

# Investigation of Tool Wear Mechanism During Oblique Metal Cutting

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## ABSTRACT

One of the many parameters that affect the effectiveness of machining process, the accuracy of dimensions, surface finish, and cost of production is tool wear. Oblique cutting involves the use of a cutting edge inclined with the direction of the cutting velocity, and it is very close to practical machining operations such as turning, milling, and drilling. Chip formation, force generation, heat generation, and tool wear are all affected significantly by the inclination angle. Tool wear mechanisms for oblique metal cutting under different cutting conditions are investigated in this paper. For experimentation, carbide cutting tools were employed to machine medium carbon steel specimens. For analyzing the evolution of wear in tools, parameters such as flank wear, crater wear, and microscopic examinations of wear surfaces of the tool were employed. It is apparent from the results that the modes of wear are abrasion, adhesion, diffusion, and oxidation, with increasing levels of wear occurring at higher feed rates and cutting speeds. For maximizing tool life and machining efficiency, an appropriate understanding of wear patterns and cutting parameters have been suggested.

**Keywords:** *Oblique Cutting, Tool Wear, Flank Wear, Crater Wear, Carbide Tool, Machining Performance, Wear Mechanism*

## Introduction

One of the most widely used technologies for the production of technical parts with high-quality surfaces and precise dimensions is cutting metals. The condition and performance characteristics of the cutting tool are critical factors in influencing the effectiveness of the entire process of machining operations. The cutting tool is under considerable mechanical stresses, heat generated by friction between the chip and work-piece, as well as between the chip and the cutting tool itself. Such harsh conditions lead to wearing out of the tool and negatively influence such parameters as cost, efficiency, surface roughness, and accuracy of machining operations. The leading edge is oriented at a certain angle relative to the cutting speed in oblique metal cutting, which is a 3-D type of cutting operation. Chips can move sideways along the rake face due to oblique cutting rather than orthogonal cutting, which causes chips to flow vertically against the cutting edge. Turning, milling, drilling, and shaping are examples of realistic cutting processes that resemble this cutting configuration. The inclination angle plays a major role in not only chip formation but also tool wear performance, tool life, cutting forces, heat generation, and stress distribution [2], [3]. This gradual removal of material from the cutting tool due to physical, chemical, and thermal phenomena occurring during machining process is referred to as tool wear. These include factors like cutting speed, feed rate, depth of cut, tool design, workpiece material type, cooling system properties, and the characteristics of the material used to make the tools among others. There is development of wear on different parts of the cutting tool throughout the process of machining until there is failure of the tool and it is then replaced [1], [4]. Very high temperatures are created between the cutting tool and the chip, as well as in the main shear zone during the process of metal cutting. Excessively high temperatures in excess of 800 degrees centigrade during the process of high-speed machining can impair the tool material in thermal terms and increase the rate of wear. A number of wear mechanisms including abrasive, adhesive, diffusion, oxidation, and plastic deformation can be facilitated by the effects of pressure and temperature [3], [5]. Flank wear results from friction between the cutting edge and newly produced surface of the work material. Friction on the cutting edge and chip flow on the rake face lead to crater wear of the rake face. Although high crater wear will make the cutting edge weak and can cause sudden tool breakage, too much flank wear may reduce machining accuracy and increase cutting forces. In any case, monitoring these types of wear becomes critical for evaluating tool condition and predicting tool life [1], [2]. Abrasive wear is one of the major

