Computational Investigation of Friction Coefficient Effects on the Contact Mechanics Between Dynamic Seal and Motor Shaft in Electric Vehicles

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***Abstract*— As most countries tend to rely on green energy, electric vehicles (EVs) are increasing in usage. However, friction losses within them are major issues, which reduce their energy efficiency. E-axle, which is a drive unit consisting of an inverter, an electric motor, and a gearbox, is one component exhibiting friction losses due to the mechanical interaction of its elements. Dynamic seals are one set of such elements, which exist between electric motor and gearbox. Considering materials that have low friction coefficients to make a dynamic seal would contribute to reduce the friction losses. Such these materials are Polytetrafluoroethylene (PTFE), Polyimide (PI) and Polyetheretherketone (PEEK). It was found that PTFE exhibits the lowest friction coefficient, about 0.038. A finite element (FE) simulation using Abaqus was done to investigate the effects of the friction coefficient of the three materials on the contact mechanics between the seal and the motor shaft. The most significant findings obtained are the maximum contact pressures, which are 96.13 MPa, 244.8 MPa and 269.7 MPa for PTFE, PI, and PEEK, respectively. It can be noticed; PTFE has the lowest contact pressure due to its minimal friction coefficient as well as low Young's Modulus. Thus, PTFE is suggested to be the most suitable material for a dynamic seal inside E-axle.**

***Keywords*—electric vehicles, dynamic seals, friction coefficient, simulation**

I. INTRODUCTION

Electric vehicles (EVs) are increasing day by day due to their efficiency in energy and environment [1]. However, friction losses are major issues within them, which occur in many components, including tires, brakes, and transmission [2]. A type of transmission, called E-axle, exists in modern EVs. This component consists of an inverter, an electric motor, and a gearbox, and it accounts for about %4 of total friction losses in EVs [3]. The main cause of the friction losses is the movement of the mechanical components. One of such components that creates friction is the dynamic seal, which is a sealing element exists between two surfaces (at least one is in motion) [4]. Fig. 1 shows an example of a dynamic seal.

Fig. 1. An example of a dynamic seal [5]

The friction from dynamic seal can be limited via considering a material that has low friction coefficient. The friction coefficient of a material is the ratio of the normal force to the frictional force of the material [6], and it plays a significant role of the friction losses. With low coefficient of friction, less force is needed for sliding, which is desired in the contact mechanics between a dynamic seal and the shaft in the E-axle of EVs. A material that experiences low friction coefficient and can withstand high operating conditions is desired for a dynamic seal. Currently, Polytetrafluoroethylene (PTFE), Polyimide (PI), and Polyetheretherketone (PEEK) exhibit the lowest friction coefficients [2]. By considering the best material of a dynamic seal to decrease friction, a rise of the energy efficiency of EVs will be achieved.

A model simulation of Abaqus is chosen to create a contact between the dynamic seal and the motor shaft, considering 3 different materials, PTFE, PEEK, and PI to investigate the effect of different coefficient of friction of these materials on the contact mechanics between the dynamic seal and the motor shaft.

II. DEFINITION OF FRICTION AND THE LAWS OF DRY FRICTION

Friction is a resistive force that opposes a sliding or rotational motion of an object against another [7]. Two scholars, Amontons and Coulomb, have formulated three laws of friction in dry condition (dry means no lubrication is present in the contact region) [8], [9], [10]. The three laws are [8], [9]:

1) Friction force is directly proportional to the applied load.

2) Friction force is independent of the apparent area of contact.

3) Friction force is independent of the sliding velocity.

To clarify the 2nd law, the friction force is “independent” of the apparent contact area, but it is “dependent” on the real area of contact [10], [11]. Fig. 2 below illustrates the difference between the apparent and real areas of contact.

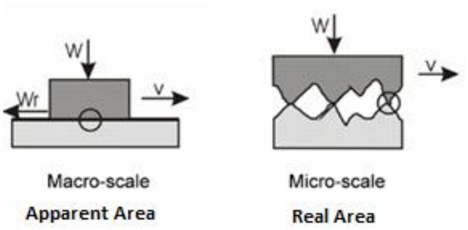


Fig. 2. Difference between apparent and real areas of contact [11]

As it can be seen in Fig. 2, the apparent area is a macro-scale that is visible to eye, whereas the real area is a micro-scale that contains irregular shapes being in contact, these shapes are called asperities [11].

