
Therefore, the newly modeled multi-plate clutch is 99.8% efficient and more acceptable than existing commercial vehicle Gray Cast Iron single plate clutch which has 0.006% deviation from the newly designed clutch.

3.3Three dimensional Modeling of MPCs

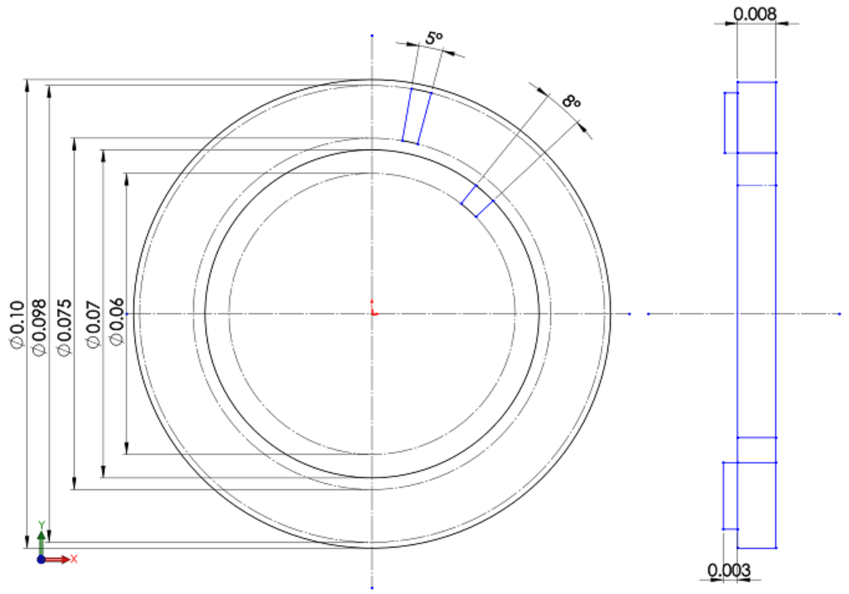
3.3.1 Selection of softwares

A lot of research was carried out initially, to determine the choice of software to achieve the desired results after the project theme had been selected. A combination of 3D modeling software was considered and looked into, so was combinations of ANSYS/FEM and Solid works were used. After deep conjecture, FEM along with additional software components was selected as the choice of software beside analytical calculations, to try and achieve the objectives of this Thesis.

Then using specifications from table 5; the 2D and 3D models for internal and external MPCs are drawn.

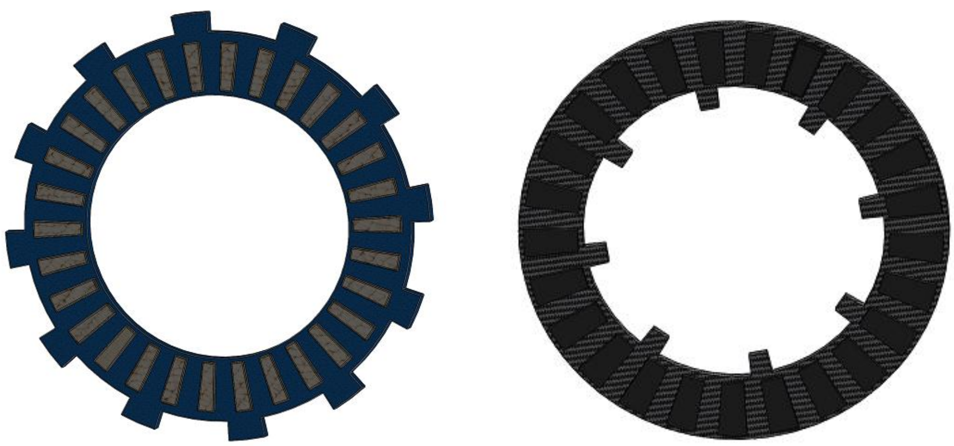


a) 2D view of external splines MPCs



b) 2D view of internal splines MPCs

Figure 13: 2D model of internal and external multi-plate clutch



a) External splines b) internal splines

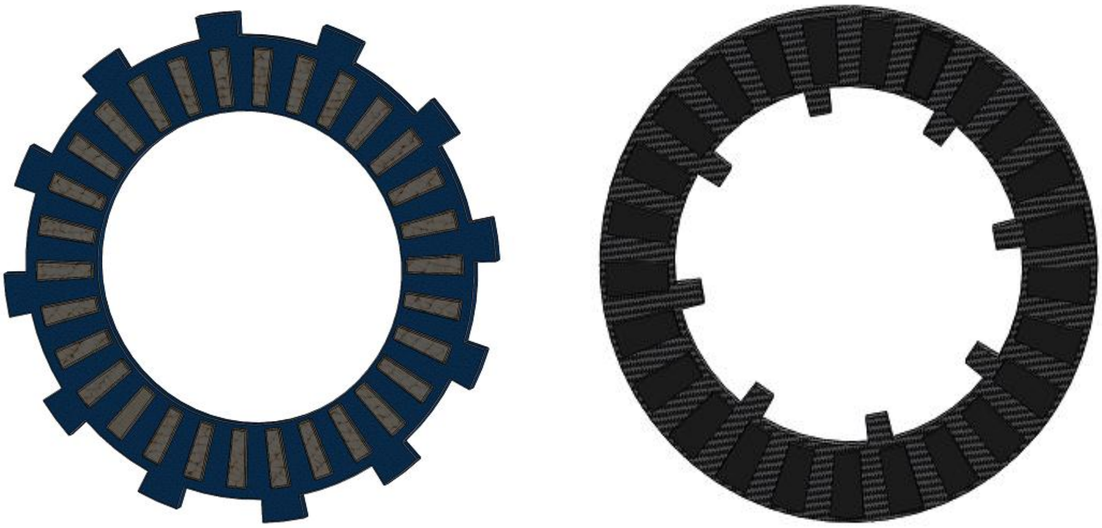
Figure14: 3D model of Multi-Plate clutch

3.4 Finite element Analysis of clutch plate

3.4.1 Static analysis

The multi plate clutch has modeled in Solid Work software and imported in ANSYS Workbench 16. The static analysis has been carried out for Aluminum alloy, Gray Cast Iron and E-Glass. Epoxy friction material clutch plate. The results of using both friction materials have been compared based on the total deformation of the friction plate.

Frictions plates often have a groove pattern to help wipe fluid away, dissipate heat, eliminate clutch noise, and change friction qualities during apply and release. A smooth plate is the coolest and slowest to apply; the waffle plate will apply the fastest, but it will have less heat removed by the oil.



(a) (b)

Figure15: a) external and, b) internal splines; 3D model of Multi-plate friction plate imported from Solid-Work 2016

The maximum pressure obtained by calculations is applied on the friction plate and results are obtained in Ansys and stress and deformation values are compared for both static and dynamic analysis of internal and external MPC materials.

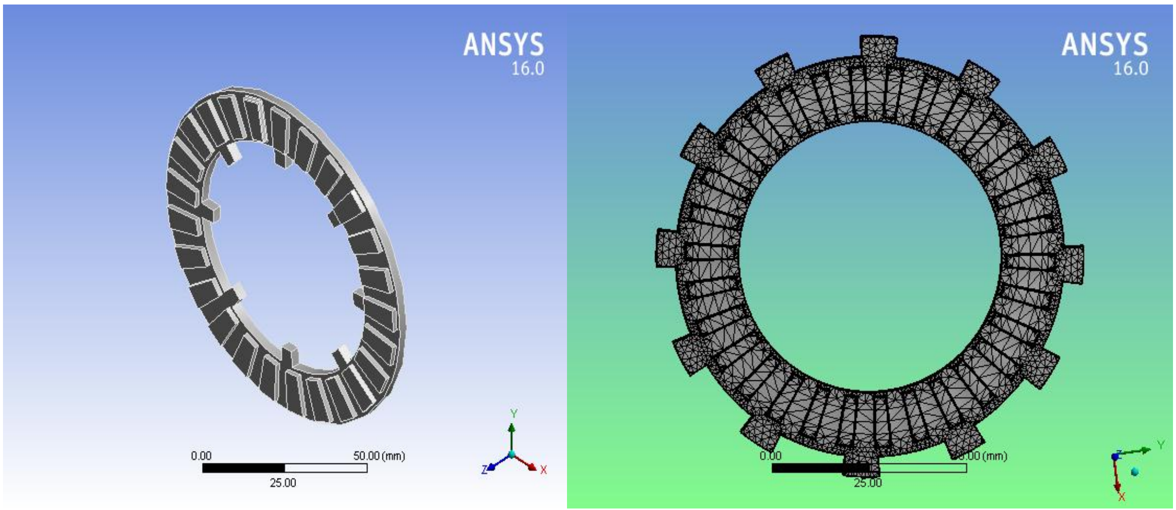
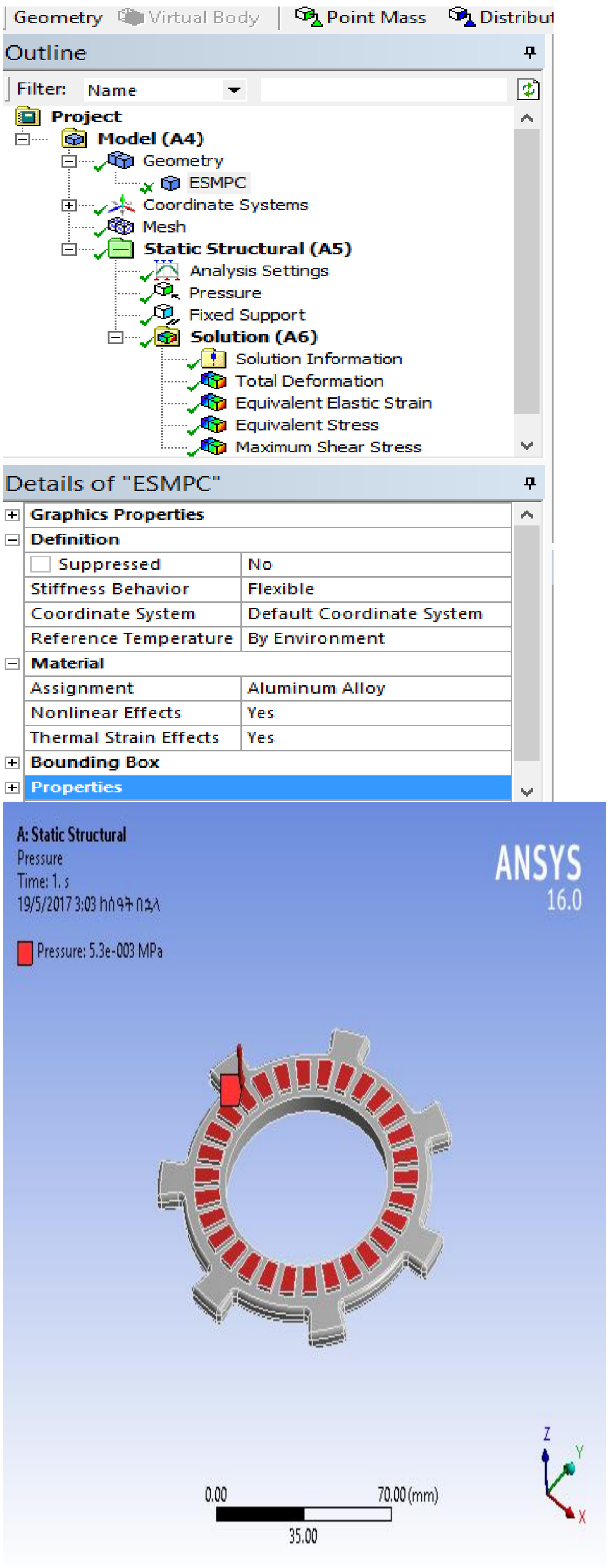


Figure 16: Export and Meshed model;

