Analysis of Carbide Cutting Tool Wear Rate In The Turning Process of Aluminum 6061

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Abstract.
Turning is widely used in manufacturing to produce components with specified dimensional accuracy and surface quality. The condition of the cutting tool, particularly the development of flank wear, plays an important role in determining machining performance and tool service life. This study investigated the progressive flank wear of a carbide cutting tool during the conventional turning of Aluminum 6061. Nine consecutive turning runs were performed under constant dry-machining conditions using a cutting speed of 150 m/min, a spindle speed of 750 rpm, a feed rate of 0.208 mm/rev, a depth of cut of 1.5 mm, a machining length of 100 mm, and a tool angle of 95°. After each run, the carbide tool was observed using an optical microscope, and the flank-wear width was measured at three locations using ImageJ. The average flank wear was calculated from the three measurement points. The results showed that the average flank-wear value increased progressively from 0.040 mm in the first run to 0.073 mm in the ninth run. Nevertheless, the maximum measured wear remained below the adopted tool-wear limit of 0.300 mm. The observed trend indicates that repeated tool–workpiece contact, friction, heat generation, and possible material adhesion contributed to gradual wear development. These findings provide practical information for monitoring carbide-tool condition during the dry turning of Aluminum 6061.
Keywords: *Aluminum 6061, carbide cutting tool, dry turning, flank wear, tool wear and conventional lathe.*

I. INTRUDUCTION

Turning is one of the most frequently applied machining processes in the manufacturing industry, particularly for producing cylindrical parts with specified dimensions and surface characteristics. During this process, the workpiece rotates around its axis while a cutting tool moves longitudinally or transversely to remove unwanted material. This working principle allows turning machines to perform several operations, including straight turning, facing, taper turning, grooving, threading, and drilling [1]. The effectiveness of a turning operation is closely related to the selection of its machining parameters. Cutting speed determines the relative velocity between the cutting edge and the rotating workpiece, whereas feed rate controls the tool displacement during each spindle revolution. Depth of cut determines the thickness of material removed in one machining pass, while cutting time represents the duration of mechanical and thermal exposure experienced by the tool. Variations in these parameters may change the cutting forces, chip formation, machining temperature, material-removal rate, and final surface condition [2]. In addition to the machining parameters, cutting-tool condition is an essential factor because a worn tool may no longer maintain the intended geometry of the machined component. Progressive tool deterioration can increase surface roughness, reduce dimensional accuracy, interrupt production, and increase the frequency of tool replacement. Consequently, suitable machining conditions and regular tool-condition evaluation are required to maintain productivity while controlling manufacturing costs.

Carbide tools are commonly selected for turning applications because they combine high hardness, good wear resistance, and the ability to retain their cutting properties at elevated temperatures. Compared with high-speed steel tools, carbide tools can generally operate at higher cutting speeds and are therefore suitable for machining processes that require high productivity. Carbide inserts are also practical for industrial use because a worn cutting edge can be indexed or replaced without replacing the entire tool holder. Nevertheless, carbide is not completely resistant to damage. Repeated contact between the tool, workpiece, and flowing chip gradually changes the geometry of the cutting edge. Research comparing coated and uncoated carbide tools has shown that tool material and coating condition influence the rate at which wear develops during machining [3]. One of the principal indicators used to evaluate cutting-tool deterioration is flank wear, commonly expressed by the symbol (VB). Flank wear develops on the clearance face because this surface continually rubs against the newly machined workpiece. An increase in spindle speed, depth of cut, and other machining loads may enlarge the worn region and shorten the effective service life of a carbide insert [4]. Although wear usually develops gradually, excessive flank wear can raise cutting forces and temperature, deteriorate the machined surface, produce dimensional errors, and eventually lead to chipping or complete tool failure. The performance differences reported among several carbide-insert grades also demonstrate that tool composition and coating characteristics affect resistance to flank wear [5].

Aluminum 6061 was selected as the workpiece material in this study because it is widely used for structural and mechanical components. This alloy belongs to the 6xxx series, in which magnesium and silicon are the main alloying elements. Their presence provides a useful combination of strength, low density, formability, corrosion resistance, and response to heat treatment. These characteristics support the use of Aluminum 6061 in transportation equipment, construction products, machine components, and other engineering applications [6]. Despite its favorable machinability, the behavior of Aluminum 6061 during cutting still requires attention. The deformation of material in the primary cutting zone and the friction occurring at the tool–chip and tool–workpiece interfaces convert part of the machining energy into heat. Aluminum is also relatively ductile and may adhere to the cutting edge under certain machining conditions. Repeated adhesion and detachment can produce a built-up edge, or BUE, which temporarily changes the effective cutting-edge geometry. A BUE may protect a small portion of the tool at one stage but may also detach irregularly and remove particles from the cutting edge. An experimental investigation of dry high-speed machining of Aluminum 6061 reported a relationship among cutting conditions, temperature, BUE formation, and carbide flank-wear development [7]. Therefore, examination of both the measured (VB) value and the physical appearance of the tool edge is important for understanding carbide-tool behavior during the turning of this alloy.

