

## Review Article

# Computer Simulation/Prediction of Wear in Mechanical Components

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Received 15 September 2020; Revised 18 November 2020; Accepted 24 November 2020; Published 8 December 2020

Academic Editor: Michael M. Khonsari

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In this paper, a state of the art on computer simulation and prediction of wear in mechanical components is reviewed. Past and recent developments as well as approaches employed in the simulation and prediction of wear are reviewed. In particular, the wear models, contact analysis schemes, and wear evolution prediction procedures as well as their application to the mechanical components (including cam-follower, gears, bearings, and cylinder/piston/piston ring wear) are reviewed. Recommendations and suggestions on possible directions for further research studies are also presented.

## 1. Introduction

There has been a considerable amount of discussion about the definition and classification of the wear phenomenon. In general, wear is defined based on the mechanism through which it occurs. Two main categories of wear mechanisms appear to emerge from previous discussions. These include pure mechanical wear and mechanical wear involving some element of active chemistry (oxidation/corrosion) [1]. In the first category, as the name suggests, the wear is purely mechanical involving the removal of material from the surface of the bodies in contact and in relative sliding. This category was mentioned in an early definition of wear that described wear as “the progressive loss of material from the operating surface of a body occurring as a result of relative motion at its surface” [2]. It is worth mentioning that in the literature [3], a phenomenon in which there is material removal from a surface when the surface is in contact with a stream of fluid or a stream of solid particles is also considered as pure mechanical wear. In the second category, removal of material from the concerned surfaces is the result of mechanical interaction between the contacting surfaces in the presence of a corrosive environment [1]. This category is referred to as corrosive wear or tribo-corrosion. A formal definition for this wear mechanism is presented in the

encyclopedia of tribology as “...the damage caused by synergistic attack of wear and corrosion when wear occurs in a corrosive environment” [4]. The two categories have further been categorized into other subcategories giving additional insight into the wear phenomenon. Supplementary details on these descriptions and categorizations can be found in [1, 3–7].

From the definition of wear, it is deduced that wear is expected to occur whenever bodies are in contact and in relative motion to each other. It is therefore inevitable that wear will be experienced in almost all engineering systems with moving parts. The problem of wear in industrial applications has been reported widely, and while wear is not catastrophic, its presence in these systems gradually degrades the performance of the systems and if left unchecked can cause damage to other system components and may eventually lead to failure or loss of functionality of the system. Consequently, there have been many studies, spanning a variety of fields, investigating wear in various systems. Table 1 gives a sample of the studies and investigations on wear in various mechanical components including gears, bearings, wheel/rail, and cylinder–piston/piston ring pair. These studies have their roots in problems experienced in real-life operation of components in mechanical systems. The objective of these studies is to increase the understanding of the

TABLE 1: Sample of wear studies on mechanical systems found in the literature.

Systems	Focus of article
Cam-follower	(i) Wear prediction on cam-followers [8–10] (ii) Running-in behavior of cam-follower [11]
Gear wear	(iii) Spur gear wear simulation and prediction [12–17] (iv) Helical gear wear simulation and prediction [15, 18–20] (v) Wear studies including experiments, testing, and performance investigation of gears (spur, helical) under various conditions [15, 16, 21–29]
Bearings wear	(vi) Wear simulation and prediction in bearings [30–33] (vii) Wear studies including experiments, testing, and performance investigation of bearings under various conditions [34–38] (viii) Monitoring of wear in bearings [39]
Wheel-rail wear	(ix) Wheel/rail wear simulation and prediction [40–55] (x) Understanding and identification of wear regimes and transitions [56, 57]
Cylinder/piston/piston ring wear	(xi) Reduction of wheel/rail wear [58] (xii) Wear prediction on cylinder/piston/piston ring wear [59–63]

wear phenomenon and thus inch closer to finding solutions to the challenges that accompany wear.

An important aspect of wear on a tribo-pair, which has elicited significant attention, is surface roughness. Surface roughness is defined as the variations in the height of the surface with respect to a reference plane [64]. In addition to contact load and relatively sliding velocity between a tribo-pair, surface roughness has been reported to significantly affect tribological properties [65]. This is to such an extent that it has become part of the technical requirement for mechanical products and components [65, 66]. Consequently, numerous studies seeking to relate tribological properties to surface roughness have been undertaken. Among the works that can be mentioned in this regard include the works of Masouros et al. [67], Kumar et al. [68], and Hanief et al. [69, 70], among others. In these works, the authors demonstrate, through numerical and experimental work, that both surface roughness and wear rate reduce with time (as wear progress). It is further demonstrated in [67, 70, 71] that wear rate increases with increasing initial surface roughness or reduces with reduced roughness. This relationship lends credence to the fact that surface roughness should be considered in the study of wear for mechanical components as it is desirable to have an appropriate roughness in order to achieve acceptable wear rate. This also further clarifies why surface roughness may be specified as a technical requirement for mechanical products and components.

In addition to the problems experienced due to wear in mechanical systems, wear has also presented a variety of challenges in biomedical products, specifically in the discipline of orthopedics. The bone surface at the joints of the human body such as the knees and hips are covered with articular cartilage, which is a smooth substance that is designed to protect the bones and to allow for movement with ease. There is also a membrane known as the synovial membrane between the joint capsule and the joint cavity. This membrane secretes a fluid, known as the synovial fluid, which serves as a lubricant for the cartilage and thus reducing the friction at the joint to a bare minimum. In the event of injury or illness (such as arthritis or other such conditions), the cartilage can become damaged (or worn

out). This would expose the opposing bones to each other and result in contact and rubbing (of the bones) during motion. The consequences of this are considerable discomfort to the patient and loss of joint functionality in severe cases. In other cases, the synovial membrane may become inflamed (or damaged) due to illness or injury and consequently reduce its ability to produce the lubrication effect. This could then damage the cartilage and once again expose the opposing bones to contact and rubbing.

