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Integrated Framework for Inspection, Functional Modeling, and Wear Compensation of Gears in Circular Production

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Abstract

Gears are among the most challenging components to reuse in circular production, since their load-bearing function demands high precision while their geometries inevitably deviate from original tolerances after service. In industrial practice, these deviations typically lead to rejection, as inspection criteria are often identical to those used for new parts. This rigid, tolerance-driven approach discards many components that may still function acceptably, highlighting the need for methods that assess gears on the basis of performance rather than dimensional conformity. This paper presents a function-oriented framework for gear wear compensation that combines high-precision metrology, functional modeling, and adaptive tolerance management. The methodology predicts gearbox performance directly from geometry measurements and restores functionality through selective pairing, adaptive manufacturing of complementary gears, or reprocessing of the worn gear itself. Functional testing in a virtual environment validates predicted outcomes prior to physical implementation. By prioritizing functional fulfillment over strict adherence to original tolerances, the proposed framework extends the usable life of gears and reduces material waste enabling circular production for complex gear systems.

Keywords: Function Modeling, Quality Control Strategies, Circular Production

1. Introduction

The reuse of end-of-life components is increasingly recognized as a key element of circular production, as it preserves embedded value and reduces resource demand [1]. In the context of circular production practice, however, the inspection and qualification of used parts pose significant challenges. It is a well-documented fact that critical load-bearing components, such as gears, are often rejected due to their geometries deviating from new-part tolerances after service. In the majority of industrial contexts, the criteria applied to the inspection of reused components are comparable to those applied to new components, resulting in the discarding of a significant proportion of components that could potentially be utilized [2].

For gears, which often are exposed to extended dynamic loading, this approach leads to significant challenges, as structurally intact gears quickly exhibit wear that exceeds the limits of new-part tolerancing. The restoration of these components to an "as-new" condition is a costly process, and frequently unnecessary, since minor deviations do not inherently compromise the functionality of the gear. Consequently, researchers have posited that uniform tolerance standards are suboptimal in the context of circular production, and that a transition towards function-oriented assessment is necessary [2]. This assertion is supported by the premise that a gear may not conform to its original dimensional requirements, yet still fulfill its function if appropriately paired.

This perspective gives rise to a number of new challenges. It is evident that each gear exhibits a unique deviation pattern, the

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result of its unique history and utilization during its initial life cycle. The classical tolerance management and selective assembly concepts were not designed with this level of individuality in mind [3]. Field observations have shown that failures frequently involve multiple simultaneous deviation modes [4], thereby complicating the process of reliable pairing. In order to surmount these obstacles, methodologies are required that establish a direct correlation between the measured geometry of worn gears and functional performance predictions. Such methodologies must also facilitate tolerance compensation through intelligent pairing or adaptive manufacturing processes.

This paper provides a framework that links measured gear geometries to functional performance predictions and outlines strategies for compensating wear through pairing, adaptive manufacturing, or reprocessing. In doing so, it establishes a basis for more reliable reuse of gears in circular production and opens pathways for future extensions towards practical implementation.

2. State of the Art

Research relevant to this work falls into two areas: Gear wear mechanisms and their impact on function (Section 2.1), and selective and adaptive assembly strategies for tolerance compensation (Section 2.2).

2.1. Gear Wear and Functional Impact

Gear performance is strongly influenced by wear processes that modify tooth geometry and surface conditions. The main wear and failure modes can be grouped as follows and are illustrated in Fig. 1 [5], [6]. *Surface fatigue*, which includes both pitting and micropitting, arises from repeated contact stresses exceeding the material fatigue limit. While pitting produces larger cavities that degrade flank geometry, micropitting generates many fine cracks that roughen the surface, leading to increased noise and vibration. *Adhesive wear*, often referred to as *scuffing*, occurs when lubrication fails, causing metal-to-metal contact. This mode is severe, creating smeared or welded areas on the flanks and often rendering gears unusable in a short time. *Abrasive wear* represents a more gradual process, in which hard particles or inadequate lubrication remove material from the tooth surface. The result is altered profiles, increased backlash, and reduced load capacity. *Corrosive wear*, by contrast, originates from chemical or electrochemical reactions that etch surfaces, thereby weakening fatigue resistance and promoting other damage modes. Finally, *bending fatigue* develops at the tooth root under cyclic stresses, leading to crack initiation and, in advanced stages, catastrophic tooth breakage.

