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Towards Reliability Analysis: Experimental Characterization of Angle Grinder Load Profiles Considering Tool Wear and Workpiece Material Effects

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Product design and reliability predictions require a detailed understanding of the operational loads acting on technical systems. This is particularly relevant for remanufactured products in circular production systems, where the reliability of each unique product depends on its usage history. As these usage histories are ultimately reflected in the loads acting on the system, realistic and representative load profiles are required for their interpretation for reliability models. Previous studies have captured load profiles of angle grinders under realistic conditions, capturing the influence of the user and application. However, key influencing factors of load profiles, including tool wear and workpiece material, remain to be investigated. Given their unavoidable presence in practice, these factors must be analyzed within realistic application scenarios. However, no experimental setup has been presented that can capture comprehensive load profiles while accounting specifically for the influence of tool wear and workpiece material.

To address this gap, a user study and an experimental setup were developed to acquire realistic load data on angle grinders, building upon the state of the art. An angle grinder with integrated sensors was used in user studies to capture external loads during cutting and grinding steel and aluminum. The proposed setup allows mechanical, electrical and thermal measurements, as well as tool wear, to be acquired and analyzed under realistic operating conditions. This expands upon existing load acquisition approaches by incorporating the influence of the workpiece material and tool wear.

Measurements confirm the feasibility of the setup and demonstrate its capability to capture relevant variations in operational loads. These initial findings establish a methodological foundation for building representative load datasets incorporating tool- and material-dependent influences. The study therefore forms an important step towards translating complex operational loads into the unique usage histories required for accurate, instance-specific reliability analysis within the framework of the Circular Factory.

Keywords: Load Profile, Experimental Setup, Tool Wear, Reliability, Angle Grinder, Circular Factory

1. Introduction

The Circular Factory (CF) envisions a future in which used products are systematically transformed into new product generations through the recombination and reconditioning of degraded subsystems, thereby minimizing resource consumption and waste while preserving value (Lanza et al. 2023). This vision is operationalized by assembling new configurations from existing subsystems - for example, combining components from multiple degraded angle grinders into a new, functionally viable system (Grauberger et al. 2024).

A simplified representation of this decision-making process is illustrated in *Fig. 1*, where two feasible configurations (blue and green) are derived from the subsystems of various degraded angle grinders. As each new feasible configuration has unique subsystems, it also has its own instance-specific reliability.

To enable informed decisions regarding which subsystems to combine, two critical pieces of information are required. First (1), the functional behavior expected from a specific subsystem combination at the time of reassembly must be predicted. Second (2), the expected reliability of the new configuration must be estimated, which depends on its current degradation state and how this state will evolve over time. Notably, two configurations may exhibit identical performance but differ significantly in remaining useful life, underscoring the necessity of instance-specific reliability models capable of predicting degradation trajectories for each possible combination. (Afifi et al. 2025)

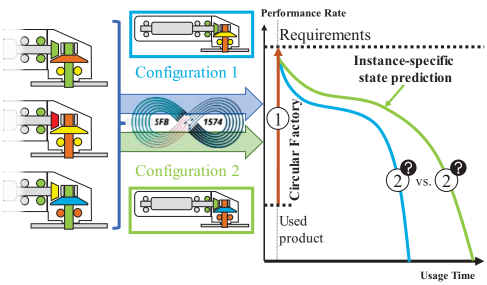

Fig. 1.Simplified representation of the decision-making process in the Circular Factory (CF) between two feasible configuration (blue and green). Feasible configurations are derived from the subsystems of various degraded angle grinders. Each of these configurations possesses its own instance-specific reliability.

Reliability models, in general, require both a deep understanding of system behavior and empirical data on degradation under operational conditions. Such data are typically obtained through controlled testing on test benches, which offer the advantages of reproducibility and safety by eliminating human exposure to hazardous conditions (Dörr, Mertens, et al. 2021; Matthiesen et al. 2018). However, to ensure accurate predictions, particularly when modeling instance-specific degradation, the load profiles applied on the test bench must reflect real-world usage as closely as possible.