Medical procedures such as knee replacement or hip replacement aim to restore joint functionality by resurfacing the joints with implants. These procedures have a high success rate in restoring joint functionality and improving the patient's quality of life. It is estimated that the replacements are successful to about 85–90% for a period of 10–15 years [72, 73]. There are, however, a number of issues that have arisen due to these procedures. Of particular interest, to the current discussion, is the wear of the implants at the joints. As in the case of mechanical components, wear on implants is not catastrophic but will cause the performance of the joint to degrade with time. In addition, the wear occurring in such joints produce debris that accumulate or spread to other areas of the body and could become problematic [74–77]. These two issues have elicited a large amount of research as researchers seek to understand the problems created by the wear on implants and develop corresponding solutions. Table 2 lists previous studies done on wear of the joint replacements. The studies reported in Table 2 include observation and fundamental studies of wear on the implants, wear experiments on the implants, studies of the effect of the wear debris from the implant on the human body, as well as wear simulation and prediction of the hip and knee replacements.

It can be inferred from the preceding discussion and the large amount of associated research that wear has indeed presented a significant challenge in the functioning of mechanical systems as well as in the field of orthopedics (with reference to joint replacements). Researchers have put in enormous efforts with the aim of addressing these challenges. As a result, research has evolved along multiple fronts that include but are not limited to fundamental studies aimed at understanding the wear phenomenon,

TABLE 2: Sample of wear studies on joint replacement (orthopedic) found in the literature.

Systems	Focus of article
Joint replacements (orthopedic)	(i) Wear studies and wear experiments for hip/knee replacements [78–83]
	(ii) Wear simulation/prediction of hip/knee replacements [84–94]
	(iii) Wear debris from hip/knee replacements [74–77, 95, 96]

experimental studies seeking the same, anti-wear design studies, wear simulation, and prediction studies, among other efforts. With the continuous and rapid development and advancements in research in this field, it may be necessary to take a critical review of the past and recent developments so as to provide a purposeful orientation for future studies. Due to the importance of simulation and prediction in all engineering fields, a review on simulation and prediction of wear is presented in this paper. Past and recent developments and approaches employed in the simulation and prediction of wear are reviewed. While there is a wide range of disciplines that can be reviewed (including wear in cam-follower, gears, bearings, cylinder/piston/piston ring, wheel-rail, and wear in orthopedic implants), the focus of this article will be limited to a few mechanical components (cam-follower, gears, bearings, cylinder/piston/piston ring wear). In particular, the focus is on the most commonly used wear model, contact analysis schemes, wear evolution prediction procedures, and their application in the selected mechanical components. Recommendations and suggestions on possible directions for further research studies are also presented.

## 2. Simulation and Prediction of Wear

Research work on simulation and prediction of wear has been ongoing for over three decades. Some of the early notable attempts (prior to the late 90s) to conduct computer simulation of the wear process included the works of Fries [8], Hugnell [9, 10], Flodin [13–15, 18, 22], and Podra [97–99]. A number of these studies sought to estimate the wear in mechanical components such as cam-followers, gears, bearings, wheel-rail wear, cylinder/piston/piston ring as previously indicated (Table 1) while others explored different techniques for wear simulation and prediction on general geometries [97–99].

A close examination of these early works (specifically for the abovementioned components) reveals a general trend in the simulation procedures that consists of the following main aspects: (1) contact analysis to determine the contact pressure (at the contact surface) and the relative surface sliding amounts; (2) application of a wear model to estimate wear; and (3) geometry updated to reflect evolution of the geometry with wear. In majority of the studies, these aspects are incorporated into a routine that is iterated until the number of desired cycles is achieved. A typical wear simulation/prediction procedure, as observed in these studies, is depicted in Figure 1.

Further exploration into later works (2005–2020) related to wear simulation and prediction on mechanical components [16, 17, 20, 60, 92, 93, 100–102] reveal that simulation/prediction procedures similar to those in the previous works

(as illustrated in Figure 1) have been adopted in (these) later works. It is therefore logical that this review scrutinizes the various aspects related to the mentioned simulation/prediction procedure more judiciously. In line with that approach, a list of references for studies on wear simulation and prediction performed on various mechanical components (including cam-follower, gears, bearings, cylinder/piston/piston ring wear) is presented in Table 3. Also listed in the table are details of the wear models, contact pressure, information on geometry update, and general comments corresponding to the various components.

An important aspect for the proper functioning of mechanical components is lubrication. Most mechanical components are lubricated with the aim of controlling friction as well as wear. When a tribo-pair (such as a variety of mechanical components) is operating under steady lubrication condition, the wear experienced is maximum in the boundary lubrication regime and then decreases in the mixed lubrication regime and becomes virtually zero in the hydrodynamic regime [131]. This behavior is depicted in Figure 2. It is observed from Figure 2 that within the boundary lubrication regime, the wear is approximately constant, whereas in the mixed lubrication regime the wear decreases approximately linearly with increasing film thickness. It is postulated that within the boundary lubrication regime, most of the load is carried by the surface asperities, whereas in the mixed lubrication regime the amount of load carried by the lubricant steadily increases until the lubricant film is developed fully (corresponding to the hydrodynamic regime) and the opposing surfaces of the tribo-pair are completely separated.