III. DYNAMIC SEALS IN ELECTRIC AXLE (E-AXLE)

Dynamic seals are sealing elements that exist between two surfaces (one or both surfaces are in reciprocating, oscillating, or rotational motion) [12], [13]. The functions of dynamic seals are to prevent fluid/gas from leaking onto another surface and to keep contaminants out [14]. In E-axle, there are two dynamic seals to prevent lubricant from gearbox to leak onto electric motor and to keep contaminants out [14]. Fig. 3 below illustrates the dynamic seals inside E-axle.

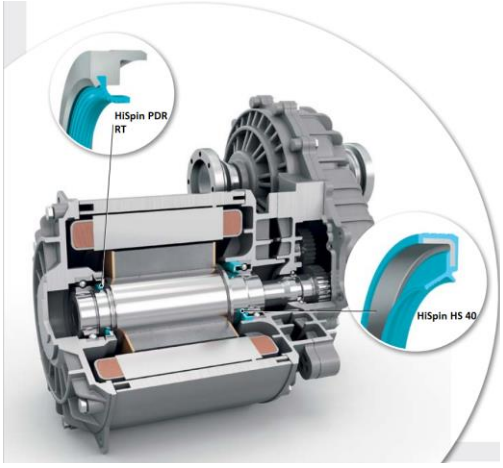


Fig. 3. Dynamic seals inside E-axle [15]

Based on Fig. 3, these seals are small and out of sight, but they are essential to exist in such moving components for proper functioning [16]. Without these seals, contaminants will accumulate, and lubricants will enter the electric motor, leading to an ultimate failure of the systems. One method to decrease the friction loss and increase the durability of the dynamic seals is to implement new materials of dynamic seals that have low friction coefficient. Current materials that have the lowest friction coefficients are PTFE, PEEK, and PI. Based on an experimental investigation on frictional behavior of the three composites under high speed (5000 rpm), the friction coefficients for them are 0.038, 0.043, and 0.047, for PTFE, PEEK, and PI respectively [17].

In addition to the low friction coefficient, high operating condition of temperature should be considered for the material of a dynamic seal inside E-axle. A summary table (Table I) shows the maximum and minimum service temperatures for PTFE, PEEK, and PI composites.

TABLE I. MAXIMUM AND MINIMUM SERVICE TEMPERATURES OF PTFE, PEEK, AND PI

Material	**Service Temperature (C)**	
	Maximum	***Minimum***
PTFE [18]	250	-268
PEEK [19]	239	-70
PI [20]	221	-248

It can be observed from Table I above that PTFE has the highest and the lowest service temperatures, 250 C and -268 C, respectively. These service temperatures of PTFE make it the most effective operational material of a dynamic seal inside E-axle.

IV. SOFTWARE USED TO DEVELOP A CONTACT MODEL BETWEEN SEAL AND SHAFT

The finite element method (FEM) software Abaqus was used for the model due to its features of creating a complex contact model and analyze the nonlinear behavior of it [21]. To simulate the real scenario of the contact between a dynamic seal and a motor shaft, some specifications were considered as following:

A. *Modelling Space*

Two-dimensional axisymmetric was considered for the seal and shaft (to simplify the model and save time of computational analysis). To simplify the model, only the contact parts of the dynamic seal and the motor shaft were modelled as shown in Fig. 4 and Fig. 5, respectively.

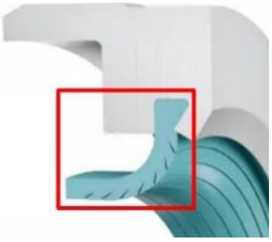


Fig. 4. Contact part modelled of the seal [5]

Fig. 5. Contact part modelled of the shaft [22]

B. *Modelling Type*

Deformable was considered for the seal and the shaft because they can be deformed under stress [23].

C. *Material Properties*

The materials properties for the motor shaft and the dynamic seal are illustrated in Table II below.

