Effect of Depth of Cut Variation on Flank Wear and Crater Wear of Carbide Tools in S45C Steel Turning

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A B S T R A C T

Selecting appropriate cutting parameters is essential to prolonging tool life and maintaining machining quality. This study analyzes the effect of depth-of-cut variation on the wear of carbide cutting tools during dry turning of S45C steel, focusing on flank wear and crater wear. An experimental method was employed using three depth-of-cut levels (1 mm, 2 mm, and 3 mm), a constant feed rate of 0.2 mm/rev, and wear measurement using a digital microscope. The results show that increasing the depth of cut from 1 mm to 3 mm increased flank wear from 0.0186011 mm to 0.0325576 mm, crater wear from 0.0005118 mm to 0.001432 mm, and cutting temperature from 28.9°C to 30.1°C. All measured wear values remained below the 0.3 mm critical limit specified by ISO 3685, yet the upward trend confirms that depth of cut meaningfully accelerates tool wear. A depth of cut of 1 mm is recommended to prolong tool life and maintain machining quality in medium-carbon steel turning

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INTRODUCTION

Turning is one of the most widely applied conventional machining processes in the manufacturing industry for producing cylindrical components with high dimensional accuracy and surface quality. The success of this process is largely determined by three main cutting parameters, namely cutting speed, feed rate, and depth of cut, since these three parameters directly influence the magnitude of the cutting force, cutting temperature, and the intensity of friction between the tool and the workpiece.

One classic problem that cannot be avoided in the turning process is tool wear. The continuous contact and friction between the tool, the workpiece, and the chip generate high temperatures and large pressures in the cutting zone, gradually eroding the tool material, degrading the surface quality of the workpiece, and reducing the dimensional accuracy of the turning result. The two most commonly observed forms of wear are flank wear and crater wear; a tool is considered to have reached its wear limit once the flank wear value reaches 0.3 mm, a threshold that is also the reference used in the ISO 3685 standard.

S45C steel is a medium-carbon steel with a carbon content of approximately 0.45% that is widely used for shafts, gears, and other machine elements because of its good combination of strength and wear resistance. Its relatively high hardness and tensile strength make this material sensitive to variations in cutting parameters, so the cutting force and heat generated during machining are relatively greater than for low-carbon steel. If tool wear develops too quickly, the industry will incur losses in the form of increased tool replacement costs, longer machine downtime, and a decline in the surface quality of the resulting workpiece.

From an economic perspective, every tool replacement requires machine downtime for removal, replacement, and resetting, which can accumulate into significant production time losses in large-scale production. Therefore, a quantitative understanding of how cutting parameters—particularly depth of cut—affect the rate of tool wear is an important part of a data-driven production cost control strategy, rather than merely an academic exercise.

Based on the above, this study aims to (1) analyze the effect of depth-of-cut variation on carbide tool wear in the turning of S45C steel, and (2) measure the flank wear and crater wear that occur as a result of this variation, with reference to the 0.3 mm critical wear limit specified by ISO 3685. The results of this study are expected to contribute scientifically to the development of more efficient machining processes and to serve as a practical reference for determining optimal cutting parameters in medium-carbon steel turning.

LITERATURE REVIEW

Wear Mechanisms of Carbide Tools

Carbide (widia) tools are widely chosen in industry because of their high hardness and superior resistance to cutting temperature compared to conventional tool steels, making them well suited for cutting medium-carbon steels such as S45C. Nevertheless, the high hardness of carbide tools does not eliminate the phenomenon of wear, especially when cutting parameters are increased. Mechanically, the greater the depth of cut, the wider the contact area between the tool and the workpiece, so the cutting force increases, the cutting temperature rises, and both abrasion and plastic deformation at the tool tip proceed more rapidly. Bernadip Umar (n.d.) noted that increasing the depth of cut on a conventional lathe increases the cutting force, reaction force, and torque, which directly increases the mechanical load on the tool tip.

Effect of Cutting Parameters on Tool Wear

Studies on the effect of cutting parameters on carbide tool wear have been carried out extensively. Anrinal et al. (2020) found that increasing the depth of cut with an HSS tool increases the load received by the tool and accelerates flank wear, while Resa Mahendra and Liston (n.d.) reported that increasing the cut thickness from 0.5 mm to 1.5 mm in turning stainless steel 316 caused a significant increase in flank wear. Fahrizal et al. (2022) concluded that feed rate has the greatest influence on tool wear in low-carbon steel turning compared to cutting speed and depth of cut, while Ntukidem et al. (2024a) confirmed that feed rate is the most dominant factor in turning medium-carbon AISI 1040 steel, although the interaction between cutting speed and depth of cut still contributes to increased wear. A somewhat different finding was reported by Gariani and Dao (2024) in dry turning of 6060 aluminium alloy, who stated that cutting speed plays the most dominant role in tool wear, while depth of cut has a relatively small effect. These differences indicate that the effect of each cutting parameter on tool wear is specific to the combination of workpiece material, tool type, and the parameter range tested.