By considering Aluminum alloy as a friction material for external splines MPC



Boundary conditions

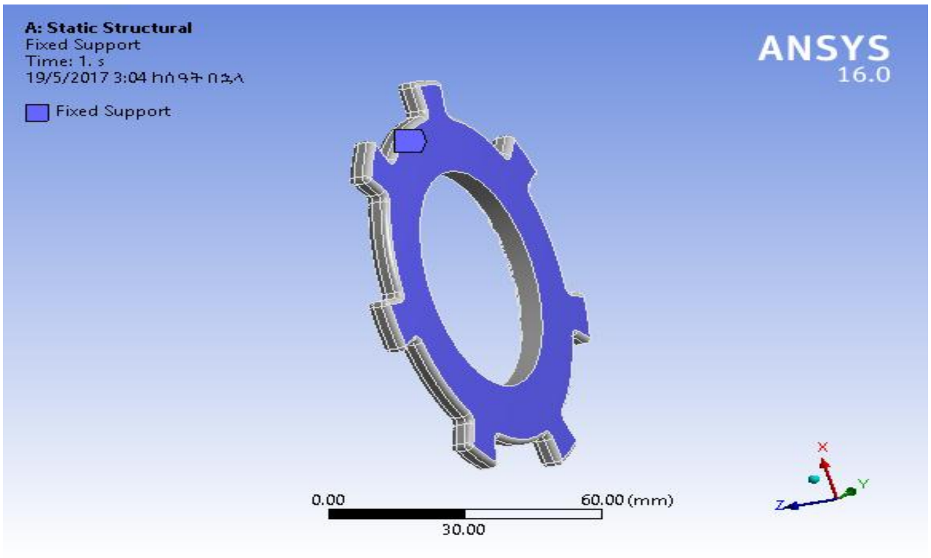
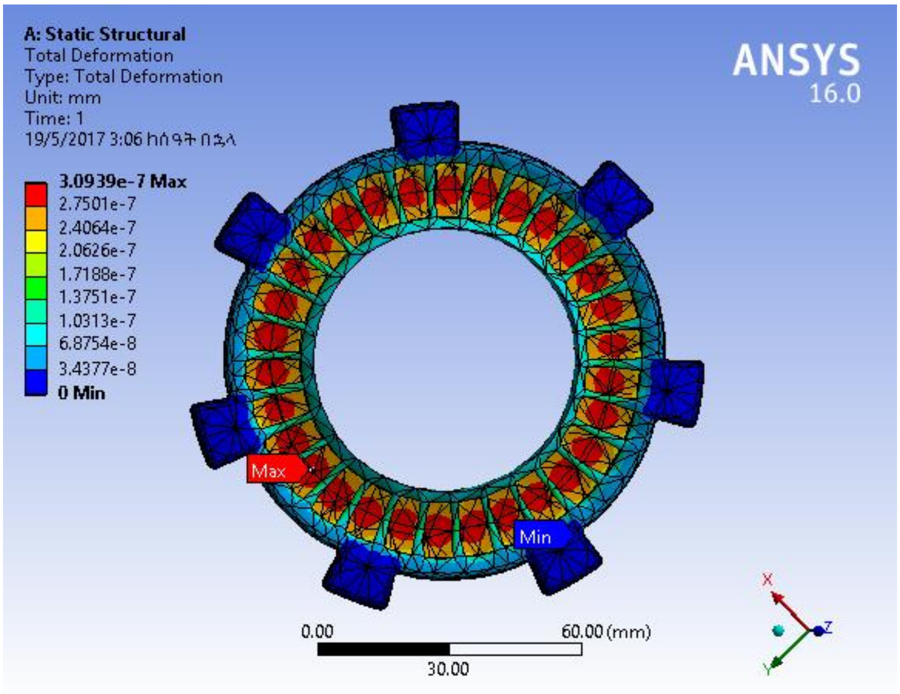
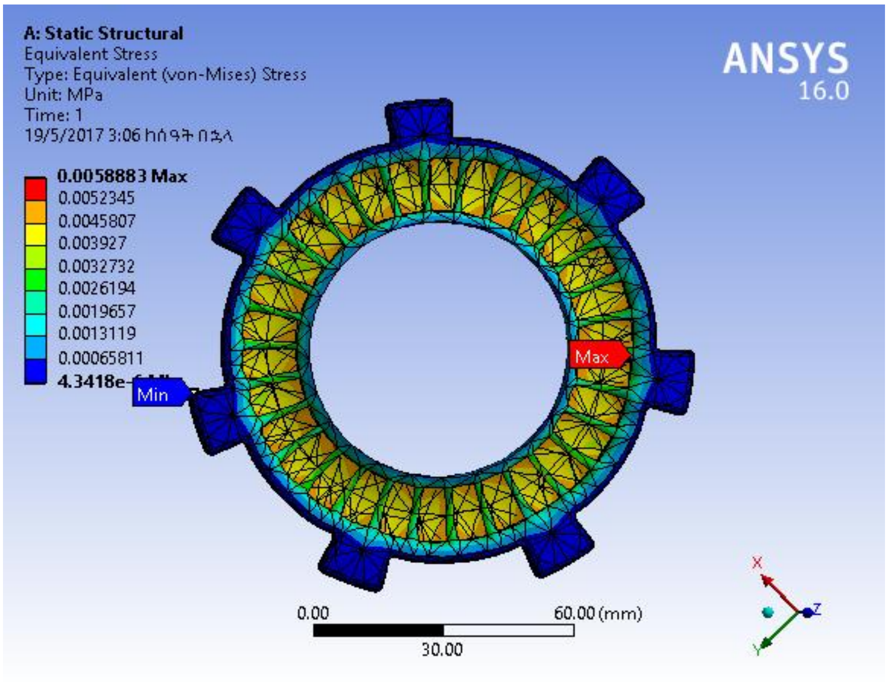


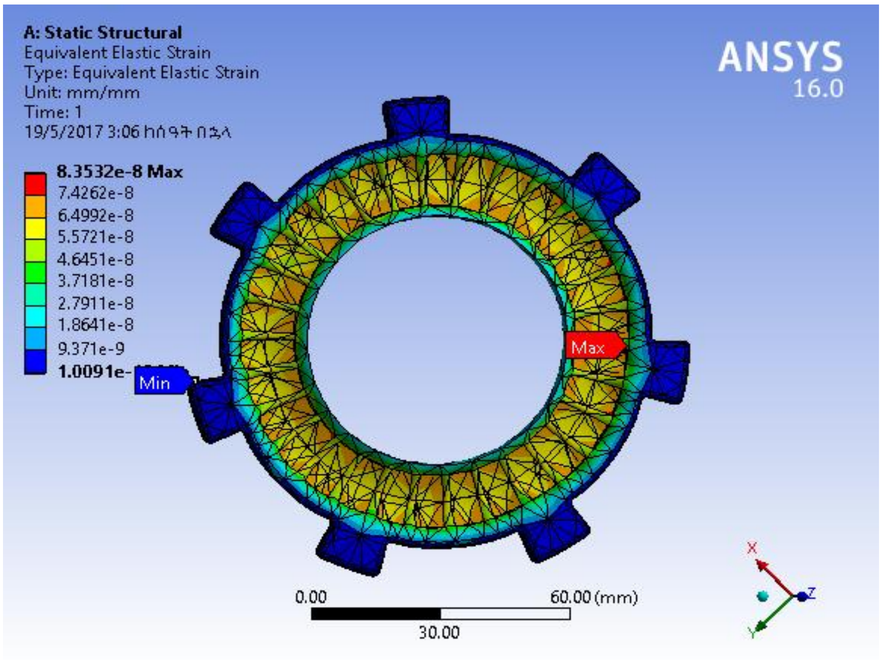
Figure17: load and boundary conditions



(a)



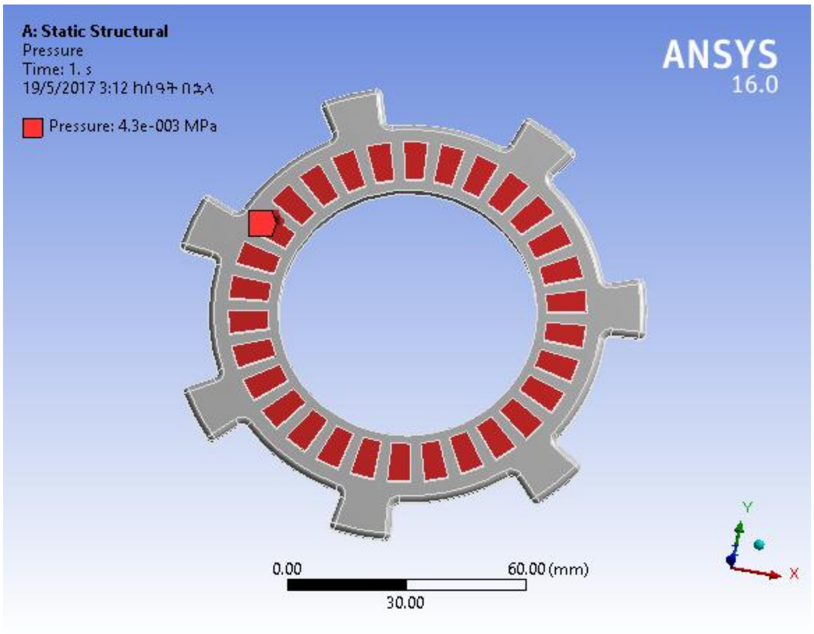
(b)



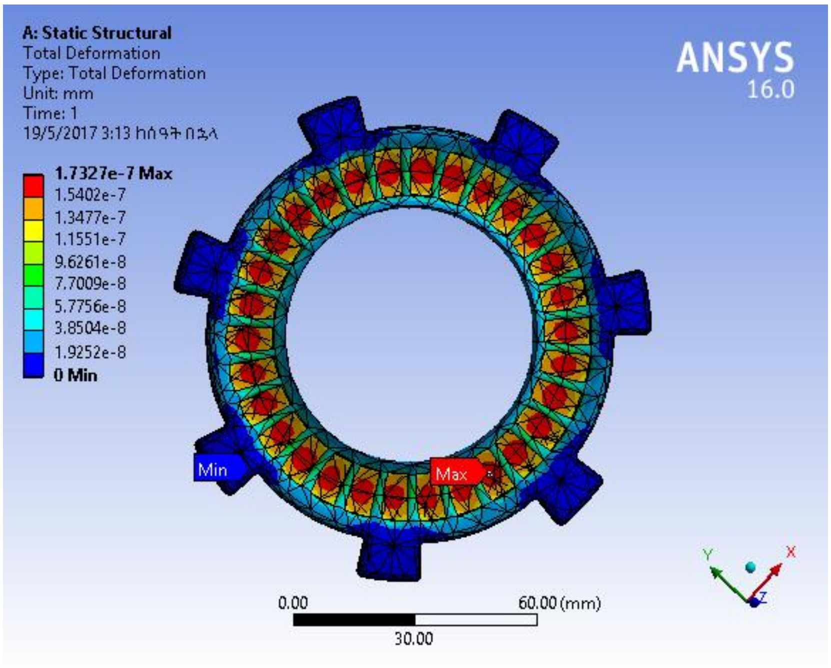
(c)

Figure 18: (a) Total deformation; (b) Equivalent Stress; (c) Equivalent strain

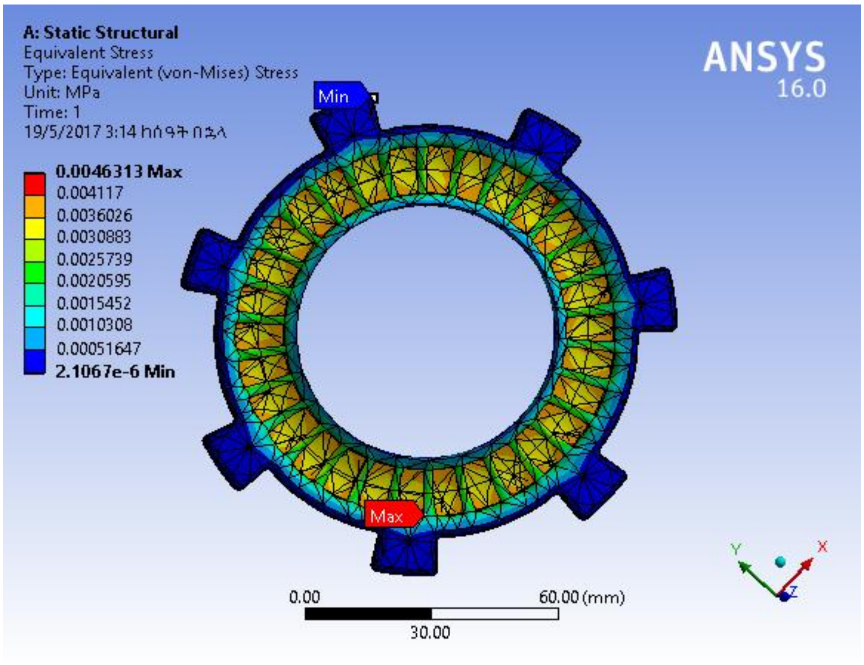
By considering Gray Cast Iron as friction material for external splines MPC


A: Static Structural
Pressure
Time: 1. s
19/5/2017 3:12
Pressure: 4.3e-003 MPa
ANSYS
16.0
0.00
60.00 (mm)
30.00
Y
X

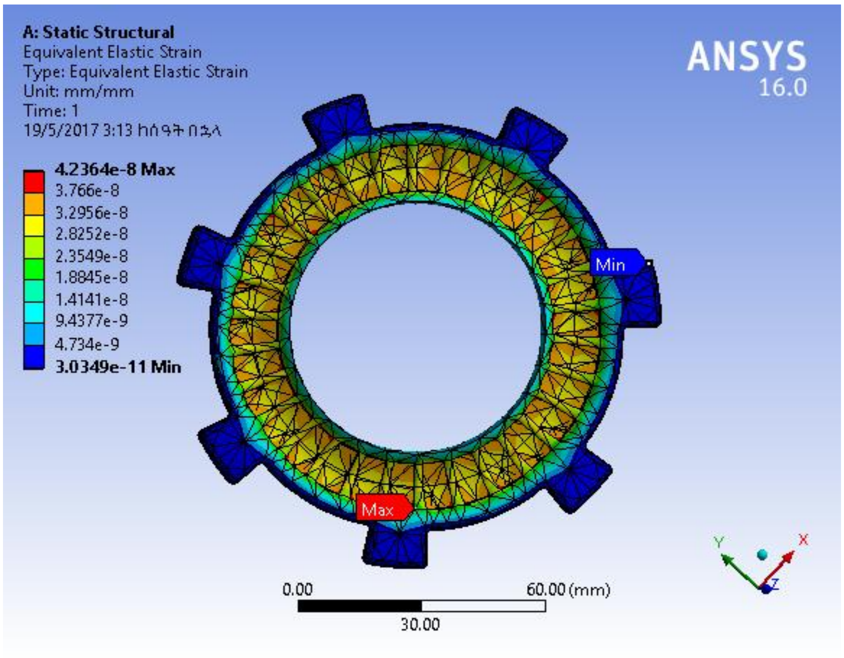
(a)


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
19/5/2017 3:13
1.7327e-7 Max
1.5402e-7
1.3477e-7
1.1551e-7
9.6261e-8
7.7009e-8
5.7756e-8
3.8504e-8
1.9252e-8
0 Min
ANSYS
16.0
Min
Max
0.00
60.00 (mm)
30.00
Y
X
Z

(b)



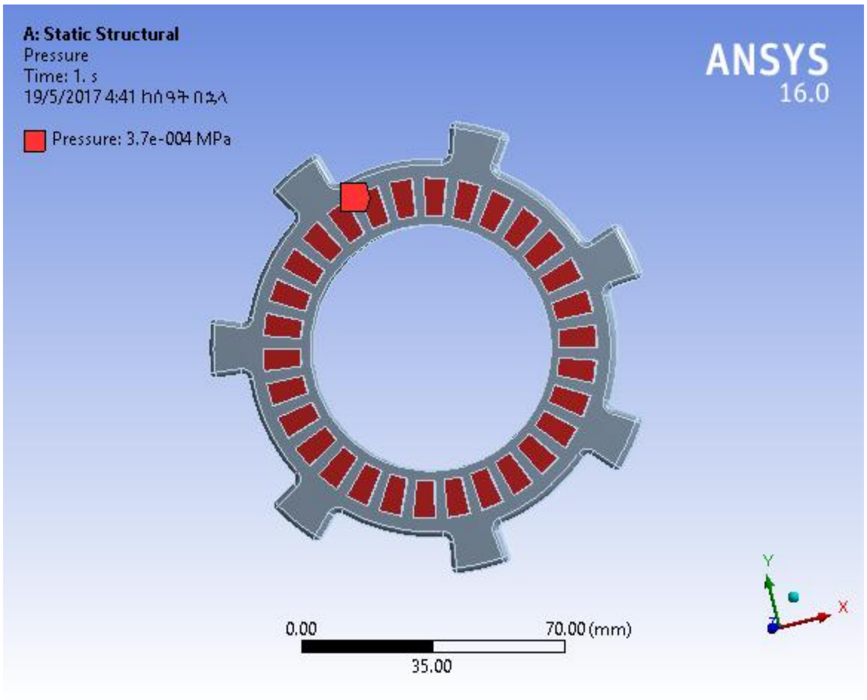
(c)