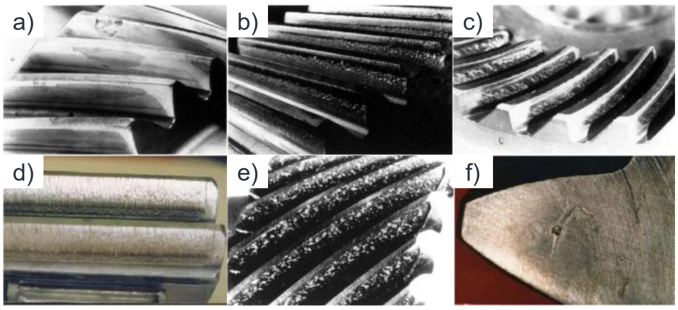

Fig. 1. Main wear and failure modes; (a) micropitting; (b) pitting; (c) scuffing; (d) abrasion; (e) corrosion; (f) bending fatigue crack; adapted from [5].

All of these mechanisms degrade functional performance by increasing backlash, transmission error, vibration, and ultimately by reducing durability. While each mode has been studied extensively, most investigations focus on isolated single effects within the functional models employed for the analyses [7]. In practice, however, gears are typically exposed to several interacting wear mechanisms at once [8], [9]. Recent research has therefore begun to address coupled processes, such as the interaction between wear and fatigue, or to adopt data-driven methods that use measured surface geometries [9], [10]. Nonetheless, comprehensive functional prediction for real, multiply worn gears remains an open challenge.

2.2. Selective Assembly and Adaptive Manufacturing

To mitigate the need for extremely tight tolerances while still ensuring functionality, researchers have developed two principal strategies. The first is selective assembly, in which components are measured, classified into tolerance groups, and subsequently paired in such a way that deviations cancel each other out. This method has long been applied in high-precision manufacturing, where economic constraints prevent holding narrow tolerances across all components [3]. More recent implementations enhance the classical approach with in-line metrology and artificial intelligence, allowing gear pairings to be optimized directly for functional outcomes such as minimal vibration and noise [11].

The second strategy is adaptive manufacturing, where instead of selecting from existing parts, one component is manufactured or modified specifically to compensate for the measured deviations of its counterpart [12]. This approach requires tight integration of metrology and machining, enabling closed-loop control and real-time adaptation of production parameters [13].

Both strategies have proven effective in reducing tolerance demands for linear production [12]. Their transfer to circular production, however, is less mature. Unlike linear manufactured parts, used components show highly variable and often unpredictable wear patterns, which weakens the assumption of reusability [14]. Some studies on remanufactured engines and gearboxes have demonstrated that grouping strategies and adaptive tolerance allocation can facilitate reuse [15]. Yet important gaps remain: existing approaches rarely integrate functional modeling of wear-induced effects, and current decision algorithms struggle to cope with the high variability of individual worn parts [14].

In summary, current research provides a solid foundation in both wear characterization and tolerance compensation for gears. However, an integrated methodology combining functional modelling of real worn components with adaptive pairing or manufacturing is still missing. The framework proposed in this paper is based on addressing this gap.

3. Proposed Framework

The methodological framework proposed in this paper for function-oriented wear compensation of gears is illustrated in Fig. 2 using the example of an angle grinder. Starting from a product that has reached the end of its first life cycle, the device is disassembled into its components or subsystems, which are then cleaned. In the next step, the disassembled parts are inspected individually, with this paper focusing particularly on the two gears. The *inspection* serves as a yes/no filter: only mechanically intact components that show no critical defects such as cracks, fractures, or broken teeth are considered suitable for reuse or reprocessing. At this stage, the gear is treated purely as a standalone component. The objective is not to predict functional behavior, but to assess its material and mechanical usability and to define potential limits for later reprocessing.

If the components pass this stage, *functional modeling* is applied. Here, the gear pair is considered as a system, and gear meshing behavior is analyzed based on the 3D measurement data. If predicted performance is satisfactory, the gears can be reused directly. If wear is too pronounced, compensation measures are applied. The framework distinguishes between *wear compensation* through pairing the gear with a suited slave gear, treating the reusable gear as the master gear, and *core reprocessing* of the master gear, if compensation through pairing is not sufficient.

In the first case, the framework derives the geometry of an ideal counterpart – the slave gear – from the measured master gear. A suitable real counterpart is then selected from an inventory, or adaptively manufactured. In the second case, the geometry of the master gear itself is reworked using additive and/or subtractive methods before pairing. Finally, functional testing evaluates the updated geometry pair virtually, using the same metrics as in the functional modeling step. This test is purely digital within the proposed framework. However, the developed models can be validated in practice by comparing simulation results against physical gear testing. The following subsections describe the four main steps in more detail.

