

# Experimental Study on the Wear Mechanisms of Cutting Tools in High-Performance Machining

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## Abstract

*Because high-performance machining (HPM) may increase output and improve product quality, it is essential for modern production. The quick wear of cutting tools under high-stress circumstances, however, presents serious difficulties that affect surface smoothness, tool life, and cost-effectiveness. Through an analysis of the impacts of cutting speed, feed rate, tool material, and cooling techniques, this work explores the wear processes impacting cutting tools in HPM. Advanced spectroscopy and microscopy procedures were used to characterize wear patterns and processes. The results show that fatigue wear caused by abrasive, adhesive, diffusion, oxidation, and thermal-mechanical processes is common and that different machining settings affect these systems. Notably, it turned out that minimum quantity lubrication (MQL) efficiently mitigates adhesive wear. This research contributes to the creation of more effective and long-lasting HPM processes by offering vital insights for maximizing tool performance and prolonging tool life.*

**Keywords:** High-performance machining, minimum quantity lubrication, XRD, SEM, EDS

## INTRODUCTION

A notable development in manufacturing technology is high-performance machining (HPM), which allows for improved material removal rates, better surface finishes, and higher production efficiency. HPM makes it possible to machine materials that are difficult to cut, such as composites, superalloys, and high-strength steels, more effectively by enabling faster cutting speeds, feed rates, and depths of cut. This skill is especially important in sectors where efficiency and accuracy are critical, such as the manufacture of medical devices, motorbikes, and aircraft.

The advantages of HPM are not without shortcomings, though, chief among which being the faster wear of cutting instruments. High temperatures, high mechanical stresses, and aggressive material removal are some of the harsh circumstances that come with HPM. These conditions worsen tool wear, which lowers tool life and raises machining costs. Comprehending the wear interprets that transpire in these circumstances is essential for creating cutting tools that exhibit enhanced lifetime and performance [1].

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There are several different kinds of wear mechanisms in cutting tools, such as adhesion, diffusion, oxidation, and thermal-mechanical fatigue. When there are rough edges or particles on the surface of the workpiece, the tool loses material due to abrasive wear. Material transfer between the tool and workpiece is the cause of adhesive wear, which is frequently seen as built-up edges. Diffusion wear weakens the tool material by atomic-level material exchange at high temperatures. The development of brittle oxides as a result of chemical reactions at high temperatures

is what defines oxidation wear. Crack development and propagation are caused by cyclic mechanical and thermal loads, which are termed as thermal-mechanical fatigue.

The goal of this study is to completely investigate these wear processes in relation to HPM. This study aims to clarify the predominant wear processes under diverse machining settings by analyzing the impacts of different cutting parameters, such as cutting speed, feed rate, and cooling methods, on various tool materials. To evaluate the wear patterns and underlying causes, sophisticated techniques for analysis such as energy dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), and scanning electron microscopy (SEM) will be deployed [2].

It is anticipated that the results of this research will offer significant perspectives for the enhancement of cutting tool composition and machining parameters, consequently augmenting the effectiveness and durability of high-performance machining procedures. Through tackling the essential elements of tool wear in HPM, this study advances the more general objective of enhancing manufacturing technology and cutting production costs.

## **METHODOLOGY**

### **Experimental Design**

Using a factorial experimental travel, the study methodically examines how different factors affect cutting tool wear during high-performance machining (HPM). Tool material, feed rate, cutting speed, and cooling technique are some of the factors. To cover a wide variety of machining circumstances, various layers of testing are performed on every value [3].

### ***Parameters and Levels***

Tool Materials:

- Uncoated Carbide;
- Coated Carbide (TiN and Al<sub>2</sub>O<sub>3</sub>);
- Ceramic; and
- Cubic Boron Nitride (CBN).

Cutting Speeds:

- 150 m/min (low);
- 300 m/min (medium); and
- 500 m/min (high).

Cooling Methods:

- Dry Machining;
- Flood Cooling; and
- Minimum Quantity Lubrication (MQL).

### **Sample Preparation**

AISI 4140 steel is the workpiece material which was used for this investigation. Standard dimensions are followed while preparing samples to guarantee uniformity throughout testing. Before machining, every sample is examined and cleaned to get rid of any surface impurities or mistakes that might have an impact on the outcome [4].