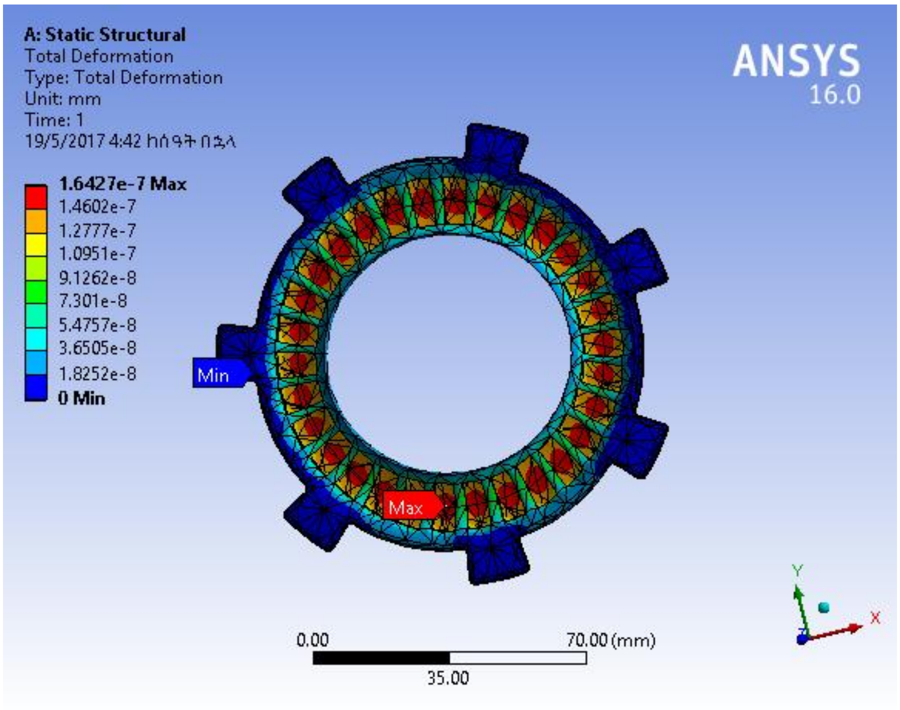
(d)

Figure 19: (a) applied maximum pressure; (b) total deformation; (c) Equivalent stress; (d) Equivalent strain

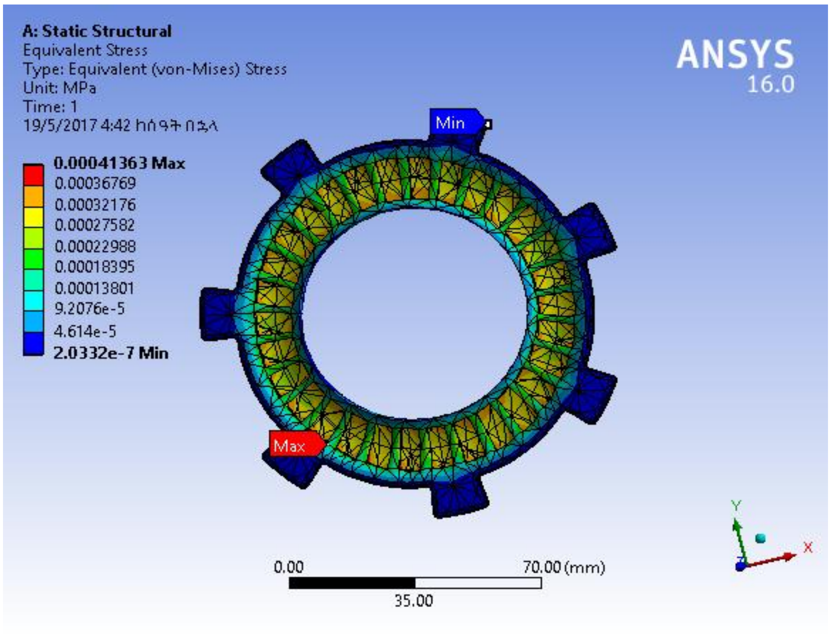
By considering E-Glass Epoxy as friction material for external splines MPC


A: Static Structural
Pressure
Time: 1. s
19/5/2017 4:41 ከሰዓት በኋላ
Pressure: 3.7e-004 MPa
ANSYS
16.0
0.00
70.00 (mm)
35.00
Y
X

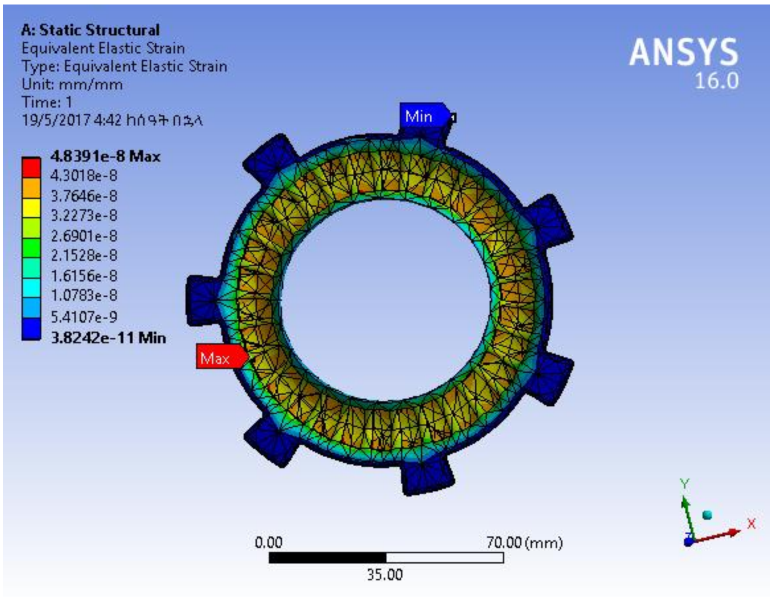
(a)


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
19/5/2017 4:42 ከሰዓት በኋላ
1.6427e-7 Max
1.4602e-7
1.2777e-7
1.0951e-7
9.1262e-8
7.301e-8
5.4757e-8
3.6505e-8
1.8252e-8
0 Min
Min
Max
ANSYS
16.0
0.00
70.00 (mm)
35.00
Y
X

(b)



(c)



(d)

Figure 20: (a) applied maximum pressure; (b) total deformation; (c) Equivalent stress; (d) Equivalent strain

The same case the dynamic analysis is done as shown on appendixes of page.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Results

In this chapter the deformation and stress characteristic for the MPCs has been investigated, the structural and model are computed are computed for dimensional radius ratio (R) and also for thickness (t). This analysis is done using ANSYS/ workbench 16. Fig.8 shows the mode shapes for internal and external splines of disc clutch for dimensional radius ratio (R) as 0.875mm.

After analysis external and external splines MPCs results have been tabulated below:

Table 10: External spline FEA /ANSYS result (static)

Selected materials	Total deformation (mm)	Equivalent elastic strain (mm/mm)	Equivalent Stress (MPa)
Aluminum alloy	$3.0939 * 10^{-7}$	$8.3532 * 10^{-8}$	0.00588
E-glass Epoxy UD	$1.6427 * 10^{-7}$	$4.8391 * 10^{-8}$	0.00041
Gray Cast Iron	$1.7327 * 10^{-7}$	$4.2364 * 10^{-8}$	0.00463

Table 11: internal spline FEA/ANSYS result (static)

Selected materials	Total deformation (mm)	Equivalent elastic strain (mm/mm)	Equivalent Stress (Mpa)
Aluminum alloy	$2.5666 * 10^{-7}$	$1.0531 * 10^{-7}$	0.007434
E-glass Epoxy UD	$1.3025 * 10^{-7}$	$5.6872 * 10^{-8}$	0.000525
Gray Cast Iron	$1.363 * 10^{-7}$	$5.142 * 10^{-8}$	0.005623

Table 12: internal spline FEA/ANSYS result (Dynamic)

Selected materials	Total deformation (mm)	Equivalent elastic strain (mm/mm)	Equivalent Stress (MPa)
Aluminum alloy	$5.94 * 10^{-5}$	$2.633 * 10^{-6}$	0.18659
E-glass Epoxy UD	$3.22 * 10^{-5}$	$1.717 * 10^{-6}$	0.01658
Gray Cast Iron	$3.21 * 10^{-5}$	$1.408 * 10^{-6}$	0.15456

Table 13: External spline FEA/ANSYS result (Dynamic)

Selected materials	Total deformation (mm)	Equivalent elastic strain (mm/mm)	Equivalent Stress (MPa)
Aluminum alloy	$3.0433 * 10^{-5}$	$7.0744 * 10^{-7}$	0.0487
E-glass Epoxy UD	$1.6118 * 10^{-5}$	$4.9203 * 10^{-7}$	0.0049
Gray Cast Iron	$1.6702 * 10^{-5}$	$4.0124 * 10^{-7}$	0.0432

4.2 Discussions

4.2.1 Static, Dynamic and Thermal Analysis

As tabulated results shown in table 10,11 12,and 13 the Total deformation for Aluminum Alloy external spline MPC is 3.0939e-7mm; that of E-glass Epoxy UD is 1.6427e-7mm and that of Gray Cast Iron is 1.7327e-7mm. And from table 10, the Total deformation for Aluminum Alloy internal spline MPC is 2.5666e-7mm; that of E-glass Epoxy UD is 1.3025e-7mm and that of Gray Cast Iron is 1.363e-7mm through ANSYS Simulation Workbench 16.

Equivalent Strain for Aluminum alloy is 8.3532e-8mm/mm; that of epoxy is 4.8391e-8 mm/mm and that of Gray Cast Iron is 4.2364e-8mm/mm through ANSYS Simulation Workbench 16.

Equivalent stress for Epoxy material is 0.00041MPa which is very less as compared to Aluminum alloy of 0.00588MPa; and that of Gray Cast Iron is 0.00463MPa through ANSYS Simulation Workbench 16, and the values obtained for the same through analytical calculations are 0.1 N/mm^2 for Aluminum alloy; 0.09 N/mm^2 for Epoxy, and 0.11 N/mm^2 for Gray Cast Iron.

Also observed that; the total deformation, equivalent strain, equivalent stress for clutch plate with E-Glass Epoxy as a friction material is less than that of Aluminum alloy and Gray Cast Iron. For same input torque stress developed in clutch plate with friction material of E-Glass Epoxy is less compared to Cast Iron and aluminum alloy. Hence it is concluded that the clutch plate with friction material E-Glass Epoxy UD gives better performance than Gray Cast Iron and Aluminum alloy.

In multi plate clutch, friction plate plays very important role in torque transmission from engine to transmission system. So the friction material property is very important in clutch design. From the above tables, it is clear that E-glass Epoxy UD material is a better friction material than Gray Cast Iron and aluminum alloy. It is also observed that total deformation, equivalent stress and equivalent strain of E-glass Epoxy UD material are in the permissible range for the ideal friction material compared to the theoretical calculations.

E-glass Epoxy UD has the low total deformation when compared to the existing conventional Gray Cast Iron friction material. Hence, it is concluded that E-glass Epoxy UD serves as a better friction material than Gray Cast Iron, and aluminum alloy and gives better clutch performance.

Another best performance of E-glass Epoxy UD friction material is its lower weight. The objective of this thesis is using materials having lower weight and better in torque transfer. As shown in table of properties of material, the density of E-glass Epoxy UD is lower than that of Aluminum alloy, and Gray Cast Iron. Since the density is the ratio of mass to it volume (ρ= m/v), and increase in mass is proportional to the density. So, Gray Cast Iron has more weight than aluminum alloy, and E-Glass Epoxy with the lowest weight of materials. This shows that E-glass Epoxy UD is the lowest in weight than that of existing commercial clutch materials mostly Gray Cast Iron.

Table 14: Results from thermal analysis

Material	Heat Flux (W/m^2)	Temperature distribution (^oc)
Aluminum Alloy 6061	0.769	247.03
Gray Cast Iron	0.82	250.05
E-Glass Epoxy UD	0.535	268.94

Table 15: Results from modal analysis

Material	Frequency in (Hrtz)
Aluminum Alloy 6061	0.231
Gray Cast Iron	0.257
E-Glass Epoxy UD	0.251

As shown in tables 14 and 15 Thermal and Modal analysis is done on the wet friction plates to verify the strength. Friction materials used are Aluminum Alloy 6061, E-Glass Epoxy, and Gray Cast Iron. By observing the analysis results, design is safe. Total Deformation and stress, Strain values are less for E-Glass Epoxy material. Cast Iron material is having capability to with stand high frequency up to 0.257 Htz.

Temperature Distribution and Heat flux values which is moderate than Aluminum Alloy and Epoxy Material. So, usage of Gray Cast Iron as surface lining is better than the other two materials. Hence, if we conclude that for multi plate clutches using E-Glass Epoxy as friction material Strength is Improved, Deformation is reduced and Material Life of the Clutch is improved. To improve Performance of clutch Lubricant Oil is maintained and servicing of Automobile is done in Perfect Time.

4.2.1 Wear Analysis Result

The different parameter can be selected to calculate objective functions as calculated under the title of wear analysis.

1. First the numbers of friction surfaces are chosen for 1, 2, 3, 4 and 5 for the same value of pressure intensity and coefficient of friction and generate the graph between the friction surfaces and the objective function
2. Second generate the graph for different values of coefficient of friction and pressure intensity and number of friction surfaces will remain same and calculate the objective function.
3. Third generate the graph for different values of pressure intensity and number of friction surfaces and the coefficient of friction will remain same and calculate the objective function.

Table 16: By varying the value of number of friction surfaces (n)

Friction surfaces (n)	Torque
1	82.62
2	165.2
3	247.9
4	330.5
5	413.1

Table 17: By varying the value of coefficient of friction.

Coefficient of friction	Torque
0.1	55.1
0.2	110.2
0.3	165.2
0.4	220.3

0.5	275.4

Table 18: By varying the value of intensity of pressure p_a

intensity of pressure	Torque
0.25	118.023
0.3	141.628
0.35	165.233
0.4	188.9
0.45	212.44

From tables 16, 17, and 18; we have seen that as the respective values of materials increases, the torque transfer also increases. And show in charts below.