Manta et al. (2024) showed that spindle speed variation significantly affects surface roughness and tool wear in turning AISI 4340 steel, with increasing spindle speed raising the cutting temperature and accelerating wear. Manta et al. (2025) reported that increasing the feed rate in turning ST41 steel with an insert tool produced a maximum tool wear of 0.021 grams. Zaida et al. (2021) examined the progression of carbide tool wear in turning C45 steel and found a progressive wear pattern closely related to the duration and intensity of cutting contact, while Briantio et al. (2024) studied ceramic tool wear in cutting AISI 4340 steel and confirmed that aggressive cutting parameters accelerate the attainment of the critical flank-wear limit. Chendri Johan et al. (2026) added that in turning ST 37 steel with tungsten-cobalt carbide tools, spindle-speed variation also affects vibration frequency and surface roughness, which is indirectly related to the intensity of friction that causes wear.

Findings from Other Machining Processes

Hidayat et al. (2023), in a study of the milling process on SKD 11 steel, found that depth of cut contributes significantly to the wear rate of carbide tool tips, even though the machining process differs from turning. Ikhtiardi et al. (2023), who studied the effect of cutting speed in turning AISI 1045 steel with a fixed depth of cut of 1 mm, showed that carbide tool wear is strongly influenced by the interaction between cutting speed and cutting duration. At the mechanical-force level, Panjaitan (n.d.) found that increasing cutting speed on S45C steel also affects plastic deformation and the quality of the turning result.

Conceptual Framework and Novelty of the Study

Based on the discussion above, it can be concluded that although cutting speed and feed rate have been widely studied as dominant variables causing tool wear, research that specifically isolates the effect of depth of cut on flank wear and crater wear in turning S45C steel with carbide tools remains relatively limited. This study is designed to fill that gap by keeping the feed rate constant at 0.2 mm/rev, so that the observed change in wear can be directly attributed to the variation in depth of cut. The conceptual framework of this study is based on the causal relationship between depth of cut, cutting force and cutting temperature, and the resulting magnitude of flank wear and crater wear on the carbide tool.

METHODOLOGY

This study uses a quantitative experimental approach with a factorial design based on one main independent variable, namely depth of cut, which was varied at three levels (1 mm, 2 mm, and 3 mm), while the feed rate was held constant at 0.2 mm/rev. The workpiece used was an S45C steel bar with a diameter of 95 mm and a length of 200 mm in the as-received condition, while the tool used was a carbide (widia) tool made of tungsten carbide in a cobalt matrix (WC-Co) with identical grade and geometry for every test; a new tool insert was used for each test to eliminate the influence of initial wear.

Supporting instruments included a caliper to measure the workpiece diameter and a USB digital microscope to observe and measure tool wear. Spindle speed (n) was adjusted to 550 rpm, 275 rpm, and 155 rpm for each depth-of-cut variation, with cutting durations of 1 minute, 3 minutes, and 6 minutes respectively, over a turning length of 73 mm. Cutting speed (Vc) was calculated using the following equation.

$Vc = (\pi \times D \times n) / 1000$ .... (1)

where Vc is the cutting speed (m/min), π = 3.14, D is the workpiece diameter (mm), and n is the spindle speed (rpm). A summary of the experimental parameter combinations is presented in Table 1.

Table 1. Combination of Experimental Parameters for Turning S45C Steel

Code	Depth of Cut (mm)	n (rpm)	Vc (m/min)	f (mm/rev)	Time
A	1	550	164.05	0.2	1 minute
B	2	275	82.035	0.2	3 minutes
C	3	155	46.235	0.2	6 minutes

The research procedure began with preparing the workpiece and mounting it on the lathe chuck in a centered position. External cylindrical turning was carried out dry (dry cutting) without any cutting fluid, using the same lathe for all tests. After each turning session was completed, the tool was removed and observed under the digital microscope to measure the flank wear width (VB) and crater wear depth (KT), together with recording the cutting temperature. The collected data were analyzed descriptively and quantitatively by presenting the measurement results in tabular form, after which the relationship between depth of cut and the level of wear was analyzed and compared with machining theory and previous research findings.

RESULTS

Tests were carried out at three depth-of-cut variations with the feed rate held constant at 0.2 mm/rev. The measurement results of flank wear (VB) together with the accompanying cutting parameters are presented in Table 2.

Table 2. Flank Wear Measurement Results

Time	n (rpm)	a (mm)	Vc (m/min)	f (mm/rev)	VB (mm)	T (°C)
1 minute	550	1	164.065	0.2	0.0186011	28.9
3 minutes	275	2	82.0325	0.2	0.0264197	29.9
6 minutes	155	3	46.2365	0.2	0.0325576	30.1

The data in Table 2 show that the flank wear value increased consistently with increasing depth of cut, from 0.0186011 mm at a depth of 1 mm to 0.0264197 mm at 2 mm, and reaching 0.0325576 mm at 3 mm. This increase occurs because the deeper the cut, the wider the area of material sheared in each tool pass, so the cutting force increases and the frictional interaction becomes more intense. All measured flank wear values remained far below the 0.3 mm critical threshold specified by ISO 3685, although the upward trend was consistent.