There have been a number of attempts to model wear in lubricated contacts for a variety of mechanical components. Among these efforts features the work of Wu et al. [12] who used a model developed for partial elasto-hydrodynamic (EHL) contacts, to model wear in spur gears while taking into account gear dynamics, lubrication (EHL), oxidation, and thermal desorption. Olofsson et al. [33] introduced a wear model, based on the Archard wear equation [133], to study the wear for a thrust bearing. A similar approach was used by Flodin [15] for spur and helical gear wear calculations. Haneef et al. [111] considered the wear in an internal combustion engine (IC) with clearance and developed a prediction model taking into account dry contact and full-film lubrication conditions. They employed Archard's equation with constant wear coefficient to estimate wear. In [134], Xiang et al. developed a wear analysis model that coupled mixed lubrication and wear in a journal bearing. In the model, wear is predicted by a wear fatigue model (which they developed), whereas a mixed lubrication model was used to analyze and predict the asperity contact as well as pressure distribution. The procedure was implemented for a journal bearing and validated

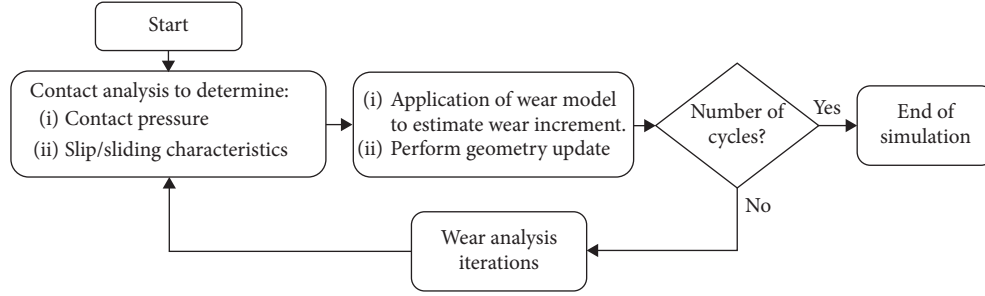


FIGURE 1: Flow chart depicting typical wear simulation procedures.

through experiments. Lyu et al. [60] established a wear prediction procedure for a piston-cylinder pair in which lubrication is considered. The procedure couples lubrication parameter and loading condition calculations and is validated through an experiment. In another recent article, Zhuang et al. [112] proposes a hybrid wear prediction model based on Archard's equation to predict wear in a revolute joint under various lubrication conditions. The hybrid model uses a time varying wear coefficient to represent three lubrication condition including dry contact, boundary lubrication, and full-film lubrication. The authors report that the model, which was tested against the wear experiment on the door of an airplane cabin, had the ability to reasonably predict the remaining useful life of a revolute joint. These efforts have enabled a better understating and therefore better simulation of the wear in mechanical components.

In addition to the wear prediction approaches outlined above, another methodology that has emerged in the study of wear simulation and prediction is the entropy and energy approaches. The approach is based on the hypothesis of the correlation between entropy and degradation of tribo-mechanical components. As will be detailed later, these approaches have been developed and used to determine the wear in mechanical components [131, 135–139] considering various conditions such as boundary lubrication, mixed lubrication, transient wear, and multiple wear mechanisms. A detailed review on this approach was presented in [140].

What follows is a more detailed review on the various aspects of the wear simulation/prediction trend as previously mentioned and depicted in Figure 1. The main aspects of the trend included (1) the most common wear model used in the simulations/prediction, (2) the techniques used in estimating the contact analysis, (3) general procedures used in the geometry update, as well as the (4) computational cost management. In addition, a brief review of the entropy and energy approach to wear estimation is presented.

**2.1. Wear Model.** There are a number of fundamental wear models (in general) that have been proposed [141]. As is evident from Table 3, the most widely used wear model is the generalized form of Archard's wear model [133]. Other models, observed in the literature related to wear simulation/prediction of mechanical components (see in Table 3), include the partial-EHL contact wear model [12, 60] used in lubrication contact and Rhee's wear formula [129].

The partial-EHL contact wear model is expressed as follows [60, 142]:

$$dw = \frac{u dt}{dA} \left[ \delta_0 e^{-(\Delta/2u\tau)} - h \right]^2 \frac{\Delta}{\delta_0}, \quad (1)$$

where  $w$ ,  $A$ ,  $v$ ,  $t$ ,  $h$ ,  $\delta_0$ , and  $\tau$  are material loss at fixed temperature, wear area, sliding velocity, sliding time, height of the roughness peak, wavelength of the roughness peak, and the delay time of the opposing material, respectively. This model has been used for simulating wear in gears and cylinder-piston-piston rings (as listed in Table 3) where the presence of lubrication is considered.

Rhee's wear model is expressed as follows:

$$\Delta w = k F^a v^b t^c, \quad (2)$$

where  $k$  and  $F$  refer to the wear rate and normal contact force, respectively. The quantities  $a$ ,  $b$ , and  $c$  refer to parameters specific to the material friction and the operating environment.

