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A Review on Different Wear Models in Tribological Systems

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Abstract: Tribological degradation remains one of the major causes of failure in engineering systems such as bearings, gears, turbines, and rotating machinery. Classical wear models, including the Archard wear equation and rolling contact fatigue theories, have long been used for wear prediction because of their simplicity and industrial applicability. However, these approaches are often limited in describing thermal effects, irreversible energy dissipation, and microstructural degradation occurring during operation. In recent years, entropy-based approaches have emerged as a promising alternative for analyzing wear and fatigue from a thermodynamic perspective. These methods relate material degradation to entropy generation caused by frictional heating, plastic deformation, and dissipative processes. This review presents a comprehensive discussion of classical wear theories, thermodynamic degradation concepts, and entropy-based damage models with applications in sliding wear, rolling contact fatigue, and bearing condition monitoring. Comparative analyses between empirical and entropy-based approaches are presented together with mathematical formulations, current challenges, and future research opportunities.

KEYWORDS: Entropy generation; Tribology; Rolling contact fatigue; Bearings; Wear modelling; Thermodynamic degradation; Condition monitoring.

I. INTRODUCTION

Tribological systems play a vital role in modern engineering applications such as rolling bearings, gears, turbines, railway wheels, automotive engines, and industrial rotating machinery. In these systems, interacting surfaces remain in relative motion under different loading and lubrication conditions, leading to friction, wear, lubrication degradation, and fatigue. These degradation mechanisms directly influence the reliability, efficiency, and service life of mechanical components. Excessive wear not only reduces system performance but also increases maintenance costs, energy consumption, and the risk of unexpected mechanical failure. Therefore, accurate prediction and monitoring of wear behaviour have become important research areas in tribology and mechanical engineering.

For several decades, wear prediction has mainly relied on empirical and semi-empirical models developed from experimental observations. Among these approaches, the Archard wear model proposed by Archard [1] remains one of the most widely used formulations because of its simplicity and practical engineering applicability. The Archard model establishes a relationship between wear volume, applied load, sliding distance, and material hardness. Although such models provide useful approximations under controlled operating conditions, they are often unable to fully describe the physical mechanisms governing material degradation. Factors such as frictional heating, oxidation, plastic deformation, microstructural changes, and irreversible energy dissipation are generally neglected in classical wear equations.

In practical tribological systems, wear and fatigue are highly complex phenomena influenced by multiple interacting parameters including temperature, lubrication regime, contact stress, sliding velocity, surface roughness, and material properties. Under severe operating conditions, frictional interactions generate significant heat at the contact interface, resulting in thermal softening, oxidation, and progressive material degradation. Classical wear models frequently fail to represent these coupled thermomechanical effects, limiting their predictive capability in real engineering environments [3,4].

To overcome these limitations, researchers have increasingly explored thermodynamics-based approaches for analysing tribological degradation. In recent years, entropy generation has emerged as an important parameter for understanding irreversible degradation processes in tribological systems. Since friction and wear are irreversible phenomena, entropy continuously increases during operation because of frictional heating, plastic deformation, crack initiation, oxidation,

and asperity interaction. Consequently, entropy generation provides a direct thermodynamic measure of energy dissipation and material degradation within the contact region [5,6].

The concept of entropy-based degradation gained considerable attention after the development of the Degradation Entropy Generation (DEG) theorem proposed by Bryant and Khonsari [8]. According to this theorem, material failure occurs when the accumulated entropy within a system reaches a critical threshold value. This approach established a direct relationship between irreversible thermodynamic dissipation and wear progression. Experimental investigations by Doelling et al. [7] demonstrated strong correlations between entropy flow and wear in machinery components, further validating the thermodynamic basis of degradation.

Subsequent studies extended entropy-based approaches to several tribological applications including dry sliding wear [3], mixed lubrication regimes [10], adhesive wear [15], fretting wear [11], and rolling contact fatigue in gears and bearings [2]. These studies showed that entropy-based methodologies provide stronger physical interpretation compared with purely empirical models because they directly incorporate thermal dissipation and irreversible degradation mechanisms.