Several earlier investigations have examined carbide-tool wear under different machining conditions. Sudjatmiko studied dry turning of Aluminum 6061 and found that an increase in cutting speed accelerated carbide-tool wear and reduced tool life [8]. A subsequent investigation by Sudjatmiko, Suprapto, and Soenoko evaluated carbide-tool life during the turning of Aluminum 6061-T by varying cutting speed and depth of cut while maintaining the feed rate at a constant value [9]. Johan, Sutresman, and Aminy also reported that cutting parameters, particularly cutting speed and feed rate, affected the development of carbide flank wear [10]. Their findings indicate that wear behavior cannot be explained solely by tool hardness because friction, temperature, and tribological interaction at the cutting zone also influence tool deterioration. Rao, Bhagyashekar, and Viswanath investigated K10 carbide inserts during intermittent facing of an Aluminum 6061–fly ash metal-matrix composite [11]. Their study compared conventionally treated and cryogenically treated inserts and showed that treatment of the carbide tool could improve wear resistance under specific operating conditions. In another material system, Chistianto, Rosehan, and Lubis examined several coated-carbide grades during the turning of AISI 4140 steel [5]. The different wear values obtained from the tested grades confirmed that insert grade and coating type contribute to tool-life performance. Research on coated and uncoated carbide tools has similarly demonstrated that differences in tool-surface condition produce different wear-growth patterns [3]. These studies provide an important basis for understanding carbide wear, although they were conducted using different materials, treatments, tool grades, or combinations of machining parameters.

The available studies reveal several areas that still require further investigation. Some previous experiments focused on steel, while others used Aluminum 6061 reinforced with fly ash rather than standard Aluminum 6061. Other studies emphasized special carbide grades, coatings, cryogenic treatments, or a limited number of machining variables. As a result, the combined relationship between conventional turning parameters and carbide flank wear during the machining of standard Aluminum 6061 has not been described consistently. A systematic experimental design is needed because testing every possible combination of cutting speed, feed rate, and depth of cut may require considerable time and material. The Taguchi method provides an efficient approach for arranging experimental combinations through an orthogonal array and evaluating the contribution of each controlled parameter. Its application in aluminum turning has shown that machining parameters can be organized and assessed systematically with fewer experimental trials than a full-factorial design [12]. However, the earlier Taguchi-based study concentrated on surface roughness rather than carbide flank wear. Therefore, the present study positions flank-wear width as the main response and considers the possible influence of cutting speed, feed rate, depth of cut, cutting time, and material adhesion. This approach is expected to provide a more focused explanation of progressive carbide-tool deterioration during conventional turning of Aluminum 6061.

Accordingly, this study aims to analyze the flank-wear level of a carbide cutting tool during the turning of Aluminum 6061. The investigation examines the development of the measured (VB) value under selected combinations of cutting speed, feed rate, and depth of cut, while also considering the influence of machining duration. Microscopic observation of the cutting edge is used to identify the dominant wear characteristics and the possible presence of adhered aluminum or BUE. The experimental combinations are arranged using the Taguchi method to determine the machining parameter that contributes most strongly to flank-wear development. The findings are expected to support the selection of appropriate turning parameters, improve the effective service life of carbide inserts, maintain the dimensional and surface quality of machined components, and reduce unnecessary tool-replacement costs in Aluminum 6061 machining.

II. METHODS

This study employed a quantitative experimental method to investigate the progressive flank wear of a carbide cutting tool during the conventional turning of Aluminum 6061. Experimental research was selected because it permits a measurable response to be examined under predetermined and controlled conditions [13]. The experiment consisted of nine consecutive turning runs. The number of completed runs was treated as the independent variable, while the average flank-wear width was treated as the dependent variable. The cutting-tool type, workpiece material, machine, measurement method, and machining conditions were maintained throughout the experiment. Operational definitions were applied so that each variable could be observed and measured consistently [14].

The original research plan also contained a Taguchi design with three cutting factors and three levels. However, the recorded test table shows that all nine completed runs used the same cutting speed, feed rate, and depth of cut. Therefore, the available experimental data principally describe progressive wear during repeated machining under constant cutting conditions. The planned Taguchi levels and the actual repeated-run conditions are both retained below because both appear in the attached methodology document.

The experimental work was conducted at the Machine Tool Workshop, Department of Mechanical Engineering, Politeknik Negeri Bengkalis, Indonesia. Workpiece preparation, conventional turning, spindle-speed verification, cutting-tool inspection, and wear measurement were performed using the workshop and laboratory facilities. A clearly identified research setting and a systematic implementation sequence are required so that the work can be understood and repeated [15]. The implementation time followed the institutional research schedule presented in Section J.