By far, the most popular wear model is Archard's wear model (see Table 3), a linear model initially proposed by Holms in 1946 [143] that estimates the wear from the contact conditions (relative sliding and contact pressure), operating conditions, and tribological data that inform about the materials in contact. In the model, it is assumed that the worn volume is directly proportional to the corresponding normal load and is expressed as

$$\frac{V}{s} = K \frac{F_N}{H}, \quad (3)$$

where  $s$  is the relative sliding between the opposing bodies,  $V$  is the amount of wear volume,  $F_N$  is the normal force (N),  $K$  is a nondimensional wear coefficient, and  $H$  refers to the Brinell hardness of the softer material in the contact pair. Since the wear depth is usually the quantity of interest, the worn volume  $V$  is usually replaced with the expression,  $V = hA$ . In addition, the dimensionless wear coefficient and the hardness are normally bundled into a dimensioned wear coefficient  $k$  (i.e.,  $k = (K/H)$  with units  $\text{Pa}^{-1}$ ). If it is further noted that the contact pressure can be expressed as  $p = (F_N/A)$ , then the wear model can be expressed in the following form:

$$h = kps. \quad (4)$$

TABLE 3: References for the various wear simulation and prediction procedures (wear models, contact analyses, and geometry update).

Applications	Reference	Wear model		Contact analysis					Geometry update	Comment
		Archard	Partial-EHL contacts wear model	Other	FEM	EFM	BEM	Other		
Cam-follower	[8]	x						x	x	Contact forces are determined analytically and the contact location is determined numerically using an iterative search.
	[9]	x						x	x	Contact pressure is determined numerically by discretizing the surface and determining the pressure in the individual surface.
	[10]	x				x			x	Pressure contact analysis base on infinite half plane assumption. Wear conducted in for three cases: 1) wear on cam alone, 2) wear on follower alone and 3) wear on both cam and follower
	[103]	x						x	x	Finite element analysis (FEA) conducted to determine contact pressure, whereas the sliding distances are determined analytically based on Hertz theory.
	[12]		x					x		
	[13]	x				x			x	
	[14]	x				x			x	
	[17]	x							x	Spur gear
	[104]	x				x			x	
	[105]	x							x	
Gear wear	[106]	x				x			x	Implicit treatment of wear by substituting Archard's wear law into the contact law (Signoroni's contact law) wherein wear is built into any particular load step being considered
	[15]	x						x	x	
Bearings wear	[16]	x						x	x	
	[18]	x				x			x	Helical gear
	[19]	x						x	x	
	[25]	x				x			x	
	[20]	x						x	x	
	[107]	x				x			x	Spur and helical gears.
	[108]	x						x	x	Hypoid gears.
	[33]	x						x	x	
	[60]	x						x	x	Two wear models are used to cover the different load-bearing conditions (presence of lubrication).
	Cylinder/piston/piston ring wear	[109]	x						x	
[110]		x								Simulation results from the first part of this study [109] are compared with the actual worn cylinder bores.
[111]		x						x		

TABLE 3: Continued.

Applications	Reference	Wear model			Contact analysis				Geometry update	Comment
		Archard	Partial-EHL contacts wear model	Other	FEM	EFM	BEM	Other		
	[97]	x				x			x	Cylinder on flat and sphere on flat configuration are considered for wear prediction.
	[98]	x			x				x	The geometry considered is of conical spinning contact.
	[99]	x			x				x	Several geometries are considered including (1) sphere on plane contact, (2) cone on cone conforming contact, (3) cone on cone nonconforming contact, and (4) cone on torus contact. The pin-on-disk tribology experiment was also simulated.
	[100]	x			x				x	Wear simulation implemented using parallel computation to speed up the analysis.
	[101]	x			x				x	Wear analysis of a revolute joint (of a slider crank mechanism) conducted within a multibody dynamics frame work coupling wear and system dynamics.
	[93]	x					x		x	A wear simulation procedure-based BEM is used to predict wear on pin-on-disk configuration. Wear is considered for the case when (1) only pin is wearing and (2) when both the pin and the disk are modeled to wear.
	[102]	x			x				x	Comparison between the FEM and EFM procedure in wear analysis of a revolute joint of a planar mechanism.
	[112]	x			x					A time-varying wear coefficient to represent three lubrication conditions including dry contact, boundary lubrication, and full-film lubrication.
	[113]	x			x				x	Wear analysis on metallic bodies in oscillatory contacts.
	[114]	x			x				x	A closed form expression for wear on a simple scotch yoke mechanism is derived.
	[115]	x			x				x	Wear simulation is conducted on a cylindrical steel roller that is configured to oscillate against a steel plate.
	[116]	x			x				x	Wear or planar multibody systems.
	[117]	x					x		x	3D wear analysis in rolling contact problems.
	[118]	x					x		x	3D fretting wear analysis.
	[119]	x					x		x	A wear test procedure (ring-on-disc wear configuration) is simulated using a BEM formulation.
	[112]	x			x				x	Time-varying wear coefficient to cater for effects on lubrication. Remeshing at contact element and the proximity of elements.
	[120]	x							x	Ball on disk tribometer experiment is simulated and compared to actual experiments.
	[121]	x					x		x	Geometry update based on moving the nodal wear. Wear analysis on 2D cylinder on flat and 3D spherical contact.
	[122]	x			x				x	Wear analysis on radial sliding laminated polymeric composite bearings contacting with rotary shaft.
	[123]	x			x				x	Wear analysis of (thermal and mechanical) spherical plain bearing. Remesh model after every cycle to reflect wear.
	[124]	x			x				x	Wear estimates on a slider crank mechanism.
	[125]	x			x				x	Remesh model after every cycle to reflect wear.
	[126]	x			x				x	Remesh model after wear cycle to reflect wear.
	[127]	x			x				x	Geometry update involves repositioning of node and remeshing.
	[128]	x			x				x	FEM-based procedure for fretting wear analysis of aero-engine spline coupling.
	[129]	x			x				x	Wear model is a modification of Rhee's wear formula.
	[130]	x							x	Contact analysis involved geometry discretization and contact properties estimated for the discretized sections.