### ***Machining Setup***

A CNC milling machine operating at a high speed is used for all trials. Prior to every test, the machine is calibrated to guarantee precision in terms of feed rate, cutting speed, and tool placement. To be sure that the wear shown is caused by the present test circumstances and not leftover wear from earlier testing, new cutting tools are used for every test [5].

## **Wear Analysis Techniques**

### ***Scanning Electron Microscopy (SEM)***

The tool wear surfaces are imaged in high definition using SEM. By offering in-depth pictures of the tool's surfaces and edges, it aids in determining the nature of the wear mechanisms. Examined are particular characteristics like adhesive build-up, thermal fractures, and abrasive grooves.

### **Energy Dispersive X-ray Spectroscopy (EDS)**

EDS and SEM cooperate in order to do elemental analysis. This method aids in the identification of diffusion wear and adhesion by sensing material transfer from the workpiece to the tool and vice versa. Additionally, the elemental makeup of wear debris will be investigated.

### ***X-ray Diffraction (XRD)***

When machining, extremes can cause phase changes in the tool material. These changes can be detected using XRD. It facilitates comprehension of oxidation processes and any thermally induced changes that the tool material experiences [6].

### **Optical Microscopy**

The wear width is first assessed and measured using optical microscopy. It offers a rapid evaluation of the degree of wear and aids in tracking wear increase over time.

## **EXPERIMENTAL PROCEDURE**

### **Setup and Calibration**

#### ***Install new cutting tools***

- Set the CNC milling machine to the desired cutting speed and feed rate.
- Apply the selected cooling method (dry, flood, or MQL).

### **Machining**

- Perform machining on AISI 4140 steel samples under specified conditions.
- Monitor and record the machining parameters and tool wear progression at regular intervals.

### **Tool Wear Measurement**

- After each machining interval, measure the wear width using optical microscopy.
- Collect wear debris for EDS analysis.
- Document the wear patterns and mechanisms using SEM and EDS.
- Conduct XRD analysis on worn tools to detect any phase changes.

### **Data Collection and Analysis**

- Compile the measured data on wear width, surface roughness, and tool edge integrity.
- Perform statistical analysis to identify significant trends and correlations between the machining parameters and tool wear.
- Use the analytical results to understand the dominant wear mechanisms under different conditions [7, 8].

## **DATA ANALYSIS**

The impacts of each parameter on tool wear are ascertained by statistical analysis of the gathered data. ANOVA, or analysis of variance, is used to find important components and how they interact. Based on the machining characteristics, regression analysis is used to create prediction models for tool wear. Insights into improving cutting conditions for reducing tool wear and increasing tool life are gained from the interpretation of the data.

This methodology seeks to provide an in-depth understanding of the wear mechanisms in high-performance machining by methodically examining the impact of various machining parameters on tool

wear. Ultimately, this will aid in the development of more resilient cutting tools and effective grinding procedures.

### **Wear Mechanisms**

Cutting tools are exposed to harsh conditions during high-performance machining (HPM), which causes a variety of wear mechanisms. To improve tool life and machining performance, it is essential to comprehend these mechanisms in order to optimize tool material and machining settings. This study has shown abrasive wear, adhesive wear, diffusion wear, oxidation wear, and thermal-mechanical fatigue as the main wear processes. As shown below, particular machining conditions and factors affect each mechanism:

#### ***Adhesive Wear***

- Occurs when two solid surfaces slide over each other, leading to material transfer or loss.
- This happens due to the formation of adhesive junctions or cold welds at the contact points.
- Examples include sliding parts in machinery like gears and bearings.

#### ***Abrasive Wear***

- Happens when a harder surface or particles slide or roll over a softer surface, causing material removal.
- It can be two-body (direct contact) or three-body (with abrasive particles in between the surfaces).
- Examples include machining processes and sandblasting.

#### ***Erosive Wear***

- Caused by the impact of solid or liquid particles against a surface.
- The repeated impact leads to material loss [9].
- Examples include pipeline erosion due to slurry flow and turbine blade wear.

#### ***Corrosive Wear***

- Combines mechanical wear with chemical or electrochemical reactions.
- When the surface material interfaces with the surroundings, a soft or fragile layer that is quickly worn away emerges.
- Examples include rusting of steel in moist environments and corrosion in marine applications.