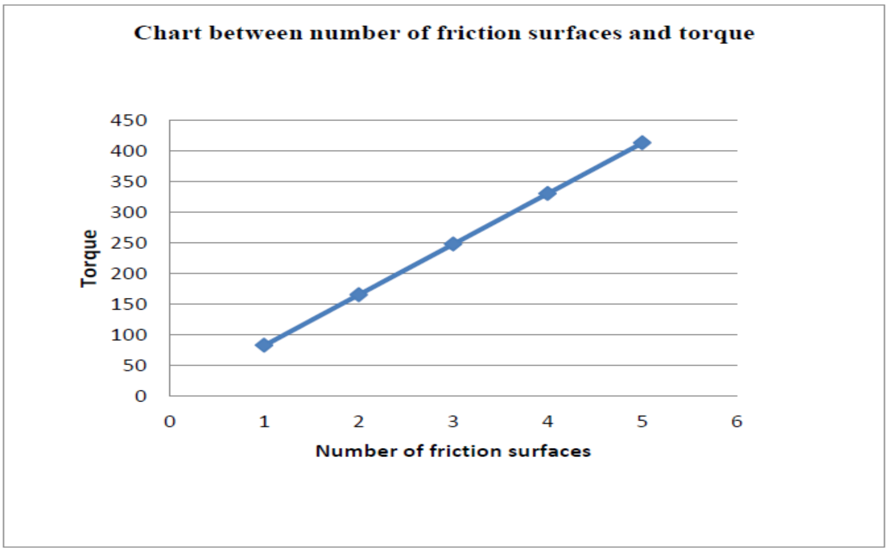


Figure 21: by varying the value of number of friction surfaces (n)

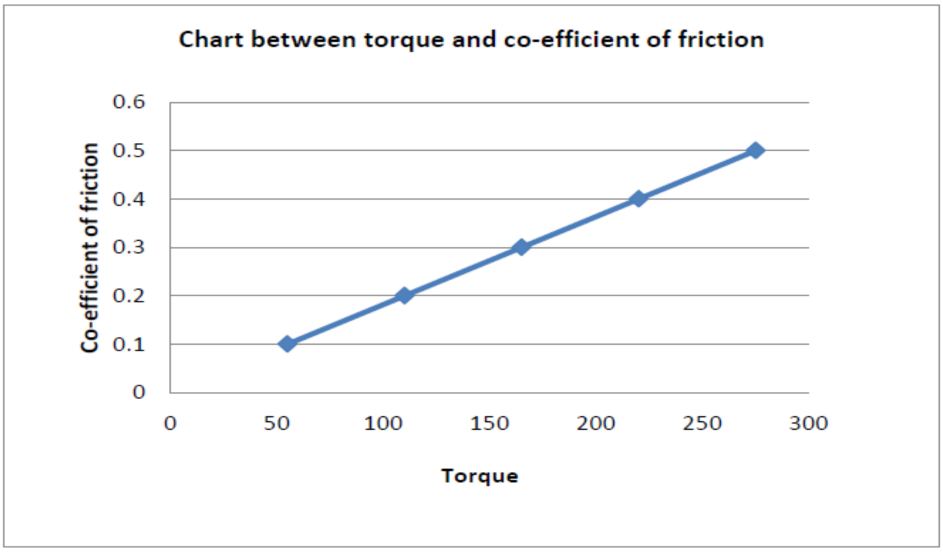


Figure 22: By varying the value of coefficient of friction

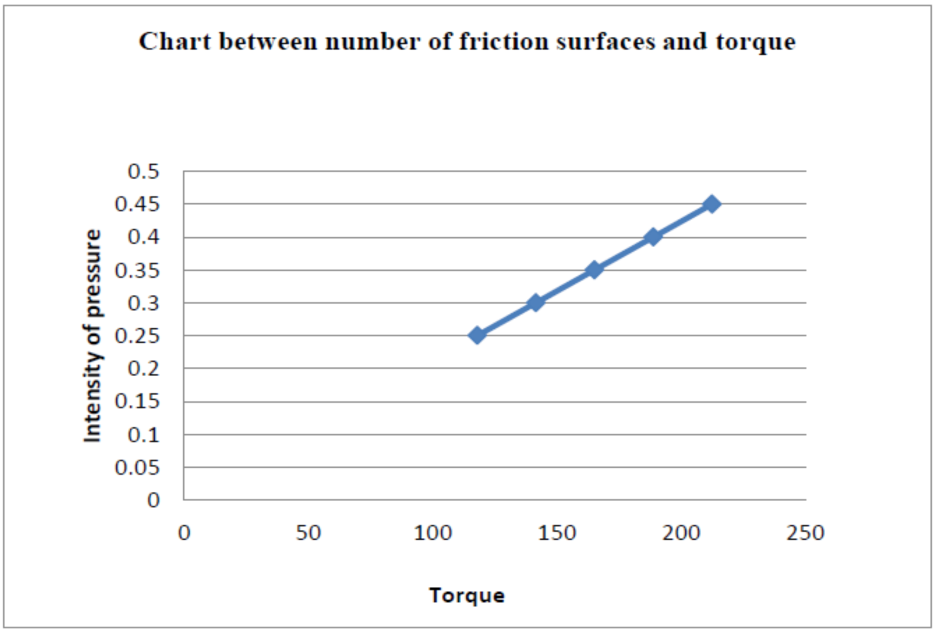


Figure 23: by varying the value of intensity of pressure

Figure 21, 22 and 23 shows that as the number of friction surfaces, intensity of pressure, and coefficient of friction increases or in case of multi plate clutches as the number of active friction faces increase the torque transfer capacity will also increases. The representative charts are shown in figures (21, 22 and 23) the advantages of these charts are that one can read the value of objective function for any specified coefficient of friction or number of friction surfaces or intensity of the pressure.

Similar charts can be prepared using the variation of the other parameters. These charts can be used for the design purpose so as to reduce the magnitude of the objective function by applying external agencies and by this method obviously we can improve the quality and life of the friction clutch disk for these above parameters. In the present work a numerical example has been solved, but this method can also be applied to any practical clutch if the information about the required data is available.

CHAPTER FIVE

CONCLUSION, RECOMMENDATIONS AND FUTURE WORK

5.1. Conclusion

There are External and Internal Multi-Plate Clutches for clutching mechanism. Both Internal and External Multi-plate Clutches are successfully modeled and mechanical property characterization is done on it using Ansys work bench. In this paper a three dimensional model of multi-plate clutches are modeled and analyzed on Solid work and ANSYS Workbench FEM softwares for analysis of lighter weight clutch materials. The plate is subjected to a manually calculated maximum pressure for each selected materials. When the maximum pressure is applied on the active faces the corresponding maximum equivalent stresses, total deformation, and equivalent strains are induced. At the same time some portion of internal face of the plate results the maximum value where some elements of the plate deforms, and this property is shown on all three material used for analysis of deformation.

From the ANSYS Workbench structural simulation and analysis in FEM is a key to facilitate the assessment of structural analysis of clutch plate which provides relatively simple method for analyzing of material strength. Besides, the analysis shows that increase in tensile yield strength of material, the maximum equivalent stress decrease and similarly the deformation rate decreases. The final result shows that E-Glass Epoxy materials have minimum deformation in their applied load and pressure conditions than other materials used, it also have high wear resistance property and lower weight than existing Gray Cast Iron, and aluminum alloy materials. Besides these, the weight of E-Glass Epoxy material is 72% lower than that of Gray Cast Iron and 26% lower than Aluminum Alloy Materials. So, this makes Epoxy Materials to be better for clutching.

5.2. Recommendation for future work

Due to lack of laboratory testing equipment and shortage of time, I haven't done the wear and Thermal analysis in detail on each clutch plates and TCT system simulations. But, for Green and light weight vehicles reduction of weight of component parts is essential. So, I recommend the next researchers to:

- ✓ Analyze wear rate and deformation of clutch plates by considering heat generated during contact and motion.
- ✓ Analyze for effective use of MPCs in TCT systems using motion simulation softwares.

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Appendix 1

FEA result

For internal splines MPCs the result would be;

Using aluminum alloy as a friction material for internal splines MPC;

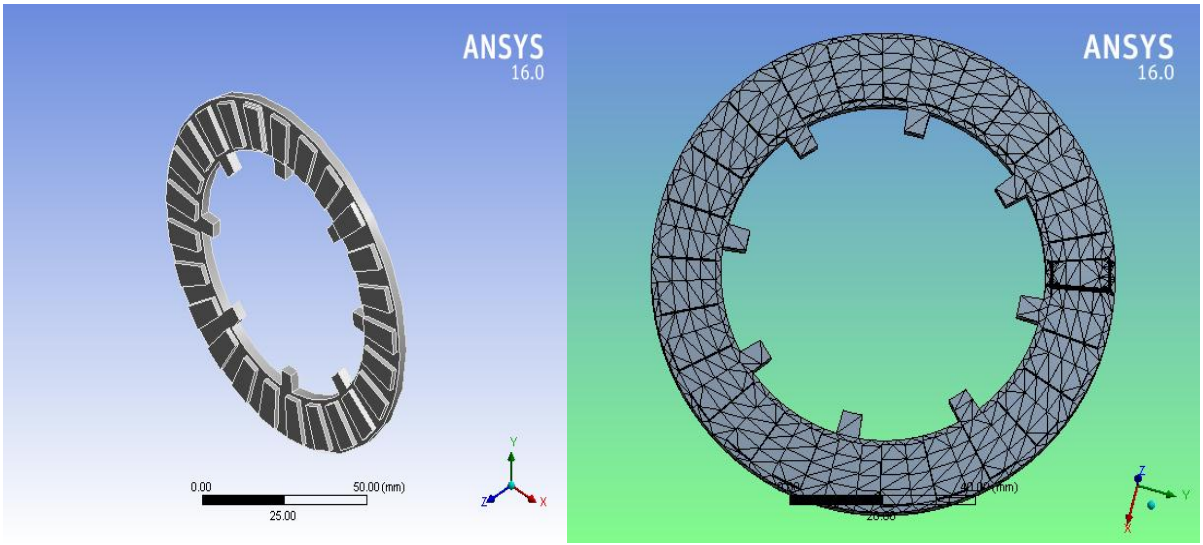
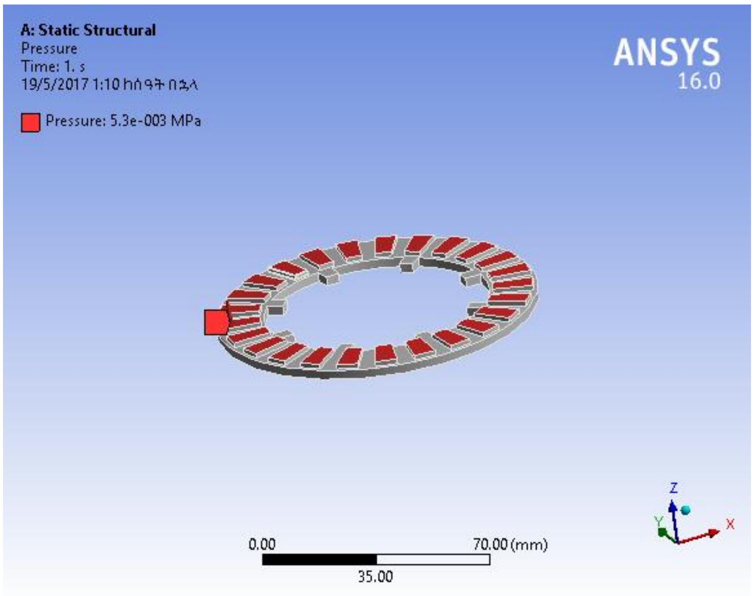


Figure 24: a) imported from Solid Work b) meshed model



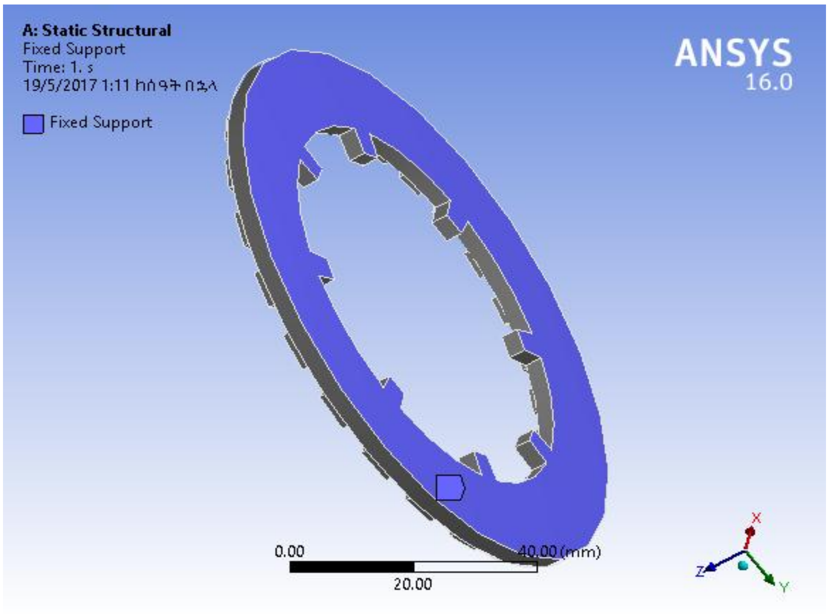
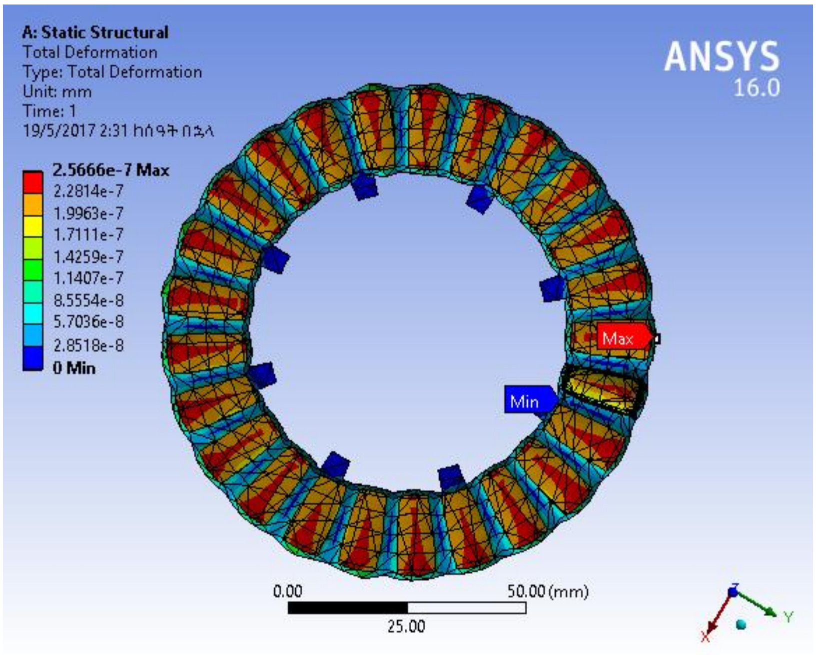
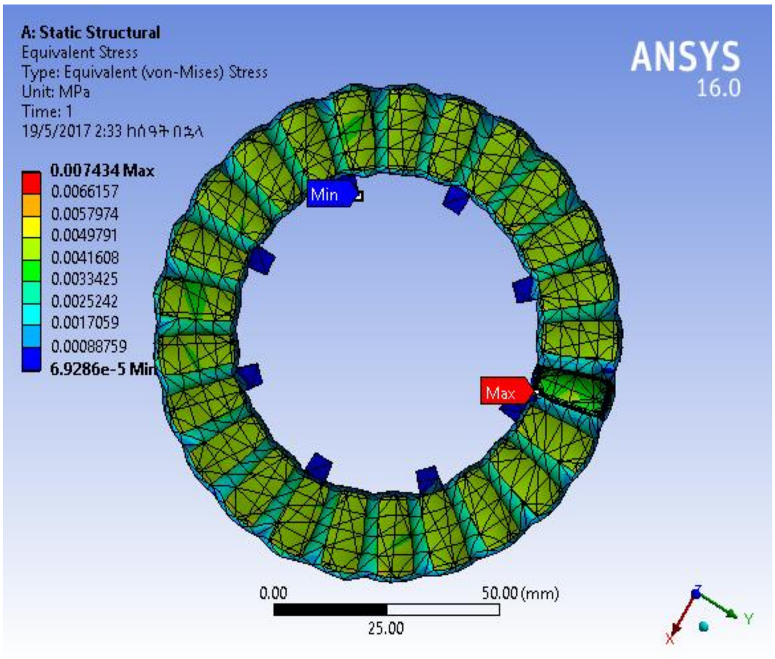