Table 3. Crater Wear Measurement Results

Time	n (rpm)	a (mm)	Vc (m/min)	f (mm/rev)	KT (mm)	T (°C)
1 minute	550	1	164.065	0.2	0.0005118	28.9
3 minutes	275	2	82.0325	0.2	0.0008952	29.9
6 minutes	155	3	46.2365	0.2	0.001432	30.1

Table 3 shows that the crater wear value also increased with increasing depth of cut, from 0.0005118 mm at a depth of 1 mm to 0.0008952 mm at 2 mm, and reaching 0.001432 mm at 3 mm. This increase is caused by the increasing chip thickness produced; a thicker chip carries more heat energy as it flows over the tool surface, so the combination of pressure and high temperature accelerates the diffusion and abrasion mechanisms. Compared with flank wear, the crater wear values obtained were much lower across all depth-of-cut variations, indicating that the dominant wear mechanism in turning S45C steel with a carbide tool is flank wear.

The data in Tables 2 and 3 also show that the cutting temperature increased with increasing depth of cut, from 28.9°C at a depth of 1 mm to 29.9°C at 2 mm, and reaching 30.1°C at 3 mm. This phenomenon occurs because most of the mechanical energy generated during the cutting process is converted into heat energy; the greater the depth of cut, the greater the energy required to cut the material, so the temperature around the tool tip rises and locally reduces the hardness of the tool surface.

DISCUSSION

Overall, the results of this study show that increasing the depth of cut from 1 mm to 3 mm consistently increased flank wear, crater wear, and cutting temperature on the carbide tool used to turn S45C steel. This finding reinforces the results of Bernadip Umar (n.d.), Anrinal et al. (2020), and Resa Mahendra and Liston (n.d.), all of whom reported that increasing the depth/thickness of cut increases the mechanical load and flank wear of the tool, even though the workpiece material and tool type in these three studies differ from the present study. This consistent pattern of increasing wear indicates that the effect of depth of cut on tool wear is consistent across different material and tool types.

Nevertheless, these findings need to be read critically in light of research highlighting the dominance of other parameters. Fahrizal et al. (2022) and Ntukidem et al. (2024a) concluded that feed rate has the greatest influence on tool wear compared to depth of cut. This difference is reasonable because both studies varied all cutting parameters simultaneously, whereas the present study specifically isolated depth of cut by keeping the feed rate constant, so that the observed change in wear can be directly attributed to the variation in depth of cut without bias from the interaction of other parameters. This result confirms that depth of cut has an independent effect on tool durability, notwithstanding its relatively smaller role compared to feed rate when all parameters are varied simultaneously.

Gariani and Dao (2024) found that cutting speed plays the most dominant role in dry turning of 6060 aluminium alloy, with depth of cut having a relatively small effect; this difference is reasonable given the much softer characteristics of aluminium compared to S45C steel. In contrast, Manta et al. (2024, 2025) in turning AISI 4340 and ST41 steel showed that increasing spindle speed and feed rate raises the cutting temperature while accelerating wear, consistent with the finding of this study that rising cutting temperature is closely associated with increased wear. Hidayat et al. (2023) in the milling process and Ikhtiardi et al. (2023) in turning AISI 1045 further reinforce the interpretation that the sensitivity of carbide tool wear to depth of cut is consistent across machining processes, while Zaida et al. (2021), Briantio et al. (2024), and Chendri Johan et al. (2026) reported progressive wear patterns that reinforce the consistency of the abrasive-adhesive wear mechanism observed in this study. The synthesis of these eleven prior studies confirms that carbide tool wear is a multifactorial phenomenon, and the main contribution of this study lies in isolating the specific effect of depth of cut on both flank wear and crater wear for the combination of S45C steel and carbide (widia) tool, which has not been extensively studied in the prior literature.

CONCLUSIONS AND RECOMMENDATIONS

Depth-of-cut variation was shown to affect the level of carbide (widia) tool wear during dry turning of S45C steel. The deeper the depth of cut applied, the higher the level of wear experienced by the tool: flank wear increased from 0.0186011 mm (1 mm) to 0.0325576 mm (3 mm), crater wear increased from 0.0005118 mm to 0.001432 mm, and cutting temperature increased from 28.9°C to 30.1°C. A depth of cut of 1 mm produced the lowest level of wear and is therefore recommended when the goal of the turning process is to obtain a longer tool life, while a greater depth of cut may be considered when productivity is the priority, provided additional mitigation is applied, such as reducing the cutting speed or using cutting fluid.

FURTHER STUDY

This study has limitations in the form of the use of a USB digital microscope with lower resolution than an SEM, changes in cutting speed and cutting duration that accompanied the depth-of-cut variation due to the limited configuration of the conventional lathe used, and the use of a single replication for each condition, meaning that statistical significance testing could not be performed. Further research is recommended using a full factorial design with repeated replication, involving simultaneous variation of cutting speed and feed rate, the use of cutting fluid, and higher-resolution measurement instruments such as an SEM, in order to obtain a more comprehensive picture of tool wear.

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