TABLE II. MATERIAL PROPERTIES OF THE COMPONENTS

Component	Material	Young's Modulus (MPa)	Poisson's Ratio
Motor Shaft	Carbon steel, AISI 1040 [24]	2.08×10^5	0.285
Dynamic Seal	PTFE (Case 1) [18]	400	0.44
	PEEK (Case 2) [19]	3760	0.44
	PI (Case 3) [20]	2070	0.39

From Table II above, the material for the motor shaft was selected as Carbon steel, AISI 1040 because it is a very common material for the motor shaft [25], and it has a very high Young's Modulus 2.08×10^5 MPa [24]. For the dynamic seal, three different materials were assigned to the seal in three different cases, PTFE, PEEK, and PI due to their very low friction coefficients.

D. *Interaction Properties*

A "Surface-to-surface-contact" interaction was selected between the seal and the shaft. Moreover, a "Tangential Behavior" was considered to assign friction coefficients to the materials in Abaqus, which are 0.038, 0.043, and 0.047 for PTFE, PEEK, and PI, respectively [17].

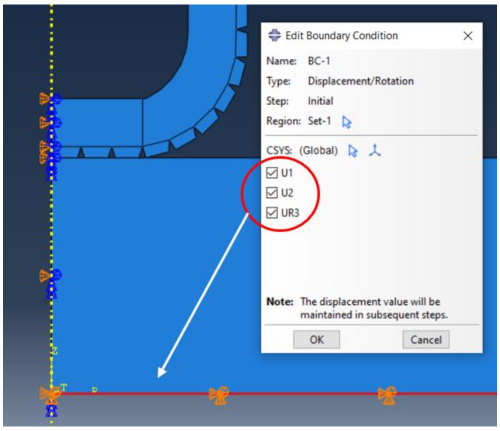
E. *Define Surfaces*

The bottom surface of the seal was defined as "slave" because it is more deformable, whereas the top surface of the shaft was defined as "master" because it is stiffer.

F. *Apply Boundary Conditions and Load*

For this model, four boundary conditions were applied in two different steps (in addition to the initial step), which are:

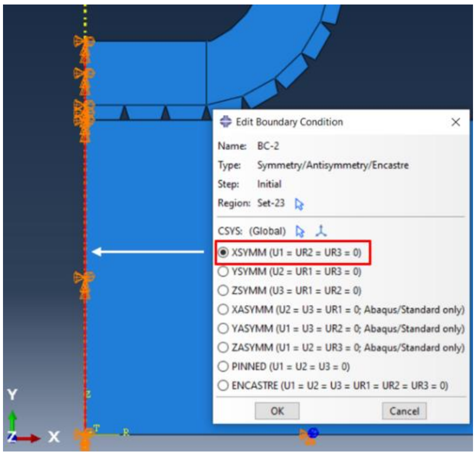
1- **Displacement/Rotation (in "Initial Step")**: to constrain all degrees of freedom (DoFs) of the bottom surface of the shaft as shown in Fig. 6.



Name: BC-1
Type: Displacement/Rotation
Step: Initial
Region: Set-1
CSYS: (Global)
☑ U1
☑ U2
☑ UR3
Note: The displacement value will be maintained in subsequent steps.

Fig. 6. Boundary condition on the bottom of the shaft

2- **Symmetry (in "Initial Step")**: to create a central line symmetry for both the seal and the shaft about x-plane as shown in Fig. 7.



Name: BC-2
Type: Symmetry/Antisymmetry/Encastre
Step: Initial
Region: Set-23
CSYS: (Global)
● XSYMM (U1 = UR2 = UR3 = 0)
○ YSYMM (U2 = UR1 = UR3 = 0)
○ ZSYMM (U3 = UR1 = UR2 = 0)
○ XASYMM (U2 = U3 = UR1 = 0; Abaqus/Standard only)
○ YASYMM (U1 = U3 = UR2 = 0; Abaqus/Standard only)
○ ZASYMM (U1 = U2 = UR3 = 0; Abaqus/Standard only)
○ PINNED (U1 = U2 = U3 = 0)
○ ENCASTRE (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0)

Fig. 7. Boundary condition on the central line of the seal and the shaft

3- **Displacement/Rotation (in "Initial Step")**: to constrain horizontal and rotational movements of the top of the seal "the metal part". The metal part is shown in Fig. 8, and the boundary condition applied is shown in Fig. 9.