Every load profile necessarily involves simplifications to enable its implementation on a test bench (Dörr, Mertens, et al. 2021). For instance, actuator frequencies may be regularized, and multiple load profiles from different applications or scenarios must be intelligently combined to depict a bigger variety in loads. To make evidence-based decisions regarding these simplifications, a comprehensive understanding of real-world load profiles and their influencing factors is essential. We hypothesize that functional behavior and consequently degradation is influenced by a multitude of environmental factors, including the operator, the specific application, and ambient conditions. While some of these influences are already known, such as the impact of different applications on load profiles (Dörr, Mertens, et al. 2021; Matthiesen, Gwosch, and Bruchmüller 2017; Matthiesen et al. 2016a), others remain to be investigated. Notably, existing studies have often neglected the effects of tool wear and workpiece material, despite their unavoidable presence in real applications. As tool wear inevitably alters the cutting efficiency and the point of force input, and as workpiece material directly influences the resistance encountered during operation, both factors are expected to significantly affect load spectra. The testing environment presented in this paper is specifically designed to capture these effects, thereby providing a foundation for evidence-based load profile generation for future test bench applications.

2. State of the Art

The following section outlines the current scientific landscape regarding the operational behavior of angle grinders, categorized into the fundamental drivers of load variability and methodologies for load acquisition.

The characterization of system behavior in manual power tools is fundamentally dictated by the specific application, such as roughing, grinding, or cutting. Research emphasizes that the generation of high-fidelity, reality-oriented load profiles is a prerequisite for meaningful investigations on mechanical test benches (Matthiesen, Gwosch, Mangold, et al. 2017). These profiles must account for diverse application scenarios to accurately reflect the loads experienced by the tool's drivetrain. By utilizing indirect measurement techniques, such as the relative displacement measurement of drive shafts, studies have successfully identified application-equivalent component loads across various tasks, including the chamfering, deburring, and rust removal of steel, as well as the processing of stone (Matthiesen et al. 2016b). Furthermore, investigations into the vibration causes within the drivetrain, monitoring gear housing acceleration, workpiece reaction forces, and differential rotation angles, confirm that both the specific application and the individual user significantly influence the resulting load collective (Matthiesen, Gwosch, and Bruchmüller 2017; Matthiesen et al. 2018).

Building on these established strategies, the present work adopts these validated techniques to characterize the baseline drivetrain behavior. This baseline serves as a reference for evaluating the additional influences of tool wear and workpiece material.

A critical challenge in reliability modeling is quantifying the sources of variability in operational loads. Literature indicates that vibration exposure is highly dependent on the specific tool-disc combination (Liljelind et al. 2010). While some findings suggest that at least one-third of estimated variability is attributable to the grinding wheel and less than one-third to the operator (Liljelind et al. 2010), other studies indicate that the operator's influence on total variability may be as low as 1% in specific cutting tasks (Liljelind et al. 2013). Key determinants for frequency-weighted acceleration include the specific machine used, the duration of the task, and critically, tool wear. The loss of weight in the grinding wheel over time has been identified as a significant factor affecting the vibration emissions and the resulting load on the user and the system (Liljelind et al. 2013).

Accurate acquisition of interaction forces between the tool and the workpiece is essential for degradation modeling. While traditional validation involves three-axis piezoelectric force sensors positioned beneath the workpiece (Ni et al. 2019; Matthiesen et al. 2018; Dörr, Ott, et al. 2021) several indirect methodologies have been developed for manual operation. These include estimating interaction forces through the measurement of input point impedance at the human hand and tool acceleration (Lim et al. 2013). Others utilize sensor-integrated "boxes" attached to the tool, which leverage machine learning to predict forces based on consumer-grade sensor data, although achieving high accuracy across all application types remains a challenge (Dörr, Ott, et al. 2021).

