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Life and damage mode modeling applied to plastic gears

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ABSTRACT

There is a need to correctly dimension gears for an application with an understanding of how the gear will deteriorate until final failure. However, this task has been difficult because engineers must consider the complexity of gear meshing phenomena combined with the gear material-specific properties and application particularities to determine the critical failure and maintenance points. This article provides a review of the multiple damage modes of plastic gears, including both general and plastic gear-exclusive modes.

This article reviews the different branches of the damage problem, performs a combined solution of finite element analysis (FEA) and validated analytical equations for plastic gears. With this knowledge, a unique system of analysis of gear utilization perspectives that evaluates all possible damaging processes is built.

By applying a range of normal loads on a plastic gear, it was verified that the damage mode depends highly on the applied load. The identification of the proper damage mode allows preventive actions to be taken because the limits of plastic gears and the optimal usage are identified. With this damage modeling strategy, the designer can skip several steps in reaching a decision regarding plastic gear applicability. This synthesis represents significant progress for plastic gear damage modeling because the major factors of plastic gear functioning and the damage factors are observed.

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1. Introduction

Because gears are key elements of many power transmission systems, their eventual failure can ultimately cause the catastrophic failure of many modern machines. Thus, the estimation of those failures is important for maintenance planning to significantly reduce downtime and cost. Such estimation will also save on material losses due to non-optimized design and life utilization planning and will prevent people from becoming injured in some cases because failure is better understood.

Therefore, there is a need to correctly dimension gears for one application with an understanding of how the gear will deteriorate until final failure. Nevertheless, this task has been difficult because engineers must consider the complexity of gear meshing phenomena combined with the gear material-specific properties and application particularities to determine critical failure and maintenance points. If this goal can be achieved, the proper dimensioning of gears will increase the safety of the system and reduce the total cost of ownership during its lifetime.

The industry appreciate the economic and technical advantages of polymer gears (ability to operate without grease or oil lubrication, low cost of production, low density, high resilience and internal damping capacity) [1,2]. The use of plastic gears is steadily increasing. Some examples of the field application of plastic gears include the automotive industry, office machines and household utensils, and food and textile machinery [2,3].

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Machine components, such as gears, bearings, and shafts, made of polymer base materials behave unlike metals during service [4]. Compared to metallic gears, which suffer from chemical corrosion, lubrication-related failures, and expensive operating and maintenance costs, plastic gears are lighter, less noisy, lower in friction and cheaper to produce in large quantities with complex shapes using injection molding processes [3].

In the specific case of gears, a major part of the differences between metallic and plastic gear behavior occurs because plastics have an elastic modulus approximately one hundred times lower than those of most steels and thirty times lower than that of aluminum. Therefore, plastic gear meshing involves an extension of the contact between the teeth outside the line of action, before the beginning and after the end of the theoretical engagement [5]. The large deformation of the tooth during meshing tends to relieve each pair of teeth in contact. In the case of gears, the low modulus of polymers was historically considered to be desirable because the transmitted load is better distributed and both noise and contact forces are reduced during motion [6].

The heat produced during meshing by friction, contact hysteresis (on the surface of the teeth) and bending hysteresis (in the tooth bulk) causes a temperature distribution with significant localized instantaneous elevations in specific regions for points in the meshing due to the Hertzian contact and the low thermal conductivity of plastics. This phenomenon is the cause of thermal degradation, which is exclusive to plastic gears [7,8].

Gears typically experience complex stresses during service and can fail by several mechanisms, such as gear tooth wear, cracking at the tooth surface, tooth root cracking and severe shape deformation [3,9–11].

In this manner, the full potential of plastic gear usage is limited by not only the poor mechanical properties but also equally poor temperature limits and poor heat conduction properties [12,13]. A review of the multiple damage modes of plastic gears is listed in Table 1. In this table, the damage modes are divided into general modes and plastic gear-exclusive modes.

Amid the complexity of plastic gears, a number of commercial standards and design methods have been developed for practical purposes, e.g., British Standard [26], Polypenco [27] and ESDU [28]. These standards have different design priorities and philosophies. Furthermore, they are intended to be practical, not to optimize gear usage. None of the standards are comprehensive. The VDI [29] plastic gear design method is the most elaborate, but the aspect of wear is the least developed.

However, none of the standards correlated well with the test results [11,24], and the polymer composite gears' potential use in power transmission is limited due to the lack of understanding of their behavior under load, the physical limits created by the low strength of polymers and the knowledge of the most critical damage mode [2].

To our knowledge, there is no global model for damage for spur plastic gears. Because various damage modes occur simultaneously in the gear tooth during meshing and they are complex phenomena, gear life sizing is performed by the selection of what is expected to be the most important damage mode [2,8,9,11,19,21,22,24].

Temperature is often described as the main cause of failure in plastic gears because of their low melting point and low conductive properties [18]. The heat generated locally remains concentrated and does not dissipate. In other situations, it is important to evaluate how much power a polymer composite gear can transmit and to investigate the fatigue strength and wear resistance of the gear to determine which is the limiting factor in application, as they are concurrent processes. For example, Breeds, Kukureka [24] found that gear life is limited by wear at low torques and that the maximum permissible surface temperature is a limiting factor in the tested acetal gears at high loads.

In this article, we review the knowledge available in the literature for plastic gear meshing behavior and damage. We use this knowledge to build a unique system of analysis of gear utilization perspectives that evaluates all possible damaging processes. This article reviews the different branches of the plastic gear damage problem (as shown in Fig .1), creates a toolbox to be used together with finite element analysis (FEA) software, and validated analytical equations and relationships for plastic gear that will enable a designer to accurately forecast the behavior of plastic gears in context. The result of this effort is a tool for determining the limiting factor for plastic gear usage by giving the designer valuable information on how to use the proposed plastic gear or to take actions to enhance its lifetime, thus extending the range of plastic gear utilization by optimizing the design.

Table 1
Literature review of the failure modes of gears and plastic gears.

Gear damage modes	
Metal and plastic	Plastic exclusive
Deformations: Due to excessive surface stresses at the contact area, the involute profile is permanently distorted [14].	*Generalized thermal failure*: Softening of the entire tooth due to the loss of mechanical properties of the material under the effect of heat hysteresis and friction [2,15,16].
Brutal rupture: The contact stress does not damage the surface, but stress is concentrated in the tooth root due to the contact position and tooth shape [17].	*Surface thermal surface*: Localized softening of the tooth profile as a result of excessive heat, resulting in the melting of the material, material tears and deterioration of the profile [11,15,18].
Root fatigue: A stress concentration in the teeth roots initiates microcracking that propagates, causing the gear to fail later in the gear life. [19,20]	
Surface fatigue: A local stress concentration at the point of contact causes the material to locally fail in the surface layers [21,22]	
Wear: The combination of applied force and relative sliding speed causes the removal of material on the tooth surface [23–25]	

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