The materials and equipment were selected according to the turning and tool-wear measurement activities. The main workpiece material was Aluminum 6061, and the cutting tool was carbide. Supporting equipment included a conventional lathe, a non-contact tachometer, a vernier caliper, a bright-field optical microscope with a USB camera, and ImageJ software. Each instrument was assigned a defined function so that data collection remained consistent with the research variables [16].

1. Conventional Lathe

A conventional lathe was used to rotate the workpiece on the spindle while the cutting tool moved linearly to remove material. The machine was operated manually and did not use a computer numerical control system.

Fig. 1 Conventional lathe used in the turning experiment.

table I general specifications of the conventional lathe

Specification	General information
Type	Conventional lathe
Motor power	1-3 HP
Spindle-speed range	100-2000 rpm
Maximum diameter	Approximately 300 mm
Maximum turning length	Approximately 1000 mm
Control system	Manual gearbox

2. Carbide Cutting Tool

A carbide cutting tool was used because of its high hardness and wear resistance. The source document states that carbide can retain its cutting edge at relatively high machining temperatures and describes it as suitable for machining AISI 1045 steel. In the present experiment, the carbide tool was used to turn Aluminum 6061 and was intended to provide stable cutting and consistent results during repeated testing.

Fig. 2 Carbide cutting tools represented in the source document.

Source link recorded in the attached document:

https://share.google/PxIjW5p1gqHq1kmSV

Table IIi General Characteristics Of The Carbide Cutting Tool

Parameter	General information
Base material	Tungsten carbide (WC)
Binder	Cobalt (Co), 6-12%
Hardness	1600-2000 HV
Temperature resistance	Approximately 800-1000 °C
Toughness	High, but relatively brittle
Tool angle used in the test	95°

3. Tachometer

A non-contact tachometer was used to measure the rotational speed of the lathe spindle in revolutions per minute. The instrument verified that the spindle speed matched the planned value, thereby supporting the accuracy of the cutting-speed setting.

Fig. 3 **Non-contact digital tachometer used to verify spindle speed.**

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Table Iii General Specifications Of The Tachometer

Specification	General information
Measurement range	2.5-99,999 rpm
Accuracy	±(0.05% + 1 digit)
Resolution	0.1 rpm at low rotational speed
Measurement distance	50-500 mm
Sampling time	Approximately 0.5 s
Sensor type	Non-contact laser
Display	Digital LCD
Power source	9 V or AAA battery

4. Vernier Caliper

A vernier caliper was used to measure workpiece length, outside diameter, inside diameter when required, and depth. Its main and vernier scales provided a finer reading than an ordinary ruler. In this study, it was used to verify the workpiece dimensions and the 100 mm machining length.

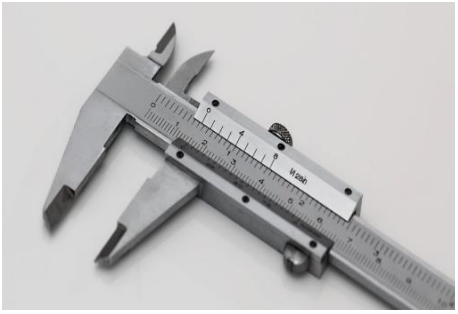

Fig. 4 **Vernier caliper used for dimensional measurement.**

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Table Iv General Specifications Of The Vernier Caliper

Description	**Information**
Instrument name	Vernier caliper
Function	Measuring length, diameter, and depth
Resolution	0.02 mm

5. Aluminum 6061 Workpiece

Aluminum 6061 was used as the workpiece material. It is an aluminum alloy containing magnesium and silicon as its principal alloying elements. The source document describes the material as relatively light, mechanically strong, corrosion resistant, and widely applied in manufacturing, automotive products, frame construction, and machine components.

Fig. 5 Aluminum 6061 workpiece material.

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Table V Chemical Composition Of Aluminum 6061

Element	**Percentage (%)**
Magnesium (Mg)	0.8-1.2
Silicon (Si)	0.4-0.8
Iron (Fe)	Maximum 0.7
Copper (Cu)	0.15-0.4
Chromium (Cr)	0.04-0.35
Zinc (Zn)	Maximum 0.25
Aluminum (Al)	Balance

6. Flank-Wear Measurement Instrument

An optical microscope was used to observe and measure the cutting edge after each turning run. The bright-field system provided magnification from 40× to 400×, LED illumination, and a USB digital camera. The microscopic image was imported into ImageJ and calibrated using a reference of known size before the flank-wear width was measured. Consistent use of the same instrument, scale, and procedure is essential for comparable quantitative observations [17].

Fig. 6 Optical microscope and digital measuring equipment used for flank-wear observation.

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Table Vi Specifications Of The Flank-Wear Measurement Instrument

Component	Specification
Type	Bright-field optical microscope
Magnification	40×-400×
Illumination	LED
Camera	Digital USB
Recorded accuracy	±0.01 mm
Image analysis	ImageJ

All completed turning tests were conducted under constant cutting conditions. The spindle speed was set at 750 rpm and verified using the tachometer. The cutting speed was 150 m/min, the feed rate was 0.208 mm/rev, and the depth of cut was 1.5 mm. Each run covered a machining length of 100 mm with a tool angle of 95°. The operation was described as dry machining without the direct application of cutting fluid. Maintaining the controlled conditions was necessary to reduce the influence of unexamined factors on the measured response [4].