While indirect methods offer better tool mobility, achieving sufficient accuracy for multi-axial loads remains a challenge. To ensure the high-fidelity data needed for reliability modeling, this study utilizes direct measurement via a three-axis piezoelectric force sensor positioned beneath the workpiece.

In the context of process parameters, modeling approaches suggest that grinding forces are a dynamic function of wheel speed, feed rate, and changes in the depth of cut (Guo et al. 2016). Material properties and thermal treatments also play a decisive role; for instance, abrasive metal cutting with ultra-thin discs shows significant variations in specific energy consumption depending on the material's resistance and the feed rate (Awan et al. 2022). Furthermore, the "grinding ratio", defined as the volume of material removed relative to the volume of wheel wear, has long been established as a primary indicator of process efficiency and tool life (Krabacher 1959).

The manual nature of angle grinder operation introduces the "human-in-the-loop" variable. Research focusing on human skills during manual grinding has demonstrated that an operator's inherent technique and experience level significantly control machining performance (Das et al. 2018). While models have been developed to associate operator profiles with process performance quantitatively, these are often limited by sample sizes.

While these studies provide a foundation for understanding operational behavior, the critical parameters of workpiece material and tool wear have not yet been comprehensively investigated.

3.Testing-Environment

The experimental setup presented in this paper is designed to achieve two primary objectives. First, it aims to explore the influence of workpiece material and tool wear on the mechanical and thermal loads experienced by the angle grinder during operation. Second, it seeks to generate the data for a representative load profile that can later be implemented on a test bench for degradation testing. These objectives impose distinct requirements on the measurement variables, which are identified and subsequently integrated into a unified measurement system.

3.1. *Testing Variables*

The *independent variables* consist of the workpiece material (aluminum and steel) and the application type (cutting and roughing). A new CG 15-125 BL (C. & E. Fein GmbH, Germany) angle grinder was used for all tests. Each application utilized a corresponding 125 mm tool from PFERD TOOLS (August Rueggeberg GmbH & Co. KG, Germany), specifically a cutting wheel and a roughing wheel. The selection of aluminum as a soft material and steel as a harder material provides a necessary contrast to highlight differences in load spectra based on material resistance. These factor levels resulted in a total of four unique application scenarios (see *Table 1*).

Table 1.Captured use cases for monitoring the loads on an angle grinder during use

Angle grinder: Fein CG15-125 BL	
Cutting with Tool PFERD EHT 125-1.6 PSF Steelox	Aluminium
Roughing with Tool PFERD E 125-4.1 PSF Steelox	Steel

The *dependent variables* of interest are the mechanical and thermal loads imposed on the angle grinder, which are quantified through a suite of sensor measurements.

For the purpose of load profile generation, the key quantities to be measured are the forces acting on the tool, rotational speed, and torque. The forces acting on the tool are derived from the ground reaction forces measured by a multi-axis force sensor (see chapter 3.2.1.) mounted in the clamping fixture, combined with angular orientation data from an inertial measurement unit mounted on the tool. Torque, which cannot be directly measured during manual operation, is estimated indirectly using the power consumption of the tool and a pre-characterized torque-speed map of the angle grinder's motor.

In addition to these direct load measurements, several indirect indicators of degradation are also monitored. These include the difference between power input and mechanical output (as a proxy for efficiency), shaft displacement (as an indicator of bearing wear), temperature, vibration levels, and acoustic emissions. These indicators provide insight into the internal state of the tool and can be correlated with external load conditions to support the development of degradation models.

3.2. *Setup*

The experiments were conducted at the Power Tool Testcenter of the Institute of Product Engineering at the Karlsruhe Institute of Technology. The environment featured an extraction system to keep the workspace free of airborne particles and used two cameras—one positioned above and one to the side—to document the trials.