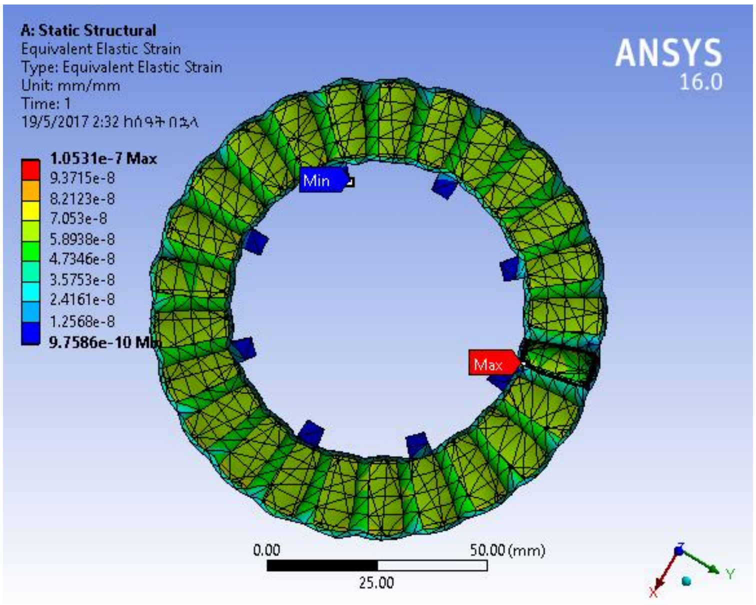
Figure25: load and boundary conditions



(a)



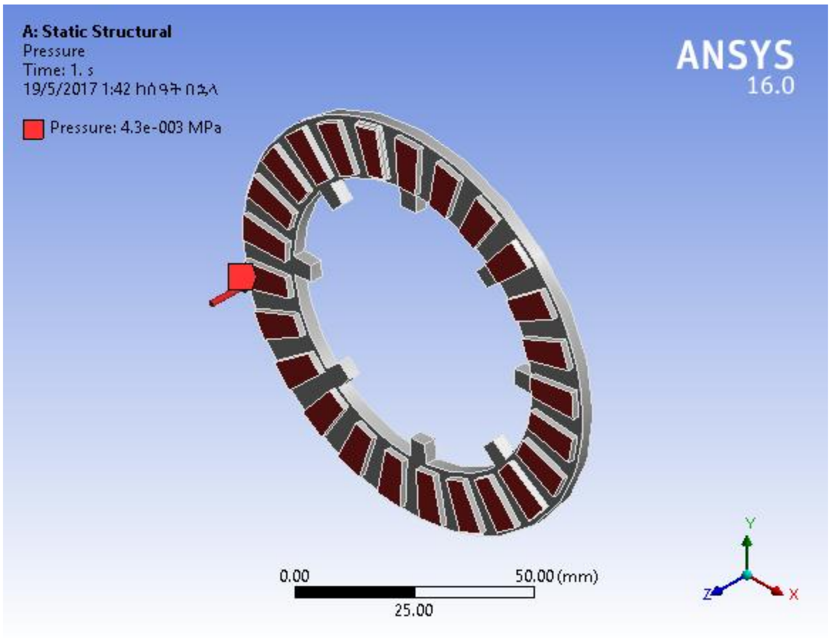
(b)



(c)

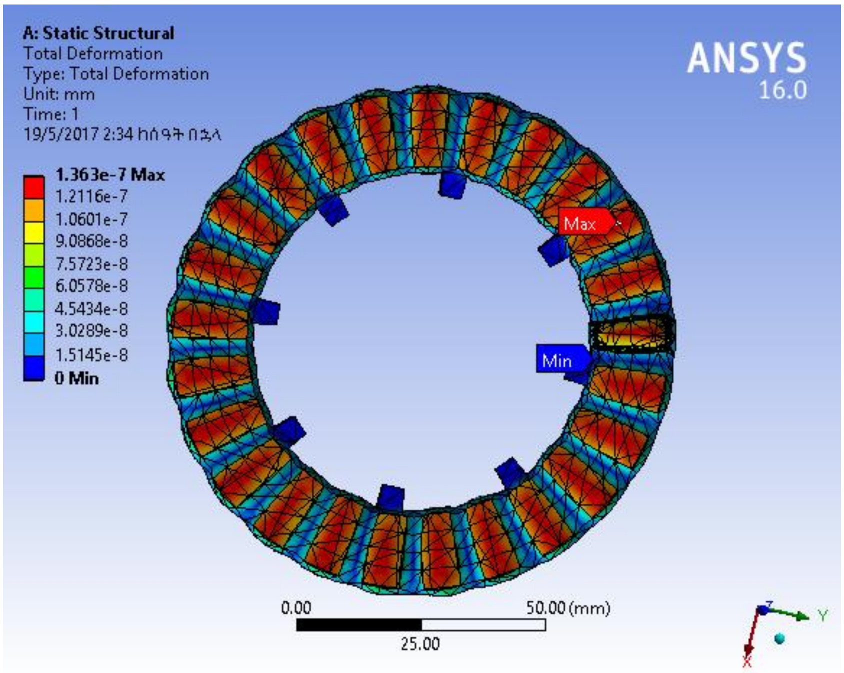
Figure26: (a) Total deformation; (b) Equivalent stress; (c) Equivalent strain

<u>And for gray cast iron using internal splines MPC</u>



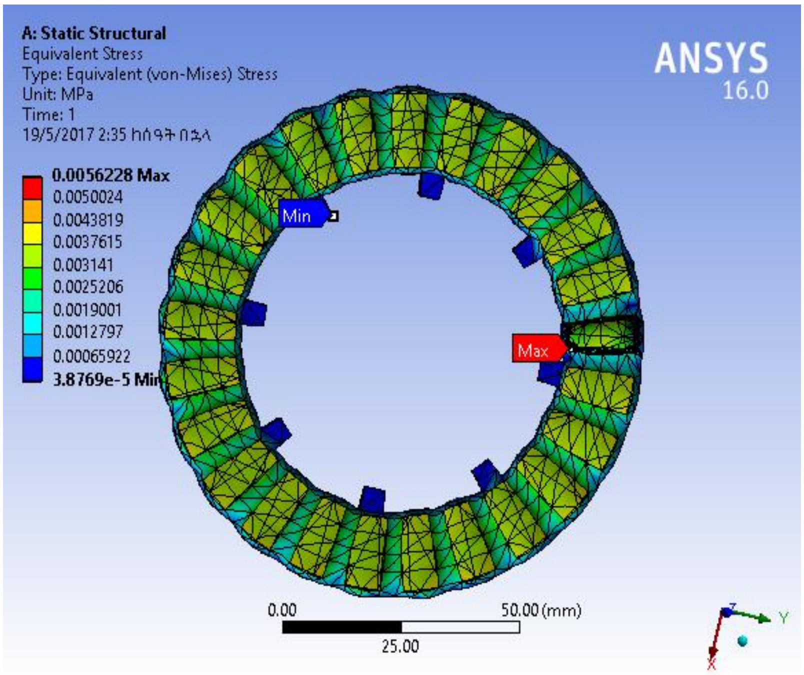
A: Static Structural
Pressure
Time: 1. s
19/5/2017 1:42 ከሰዓት በኋላ
Pressure: 4.3e-003 MPa
ANSYS
16.0
0.00
25.00
50.00 (mm)
Y
Z
X

(a)

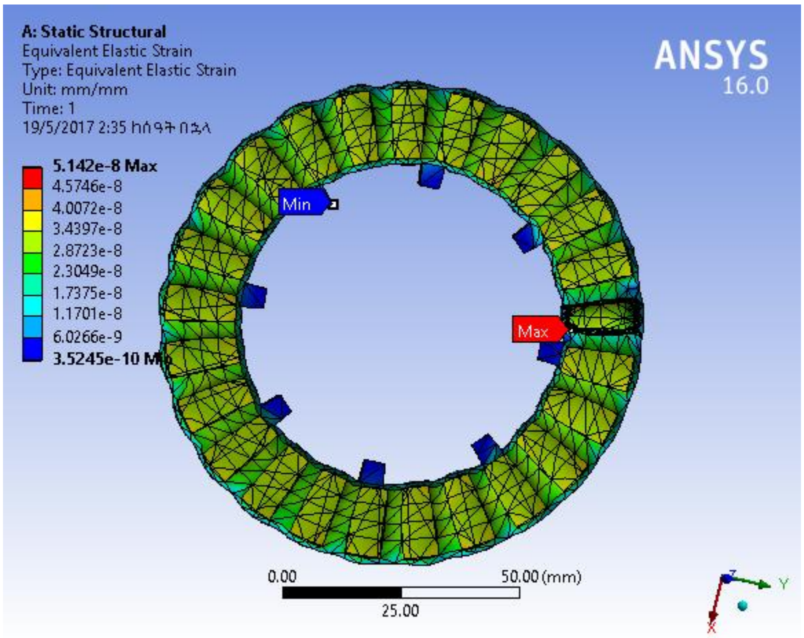


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
19/5/2017 2:34 ከሰዓት በኋላ
1.363e-7 Max
1.2116e-7
1.0601e-7
9.0868e-8
7.5723e-8
6.0578e-8
4.5434e-8
3.0289e-8
1.5145e-8
0 Min
ANSYS
16.0
Max
Min
0.00
25.00
50.00 (mm)
Y
X

(b)



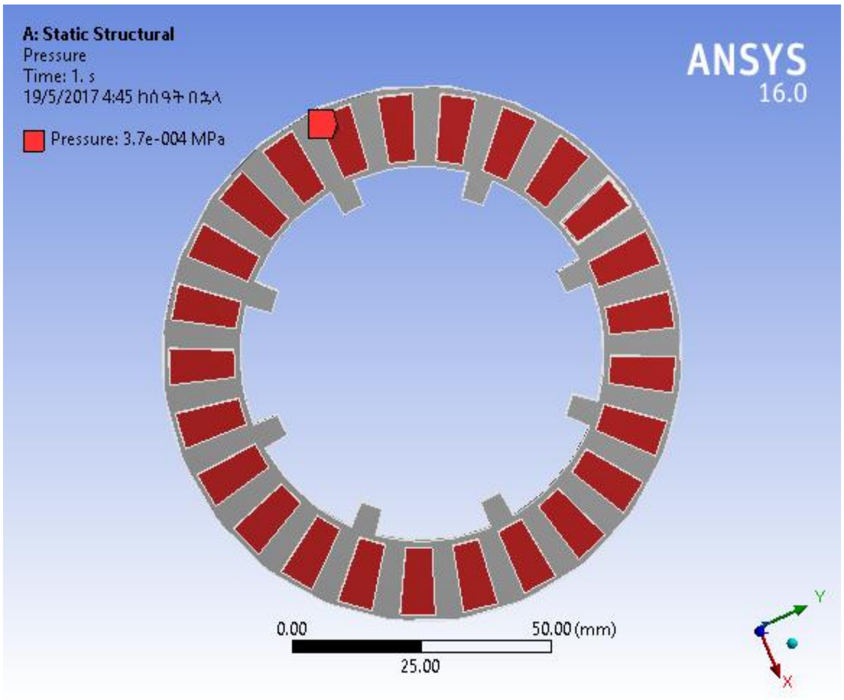
(c)



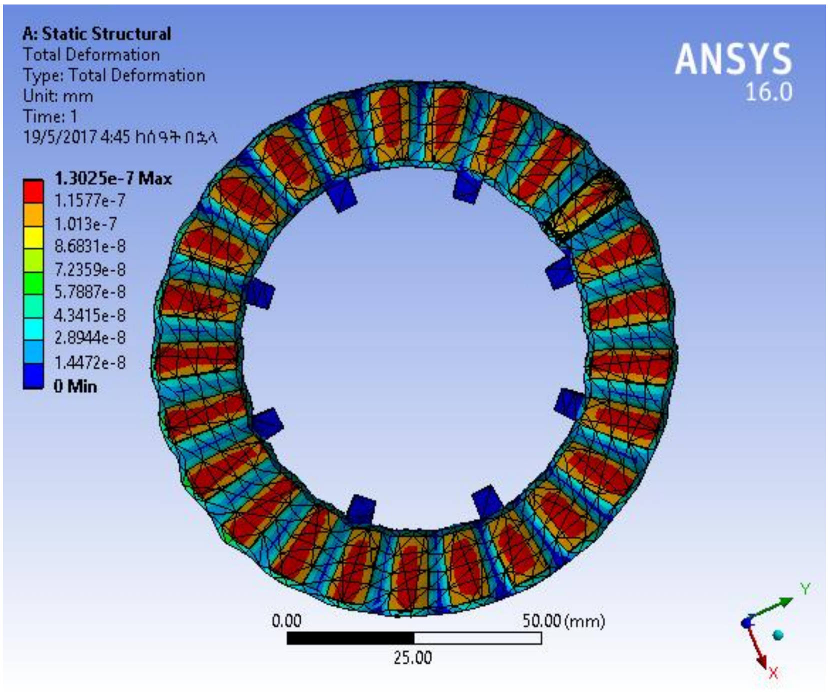
(d)