TABLE VIII ACTUAL CUTTING CONDITIONS

Parameter	Symbol	Value
Workpiece material	-	Aluminum 6061
Cutting-tool material	-	Carbide
Spindle speed	n	750 rpm
Cutting speed	Vc	150 m/min
Feed rate	f	0.208 mm/rev
Depth of cut	ap	1.5 mm
Machining length	L	100 mm
Tool angle	-	95°
Machining condition	-	Dry machining
Number of runs	-	9

The Taguchi method was included in the original plan as a design-of-experiments approach for assessing the effects of cutting speed, feed rate, and depth of cut on carbide flank wear. The method was developed by Genichi Taguchi to obtain a robust process through a systematic statistical arrangement of experimental factors.

Because the desired response was minimum wear, the proposed analysis used the smaller-the-better signal-to-noise ratio:

$$S/N = -10\log(n1\sum y2)$$

where y_i is the measured VB value for observation i and n is the number of repetitions. A larger S/N value indicates a smaller and more stable wear response.

Table Viii Planned Taguchi Factors And Levels

Parameter	Level 1	Level 2	Level 3
Cutting speed, Vc	100 m/min	150 m/min	200 m/min

Feed rate, f	0.10 mm/rev	0.15 mm/rev	0.20 mm/rev
Depth of cut, ap	0.5 mm	1.0 mm	1.5 mm

The completed test table did not contain nine different Taguchi combinations. Instead, every recorded run used 150 m/min, 0.208 mm/rev, and 1.5 mm. Thus, Table VIII represents the planned factor levels, whereas Tables VII and IX represent the actual repeated-run conditions available for analysis.

The independent variable was the number of repeated turning operations, consisting of Run 1 through Run 9. The purpose of repetition was to observe the development of carbide-tool wear as the same cutting edge accumulated additional use. Although cutting speed, feed rate, and depth of cut were originally listed as Taguchi factors, they remained constant in the completed test table and therefore functioned as controlled conditions in the available experiment.

The dependent variable was the average flank-wear width, VBavg. The wear width was measured at three locations, denoted VB_1, VB_2, and VB_3. The average value served as the indicator of tool wear and tool-life condition.

The controlled variables were:

1. carbide as the cutting-tool material;
2. Aluminum 6061 as the workpiece material;
3. a conventional lathe as the machine tool;
4. dry machining as the cutting method;
5. a tool-wear limit of VB = 0.3 mm, stated in the source document as referring to ISO 3685;
6. the same optical-microscope measurement method for every run;
7. a spindle speed of 750 rpm;
8. a cutting speed of 150 m/min;
9. a feed rate of 0.208 mm/rev;
10. a depth of cut of 1.5 mm;
11. a machining length of 100 mm; and
12. a tool angle of 95°.

Before machining, the conventional lathe, Aluminum 6061 workpiece, carbide cutting tool, tachometer, vernier caliper, microscope, and supporting equipment were prepared and inspected. The workpiece was secured in the chuck and aligned to reduce eccentric rotation and excessive vibration. The carbide tool was installed in the holder at a tool angle of 95°. The spindle was then set at 750 rpm and verified with the non-contact tachometer.

The feed rate was set to 0.208 mm/rev, and the depth of cut was adjusted to 1.5 mm. Each turning run removed material over a length of 100 mm at a cutting speed of 150 m/min. After one run was completed, the machine was stopped and the cutting tool was inspected. The same cutting edge was then used for the next run under identical settings until nine runs had been completed. Applying the same sequence in every run supported procedural consistency [18].

After each run, the carbide cutting tool was cleaned to remove chips and adhering material from the cutting edge. The flank face was positioned under the bright-field optical microscope and recorded with the USB digital camera. The image was calibrated in ImageJ using a known dimensional reference. Flank wear was measured at three locations to reduce the influence of a nonuniform wear band.

$$VBavg = (VB_1 + VB_2 + VB_3) / n \quad (2)$$

where VBavg is the average flank-wear width in millimeters, VB_1, VB_2, and VB_3 are the three measured wear widths, and n is the number of measurement points.

$$VBavg = (VB_1 + VB_2 + VB_3) / 3 \quad (3)$$

The calculated average was used as the principal indicator of carbide-tool condition. A flank-wear width of 0.3 mm was adopted as the tool-wear criterion in the attached methodology document, with reference to ISO 3685.

The three measured values were recorded for every run and averaged using Eq. (3). The average wear values were then tabulated and plotted against the run number to examine whether wear increased progressively with continued use of the same carbide edge. The descriptive analysis compared Run 1 with Run 9 and evaluated the direction and consistency of the wear trend.