Another important advantage of entropy-based approaches is their compatibility with condition-monitoring and predictive-maintenance systems. Parameters such as interface temperature, friction coefficient, heat dissipation, vibration, and friction torque can be experimentally measured and correlated with entropy generation. This enables real-time health monitoring and remaining useful life estimation for tribological components such as bearings and gears. Thermodynamic degradation models have therefore attracted growing interest in applications involving rotating machinery, aerospace systems, and industrial maintenance [13,16,17].

Despite significant progress, several challenges still remain in the practical implementation of entropy-based wear models. Accurate measurement of entropy generation at contact interfaces remains difficult under high-speed and variable loading conditions. Furthermore, the determination of a universal critical entropy threshold applicable across different materials and lubrication regimes remains an open research problem. Nevertheless, entropy-based approaches continue to gain importance because of their ability to provide a unified framework for analysing wear, fatigue, and irreversible degradation processes.

This review paper presents a detailed discussion of classical wear theories, thermodynamic degradation concepts, and entropy-based damage models used in tribological systems. Applications related to sliding wear, rolling contact fatigue, and bearing condition monitoring are examined together with comparative analyses between empirical and entropy-based approaches. Current research challenges and future opportunities associated with entropy-based tribological modelling are also discussed.

II. MODELS BASED ON ASPERITY THEORY

Classical wear models have played a fundamental role in the development of tribological engineering and continue to be widely used for predicting material degradation in mechanical systems. These models were primarily developed from experimental observations and empirical relationships between operating parameters and wear behaviour. Their simplicity, ease of implementation, and low computational requirements have made them highly useful in practical engineering applications such as bearings, gears, brakes, railway wheels, cutting tools, and sliding machine elements. One of the earliest and most influential contributions to wear modelling was made by Archard [1], who proposed a relationship between wear volume and contact conditions. The Archard wear equation is expressed as:

$$V=KWL/H$$

where:

- V is the wear volume,
- K is the dimensionless wear coefficient,
- W is the applied normal load,
- L is the sliding distance,
- H is the hardness of the softer material.

The Archard model assumes that wear occurs because of asperity interactions at the contact interface. During sliding motion, microscopic surface asperities deform plastically and eventually detach as wear debris. According to the model, wear volume increases proportionally with applied load and sliding distance while decreasing with increasing material hardness.

Because of its simplicity and engineering usefulness, the Archard wear equation has been extensively applied in tribological analysis of sliding and rolling contacts. The model is particularly effective under steady-state operating conditions where contact parameters remain relatively constant. It has been used in the design and analysis of gears, bearings, cam-follower systems, and machining operations.

Despite its widespread application, the Archard wear model has several important limitations. One of the primary shortcomings is that the wear coefficient K is generally treated as a constant parameter, although in reality it varies significantly with operating conditions such as temperature, lubrication regime, contact pressure, sliding velocity, and surface roughness. Consequently, the predictive accuracy of the model decreases under variable loading and severe operating environments [3,4].

Another important limitation is the inability of classical wear models to explicitly incorporate thermal effects. In practical tribological systems, frictional interactions generate considerable heat at the contact interface. This frictional heating can alter material hardness, accelerate oxidation, influence lubricant behaviour, and promote microstructural degradation. Since the Archard equation does not directly account for thermal dissipation and entropy generation, it cannot fully represent the actual degradation mechanisms occurring during wear processes.

Classical wear theories also generally neglect irreversible thermodynamic effects associated with plastic deformation and energy dissipation. Wear is fundamentally an irreversible process involving continuous conversion of mechanical energy into heat and material damage. However, empirical wear equations primarily focus on geometric material loss without considering the underlying physics governing degradation [5,6].