Figure27: (a) applied maximum pressure; (b) total deformation; (c) Equivalent stress; (d) Equivalent strain

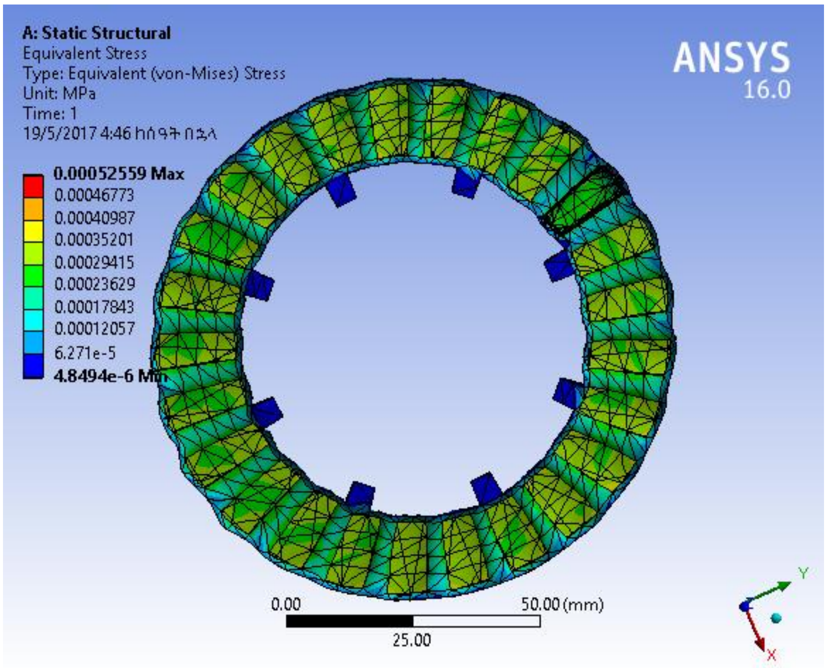
Using E-Glass Epoxy as a friction material for internal spline


A: Static Structural
Pressure
Time: 1. s
19/5/2017 4:45 ከሰዓት በኋላ
Pressure: 3.7e-004 MPa
ANSYS
16.0
0.00
25.00
50.00 (mm)
Y
X

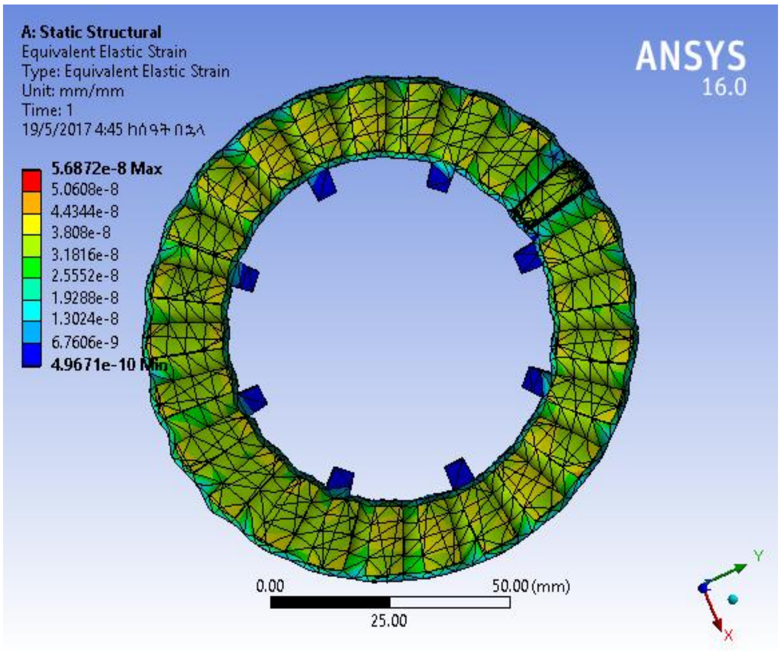
(a)


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
19/5/2017 4:45 ከሰዓት በኋላ
1.3025e-7 Max
1.1577e-7
1.013e-7
8.6831e-8
7.2359e-8
5.7887e-8
4.3415e-8
2.8944e-8
1.4472e-8
0 Min
ANSYS
16.0
0.00
25.00
50.00 (mm)
Y
X

(b)



(c)



(d)

Figure28: (a) applied maximum pressure; (b) total deformation; (c) Equivalent stress; (d) Equivalent strain

Appendix 2

Dynamic Analysis

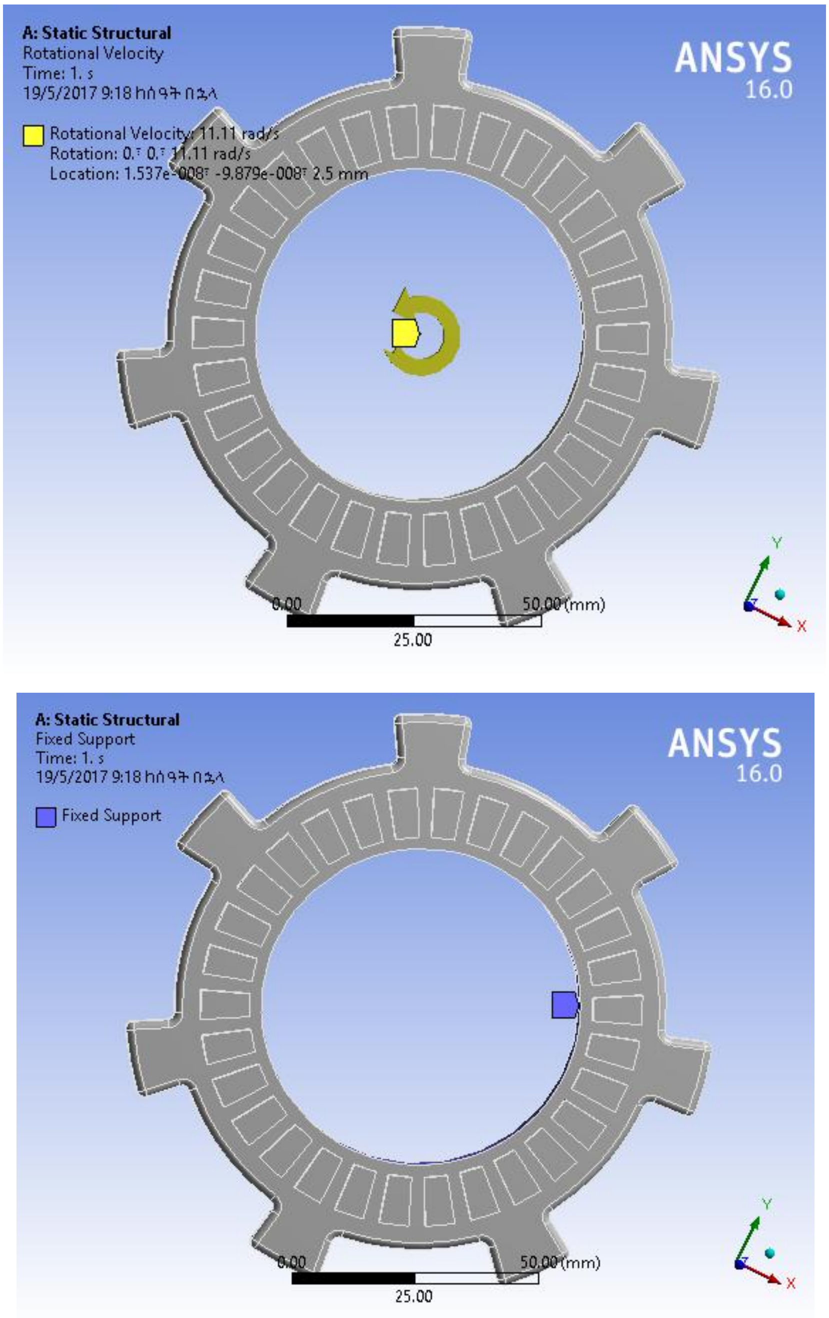
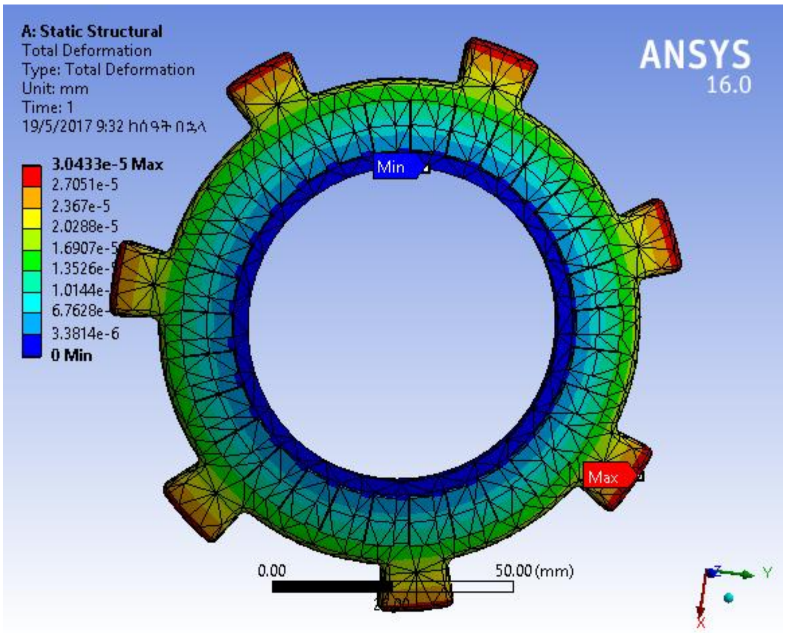
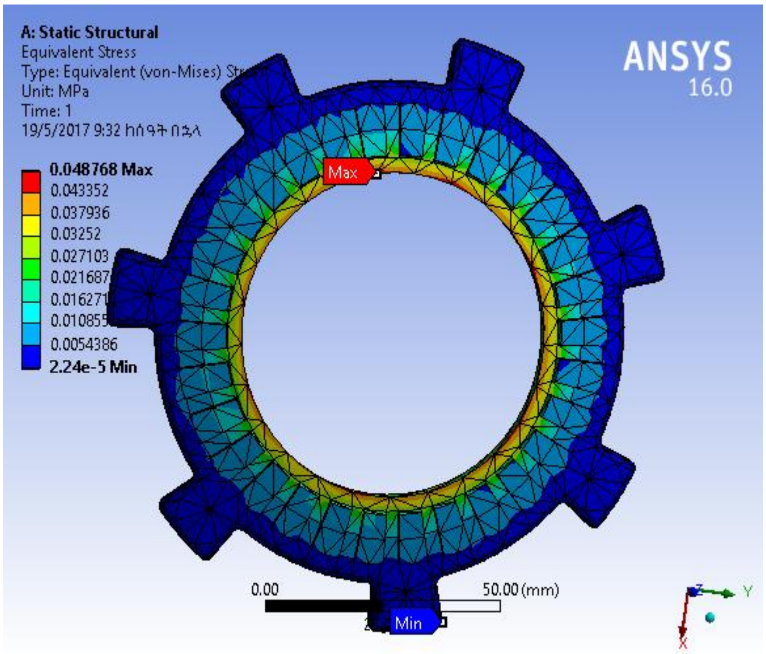


Figure29: Loads and boundary conditions

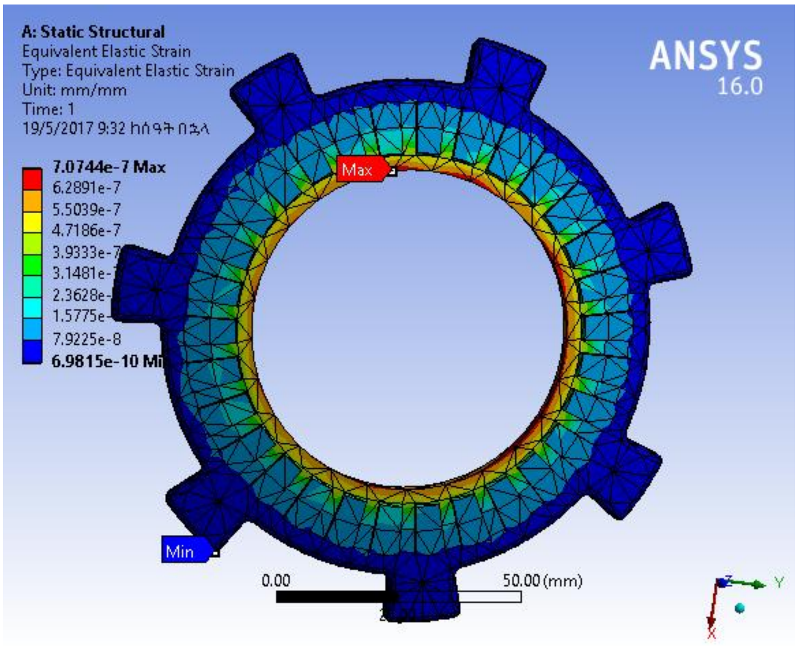
<u>By considering Aluminum alloy as a friction material for external splines MPC</u>


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
19/5/2017 9:32 ከሰዓት በኋላ
3.0433e-5 Max
2.7051e-5
2.367e-5
2.0288e-5
0 Min
Min
Max
ANSYS
16.0
0.00
50.00 (mm)

(a)


A: Static Structural
Equivalent Stress
Unit: MPa
Time: 1
19/5/2017 9:32 ከሰዓት በኋላ
0.048768 Max
0.043352
0.037936
0.03252
0.027103
0.0054386
2.24e-5 Min
Max
Min
ANSYS
16.0
0.00
50.00 (mm)

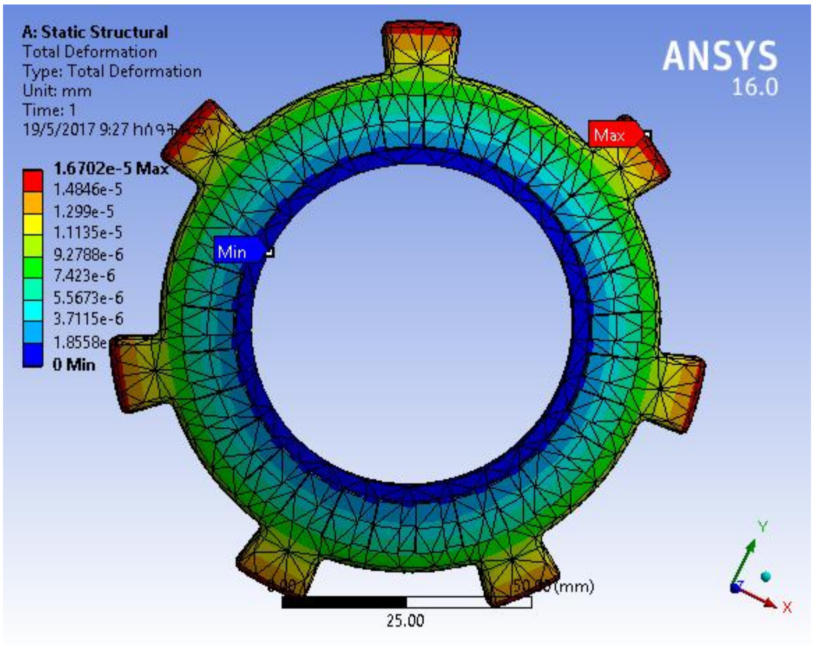
(b)