TABLE IX RECORDED TURNING CONDITIONS FOR EACH RUN

Run	Spindle speed (rpm)	Cutting length (mm)	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Tool angle
1	750	100	150	0.208	1.5	95°
2	750	100	150	0.208	1.5	95°
3	750	100	150	0.208	1.5	95°
4	750	100	150	0.208	1.5	95°
5	750	100	150	0.208	1.5	95°
6	750	100	150	0.208	1.5	95°
7	750	100	150	0.208	1.5	95°
8	750	100	150	0.208	1.5	95°
9	750	100	150	0.208	1.5	95°

The attached methodology document also records three outcome statements: the VB value increased with cutting time, the observed wear was dominated by light abrasive wear, and no significant crater wear was found because Aluminum 6061 was considered relatively soft. These statements are retained here to preserve all source data, although they describe findings and are more appropriately presented in the Results and Discussion section.

The research sequence began with a literature review and preparation of the equipment and materials. The machining parameters were then determined, Aluminum 6061 was turned, carbide-tool wear was measured, and the data were collected and processed. The final stages comprised wear analysis and drawing conclusions.

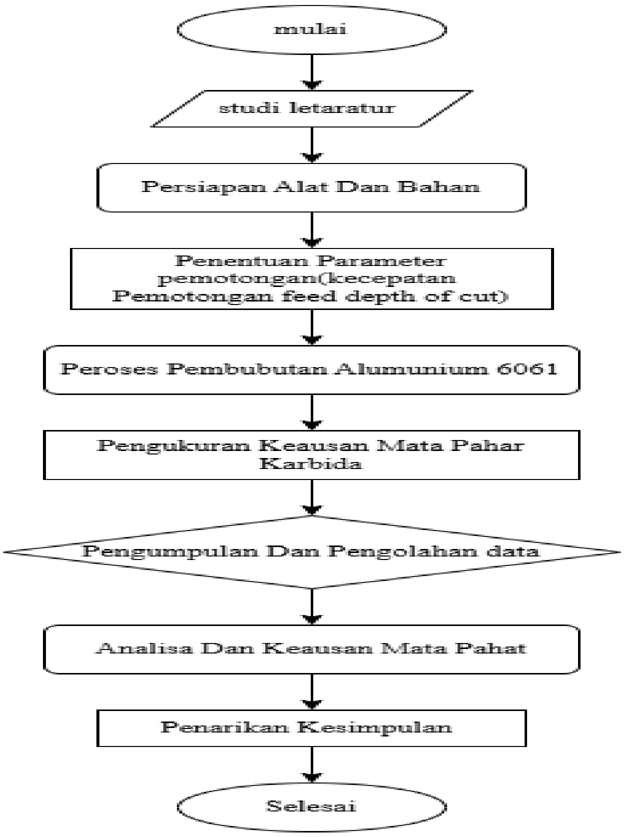

Fig. 7 Research flowchart reproduced from the attached methodology document. Source: research documentation.

The study was scheduled for implementation in 2026 at the Machine Tool Workshop, Department of Mechanical Engineering, Politeknik Negeri Bengkalis. The schedule includes proposal submission, proposal guidance, proposal seminar, data analysis and processing, thesis-research implementation, and thesis revision and examination.

TABLE X RESEARCH SCHEDULE FOR 2026

No.	Kegiatan	2026																																			
		Januari				Februari				Maret				April				Mei				Juni				Juli				Agustus				September			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	Pengajuan Proposal																																				
2	Bimbingan proposal																																				
3	Seminar proposal																																				
4	Analisa dan pengolahan data																																				
5	Pelaksanaan penelitian skripsi																																				
6	Revisi skripsi dan pengujian																																				

The source document includes the following estimated budget for materials and supporting activities. The values are reproduced as recorded in the document. Because several unit prices do not arithmetically match the stated line totals, the figures should be checked against actual purchase records before final submission. The budget also lists coolant even though the machining procedure is described as dry machining.

Table Xi Estimated Final-Project Budget

No.	Equipment or material	Volume	Unit price	Recorded amount
1	Aluminum 6061	1 piece	Rp180.000,00	Rp1.500.000,00
2	Carbide cutting tool	2 pieces	Rp230.000,00	Rp430.000,00
3	Stationery	1 package	Rp100.000,00	Rp100.000,00
4	Unforeseen expenses	-	Rp500.000,00	Rp500.000,00
5	Coolant	2 units	Rp200.000,00	Rp200.000,00
	TOTAL EQUIPMENT + MATERIALS			Rp2.730.000,00

III. RESULT AND DISCUSSION

3.1 Experimental Conditions and Test Documentation

The turning tests were performed on Aluminum 6061 using a conventional lathe and a carbide cutting tool. Nine consecutive runs were completed with the same cutting edge. The cutting conditions were intentionally maintained at constant values so that the measured change in flank wear represented the cumulative effect of repeated machining rather than a change in the machining parameters. The parameters recorded in the source document are summarized in Table I.