Other components and general geometries

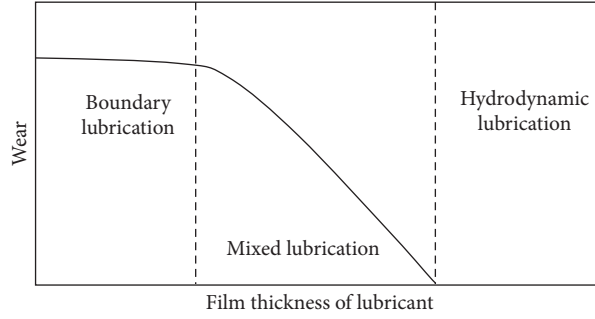


FIGURE 2: Relation between wear and lubricant film thickness in various regimes (adopted from [131, 132]).

It is important to note that the dimensioned wear coefficient in equation (4) is obtained through experiments, similar to those described in [113, 144, 145], for a given pair of materials in contact and for a specific operating condition. Although there are a variety of wear coefficient test procedures, the experiments usually involve a pin-on-disc setup and are performed on tribometers. In a typical test, a load of known magnitude is applied on the pin which is in contact with the counter surface (usually a disc). A relative sliding motion is then administered between the pin and the disk through a reciprocation motion or rotary motion of the disc (with a fixed pin position) as shown in Figure 3. The relative sliding distance can be determined by keeping track of the reciprocation cycles (or the disc rotations). The wear coefficient can then be determined, after the mass lost in the test is measured, as in the following expression:

$$k = \frac{(\Delta m/\rho)}{d_s F_N}, \quad (5)$$

where  $\Delta m$  is the total mass lost (wear),  $\rho$  is the density of the test sample,  $d_s$  is the total sliding distance, and  $F_N$  is the normal force between the pin and the disc. Experimental data on the wear coefficient usually have large scatter which may significantly affect the wear prediction. It is thus important to place extra caution in obtaining these values especially when these values are to be used for wear simulation and prediction. It may be worth the while to conduct uncertainty analysis for measured wear coefficients as done in the works of Schmitz [144].

It is possible to employ equation (4) to estimate worn geometry based on initial contact conditions (initial contact geometry). This would assume that the geometry and thus the contact pressure do not evolve with wear. Thus, only a single iteration of equation (4) extrapolated to the number of desired cycles would be required to determine the final worn geometry. It has been argued that this approach would almost certainly produce erroneous results [103, 113, 114]. It is, therefore, more accurate to consider the wear process as a dynamic process where the geometry is continuously evolving, with the contact condition evolving subsequently. Equation (4) is thus usually expressed as a first-order differential equation of the following form:

$$\frac{dh}{ds} = kp(s), \quad (6)$$

where the contact pressure is considered a function of the sliding distance. Majority of the wear simulation studies in the literature utilize a temporal discretization of equation (6), which leads to a numerical solution for the wear depth as follows:

$$h_j = h_{j-1} + kp_j \Delta s_j. \quad (7)$$

The term on the left hand side of equation (7) is the total wear depth at the current iteration ( $j$ ), whereas the first term on the right hand side refers to the total wear depth in the previous iteration ( $j-1$ ). The last term on the right hand side of equation (7) is an estimate of the incremental wear ( $\Delta h_j = kp_j \Delta s_j$ ) at the current iteration and is dependent on the wear coefficient ( $k$ ), the contact pressure ( $p_j$ ), and incremental sliding distance ( $\Delta s_j$ ) (at the current iteration). The expression in equation (7) has been used in numerous works (in various forms) for simulation and prediction of wear for both mechanical [18, 19, 97–102, 104, 113, 115, 116] and medical applications [85, 86].

**2.2. Contact Analysis.** Majority, if not all, of the encountered wear laws require results data about contact between the interacting surfaces. The data which include the contact pressure field and the sliding amounts are obtained via various contact analysis procedures. A number of contact analysis procedures have previously been used in the simulation/prediction of wear. These include the Finite Element Method (FEM), the Elastic Foundation Model (EFM), and the Boundary Element Method (BEM) in addition to other analytical procedures.