forms of wear observed in machining. This occurs where inclusions, carbides, or other hard substances within the material move along the face of the cutting tool, removing material from the cutting tool face. Abrasive wear is the primary cause of flank wear and generally causes scratches and grooves on the flank face. Abrasive wear tends to be more pronounced during operations that involve cutting of harder metals or higher speeds and feeds [5], [6]. Adhesive wear is another form of wear that may occur during metal cutting processes. Adhesion of microscopic welds between the tool and chip can occur under extreme temperature and pressure conditions, resulting in material removal from the tool face. The formation of the built-up edge (BUE), leading to poor surface finish and poor dimensional accuracy, is often associated with adhesive wear. It has been shown that adhesion wear plays an important role in determining tool life in conventional and high-speed operations [7], [8]. As temperature increases, diffusion wear is more prevalent, particularly during the machining of alloy steel, stainless steel, and superalloys at high speeds. Diffusion wear causes gradual damage to the tool microstructure due to the movement of atoms from one material to another. Diffusion wear is predominantly observed on the rake face, where temperatures are the highest. Diffusion wear plays a vital role in the generation of craters and rapid failure of tools under extremely harsh machining conditions [3], [8]. Oxidation wear occurs due to chemical reactions between oxygen in the surrounding environment and the heated surfaces of the cutting tool. These oxide layers are usually brittle in nature, which means that they can be stripped off easily during the process of cutting to expose new layers to oxidation. Oxidation wear is not as important as abrasion wear or adhesion wear under normal conditions, but it becomes more significant at high temperatures and long cutting periods [5], [9]. Advancements in cutting tool technology have involved developing better wear resistance by improving the quality of tool materials and coatings. Today, cutting tools made of PCD, coated carbides, ceramics, and CBN are highly resistant to wear caused by abrasion, adhesion, and diffusion. In order to reduce cutting temperature and enhance tool life, advanced cooling techniques and lubrications including MQL, cryogenic machining, and nanofluid assisted cooling have been devised. However, tool wear continues to remain a major issue in machining processes even after such advancements, particularly in case of high-speed machining and dry machining [4], [5], [10]. Therefore, it becomes imperative for scientists and engineers to study the mechanism of tool wear in oblique metal cutting processes. Optimization of cutting conditions, better tool design, reduced machining costs, and improvement in product quality are among the many benefits of such an understanding of tool wear. The present study aims to evaluate the effect of machining parameters on wear development and tool life and identify the wear modes involved in oblique machining of metals. The results obtained through this study would assist in developing machining processes that are economical and efficient [2], [3], [8].

## Material & Method

The objective of the experimental study was to investigate the processes of tool wear generated through oblique metal cutting under different machining environments. In order to conduct the experiment, considering the common availability and superior machinability of AISI 1045 medium carbon steel in industrial applications, this material was selected as the workpiece. Oblique cutting environments were simulated by performing the machining process using uncoated tungsten carbide tools inclined at an angle of  $15^\circ$  to cylindrical workpieces. To eliminate the effect of cutting fluid on wear generation, the experiments were carried out under dry machining environment on a center lathe machine. Measurement of tool flank and crater wear was done using a toolmakers microscope while wear morphology analysis was performed using an optical microscope. The experimental methodology was designed to investigate the influence of cutting speed and feed rate on tool wear progression and tool life [1]–[3].

Table 1. Workpiece Material Specifications

| Parameter        | Value                         |
|------------------|-------------------------------|
| Material         | AISI 1045 Medium Carbon Steel |
| Density          | 7.85 g/cm <sup>3</sup>        |
| Tensile Strength | 585 MPa                       |
| Yield Strength   | 530 MPa                       |
| Hardness         | 170–210 HB                    |
| Elastic Modulus  | 210 GPa                       |

Tungsten Carbide (WC) uncoated insert was selected as the cutting tool in this study owing to its high wear resistance, hardness, and capability to perform cutting even under high temperature conditions. The geometry of the tool was selected based on the need for consistent cutting and chip formation as per the conventional machining practices. Similar to oblique cutting process, an angle of inclination provided three-dimensional cutting resulting in sideways chip flow across the rake face.

**Table 2. Cutting Tool Geometry and Specifications**

| Parameter         | Value                     |
|-------------------|---------------------------|
| Tool Material     | Tungsten Carbide          |
| Tool Type         | Single Point Cutting Tool |
| Rake Angle        | 10°                       |
| Clearance Angle   | 6°                        |
| Inclination Angle | 15°                       |
| Nose Radius       | 0.8 mm                    |

Machining tests were carried out by maintaining a constant depth of cut of 1 mm while varying the cutting speed and feed rate. The parameters selected to determine the effect of higher mechanical and thermal stresses on wear characteristics are typical of practical cases of machining in industries. After a certain pre-determined period of machining in each case, the tool was inspected, and wear readings were taken [1], [5].

**Table 3. Machining Parameters Used in Experiments**

| Experiment No. | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) |
|----------------|-----------------------|--------------------|-------------------|
| E1             | 80                    | 0.10               | 1.0               |
| E2             | 100                   | 0.15               | 1.0               |
| E3             | 120                   | 0.20               | 1.0               |
| E4             | 140                   | 0.25               | 1.0               |

An accurate evaluation of the tool wear state could be carried out using accurate measurement tools to measure the wear state of the tool. To calculate the tool wear state using flank wear VB, its clearance surface was measured. To evaluate the crater wear KT, the rake face was utilized. Abrasion, adhesion, diffusion, and oxidation wear states were confirmed using a microscope. The correlation between the machining process parameters and wear state under oblique cutting operations could be determined using the collected data [3], [5], and [6].

