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TRIBOLOGICAL CHARACTERIZATION AND PREDICTIVE MODELLING OF TOOL WEAR IN DRY CNC MILLING OF BRITTLE CERAMIC CORES USING MACHINE LEARNING METHODS

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ABSTRACT
Ceramic cores used in investment casting of high-performance turbine blades require precise post-casting finishing to remove flash, dye lines, and tie bars without inducing microcracks or dimensional distortion. Traditionally performed manually, these operations pose challenges for throughput, repeatability, and structural consistency. As ceramic-core manufacturers transition toward automated CNC finishing, understanding the underlying tribological interactions between cutting tools and brittle ceramic materials becomes critical particularly in dry milling environments where abrasive wear is severe. At the same time, emerging machine-learning techniques provide new opportunities to model wear behaviour, optimise tool selection, and enable predictive maintenance strategies [2].

This paper presents an integrated experimental and computational study combining tribological analysis with early-stage machine-learning modelling. The experimental work evaluates tool wear mechanisms during CNC dry milling using a range of tool types including diamond-coated carbide, polycrystalline diamond (PCD), and novel ceramic cutting tools applied to representative flash, dye-line, and tie-bar removal tasks on silica- and alumina-based cores. Tool degradation is quantified through microscopic wear measurement, analysis of abrasive and edge-chipping mechanisms, and correlation with surface integrity metrics on the finished cores. Prior studies on PCD and CVD diamond tools in brittle ceramic machining document wear pathways such as abrasive scratching, edge chipping, coating delamination, and thermal fracture, providing relevant comparison baselines for this work [1, 2].

Layered onto this tribological foundation, a lightweight machine-learning pipeline is introduced to explore predictive relationships between machining parameters (e.g., spindle speed, local geometry, material heterogeneity, toolpath curvature) and observed wear progression. Feature-engineering strategies are used to incorporate local geometric complexity such as tie-bar orientation and channel-intersection sharpness to capture the brittleness-driven fracture behaviours unique to ceramic finishing. Initial regression and classification models demonstrate the ability to distinguish between wear modes and forecast tool-degradation trends, laying the groundwork for future real-time monitoring and adaptive toolpath planning. Although tool-wear modelling in ceramics is dominated by tribological studies, emerging opportunities exist to fuse experimental wear characterisation with data-driven predictive modelling [3].

The combined findings highlight how tool-material microstructure, thermal and abrasive interactions, and geometric loading conditions jointly influence wear pathways during dry milling of brittle ceramics. By integrating machine learning with tribological experimentation, this work provides a framework for predictive tool-wear modelling that supports CNC process optimisation and long-term automation of ceramic-core finishing. This approach accelerates the industry's shift from manual craftsmanship toward data-driven, consistent, and scalable manufacturing of turbine-core components [4].

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