To improve understanding of wear mechanisms, several researchers introduced wear mechanism maps and energy-based approaches. Lim and Ashby developed wear mechanism maps that classify dominant wear regimes according to operating conditions such as load, sliding velocity, and temperature. These maps provide qualitative insight into transitions between adhesive, abrasive, oxidative, and delamination wear. Although useful for identifying dominant mechanisms, wear maps are not fully predictive and often require extensive experimental calibration.

Energy-based wear models later emerged as intermediate approaches between purely empirical and thermodynamics-based models. These formulations relate wear to dissipated frictional energy rather than only geometric contact parameters. Choudhry et al. [4] proposed an energy-based modification of Archard's wear model to improve predictive capability under varying operating conditions. Similarly, Klamecki [5] investigated entropy-based dissipation associated with plastic deformation in sliding contacts.

In rolling contact applications such as bearings and gears, fatigue-based classical models have also been widely employed. Lundberg–Palmgren rolling contact fatigue theory became one of the earliest approaches for bearing life estimation. These models predict bearing life statistically based on subsurface stress distributions and fatigue probability. Harris [17] later expanded rolling bearing analysis for practical engineering applications involving lubrication, contact mechanics, and fatigue failure.

Although classical rolling contact fatigue models remain widely used in industry, they also suffer from several limitations. These approaches generally rely on statistical assumptions and do not directly incorporate thermal degradation, frictional energy dissipation, or entropy generation. Under modern high-speed and high-load operating conditions, these neglected factors become increasingly important for accurate wear and fatigue prediction.

The growing limitations of empirical wear equations under complex operating conditions motivated researchers to explore thermodynamic and entropy-based approaches for analysing tribological degradation. Unlike classical models, entropy-based methodologies provide stronger physical interpretation by directly incorporating irreversible energy dissipation, frictional heating, and degradation accumulation. Nevertheless, classical wear models continue to remain important because of their simplicity, practical applicability, and widespread industrial acceptance.

III. BASED ON IRREVERSIBLE PROCESSES

The thermodynamic framework of wear is based on the principle that tribological degradation is fundamentally an irreversible process involving continuous energy dissipation. In tribological systems such as bearings, gears, brakes, and sliding contacts, mechanical energy supplied to the system is continuously transformed into frictional heat, plastic deformation, crack formation, and material removal. Unlike classical empirical wear models that primarily focus on material loss, thermodynamic approaches attempt to explain the physical mechanisms responsible for degradation through the laws of thermodynamics [5,6].

The first law of thermodynamics states that energy within a system is conserved. During sliding or rolling contact, the external mechanical work applied to the system is divided into several components. A portion of the energy is stored elastically within the contacting materials, while the remaining part is dissipated through irreversible processes such as frictional heating, plastic deformation, oxidation, and crack propagation. The dissipated energy contributes directly to material degradation and wear progression.

The second law of thermodynamics introduces the concept of entropy, which measures the degree of irreversibility within a system. Since friction and wear are irreversible processes, entropy generation continuously increases during tribological interactions. This makes entropy generation an important parameter for describing degradation behaviour in tribological systems.

The entropy generation rate may be expressed as:

$$\dot{S}_{\text{gen}} = \dot{Q}/T$$

where:

\dot{S}_{gen} is the entropy generation rate,

\dot{Q} is the rate of heat dissipation,

T is the absolute interface temperature.

This relationship indicates that entropy generation depends directly on frictional heat dissipation and operating temperature. Under severe operating conditions involving high load and sliding velocity, frictional heat generation increases significantly, resulting in higher entropy production and accelerated wear progression.

Frictional power dissipation in sliding contacts may be expressed as:

$$P_f = \mu Wv$$

where:

μ is the coefficient of friction,

W is the applied normal load,

v is the sliding velocity.

Combining frictional power dissipation with thermodynamic principles gives the entropy generation rate associated with frictional heating:

$$\dot{S}_{\text{gen}} = \mu Wv/T$$

This formulation demonstrates the direct relationship between friction, heat generation, and entropy production during wear processes.