The FEM approach involves solving a complex nonlinear boundary problem in which the contact boundary as well as the contact stresses is initially unknown. This is in addition to the abrupt change in the contact forces during the contact process. Details of the contact problem and solution procedures are well beyond the scope of this article and the reader is referred to works of nonlinear finite element method such as [146] for further explanations. The FEM approach has been used in various studies [100–102, 113] and has been found to produce good estimates of the contact pressure for wear computations. Of the three mentioned approaches, the FEM approach appears to be the most widely used technique. This is perhaps due to its ability to model complex geometry as well as produce relatively good

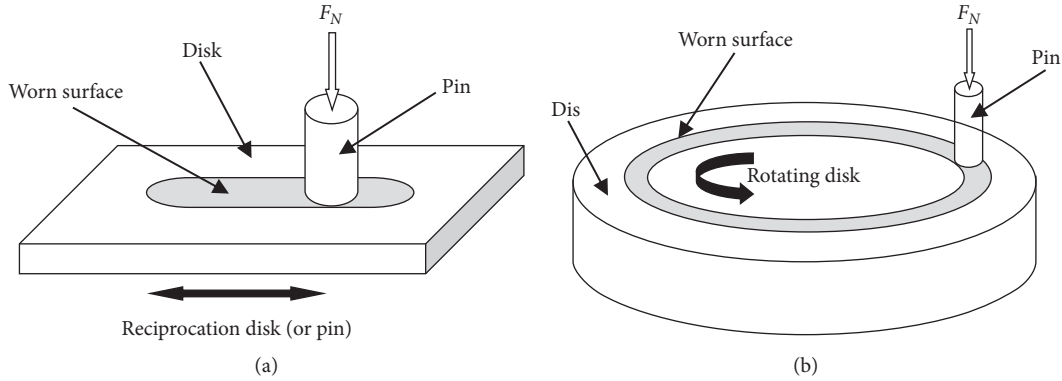


FIGURE 3: Illustration of the principle behind the pin-on-disk wear test.

estimates of the contact pressure. There are also readily available finite element packages such as ANSYS and ABAQUS.

In contrast to the FEM, the EFM is a much simpler method to estimate the contact pressure. The technique is derived from plane elastic strain theory for an elastic layer in contact with a rigid surface [147]. The term “elastic foundation” is essentially a reference to the use of a set of elastic spring elements, spread over the regions of contact, to represent the contact surface.

In the EFM, it is assumed that the spring elements act independent of each other. Consequently, the effect of how the pressure applied in one location affects the deformation in neighboring locations is neglected. While this assumption violates the very essence of contact problems, the model has been used in numerous applications due to its simplicity and ability to offer a cheaper alternative in the estimation of contact pressure, for layered contact as well as nonlinear materials [148].

The concept of the EFM is illustrated in Figure 4. In this diagram, the contact force between the two surfaces is indicated by  $F_N$ . The contact pressure on any spring element within the elastic layer is obtained from

$$p_i = \frac{E_W}{L_i} \delta_i, \quad (8)$$

where  $E_W$ ,  $L_i$ , and  $\delta_i$  refer to the modulus of elasticity of the elastic layer, thickness of the elastic layer, and the spring deformation, respectively. In the event that both bodies in contact are elastic,  $E_W$  will be a composite elastic modulus for the two bodies. Procedures to determine  $E_W$  can be found in [97, 147].

The load supported by the entire elastic layer can be determined by summing the load supported by the individual spring elements that make up the layer. The corresponding expression is given as

$$F_N = \sum p_i A_i. \quad (9)$$

In equation (9),  $A_i$  refers to the contact area of the individual springs. The force  $F_N$ , in equation (9), corresponds to the load (total reaction) between the two bodies in contact responsible for the contact pressure being determined.

Although the EFM approach does not produce accurate contact pressure estimates (in comparison to the FEM), it has been used in various studies [9, 10, 13–15, 18, 97, 102] and has been found to provide useful results when conducting wear computations.

A third technique used in studies to estimate the contact pressure is the BEM. The BEM is a numerical procedure largely used by mathematicians but has recently found use in the engineering community. It is a numerical computational technique used to solve partial differential equations in their integral formulation (boundary integrals). In the BEM, only the boundary is discretized and the solution is determined at the boundary. The procedure to convert the partial differential equations into their boundary integral forms as well as discretization procedure are well beyond the scope of this work and readers are referred to the works of [92, 93, 117] for further details.

From the literature, the BEM approach appears not to have been widely used in wear simulation and prediction. Nevertheless, this approach has been reported to have at least two major advantages that include (1) its appropriateness for modeling contact problems as the contact occurs only at the boundary [93] where the solutions are obtained and (2) it facilitates geometry updates to represent the wear evolution as the BEM has only boundary elements and thus only these elements are modified to reflect the wear. It has also been noted to reduce computational costs when compared to the FEM [121].

**2.3. Geometry Update Model.** Majority of the recent works on wear simulation and prediction employ some form of geometry update scheme to represent the effect of evolving geometry as dictated by wear. Indeed, the evolution of the geometry has an effect on the contact conditions. As wear occurs, the concerned geometry is altered, which in turn changes the contact pressure and to some extent the sliding conditions. Neglecting geometry changes and estimating the entire wear in a single wear cycle will in most cases lead to erroneous results as previously reported [103, 113, 114].

Geometry update schemes generally involved moving of the affected contact boundary by an amount equivalent to the estimated wear. In studies where the EFM approach have



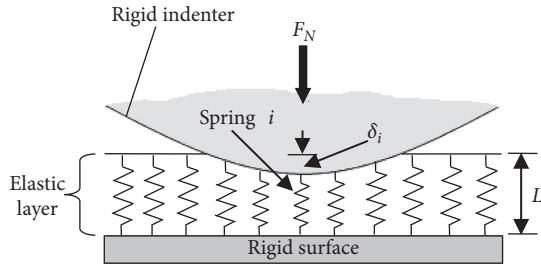


FIGURE 4: Elastic foundation model.

been used [9, 10, 13–15, 18, 102, 116], geometry update is accomplished by moving the boundary elements normal to the surface by an amount equal to the wear. The same approach was used in BEM-based wear prediction studies [92–94, 117, 118, 121]. In this case, the contact boundary is updated to reflect the wear by displacing the boundary nodes normal to the contact surface by an amount equal to the estimated wear.

