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Investigation of Surface Roughness and Tool Wear in Helical Plunge Milling of AISI 1045 Material

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Highlights

- This paper focuses on helical plunge milling in medium carbon steel.
- The surface roughness values deteriorated after machining
- The tool wear increased dramatically, because of excessive heat generation.

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Abstract

Pocket milling operations are one of the most common machining operations. In pocket milling operations, various cutting methods can be adopted according to the geometry of the workpiece. The helical plunge milling method (helical interpolation) can be advantageous in tight cavity geometries as a high-speed machining technique. In this method, parameters such as helix angle, depth of cut, cutting speed, and feed rate have a direct effect on both surface roughness and tool life. With the increasing demand for high-speed machining, it is crucial to investigate this method. In this study, AISI 1045 (C45W) steel was machined using helical plunge milling. The helix angle used was 1°. The axial and radial depths of cut values were set to 1 mm and 0.2 mm, respectively. A total of 16 passes were performed, and surface roughness values were measured at each pass. In general, the surface roughness values deteriorated after each experiment. After the experiments, the sharp corners of the tool were fractured, and evident built-up edge (BUE) formations were observed.

1. INTRODUCTION

Machining, as a manufacturing method, can be utilized for a wide range of manufacturing requirements. High dimensional accuracy, tight tolerances, and superior surface finishes enhance the capabilities of this method. For each manufacturing requirement, the machining approach can be modified, and new methods can be attempted to achieve the desired results. In particular, tool wear and surface roughness are directly affected by machining parameters [1].

In helical milling, the rotating endmill follows a helical trajectory as it rotates around its own axis. Helical milling enables the manufacture of holes with varying diameters—such as conical and complex-shaped (tapered) holes—in the workpiece. It also eliminates the need for tool changes during finishing operations [2]. In addition, helical milling (orbital drilling) significantly reduces delamination and thermal damage in composite materials compared to conventional drilling [3]. Better chip evacuation, higher surface quality, and lower thrust forces can be achieved with this method, and the wear mechanism can be better monitored and understood [4]. Helical milling and orbital drilling are similar methods. In the orbital drilling process, the cutting tool is mounted on a spindle that rotates eccentrically around a planetary rotation spindle and rotates independently [5]. Helical milling can be used for both pocket milling and drilling. In drilling, the quality of the hole (circularity, cylindricity, and surface roughness) depends on the cutting speed and lubrication [6]. In some research, instead of helix angle, axial depth of cut (helical pitch) can also be used [7].

In their study, Qin et al. [8] used four cutting speeds, four axial feeds per helical revolution, and four tangential feeds per tooth for machining. In their study, increasing the feed (axial and radial) increased the

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force and the cutting speed but reduced the cutting forces. Utilizing cutting fluid, or MQL, had almost the same effect and reduced the cutting force. Concerning tool life, they claimed that cutting fluid or lubricant had a great outcome. Under dry conditions, only 40 holes were drilled, compared to 160 with MQL and 145 with flood cooling. They also observed uniform flank wear, micro-chipping, and edge wear were the main types of tool failure. Diffusion wear and oxidation also occurred. They claimed that at high temperatures, tungsten carbide (WC) and cobalt (Co) binder from the cutting edge made an oxidation reaction with oxygen (O). They reported that increasing the feed rate increased the surface roughness. An increase in the spindle speed slightly reduced the surface roughness.

As a medium carbon steel, AISI 1045 provides sufficient strength and durability appropriate for most engineering applications. AISI 1045 material can be heat treated to improve its mechanical properties. After the heat treatment, the hardness and toughness of the material can be increased by 19% and 27%, respectively. Because of these capabilities, AISI 1045 has been used extensively in manufacturing requirements [9-10].

Costa et al. [11] used helical milling on AISI 1045 steel. The experiments were performed with cutting speed (100, 150, 200 (m/min)), circular feed per tooth (0.15, 0.20, 0.30 (mm/rev)), and axial feed per tooth (1, 1.5, 2.5 (μm/rev)). Lower feed rates and higher cutting speeds resulted in lower surface roughness and improved hole quality. It was found that when a through-hole was machined, a minor burr formation was observed at the exit of the hole.

Pimenov et al. [12] investigated surface roughness, tool wear, and energy consumption during the milling of AISI 1045 steel. The researchers used Grey Relational Analysis (GRA) to find the optimum experimental parameters. They claimed that increasing cutting speed and decreasing feed rate reduced surface roughness and increased tool wear. They also reported that increasing cutting speed and feed rate increased energy consumption.