The testing environment featured an extraction hood, two cameras to document the trials, a clamping fixture, the sensor-integrated angle grinder and a dedicated camera system employed to quantify the diameter of the cutting discs (see Fig. 2).

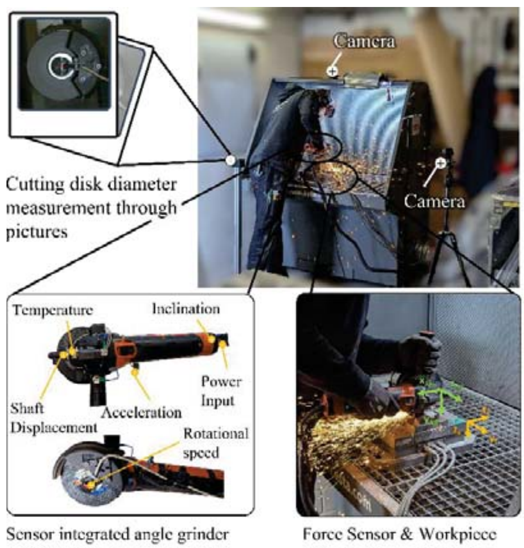

Fig. 2.Overall testing hardware. Top left: picture of angle grinder cutting wheel while it is running. Used for diameter measurements. Top right: extraction hood and work area. Bottom left: Sensor integrated angle grinder. Bottom right: Force sensor and workpiece during test run *cutting steel*.

3.2.1. *Clamping fixture*

The clamping fixture (Fig. 3) was engineered for high stiffness, ensuring a rigid connection between the sample and the Kistler Type Z 3393 (SN: 57068, Kistler Instrumente AG, Swiss) three-dimensional force sensor. To protect the piezo-based sensor from temperature-induced errors, a thermally insulating material (KELUX 600M) was placed between the fixture and the sensor. The fixture itself was firmly attached to the extraction hood, and the design allowed for rapid sample changes to minimize downtime between trials.

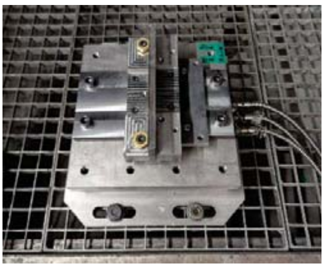

Fig. 3.Clamping fixture and force sensor. Depending on the use case the work piece will be clamped differently. The fixture itself is thermally insulated from the force sensor.

3.2.2.*Sensor equipped angle grinder*

The angle grinder was instrumented with multiple sensors, according to the measurement variables stated in chapter 3.1. In order to minimize the impact on the handling of the angle grinder, care was taken to ensure that the sensors were as small as possible and positioned in such a way that they did not need to be touched during the grinding and cutting process (see Fig. 4 and Fig. 5).

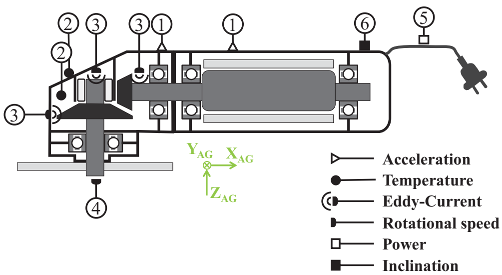

Fig. 4.Sensor types and measuring points of the sensor equipped angle grinder.

Power consumption was measured via current and voltage sensors (CASR 25-NP and LV 25-P, LEM International SA, Schweiz) at the power cable. For **speed measurement**, a custom circuit board with an ams AS5134 (ams-OSRAM AG, Austria) Hall sensor was placed in front of the output spindle, with a diametric magnet integrated into the clamping nut. **Shaft displacement** was captured using eddy current sensors (T05-G-KA-112 & T05-G-KA-VK10-112, eddylab GmbH, Germany) positioned to measure the radial position of the output bevel gear, the axial position of the output spindle and the radial position of the input shaft at the small bevel gear.