In the prediction/simulation studies where the FEM method was used [25, 86–91, 98–100, 102, 104, 113, 115, 116], geometry evolution is achieved by displacing the boundary nodes at the contact locations normal to the contact surface by amounts equivalent to the wear. This approach is depicted in Figure 5. In this figure, it is seen that a new contact boundary is created by displacing the nodes on the old contact boundary in the direction normal to the contact surface.

Unlike in the case of the EFM and BEM, update procedures displacing the boundary in the FEM is only practical when the amount of expected wear is small relative to the boundary element dimensions. From Figure 5, it can be observed that if the wear is large, then the elements on the contact geometry will become distorted (when the boundary is moved to reflect the wear) and may lead to erroneous results in the finite element analysis. In the event of the element sizes at the contact region being small (e.g., to increase the accuracy of the finite element analysis), other update techniques are required, such as remeshing the geometry to incorporate the wear [122, 123, 125].

Another geometry update procedure that has previously been used in conjunction with the FEM in wear analysis is the boundary displacement approach. The procedure involves repositioning the boundary nodes as well as the internal nodes to reflect wear in such a manner that the distortion of the boundary elements is prevented. The procedure is depicted in Figure 6. This technique was used in [102, 113, 116]. A detailed discussion of the procedure can be found in [116, 149].

**2.4. Extrapolation.** Typical wear analysis problems involve numerous wear simulation cycles that require the solution of contact problems after every geometry update. While individual contact analysis may not be expensive computationally, the overall wear analysis study may become considerably expensive due to a large number of contact analyses that need to be performed. To alleviate this problem, extrapolation is often used as a means to speed up

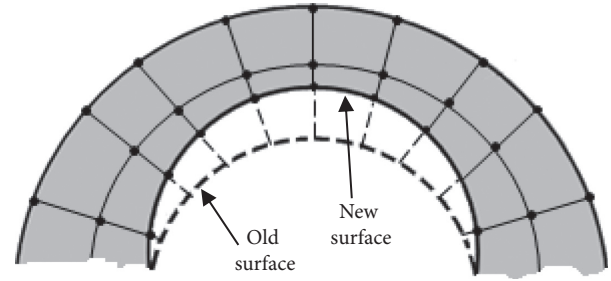


FIGURE 5: Geometry update schemes for FEM approach. Shifting on surface by moving boundary nodes normal to the surface.

the wear analysis. Extrapolations have been implemented in various forms. In previous wear prediction/simulation procedures [84, 89], a linear wear evolution model was used where it was assumed that no geometry evolution occurs and thus the wear for a desired number of wear iterations is linearly extrapolated from a single iteration of the wear analysis. In cases where wear evolution is minimal, this approach is ideal. However, where the wear evolution is large, then this extrapolation procedure will more than likely result in erroneous results as reported in [103, 113, 114].

Another extrapolation scheme (used when geometry evolution is important) involves allowing one cycle of wear analysis to represent a number of actual wear cycles. If  $A_j$  is taken as the extrapolation factor, the extrapolation procedure can be expressed as follows:

$$h_j = h_{j-1} + kA_j p_j \Delta s_j. \quad (10)$$

While this extrapolation technique provides a remedy of the computational expense of wear analysis, the challenge lies in determining the appropriate extrapolation size. The contact pressure distribution (determined using the EFM, FEM, or BEM) over the mating surfaces is generally not perfectly smooth. When large extrapolation sizes are used, the nonsmooth pressure distribution is magnified, thereby leading to unrealistic geometry evolution that fluctuates with every cycle of wear analysis. On the other hand, small extrapolation will provide an unsatisfactory solution to the problem of computational costs. Some guidelines in the selection of the extrapolation size were presented in [116].

**2.5. Thermodynamics Approach to Wear Analysis.** Entropy and energy approaches have, in the recent past, been developed and employed for the determination of wear in tribo-mechanical components. The concept behind this approach is that the irreversible degradation of mechanical components (such as wear) can be related to the generation of entropy by both dynamic and degenerative forces [137]. This gave rise to the “degradation entropy generation” (DEG) theorem [137]. The theorem has since provided the basis for the development of degradation models that are congruent with thermodynamics laws.

According to the DEG theorem, the wear rate (volume) is expressed as

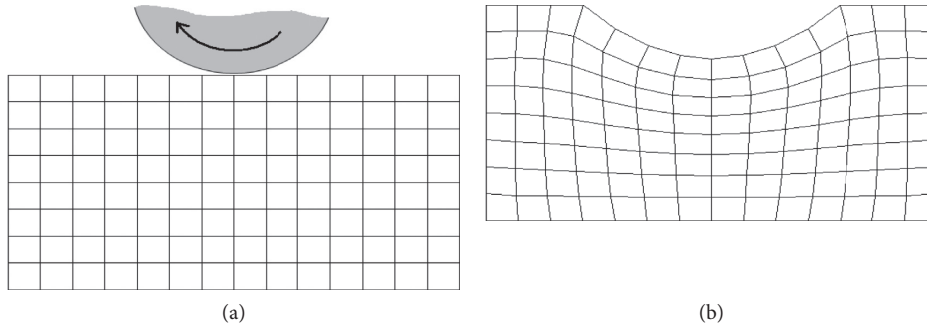


FIGURE 6: Boundary displacement technique for geometry update schemes in the FEM approach. (a) Initial geometry. (b) Updated geometry.

$$\dot{w} = B \frac{\mu NV}{T}, \quad (11)$$

where,  $\mu$ ,  $N$ ,  $V$ , and  $T$  refer to the friction coefficient of the tribo-pair, the applied force, the sliding velocity, and the contact temperature, respectively. In equation (11), the term  $B$  is a degradation coefficient, proposed by Bryant et al. [137], that characterizes the degradation (irreversible) of the tribo-system through entropy generation.