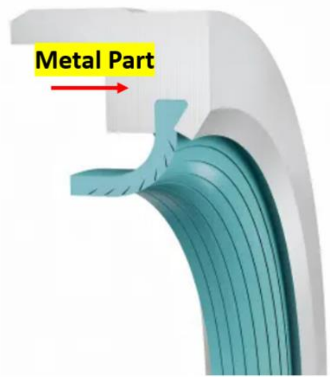
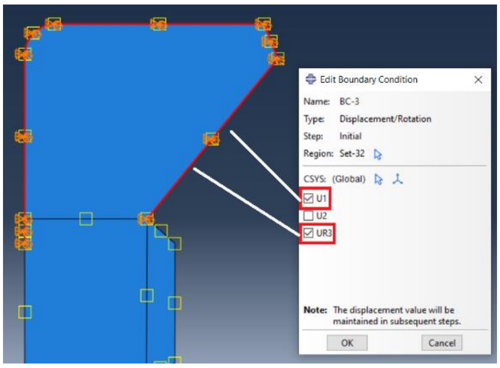


Fig. 8. Metal part of the seal



Name: BC-3
Type: Displacement/Rotation
Step: Initial
Region: Set-32
CSYS: (Global)
☑ U1
☐ U2
☑ UR3
Note: The displacement value will be maintained in subsequent steps.

Fig. 9. Boundary condition on the top of the seal

4- **Displacement/Rotation (in "Step 1")**: to apply an initial vertical displacement on the contact surfaces of the seal “-0.0011 mm” [26]. The boundary condition is shown in Fig. 10.

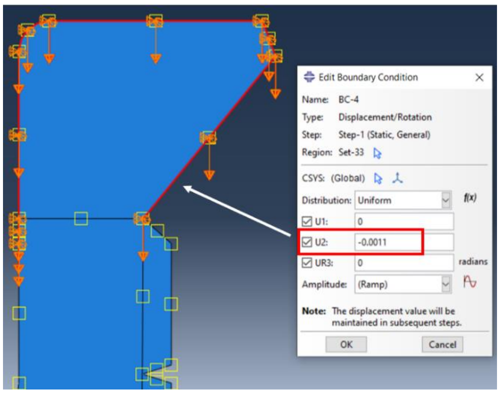

Edit Boundary Condition
Name: BC-4
Type: Displacement/Rotation
Step: Step-1 (Static, General)
Region: Set-33
CSYS: (Global)
Distribution: Uniform
☑ U1: 0
☑ U2: -0.0011
☑ UR3: 0 radians
Amplitude: (Ramp)
Note: The displacement value will be maintained in subsequent steps.

Fig. 10. Displacement boundary condition on the top of the seal

5- **Load (in “Step 2”)**: a load was applied to the model, but the vertical displacement from boundary condition 4 (in “Step 1”) was released first to allow the load impacts on the seal. The load type is “Uniform Pressure” on the top of the seal with a magnitude of 2 MPa [17]. The load applied is shown in Fig 11.

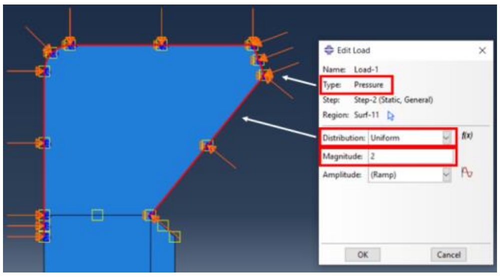

Edit Load
Name: Load-1
Type: Pressure
Step: Step-2 (Static, General)
Region: Surf-11
Distribution: Uniform
Magnitude: 2
Amplitude: (Ramp)

Fig. 11. Uniform pressure load on the top of the seal

G. *Meshing*

A mesh convergence study was done on the model to verify it. The aim is to get accurate results with a sensible computational time. Six different element sizes were considered for the critical edges of the seal (shown in Table III below).

TABLE III. MESH CONVERGENCE STUDY

PTFE Seal	
Element Size (mm)	***Maximum Contact Pressure (MPa)***
0.25	21.53
0.125	32.03
0.0625	49.11
0.03125	72.73
0.015625	82.8
0.0078125	95.65

From Table III, the solution was converged at 0.0078125 mm with number of nodes of 38108.