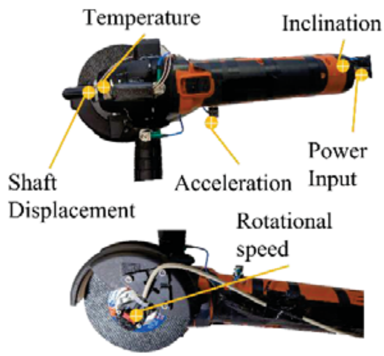

Fig. 5.Sensor equipped angle grinder.

Temperatures were monitored both on the gear housing and inside the tool using 1-T-B10-2M-F11TX-CL1 thermocouples (TC Mess- und Regeltechnik GmbH, Germany) with the Pro II-TC-8 ISO Rev. E measurement card (Jäger Computergesteuerte Messtechnik GmbH, Germany). **Accelerations** were recorded at the handle, housing, and gearbox using PCB-356B21 (PCB Piezotronics, USA) sensors, with placement following DIN EN ISO 28927-1:2019. An additional sensor is placed onto the gearbox housing to capture accelerations in immediate proximity to the gearing. This configuration is essential because the aluminum housing functions as the primary structural component for the shaft bearings, making it a critical location for monitoring the mechanical vibrations and potential degradation of the drive train. Finally, a BNO055 (Adafruit Industries, LLC, USA) orientation sensor was used to track the **tool's inclination**, allowing for the alignment of the tool's coordinate system with that of the force sensor.

3.2.3.*Cutting disk measurement*

To quantify tool wear, a photo (camera acA1440-220uc, SN: 40331689, Basler AG, Germany & Basler lens 1:1,8/25mm) of the cutting disc is taken after each completed cutting process, from which the diameter of the disc can then be recorded. In addition to the visual analysis, the mass of the cutting disc is determined using a precision scale (DS 8K0.05, KERN & Sohn GmbH, Germany), both in new condition before the start of the test and after completion of the entire series of measurements.

For the evaluation of the image data, additional photos of a calibration board are taken so that the diameter can later be measured from the photo of the tool disc on the running angle grinder using the MATLAB Computer Vision Toolbox (The MathWorks, Inc., USA).

3.3. *Test run*

The study involved ten participants. This sample size exceeds the minimum requirement of three operators mandated by DIN EN ISO 28927-1:2019 (Deutsches Institut für Normung e. V. 2020) for measuring the vibration emissions of hand-held power tools. This provides a more comprehensive dataset for analyzing user-induced variability. The group comprised a mix of professional experts and novices, categorized through a structured assessment of their prior experience and frequency of tool use. Experts were defined as individuals with formal training and regular professional or private experience with angle grinders, while novices were defined as users with minimal or no prior exposure to such equipment. Although the study primarily focused on right-handed users, one left-handed novice was specifically included to account for potential variations in force transmission and handling dynamics. The final sample size of ten subjects provided a sufficient methodological buffer to ensure data integrity and capture a wide spectrum of operational behaviors.

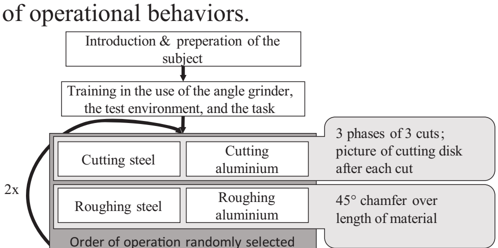

Fig. 6. Flowchart of full testing procedure. Each participant does two runs of each application: cutting steel, cutting aluminium, roughing steel, roughing aluminium

The experimental procedure began with an introduction, followed by a familiarization phase where subjects became accustomed to the tool and the task (see Fig. 6). Each of the four applications was repeated twice, totaling eight trials per subject.