3.1. Component Inspection

The inspection focuses on the individual examination of the components or gears and comprises two steps. First, optical methods such as high-resolution imaging detect critical damage patterns like pitting, cracks, or broken teeth, which lead to immediate exclusion of the inspected gear. Second, high-precision optical 3D metrology provides point clouds of all remaining gears. These are compared against the nominal CAD model to assess residual surface layer thickness and geometric deviations. The result is a binary decision: either the gear is mechanically usable due to a sufficient residual hardness layer and passed forward, or it is rejected. If usable, the data also enables the derivation of the maximum permissible reprocessing depth for later steps.

3.2. Functional Modeling

The functional model determines all gear performance characteristics relevant for gearbox operation depending on manufacturing deviations and wear. Within this framework, transmission error, backlash, and contact pattern distribution are evaluated against limits defined by the user or provided by input data. Classical tooth contact analysis (TCA) methods can be employed as a basis for the modeling approach [16]. In contrast to inspection, this step considers the gear pair as a functional system rather than individual parts. Deformation and strength checks are excluded, as they have already been roughly addressed in the inspection.

A central challenge for the functional model is the representation of gear geometries and ensuring robustness with respect to the wide variability of possible defect patterns. Classical approaches often rely on region-of-interest definitions on tooth flanks, which may not be adequate when wear produces discontinuous or localized geometry changes. In contrast, the proposed framework incorporates the full tooth geometry during contact analysis, enabling the consideration of edge cases and localized wear phenomena. Another challenge is the precise spatial alignment of the two gears, which depends

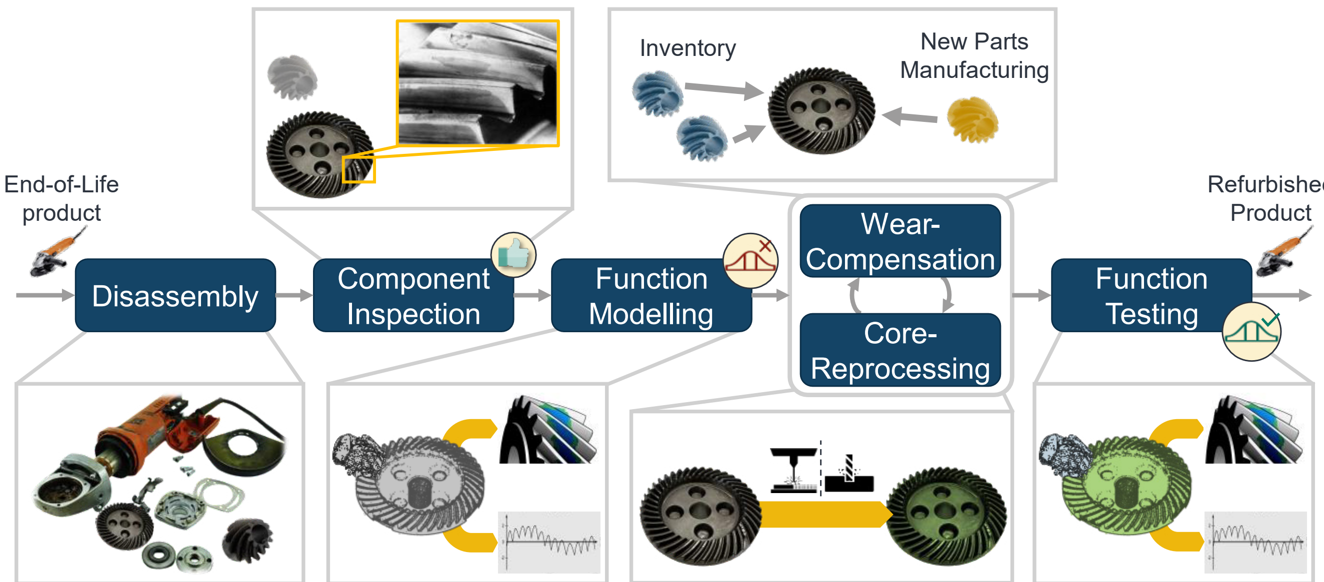

Fig. 2. Proposed framework for wear compensation in gear systems; detail image in yellow box adapted from [5].

on other system components such as bearings and shafts. This requires measurement data captured prior to subsystem disassembly. Finally, measurement uncertainty must be propagated into the model. This can be achieved by perturbing the measured points within their tolerance bounds and re-running the functional analysis for each gear instance, effectively providing a robustness assessment under metrology uncertainty.