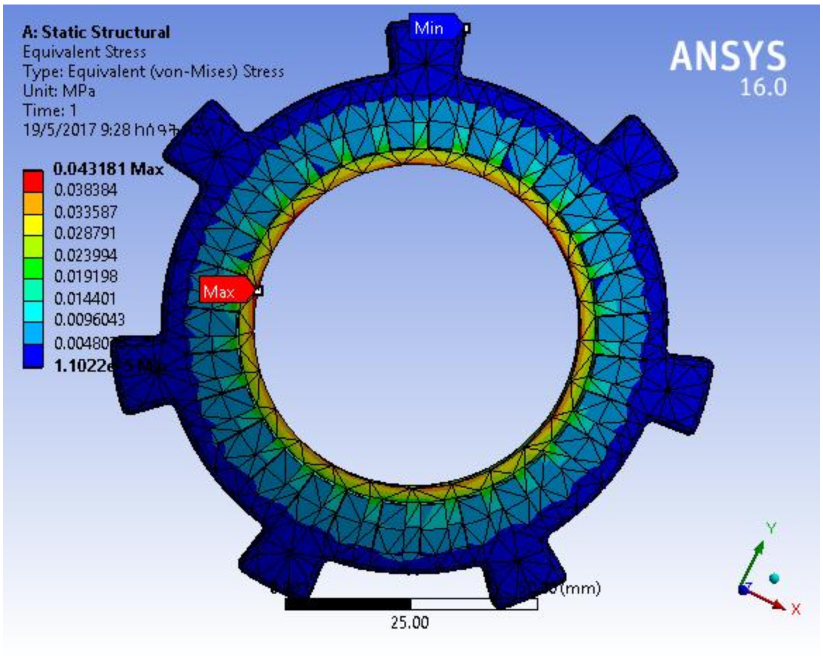
(c)

Figure30: (a) total deformation; (b) Equivalent stress; (c) Equivalent strain

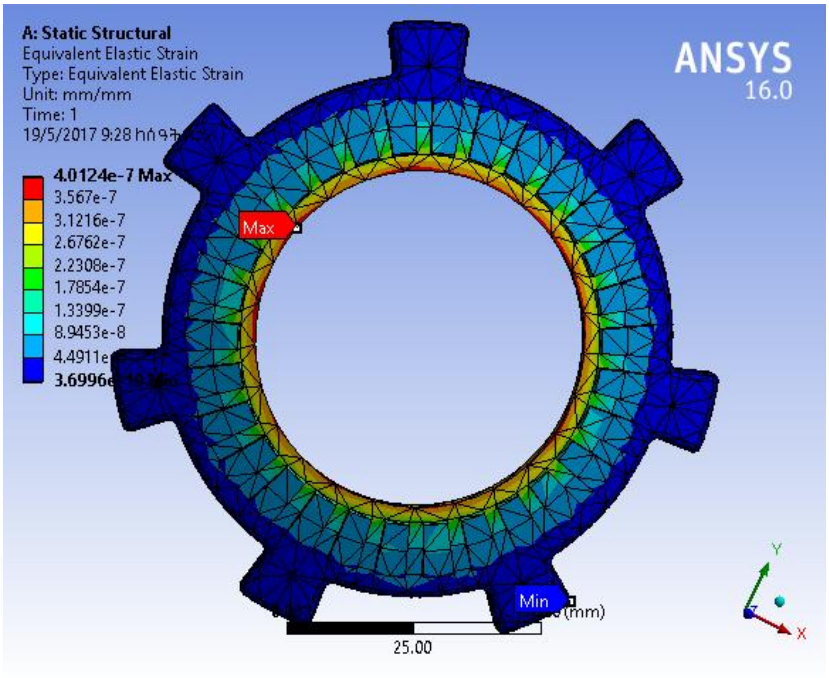
<u>By considering Gray Cast Iron as friction material for external splines MPC</u>



(a)



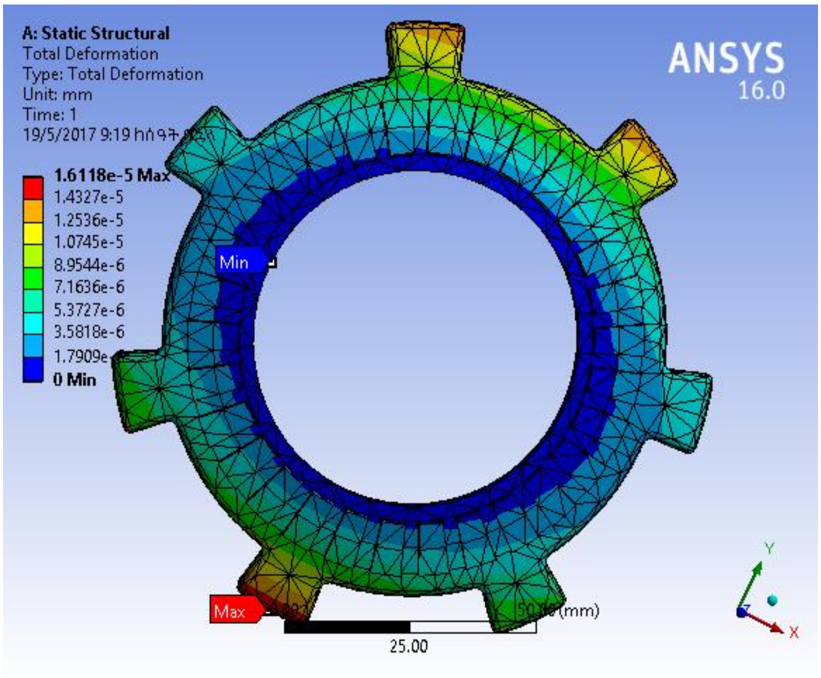
(b)



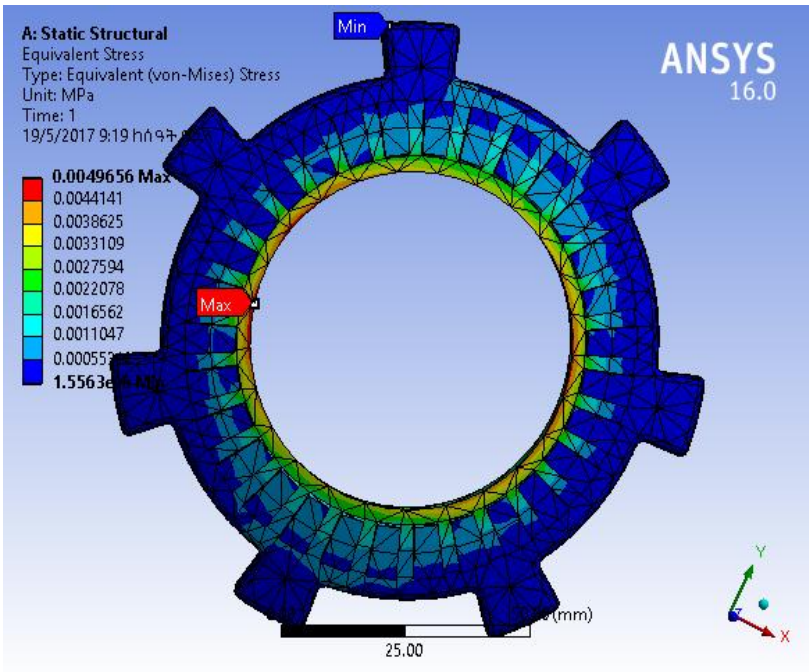
(c)

Figure 31: (a) total deformation; (b) Equivalent stress; (c) Equivalent strain

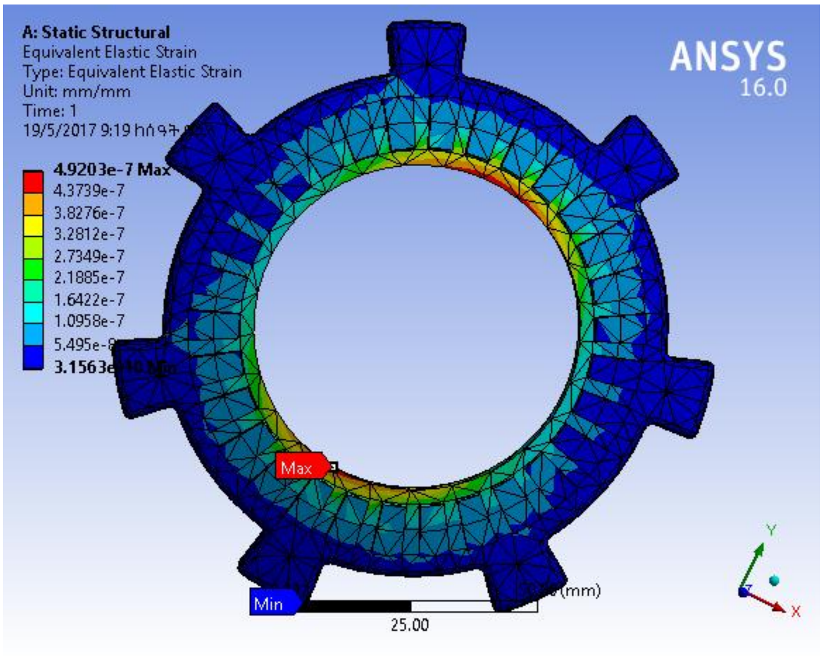
<u>By considering E-Glass Epoxy as friction material for external splines MPC</u>


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
19/5/2017 9:19
1.6118e-5 Max
1.4327e-5
1.2536e-5
1.0745e-5
8.9544e-6
7.1636e-6
5.3727e-6
3.5818e-6
0 Min
ANSYS
16.0
Min
Max
(mm)
25.00
Y
X

(a)


A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
19/5/2017 9:19
0.0049656 Max
0.0044141
0.0038625
0.0033109
0.0027594
0.0022078
0.0016562
0.0011047
ANSYS
16.0
Min
Max
(mm)
25.00
Y
X

(b)



(c)

Figure 32: (a) total deformation; (b) Equivalent stress; (c) Equivalent strain

Appendix 3

For internal splines the result would be;

Using aluminum alloy as a friction material for internal splines MPC;

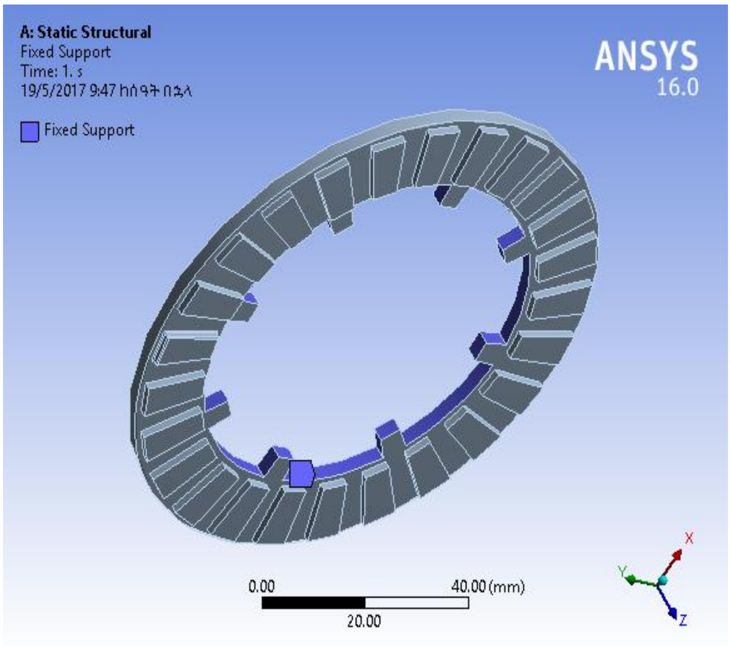
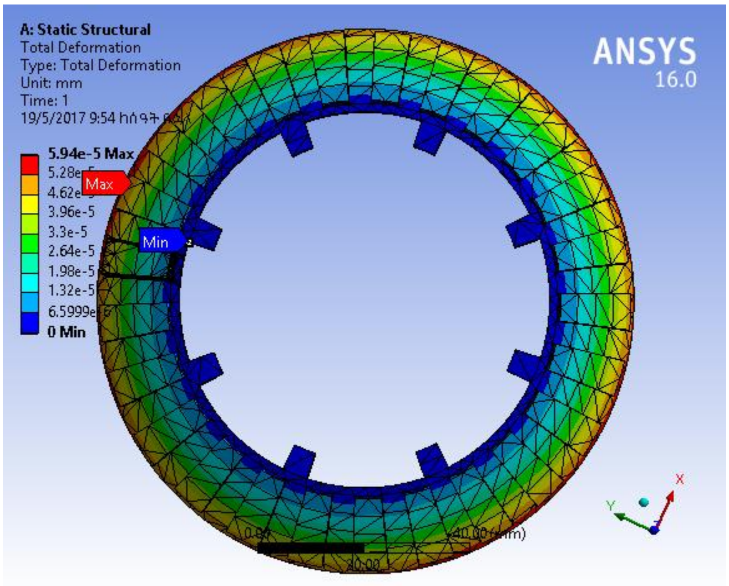
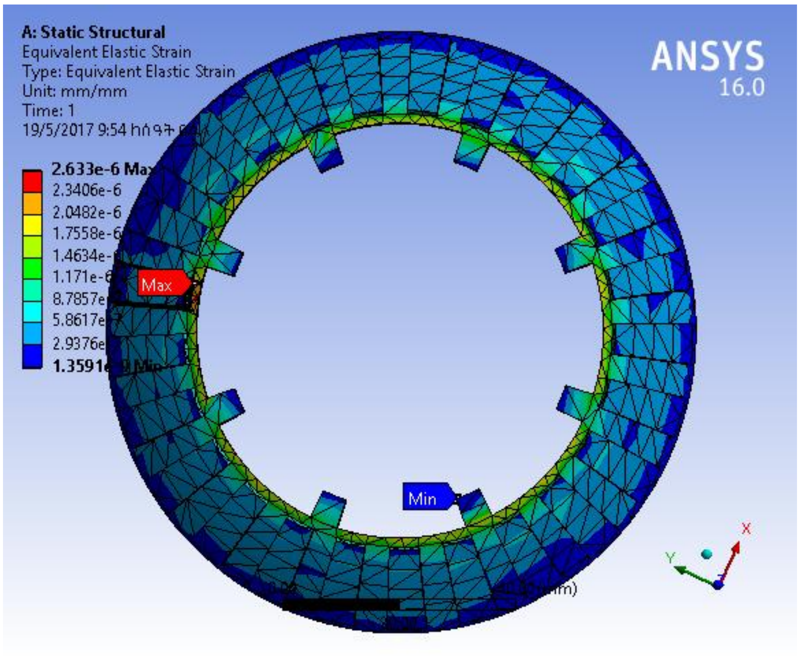