A single cut (Fig. 7 left) involved cutting a 10 mm thick and 80 mm wide piece of aluminum or steel. The sample was clamped flat for this purpose. During cutting tasks, three cuts were performed per phase. The cutting task involved three phases, totaling nine cuts per repetition. However, trials were stopped if the disc became unusable.

For roughing (Fig. 7 right), participants worked the entire length of the sample (200 mm x 80 mm x 10 mm) to a 45° angle. To minimize carry-over effects, the sequence of applications was randomized, and participants were allowed to take breaks as needed.

Fig. 7. Test run. Left roughing aluminium. Right cutting steel. Both material samples are the same size of 200 mm x 80 mm x 10 mm clamped and oriented in different ways.

4. Validation of the test setup

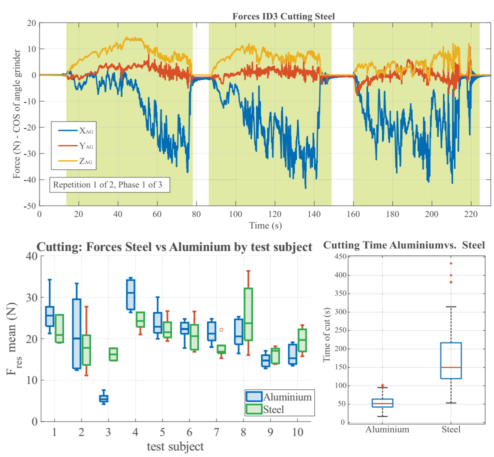

Fig. 8. Initial test results of the presented setup. Top: Example of cutting forces in axial direction of the

output shaft of the angle grinder. Bottom left: Mean total forces on angle grinder during cutting for different subjects and materials. Bottom right: mean time of cutting steel vs. aluminum.

Preliminary analysis of mean values reveals visible trends; for instance, forces during cutting differ only slightly between materials for the same test subject. Also test subjects themselves have a big influence on cutting forces (Fig. 8 bottom left). Cutting times vary greatly while cutting different materials (Fig. 8 bottom right).

5. Discussion

The developed setup successfully enables the simultaneous measurement of loads, tool wear and indicators for the state of degradation of the angle grinder across different applications and materials. This configuration allows for the characterization of the "as-is" state of a new angle grinder under realistic conditions. A unique contribution of this work is the ability to directly compare interaction forces between the tool and material with internal degradation indicators, such as bearing clearance measured via shaft displacement. This comparison is expected to provide deeper insights into the behavior of the system under real-world conditions.

While previous studies often measure tool wear only before and after a task, this setup allows for the measurement of disc wear in several stages during the trial. This provides a more detailed view of how the system behavior changes as the tool degrades. Additionally, the experimental setup remained functional under the harsh working conditions of the study, proving its practical suitability for manual power tool research.

However, there are some limitations to consider. While radial shaft displacement is captured, the setup does not measure the axial play of the input shaft. Furthermore, torque is measured only indirectly through electrical power consumption, and the setup lacks a way to directly measure the wear of the power tool itself. There is also a potential influence from the workpiece clamping; the rigid mounting required for the force sensors likely affects the operator's posture and handling compared to unconstrained work. Future studies could investigate how different clamping configurations change the resulting load profiles. Finally, while ten participants provide a baseline for user-induced variability, this sample size may not be large enough to support generalized conclusions across the broader population.

The knowledge gained from these trials will serve as an evidence-based foundation for deriving load profiles for future test bench degradation studies. Furthermore, the investigation of these effects can lead to improvements in the overall system behavior of angle grinders. While a full evaluation of the data is still pending and the setup is currently system-specific, the measurement principles and the methodology for isolating relevant variables can be adapted by other researchers in the field.

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While preparing this work, the authors used AI tools such as deepl.com and Gemini 3 to improve readability and language. After utilizing these tools, the authors reviewed and edited the content as necessary. The authors take full responsibility for the publication’s content.

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