Table Xii Turning Parameters Used In The Experiment

Parameter	Value
Workpiece material	Aluminum 6061
Cutting-tool material	Carbide
Cutting speed, Vc	150 m/min
Spindle speed, n	750 rpm
Feed rate, f	0.208 mm/rev
Depth of cut, ap	1.5 mm
Tool angle	95°
Number of tests	9 runs

Source: Research documentation, 2026.

Before testing, the machine, workpieces, and cutting tool were prepared in accordance with the experimental procedure. Each specimen was turned over the specified cutting length, after which the specimen and the carbide tool were documented. Figures 1–4 reproduce the testing documentation contained in the source file.

Fig. 8 Conventional turning test setup.
Source: Research documentation, 2026.

Fig. 9 Turning operation on the conventional lathe.
Source: Research documentation, 2026.

Fig. 10 Aluminum 6061 specimens after turning.
Source: Research documentation, 2026.

Fig. 11 Carbide tool after use.
Source: Research documentation, 2026.

3.2 Microscopic Observation and ImageJ Measurement

After completion of each turning run, the carbide tool was cleaned to remove chips and loosely attached material. The flank face was then observed using a digital microscope to locate the worn region that had been in direct contact with the newly machined surface. The microscopic image was imported into ImageJ, calibrated against a known dimensional reference, and measured in millimeters.

Three locations were selected on the flank-wear band and identified as VB_1, VB_2, and VB_3. This approach reduced the influence of local variation in the wear width and provided a representative average for each run. The microscope image, scale-calibration screen, and three-point measurement arrangement are shown in Figures 5–7.

Fig. 12 Carbide flank face observed using a digital microscope.
Source: Research documentation, 2026.

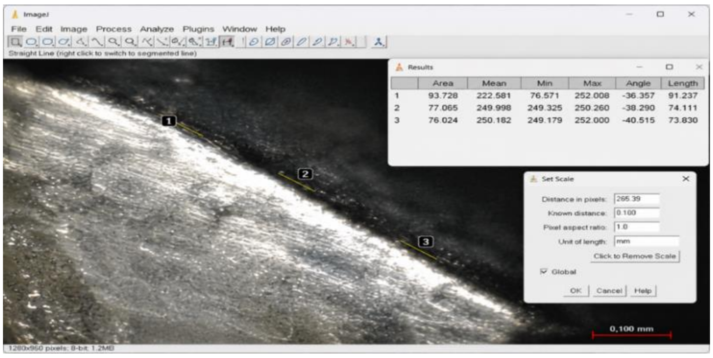

Fig. 13 Scale calibration and flank-wear measurement in ImageJ.

Source: Research documentation, 2026.

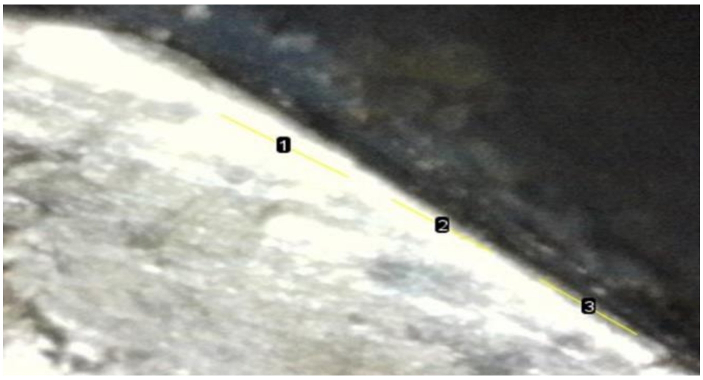

Fig. 14 Locations of VB_1, VB_2, and VB_3 on the flank-wear region.

Source: Research documentation, 2026.

3.3 Flank-Wear Measurement Results

Table II presents the three measured wear widths and the average value obtained for each run. All three measurements increased with continued tool use, and the differences among VB_1, VB_2, and VB_3 remained small. The close agreement among the three locations indicates that the recorded average was not controlled by a single isolated measurement point.

Table Xiii Measured Carbide Flank Wear

Run	VB_1 (mm)	VB_2 (mm)	VB_3 (mm)	Average VB (mm)
1	0.040	0.041	0.039	0.040
2	0.042	0.043	0.041	0.042
3	0.045	0.046	0.044	0.045
4	0.048	0.049	0.047	0.048
5	0.052	0.053	0.051	0.052
6	0.056	0.057	0.055	0.056
7	0.061	0.062	0.060	0.061
8	0.067	0.068	0.066	0.067
9	0.073	0.074	0.072	0.073

The average flank wear increased from 0.040 mm in Run 1 to 0.073 mm in Run 9. Thus, the total increase over the experimental sequence was 0.033 mm. The maximum value remained below the 0.300 mm wear criterion adopted in the methodology, indicating that the cutting edge had not reached the specified end-of-life limit during the nine recorded runs.