**Table 4. Experimental Equipment and Measurement Instruments**

| Equipment                | Specification                           |
|--------------------------|-----------------------------------------|
| Lathe Machine            | Precision Center Lathe                  |
| Toolmaker's Microscope   | Accuracy $\pm 0.001$ mm                 |
| Optical Microscope       | 50 $\times$ –500 $\times$ Magnification |
| Digital Vernier Caliper  | Accuracy $\pm 0.02$ mm                  |
| Surface Roughness Tester | Portable Type                           |

#### Experiment Details

Purpose of the experimental investigation was to analyze wear processes that occur in carbide cutting tools during oblique cutting of AISI 1045 medium carbon steel. In order to observe the natural process of wear development in the absence of influence of cutting fluids, the cutting tests were performed on the center lathe machine under the

conditions of dry cutting. For providing oblique cutting, the cutting tool was mounted at an inclination of  $15^\circ$ . In order to ensure stable machining and avoid vibrations, workpieces were tightly secured in the chuck. A new sharp cutting edge was used in each test.

**Table 5. Experimental Conditions**

| Parameter              | Value                     |
|------------------------|---------------------------|
| Workpiece Material     | AISI 1045 Steel           |
| Tool Material          | Uncoated Tungsten Carbide |
| Machining Process      | Oblique Turning           |
| Cutting Environment    | Dry Machining             |
| Inclination Angle      | $15^\circ$                |
| Depth of Cut           | 1.0 mm                    |
| Tool Failure Criterion | VB = 0.30 mm              |

The objectives of the experiments were to determine how feed rate and speed influence the formation of tool wear by maintaining the depth of cut at a constant value. Four different machining operations were carried out. The cutting tool was withdrawn, washed, and then analyzed after each machining process. Measurements for flank wear and crater wear were taken using a toolmakers' microscope. Machining was repeated until the flank wear reached the pre-specified criteria for tool failure.

**Table 6. Experimental Design Matrix**

| Experiment No. | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) |
|----------------|-----------------------|--------------------|-------------------|
| E1             | 80                    | 0.10               | 1.0               |
| E2             | 100                   | 0.15               | 1.0               |
| E3             | 120                   | 0.20               | 1.0               |
| E4             | 140                   | 0.25               | 1.0               |

Wear analysis was done by taking wear readings at constant intervals during the machining process. The flank wear was evaluated using the clearance surface of the cutting tool, while crater wear was analyzed using the rake surface of the tool. Tool wear readings were taken for various cutting parameters, and the effect of variations in feed rate and speed was studied in detail.

**Table 7: Wear Measurement Parameters**

| Wear Parameter   | Measurement Location | Unit               |
|------------------|----------------------|--------------------|
| Flank Wear (VB)  | Clearance Face       | mm                 |
| Crater Wear (KT) | Rake Face            | mm                 |
| Tool Life        | Total Cutting Time   | min                |
| Wear Morphology  | Tool Surface         | Visual/Microscopic |

The worn tool surfaces were examined using an optical microscope at the end of each experimental run for determining the major modes of wear. Surface observations covered abrasion marks, adhesive spots, cratering, oxidation, and edge breakage. The machining variables were correlated with the corresponding wear values. The effects of machining conditions on tool wear behavior and tool life in the case of oblique metal cutting were analyzed based on the results obtained from experiments.

**Table 8. Equipment Used**

| Equipment                | Specification                           |
|--------------------------|-----------------------------------------|
| Lathe Machine            | Precision Center Lathe                  |
| Toolmaker's Microscope   | Accuracy $\pm 0.001$ mm                 |
| Optical Microscope       | 50 $\times$ –500 $\times$ Magnification |
| Digital Vernier Caliper  | Accuracy $\pm 0.02$ mm                  |
| Surface Roughness Tester | Portable Type                           |

## Result & Discussion

Based on the findings of the experimental work, the wear behavior of carbide cutting tools in the case of metal cutting performed in an inclined manner depended heavily on the speed and feed rate. Under any circumstances in cutting operations, wear steadily grew throughout the process of machining. There were two primary types of wear observed, including crater wear occurring on the rake face and flank wear occurring on the clearance face. High temperature and friction were achieved when there was an increase in the cutting speed and feed rate, making the wear phenomenon take place faster. Microscopic examination showed that there were four types of wear mechanisms experienced, namely oxidation, diffusion, adhesion, and abrasion.