The degradation coefficient has been used successfully by various researchers to characterize various wear conditions. These include steady state wear degradation [150–152], boundary and mixed lubrication systems [131], transient wear [153], and multiple wear mechanisms [154].

The research work published in the literature on the thermodynamic approach for wear analysis, which involves both theoretical and experimental work [151, 153, 154], and in some cases has been cross-validated through available experimental data [131, 151, 154], has shown some superiority to the previously existing wear analysis approaches (in certain regards). For instance, it has been reported that the Archard coefficient is incapable of accurately characterizing the wear under transient conditions such as running-in [131] and can deviate by large values if running-in is incorporated into the analysis [153]. Lijesh et al. proposed an integrated model, via thermodynamic approach, for adhesive wear that would cater effectively for both the transient running-in phase and the steady-state phase [153]. The Archard equation with the constant coefficient was also found to be inadequate when applied to wear analysis of the mixed lubrication regime [131]. Various solutions to this were proposed including thermodynamics-based approaches by Doelling et al. [135] and Lijesh et al. [131]. Finally, it has also been reported that previously existing wear models assume single wear mechanisms, whereas in reality wear on a tribo-pair typically exhibits multiple wear mechanisms and as such, these models would fall short in characterizing the actual wear process. Recently, Lijesh [154] et al. applied the DEG theorem to develop a procedure to analyze wear involving several wear mechanisms. The work is validated through experiments and results from the literature. The authors report that the approach (using multiple degradation coefficients representing various wear regimes) produced reasonable results that deviated from

experiments by about 9%, whereas when a single degradation coefficient was used, the results differed with experiments by as much as 44%.

### 3. Concluding Remarks and Recommendations

In this work, procedures to predict/simulate wear as applied to various mechanical components, including cam-follower, gears, bearings, cylinder/piston/piston ring wear, were reviewed. In particular, the wear models, contact analysis schemes, wear evolution procedures, and extrapolation approaches were examined. Table 3 presents a list of references for the widely used wear simulation/prediction processes with corresponding wear models, contact pressure determination procedures, and geometry update information for these components. It can be deduced from the table that the most widely used wear simulation/procedures are based on Archard's wear model, and the FEM procedure is the most widely used approach to estimate the contact pressure at the contact boundary and that geometry update is an essential aspect in the simulation and prediction of wear without which wear simulations will be inaccurate as correct geometry profiles cannot be determined.

A thermodynamic approach to wear analysis was also presented in this work. The concept behind this approach is that the irreversible degradation of mechanical components can be related to the generation of entropy by both dynamic and degenerative forces. This approach has been applied to characterize various wear conditions including steady state wear degradation, boundary and mixed lubrication systems, transient wear, and multiple wear mechanisms. The approach appears to be promising, especially in application where the resulting wear volume rather than the wear profile is required.

A substantial amount of research has been conducted on the simulation and prediction of wear in mechanical components. This work presented some of the major trends in this area of research. There are a number of possible future directions and suggestions for research. Three suggestions are proposed here. The first suggestion is the inclusion of a third body in the analysis of wear between two mating surfaces. This scenario, commonly referred to as three-body wear, is an important aspect in the wear phenomenon since

the two bodies in contact and in relative motion will usually have a third body between them, whether the body is a foreign body or wear debris. The third body indeed affects the wear and successful simulations of this condition would introduce a useful tool in studying the aspects of this wear phenomenon including the effect of the size, shape, and quantity of the third body on the wear of the parent bodies.

The second suggestion is an increase in emphasis on 3D wear simulation/prediction. Majority of the work observed in the literature has focused on wear simulation/prediction in 2D. While in many mechanical components, the 2D assumption is reasonable, this assumption may not be acceptable in certain scenarios such as the estimation of wear on the ball joint of a spatial slider crank mechanism or wear prediction on a revolute joint with misalignments. For such cases, a 2D wear analysis will fail to capture the reality of the wear. It would thus be necessary to perform a three-dimensional analysis.

The final suggestion is related to the widely used wear model previously presented in equation (4). Most studies observed in the literature utilize the Euler integration scheme (5) as a solution to this differential equation. It is, however, known that the Euler integration results in a larger error in comparison to other advanced schemes such as the 4th order Runge Kutta method, and the error will increase as the number of wear cycles increase. There are, however, challenges that need to be overcome when using these techniques. For instance, majority of these advanced techniques would require a number of contact analyses within one iteration to estimate the wear for that iteration. This would make the wear analysis in general more expensive. It, however, remains to be seen whether an increase in computational costs is justifiable in place of accuracy.

## Data Availability

All data used to support the conclusions are included in the article.

## Conflicts of Interest

The author declares that there are no conflicts of interest.

## Acknowledgments

The author is grateful, in general, for the support of the Mechanical Engineering Department and the College of Engineering at Qassim University for providing a conducive environment.

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