3.4 Calculation of Average Flank Wear

The representative flank-wear value was calculated as the arithmetic mean of the three measurement points:

$$VB = \frac{VB_1 + VB_2 + VB_3}{3}$$

where VB is the average flank-wear width in millimeters, and VB_1, VB_2, and VB_3 are the wear widths measured at the first, second, and third locations, respectively. The substitutions and results for all nine runs are reproduced below.

Run 1

$$VB = \frac{0{,}040 + 0{,}041 + 0{,}039}{3}$$
$$VB = \frac{0{,}120}{3}$$
$$VB = 0{,}040 \text{ mm}$$

Run 2

$$VB = \frac{0{,}042 + 0{,}043 + 0{,}041}{3}$$
$$VB = \frac{0{,}126}{3}$$
$$VB = 0{,}042 \text{ mm}$$

Run 3

$$VB = \frac{0{,}045 + 0{,}046 + 0{,}044}{3}$$
$$VB = \frac{0{,}135}{3}$$
$$VB = 0{,}045 \text{ mm}$$

Run 4

$$VB = \frac{0{,}048 + 0{,}049 + 0{,}047}{3}$$
$$VB = \frac{0{,}144}{3}$$
$$VB = 0{,}048 \text{ mm}$$

Run 5

$$VB = \frac{0{,}052 + 0{,}053 + 0{,}051}{3}$$
$$VB = \frac{0{,}156}{3}$$
$$VB = 0{,}052 \text{ mm}$$

Run 6

$$VB = \frac{0{,}056 + 0{,}057 + 0{,}055}{3}$$
$$VB = \frac{0{,}168}{3}$$
$$VB = 0{,}056 \text{ mm}$$

Run 7

$$VB = \frac{0{,}061 + 0{,}062 + 0{,}060}{3}$$
$$VB = \frac{0{,}183}{3}$$
$$VB = 0{,}061 \text{ mm}$$

Run 8

$$VB = \frac{0{,}067 + 0{,}068 + 0{,}066}{3}$$
$$VB = \frac{0{,}201}{3}$$
$$VB = 0{,}067 \text{ mm}$$

Run 9

$$VB = \frac{0{,}073 + 0{,}074 + 0{,}072}{3}$$

$$VB = \frac{0{,}219}{3}$$

$$VB = 0{,}073 \text{ mm}$$

The calculation confirms a continuous increase in average VB from the first to the ninth run. No calculated average decreased relative to the preceding run, demonstrating that the measured wear was cumulative.

3.5 Development of Carbide-Tool Flank Wear

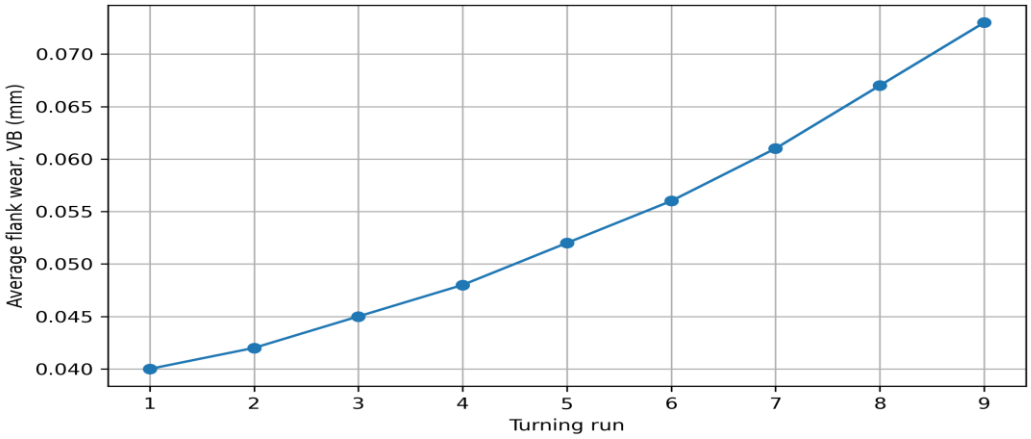

Fig. 15 Development of average carbide flank wear with the number of turning runs.

Figure 8 shows a monotonic rise in flank wear throughout the test sequence. During the early runs, the increase was relatively small, whereas slightly larger increments appeared toward the final runs. Nevertheless, the overall trend remained close to linear, consistent with the pattern described in the source document. Because the cutting speed, feed rate, and depth of cut were fixed, the horizontal axis represents increasing cumulative tool use rather than different machining-parameter combinations.

The progressive trend is consistent with observations from dry turning of Aluminum 6061, where continued tool–workpiece interaction leads to a gradual enlargement of the flank-wear band [7].

3.6 Discussion of Wear Development

The increase in VB can primarily be related to repeated rubbing between the clearance face of the carbide tool and the newly generated surface of the Aluminum 6061 workpiece. Each turning pass extended the period of mechanical contact, so small losses of tool material accumulated at the flank face. The absence of a reduction between successive runs confirms that this deterioration was irreversible within the test sequence.