3.3. Wear Compensation

If functional requirements cannot be met with the existing components, the next step determines whether the reusable master gear can be paired with a suitable slave gear from an inventory. Classical selective assembly approaches often employ Monte Carlo simulations to explore all possible gear pairings and their functional outcomes [17]. However, the computational effort for such methods becomes prohibitive when the functional model complexity and the number of possible combinations is large. Instead, the proposed framework introduces a methodological procedure to derive the ideal slave geometry directly from the measured master gear. Conceptually, this is achieved by virtually rotating the master geometry over a generic start volume, which represents the design space for the potential slave counterpart.

At each angular increment, regions of the slave volume that intersect with the master gear are removed. Over multiple revolutions, this process can be used to outline the complete ideal slave geometry. Based on this idealized counterpart, a similarity analysis can then be performed between the theoretical slave geometry and the measured data of available slave gears, thereby selecting the most compatible counterpart.

If available slave gears cannot provide sufficient compensation, or if economic considerations make it preferable, adaptive manufacturing methods are considered. By adjusting process parameters such as tool path or machine offsets, a new gear can be produced that closely matches the derived geometry. This targeted adjustment relies on a geometric process model that captures the effect of parameter variations within the bounds of process variability.

3.4. Core Reprocessing

Despite the compensation strategies in Section 3.3, functional testing may still fail. This is particularly likely in cases of non-rotationally symmetric wear patterns. Because gear pairs are typically designed with a relatively prime number of teeth to avoid repeat contact patterns, local wear on the master gear cannot be compensated by localized geometry variations in the slave gear alone. In such cases, direct reprocessing of the master gear is required. The required reworking depth is treated as a design variable within the framework, as it depends on the specific master gear geometry and the potential slave counterparts. The reprocessing depth is therefore varied iteratively: a new master geometry can be derived using a process model of the regrinding operation, and the resulting geometry can be paired with the ideal slave gear determined in Section 3.3. If the function is indicated as satisfactory in subsequent testing, the master gear can be physically reprocessed with the corresponding process parameters. If not, the reworking depth is increased in the next iteration and the cycle repeated until functional requirements are achieved or a defined maximum reprocessing limit is reached.

4. Discussion

The novelty of the proposed framework lies in three main aspects. First, it introduces function-oriented modeling of gears directly based on measurement data, enabling the evaluation of geometries that include multiple and interacting types of wear. This extends beyond the common practice of analyzing isolated wear mechanisms or idealized geometries. Second, the framework integrates selective assembly and adaptive manufacturing methods as systematic wear compensation strategies. By deriving an ideal counterpart geometry from the measured master gear, it allows for tailored selective assembly or targeted production of slave gears that restore functionality despite irregular deviations. Third, the framework explicitly considers reprocessing in conjunction with selective assembly and adaptive manufacturing, providing a comprehensive set of strategies for enabling gear reuse. Together, these contributions shift the reuse decision from rigid tolerance compliance to function-oriented assessment, thereby facilitating a higher recovery rate of gears in circular production.

While the framework demonstrates conceptual feasibility, several limitations remain. First, the current functional model does not fully capture load-dependent and dynamic effects such as transient stresses, lubrication, or thermally induced deformation, which are highly relevant in practical gear operation. Second, the approach presumes reliable high-resolution metrology. In practice, uncertainties in measurement and positioning may significantly affect prediction accuracy. Third, the computational demand of full-geometry contact analysis and slave-gear derivation can become prohibitive for large-scale industrial applications, necessitating simplifications or surrogate models.

5. Summary and Outlook

This paper proposed a framework for function-oriented wear compensation to enable the reuse of cost-intensive gears in circular production. Instead of relying on rigid dimensional tolerances, the approach evaluates the functional performance of gear pairs, allowing structurally intact but worn components to be returned to service through selective assembly, adaptive manufacturing of mating gears, or reprocessing of master gears. This reduces costs, minimizes material waste, and extends component lifetimes while ensuring reliable functionality.

Future research will concentrate on the implementation and validation of the framework's subsystems using representative use cases such as angle grinders and standard spur gears. Through systematic testing, the methodology will be refined to handle diverse wear phenomena and to optimize adaptive manufacturing strategies, ultimately supporting economically viable and sustainable gear reuse.

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