**Table 9. Measured Flank Wear under Different Cutting Conditions**

| Experiment No. | Cutting Speed (m/min) | Feed Rate (mm/rev) | Flank Wear VB (mm) |
|----------------|-----------------------|--------------------|--------------------|
| E1             | 80                    | 0.10               | 0.12               |
| E2             | 100                   | 0.15               | 0.18               |
| E3             | 120                   | 0.20               | 0.25               |
| E4             | 140                   | 0.25               | 0.34               |

As shown in Table 1, there is a progressive growth in flank wear as the speed and feed of machining increase. At the lowest machining conditions (E1), the average flank wear is 0.12 mm, indicating stable machining conditions. Nonetheless, at the highest machining conditions (E4), flank wear exceeds the recommended limit for wear at 0.34 mm. This is due to abrasive action as well as increased friction on the machined surface, resulting in faster removal of material.

**Table 10: Crater Wear Measurements**

| Experiment No. | Cutting Speed (m/min) | Feed Rate (mm/rev) | Crater Wear KT (mm) |
|----------------|-----------------------|--------------------|---------------------|
| E1             | 80                    | 0.10               | 0.05                |
| E2             | 100                   | 0.15               | 0.09                |
| E3             | 120                   | 0.20               | 0.15                |
| E4             | 140                   | 0.25               | 0.22                |

Additionally, there was a noticeable rise in crater wear with cutting speed. Intense chip-tool interaction produced high temperatures on the rake face during higher machining settings, which encouraged diffusion and adhesion wear. At 80 m/min, the crater depth was 0.05 mm; at 140 m/min, it was 0.22 mm. The findings show that crater formation during oblique cutting operations is significantly influenced by temperature influences.

**Table 11: Tool Life under Different Machining Conditions**

| Experiment No. | Cutting Speed (m/min) | Feed Rate (mm/rev) | Tool Life (min) |
|----------------|-----------------------|--------------------|-----------------|
| E1             | 80                    | 0.10               | 60              |
| E2             | 100                   | 0.15               | 45              |
| E3             | 120                   | 0.20               | 30              |
| E4             | 140                   | 0.25               | 20              |

From the tool life analysis, it is clear that if there is an increase in the cutting speed and feed rate, then there will be a decrease in tool life. At the lower cutting speed condition, the tool life for the carbide tool was sixty minutes, but at the highest cutting speed condition, the tool life was twenty minutes. This is due to the increased heat production, increased stress on the cutting edge, and rapid wear.

**Table 4. Observed Wear Mechanisms**

| Experiment No. | Dominant Wear Mechanism | Observations                       |
|----------------|-------------------------|------------------------------------|
| E1             | Abrasion                | Minor grooves on flank face        |
| E2             | Abrasion + Adhesion     | Material transfer observed         |
| E3             | Adhesion + Diffusion    | Crater formation initiated         |
| E4             | Diffusion + Oxidation   | Severe crater wear and edge damage |

Various types of wear were observed when examining the used tools using the microscope. The type of wear occurring in low cutting speeds is abrasion and involved scratching and grooving of the flank face by small particles. With an increase in the cutting speed, the occurrence of adhesion increased with material transfer and welding forming between the chip and the cutting tool. With an increase in the cutting speed, the effects of oxidation and diffusion resulted in the creation of craters in the rake face.

The results indicate that oblique cutting exposes the cutting tool to complex mechanical and thermal loading conditions. While the temperature distribution in this regard becomes more conducive to diffusion and oxidation wear with increased cutting speeds, an advantage in terms of easier chip flow is derived from the inclined cutting edge. Hence, selecting appropriate machining parameters becomes extremely essential when it comes to controlling the wear progression and increasing tool life. Generally, one can conclude that in case of oblique metal cutting operations, cutting speed turns out to be the most significant factor when it comes to tool wear. While the use of extremely tough machining parameters results in an enormous increase in wear mechanisms and reduces the efficiency of cutting tools, moderate values for cutting speed and feed turn out to be optimal.

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