In practical tribological systems, entropy generation is not caused solely by frictional heating. Several irreversible mechanisms contribute simultaneously to degradation, including:

- plastic deformation of surface asperities,
- oxidation and chemical reactions,
- crack initiation and crack propagation,
- subsurface fatigue,
- material transfer,
- lubricant degradation,
- microstructural transformations.

These irreversible phenomena collectively increase entropy generation within the contact region and accelerate material degradation.

One of the earliest thermodynamic approaches to wear was proposed by Klamecki [5], who investigated entropy-based plastic deformation energy dissipation in sliding contacts. Later, Basaran and Nie [6] extended irreversible thermodynamics concepts to damage mechanics of solids, establishing a theoretical basis for entropy-based degradation modelling.

Bryant and Khonsari [8] further developed thermodynamic degradation theory and proposed that wear and fatigue processes can be analysed using entropy accumulation principles. Their work established a strong relationship between irreversible thermodynamic dissipation and material degradation. Experimental investigations by Doelling et al. [7] demonstrated a measurable correlation between entropy flow and wear in machinery components, providing experimental support for thermodynamic degradation models.

The thermodynamic framework offers several important advantages over purely empirical wear equations. First, it provides a stronger physical interpretation of wear processes because it directly incorporates irreversible energy dissipation mechanisms. Second, it enables simultaneous analysis of wear and fatigue within a unified framework. Third, it supports integration with real-time condition-monitoring systems using measurable quantities such as interface temperature, vibration, friction coefficient, and heat flux.

Another significant advantage of thermodynamic approaches is their applicability under variable operating conditions. Classical wear equations often become inaccurate when operating parameters such as load, speed, and temperature fluctuate. In contrast, entropy-based formulations naturally account for these variations through continuous energy dissipation and entropy accumulation.

Thermodynamic degradation theories have also been applied to rolling contact fatigue analysis in bearings and gears. During repeated cyclic loading, subsurface stresses generate plastic deformation and crack initiation beneath the contact surface. These irreversible processes produce entropy, which accumulates progressively until failure occurs. Recent studies have successfully applied entropy-based approaches for predicting gear wear, bearing degradation, and lubrication failure [2,9,10].

Despite these advantages, several challenges still exist in the practical implementation of thermodynamic wear models. Accurate measurement of interface temperature and frictional heat dissipation remains difficult under high-speed and heavily loaded operating conditions. In addition, separating entropy contributions from different degradation mechanisms requires advanced experimental and computational techniques.

Another major challenge involves determining the critical entropy threshold associated with material failure. Experimental studies have shown that this threshold varies depending on material properties, lubrication conditions, operating environment, and loading history. Consequently, establishing a universal entropy-based failure criterion remains an active area of research.

Nevertheless, the thermodynamic framework of wear represents an important advancement in tribology because it links wear and fatigue directly with irreversible physical processes. By incorporating frictional dissipation, thermal effects, and entropy accumulation, thermodynamic approaches provide a more comprehensive understanding of tribological degradation compared with traditional empirical models.

IV. APPLICATIONS

4.1 Sliding Wear

Sliding wear occurs in brake systems, bearings, gears, and piston rings. During sliding contact, frictional forces generate heat that contributes directly to entropy production.

The frictional power dissipation may be expressed as:

$$P_f = \mu W v$$

where:

- μ is coefficient of friction,
- W is normal load,
- v is sliding velocity.

The corresponding entropy generation rate becomes:

$$\dot{S}_{\text{gen}} = \mu Wv/T$$

Aghdam and Khonsari [3] showed that entropy generation strongly correlates with wear behaviour in dry sliding conditions.

4.2 Rolling Contact Fatigue

Rolling contact fatigue is a critical failure mode in bearings and gears. Repeated cyclic stresses generate subsurface cracks that propagate toward the surface.