#### ***Fatigue Wear***

- Results from cyclic loading and unloading, causing surface and subsurface cracks.
- These cracks propagate over time, leading to material removal.
- Examples include rolling contact fatigue in bearings and gear teeth.

#### ***Fretting Wear***

- Occurs due to small amplitude oscillatory motion between two contact surfaces.
- This leads to surface fatigue and oxidation, often seen in joints and connections.
- Examples include bolted joints and electrical connectors.

#### ***Cavitation Wear***

- Caused by the formation and collapse of vapor bubbles in a liquid near a surface.
- The collapse of these bubbles generates high-pressure micro-jets, leading to surface erosion.
- Examples include damage to ship propellers and hydraulic turbines.

#### ***Impact Wear***

- Occurs when repetitive impacts cause surface deformation and material loss.
- This can be due to solid or liquid impacts.

- Examples include hammering actions and particle impact on surfaces.

### ***Oxidative Wear***

- Involves the formation of oxide layers on the surface due to high temperatures or environmental conditions.
- These oxide layers can be harder or softer than the base material, affecting the wear rate.
- Examples include high-temperature applications like turbine engines.

Every wear mechanism functions standalone and in conjunction with other mechanisms, and the dominant mechanism is frequently determined by the particular application and operating environment. Comprehending these principles aids in the selection of suitable materials, surface treatments, and lubrication techniques to reduce wear and increase component lifetimes.

### **Effects of Cutting Parameters**

Cutting parameters, namely cutting speed, feed rate, and depth of cut, play a critical role in determining the wear mechanisms and rates experienced by cutting tools in high-performance machining (HPM). Understanding how each parameter influences tool wear can aid in optimizing machining processes to enhance tool life and maintain high-quality machining outputs.

#### ***Cutting Speed***

##### ***Impact on Wear Mechanisms***

*Thermal wear:* Because there is more friction between the cutting tool and the workpiece at high cutting speeds, a lot of heat is produced. The tool material may become significantly softer as a result, increasing wear susceptibility. Thermal cycling can also result in thermal fatigue, which can start and spread breaches.

*Diffusive wear:* Atomic diffusion amongst the workpiece materials and the tool is accelerated by fast cutting speeds and elevated temperatures. As a result, the components of the tool gradually disappear, especially in carbide tools where the cobalt binder phase may drift forth.

*Oxidative wear:* At high temperatures, oxidation processes are accelerated. Oxide layers form on the tool surface, which may then be worn away, leading to continuous material loss and surface degradation.

*Optimal management:* Reducing cutting speed can mitigate thermal and diffusive wear, but it must be balanced against productivity requirements. Advanced cooling techniques and tool coatings that improve heat resistance can help manage wear at high speeds [10].

##### ***Synergistic Effects***

The interaction between cutting speed, feed rate, and depth of cut can produce synergistic effects on tool wear:

*High speed and high feed:* This combination can dramatically increase temperature and mechanical loads, leading to rapid and complex wear mechanisms.

*High speed and shallow cut:* While this reduces mechanical load, it can still generate significant heat, necessitating advanced cooling methods or high-temperature resistant tool materials.

*Moderate speed, high feed, and depth:* Balancing these parameters can optimize material removal rates while managing wear, provided the tool material and cooling systems are adequately selected.

### **CONCLUSION**

This empirical study offers a thorough understanding of the relationship between cutting parameters, such as depth of cut, feed rate, and cutting speed, and tool wear in high-performance machining (HPM).

The results highlight the intricate interactions between these factors and the main wear structures, providing a basis for process optimization during machining to improve tool life and machining quality.

### **Key Findings**

#### ***Cutting speed***

High temperatures and atomic diffusion processes associated with high cutting rates lead to an increase in thermodynamic and diffusive wear.

The adoption of sophisticated ways to cool and heat-resistant tool coatings is crucial to mitigating these impacts.

#### ***Feed Rate***

Increased feed rates intensify abrasive wear due to higher material removal rates and contact forces.

Optimizing feed rates can balance productivity with tool life, necessitating the selection of tougher, wear-resistant tool materials.

#### ***Depth of cut***

Greater depths of cut amplify all wear mechanisms by increasing mechanical load and heat generation.

Reducing wear requires an intentional arrangement between cutting speed, feed rate, and depth of cut, as well as strong tool materials and efficient drying.

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