The seal and the shaft were meshed separately (before creating the assembly). The meshing specifications are as follow:

- Element Shape: Quad-dominated was considered because it primary uses quadratic shapes as well as it allows using triangles in the transition regions (this is needed between the transition regions of the seal from top-to-core and from core-to-bottom as shown in Fig. 12 below).

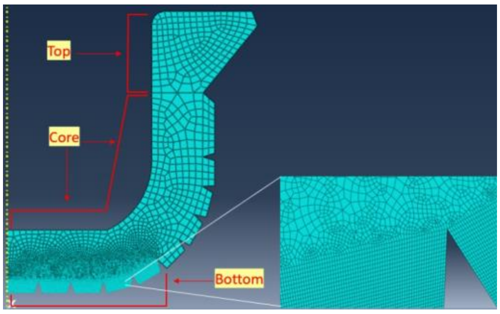


Fig. 12. Transition regions of the seal

- Technique: Free was considered “rather than structured” to apply bias to the critical edges of the seal (shown in Fig. 13 below).

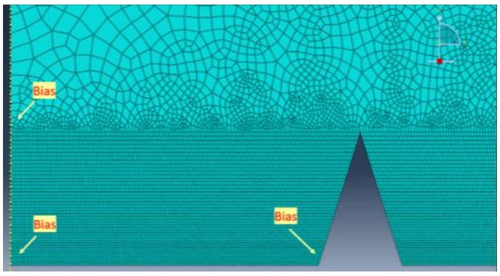


Fig. 13. Applying bias to the seal

V. RESULTS AND ANALYSIS OF THE CONTACT MODEL

Throughout this chapter, obtained results of maximum contact pressure and Von Mises stress for PTFE, PI, and PEEK are presented and analyzed.

A. *Maximum Contact Pressure Results*

Maximum contact pressure is essential to be considered in contact problems because it gives an indication of how materials behave. For this reason, the three materials, PTFE, PI, and PEEK are assigned to the seal to investigate their contact pressure results in the contact mechanics. Table IV below shows the output of maximum pressure of the three composites when being under the boundary conditions.

TABLE IV. MAXIMUM CONTACT PRESSURE OF THE THREE MATERIALS

Material	**Maximum Contact Pressure (MPa)**
PTFE	96.13
PEEK	269.7
PI	244.8

It can be noticed from Table IV above, PTFE exhibits the lowest contact pressure, 96.13 MPa, compared to PEEK and PI that exhibit 269.7 MPa and 244.8 MPa contact pressures, respectively.

B. *Von Mises Stress of the Materials*

Von Mises stress results are presented in this section due to the ductility of the composites PTFE, PI, and PEEK [27]. Von Mises theory is concerned with the distortion of energy of a material when stress reaches the yield point of that material [28]. The yield strength of the materials is shown in Table V below.

TABLE V. YIELD STRENGTH OF THE MATERIALS

Material	**Yield Strength (MPa)**
PTFE [18]	19.7
PEEK [19]	90.0
PI [20]	86.2

In this project, Von Mises stress for all materials is high due to the load applied at the top of the seal (2 MPa). Table VI below presents the Von Mises stress results.

TABLE VI. VON MISES STRESS OF THE MATERIALS

Material	**Von Mises Stress (MPa)**
PTFE	69.8
PEEK	198.0
PI	168.4

Based on Table VI, the lowest Von Mises stress is for PTFE due to its low Young’s Modulus and stiffness.

VI. CONCLUSION

Generally, PTFE, PEEK, and PI are suitable to make a dynamic seal in terms of friction coefficients. The key findings of the project are the maximum contact pressures of PTFE, PEEK, and PI composites, 96.13 MPa, 269.7 MPa and 244.8 MPa, respectively. PTFE exhibits the lowest contact pressure due to its lowest friction coefficient “0.038” and lowest Young’s Modulus “400 MPa”. In addition, PTFE can withstand very high and low temperatures, 250 and -268 C, respectively, and a very high speed, 60 m/s [17], [18]. These features of PTFE with the minimal friction make it the best material of a dynamic seal to be operational inside E-axle of EVs under severe conditions.

The project can be further developed by obtaining accurate dimensions of the bottom edges of the seal to get contact pressure results near to reality, as the presented contact pressure results are very high because the seal edges design was estimated.

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