Heat generation also contributed to the cutting environment. Plastic deformation in the shear zone and friction at the tool–chip and tool–workpiece interfaces converted part of the machining energy into heat. Although the present study did not directly measure cutting temperature or force, previous carbide-turning research has shown that thermal and tribological loading influences the growth of tool wear [3].

Aluminum 6061 is comparatively soft, but its ductility can promote local adhesion at the cutting edge during dry machining. Adhesive transfer and built-up-edge formation are therefore plausible contributors to edge-condition changes. However, the supplied microscopic images were used mainly for VB measurement and do not independently quantify the amount of adhered material or prove a specific wear mechanism. A previous dry-turning study on Aluminum 6061 reported an association among cutting conditions, temperature, built-up edge, and flank-wear development [7].

The observed images indicate a relatively narrow flank-wear region, and no pronounced crater was documented in the supplied results. The recorded maximum VB of 0.073 mm is also consistent with an early or mild wear stage rather than severe cutting-edge failure. Nevertheless, definitive classification of abrasive, adhesive, diffusive, or oxidative wear would require higher-resolution surface characterization.

3.7 Interpretation of the Cutting Parameters

The experiment used a cutting speed of 150 m/min, a feed rate of 0.208 mm/rev, and a depth of cut of 1.5 mm in every run. Consequently, the present results cannot separate the individual effects of cutting speed, feed rate, or depth of cut. Studies that deliberately varied these parameters have reported that spindle speed, feed, and depth of cut can alter carbide wear [4]. In the present dataset, however, the valid interpretation is limited to the effect of repeated use under one constant cutting condition.

Differences in carbide grade and coating can also change wear resistance. Research on AISI 4140 demonstrated that different carbide-insert grades produced different wear values under otherwise controlled machining conditions [5]. Because only one carbide-tool condition was used in the present work, grade-related effects were not evaluated.

3.8 Comparison with Previous Research

The monotonic rise in flank wear agrees with earlier findings that increasing machining exposure promotes progressive deterioration of the carbide flank face. Johan, Sutresman, and Aminy reported that cutting parameters, particularly cutting speed and feed rate, affected carbide flank wear [10].

Sudjatmiko found that higher cutting speed accelerated carbide-tool wear and shortened tool life during dry turning of Aluminum 6061 [8]. The present tests did not vary cutting speed, but the observed accumulation of VB with continued machining is consistent with the general tool-life behavior described in that study.

A related investigation of Aluminum 6061-T also showed that carbide-tool life and wear were influenced by cutting speed and depth of cut [11]. The smaller wear values obtained in the present work may reflect differences in tool grade, geometry, machining duration, workpiece condition, and measurement procedure.

Rao, Bhagyashekar, and Viswanath investigated K10 carbide inserts during intermittent facing of an Aluminum 6061–fly ash composite and showed that tool treatment could modify wear resistance [11]. Direct numerical comparison is inappropriate because their workpiece and tool treatment differed from those used here, but both studies demonstrate that carbide wear develops with continued machining of aluminum-based materials.

The experimental results demonstrate that repeated conventional turning of Aluminum 6061 produced a gradual and cumulative increase in carbide flank wear. The average VB rose from 0.040 mm in Run 1 to 0.073 mm in Run 9. All measurements remained below the 0.300 mm criterion adopted in the study. Under the constant conditions of 150 m/min cutting speed, 0.208 mm/rev feed rate, and 1.5 mm depth of cut, the principal variable represented by the data was cumulative tool use. The results therefore support conclusions concerning progressive wear with repeated machining, but they do not establish the separate contribution or statistical dominance of the three cutting parameters..

IV. CONCLUSION

This study evaluated the progressive flank wear of a carbide cutting tool during the conventional turning of Aluminum 6061. Nine consecutive turning runs were conducted under constant machining conditions consisting of a cutting speed of 150 m/min, a spindle speed of 750 rpm, a feed rate of 0.208 mm/rev, a depth of cut of 1.5 mm, a machining length of 100 mm, and a tool angle of 95°. The average flank-wear value increased consistently from 0.040 mm in the first run to 0.073 mm in the ninth run. This result demonstrates that repeated use of the same carbide cutting edge caused cumulative and progressive tool wear.

The measured flank wear remained below the adopted tool-wear limit of 0.300 mm throughout the experiment. Therefore, the carbide cutting tool had not reached the specified end-of-life criterion after nine turning runs. The observed wear pattern was relatively gradual, and no severe crater wear or catastrophic cutting-edge failure was recorded. Friction, cumulative contact time, heat generation, and possible adhesion of Aluminum 6061 to the cutting edge were considered relevant factors in the development of flank wear.

Because cutting speed, feed rate, and depth of cut were maintained at the same values in all experimental runs, the present results cannot determine the separate contribution or statistical dominance of each machining parameter. The conclusions are therefore limited to the development of carbide flank wear under repeated turning with constant cutting conditions. Further experiments using different parameter combinations and a complete Taguchi orthogonal array are required to identify the machining factor that has the greatest influence on carbide-tool wear.

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