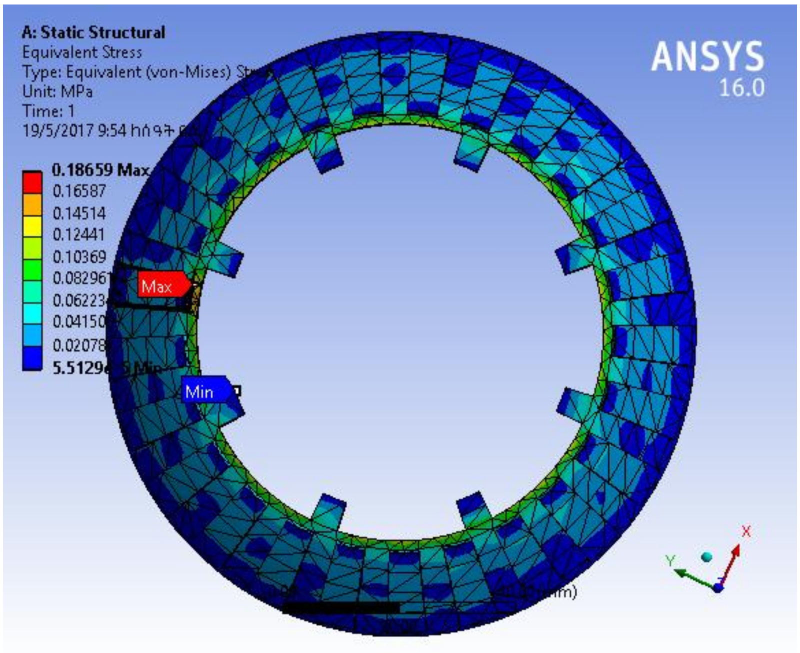
Figure33: Boundary conditions



(a)



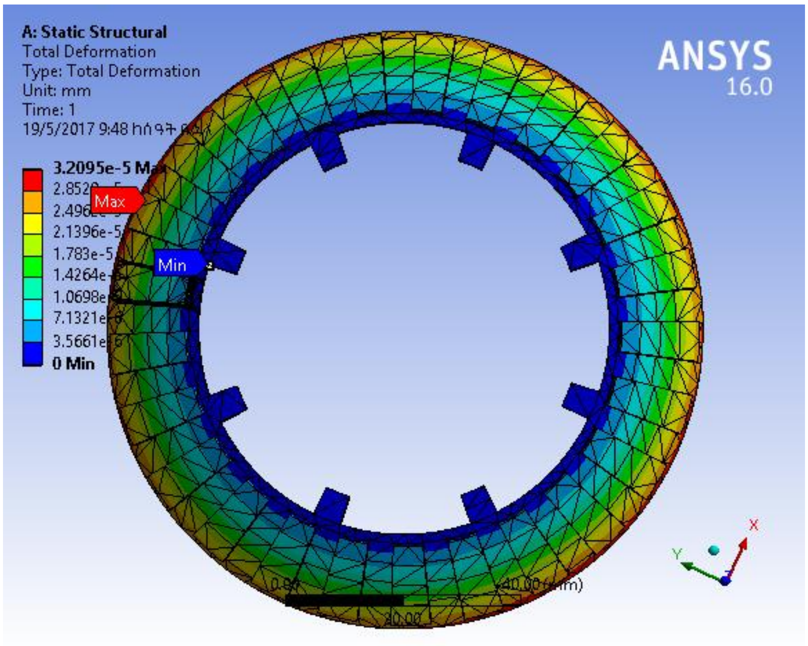
(b)



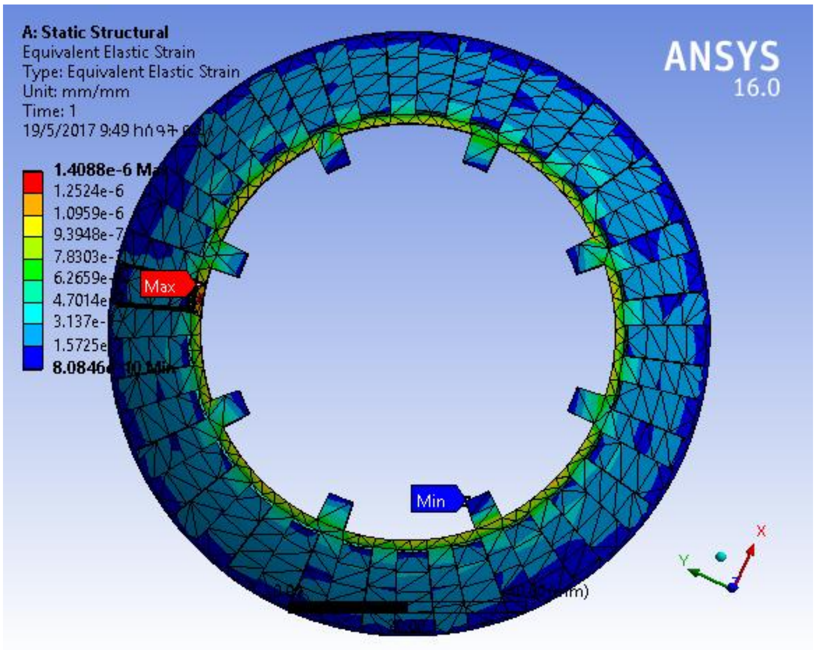
(c)

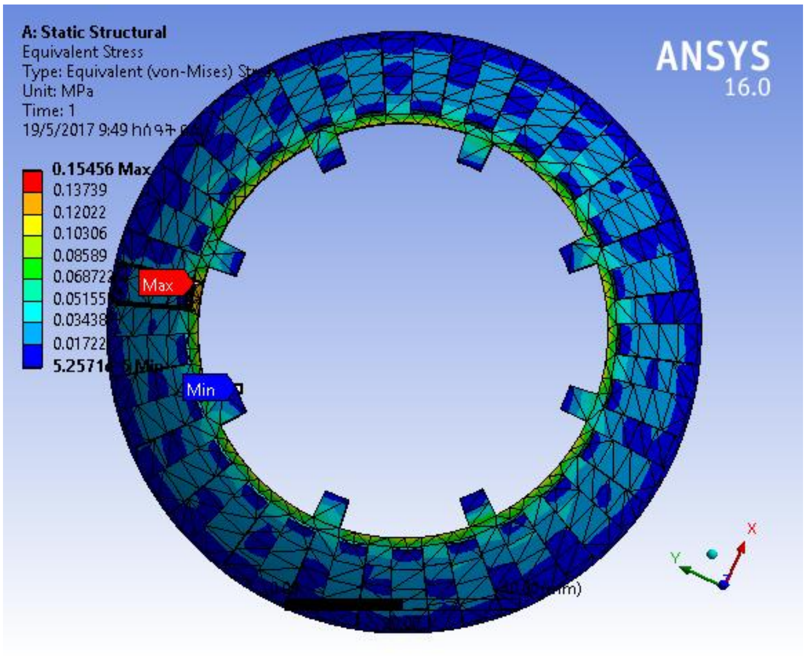
Figure34: (a) total deformation; (b) Equivalent stress; (c) Equivalent strain

<u>And for gray cast iron using internal splines MPC</u>


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
ANSYS
16.0
3.2095e-5 Max
2.1396e-5
1.783e-5
1.4264e-5
0 Min
Max
Min
0.00
40.00
20.00

(a)

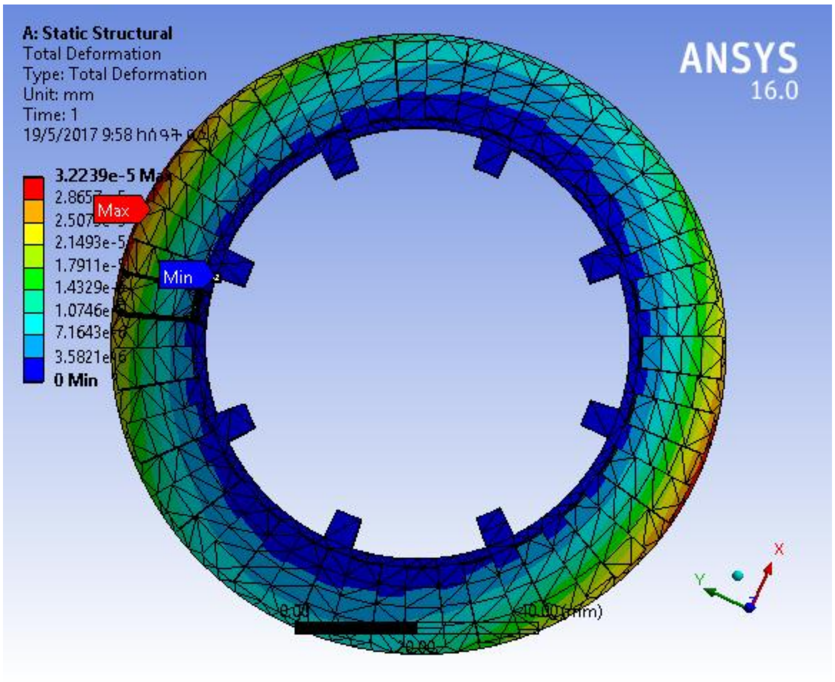

A: Static Structural
Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: mm/mm
Time: 1
ANSYS
16.0
1.4088e-6 Max
1.2524e-6
1.0959e-6
Max
Min



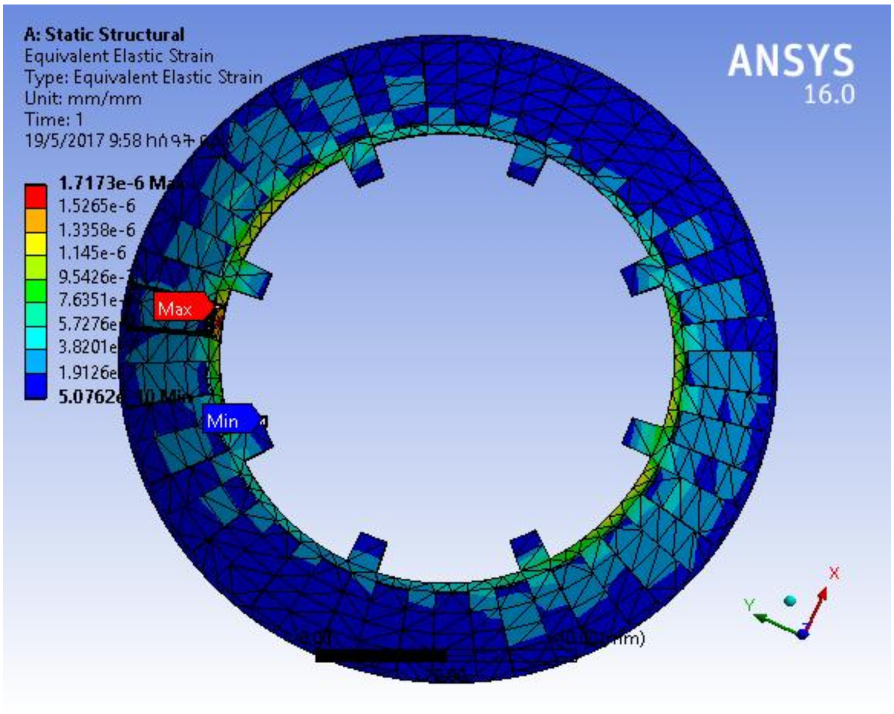
(c)

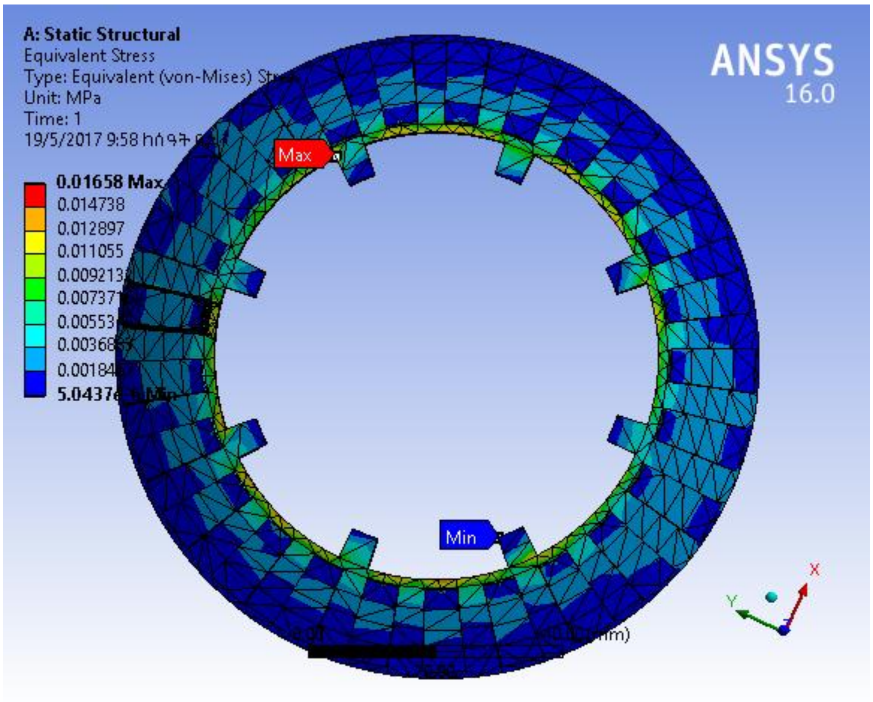
Figure 35: (a) total deformation; (b) Equivalent stress; (c) Equivalent strain

<u>Using E-Glass Epoxy as a friction material for internal spline</u>



(a)





(c)

Figure36: (a) total deformation; (b) Equivalent stress; (c) Equivalent strain