Entropy-based rolling contact fatigue models analyze cumulative irreversible energy dissipation during repeated loading cycles. Entropy accumulation eventually reaches a critical threshold leading to pitting and spalling.

Lin et al. [2] recently applied the DEG theorem to gear wear prediction and demonstrated improved predictive capability compared with conventional wear equations. Their work highlighted the applicability of entropy-based methodologies in modern gear tribology.

4.3 Bearings and Rotating Machinery

Bearings are critical components in rotating machinery. Failure of rolling bearings can cause major operational disruptions.

Entropy-based approaches have been increasingly applied for bearing condition monitoring using measurable quantities such as:

- vibration,
- temperature rise,
- friction torque,
- thermal preload,
- heat dissipation.

Belmiloud et al. [13] proposed a thermodynamic model for ball-bearing degradation under variable operating conditions. Harris and Barnsby [16] investigated tribological performance prediction for aircraft gas turbine bearings, while Harris [17] discussed rolling bearing analysis for practical engineering systems.

Entropy-based methodologies support predictive maintenance and remaining useful life estimation for rotating machinery.

V. COMPARATIVE ANALYSIS

The comparison between classical wear models and entropy-based approaches highlights significant differences in their theoretical foundations, governing parameters, predictive capabilities, and practical applications. Classical models have historically dominated tribological engineering because of their simplicity and ease of implementation, whereas entropy-based methodologies provide a more physically meaningful interpretation of degradation processes through thermodynamic principles.

Classical wear theories, such as the Archard wear equation, are primarily empirical in nature. These models establish relationships between wear volume and operating parameters including load, sliding distance, and material hardness. Because of their mathematical simplicity, they are widely used in industrial design and engineering calculations. However, empirical wear equations generally do not explicitly incorporate thermal effects, irreversible energy dissipation, oxidation, or microstructural changes occurring during operation [1,4].

Parameter	Classical Models	Entropy-Based Models
Basis	Empirical	Thermodynamic
Governing Parameter	Wear coefficient	Entropy generation
Thermal Effects	Limited	Explicitly included
Fatigue Analysis	Separate	Unified framework
Physical Interpretation	Limited	Strong
Variable Loading	Limited capability	Naturally incorporated
Real-Time Monitoring	Difficult	Feasible
Failure Criterion	Statistical/empirical	Critical entropy

Classical wear models remain useful for engineering design because of their simplicity and low computational cost. However, entropy-based methodologies provide a more physically meaningful description of degradation mechanisms.

VI. RESEARCH CHALLENGES AND FUTURE SCOPE

Although entropy-based wear modelling has shown promising results, several important challenges remain unresolved. One major challenge involves determining a universal critical entropy threshold applicable across different materials and operating conditions.

Another issue concerns accurate measurement of entropy generation at tribological interfaces. Reliable estimation of interface temperature and heat dissipation remains difficult under high-speed operating conditions.

Future research directions include:

- hybrid entropy–AI models,
- digital twin technology,
- multiscale degradation modelling,
- entropy-based finite element analysis,
- advanced thermal sensing systems,
- intelligent predictive maintenance platforms.

Machine learning combined with entropy-based approaches may significantly improve remaining useful life prediction and fault diagnosis.

VII. CONCLUSION

Classical wear models have played a major role in tribological engineering because of their simplicity and practical usefulness. However, these approaches often fail to represent irreversible thermodynamic degradation mechanisms occurring during operation.

Entropy-based methodologies provide a stronger physical framework by relating wear and fatigue to irreversible energy dissipation and entropy generation. Their ability to incorporate thermal effects, cumulative degradation, and real-time monitoring capabilities makes them promising tools for advanced wear prediction and predictive maintenance applications.

Although several challenges remain regarding entropy measurement and experimental validation, entropy-based approaches are expected to become increasingly important for future tribological research and intelligent condition-monitoring systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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