Rao et al. [13] studied helical milling operations on AISI 1020, AISI 4340, and AISI D2 steels with different levels of spindle speeds, orbital speeds, and axial depth of cuts. In their experiments, they found that higher chip thickness increases cutting forces. The force levels varied with steel type: lowest for AISI 1020, moderate for AISI 4340, and highest for AISI D2. Additionally, increased feed resulted in higher power requirements and unwanted cutter displacement.

Pereira et al. [14] studied the helical milling of AISI H13 steel using a 10-mm cutting tool with a 3° helix angle and a 0.3-mm cutting depth. Similar wear behavior was observed in flank wear measurements at different cutting speeds (60 m/min and 175 m/min) initially (up to 50 μm); however, six to eight times less wear occurred at the lower speed. The cutting life was 550 minutes at the lower speed, considering a worn tool at 150 μm, compared to 160 minutes at high cutting speeds. BUE and adhesion were observed, and oxidation was determined due to the presence of O atoms. The coating layer was delaminated at both speeds, and the higher speed led to tool fracture.

Ramezani et al. [15] performed helical milling on AISI D2 steel and compared it with regular drilling operations in a milling machine. In their experiments, the researchers used a 50 m/min cutting speed and a 0.1 depth of cut. Helical milling produced two times better surface roughness results and extremely low cutting forces. On the contrary, the relatively low material removal rates of helical milling led to longer machining times.

Wang et al. [16] studied ball helical milling. In their experiments, the authors used three spindle speeds, three axial depths of cut, and three tangential feed rates. According to the results, increasing the axial cutting depth and tangential feed rates resulted in higher surface roughness. Conversely, increasing the spindle speed reduced surface roughness.

De Assis et al. [17] conducted a study on the impact of three toolpath strategies—helical, offset, and raster milling—on low-carbon steel using micro-end mills. The researchers found that helical milling produced lower surface roughness at high feed rates and low cutting speeds. Additionally, helical milling resulted in fewer surface defects than the other milling strategies.

Kharka et al. [18] conducted helical milling experiments on 304 stainless steel materials, creating holes using a 3 mm end mill. Following preliminary experiments, the researchers used a cutting speed of 28.3 m/min, a feed rate of 0.01 mm/tooth, and an axial depth of cut of 0.2 mm. Flank wear and deviation in cylindricity increased gradually with the number of machined holes. Burr formation and chipping were also detected.

Although the literature extensively studies the machining of AISI 1045, limited studies research has addressed the development of tool wear and its effect on surface roughness. Moreover, it was observed that this issue has not been sufficiently discussed. To overcome the lack of scientific studies on helical milling, in this study, AISI 1045 steel material was subjected to helical plunge milling to machine cylindrical pockets. A total of 16 passes were carried out, and the surface roughness values were measured after each pass. At the end of the experiments, SEM and SEM&EDX analyses were also carried out to analyze tool wear.

Citations must be given in brackets [1]. If there are two citations, use comma to separate [2,3]. If citations are more than two and in consecutive order, give the starting number and the last number [4-8]. For multiple citations with/without consequence, use the combination of the rules above [9,15,17-20].

2. MATERIAL METHOD

The cold-rolled AISI 1045 (C45W, 1.1730) steel material was utilized in the study. As a medium carbon steel, AISI 1045 is one of the most commonly used steels in industrial applications. Tables 1 and 2 provide the mechanical properties and chemical composition of the material, respectively. In addition, spectral analysis was employed to confirm the chemical composition of the material.

Table 1. *The Chemical composition of AISI 1045 material*

Chemical composition (%)						
Elements	C	Si	Mn	P	S	Fe
Technical values	0.42-0.50	0.15-0.40	0.60-0.80	Max 0.03	Max 0.03	Balance
Spectral analysis	0.46	0.24	0.67	0.01	0.006	Balance

Table 2. *The mechanical properties of AISI 1045 material*

Mechanical properties				
Tensile strength (MPa)	Yield strength (MPa)	Hardness (HB)	Modulus of Elasticity (GPa)	Thermal conductivity (W/m °K)
625	530	179	206	50

AISI 1045 material (Ø35 mm x 30 mm) was clamped in a CNC machining center (GMT MCV 740), and the top surface of the workpiece was machined with a face milling tool to eliminate any surface defects. After that, eight different machining experiments were carried out. After these operations, the workpiece was unclamped, turned upside down, and clamped again to machine the back of the workpiece. As a result, the same operations performed on the front of the part were also performed on the back, making a total of 16 machining passes (Figure 1a). No lubricant or cutting fluid was used, in order to make the tool wear more visible.

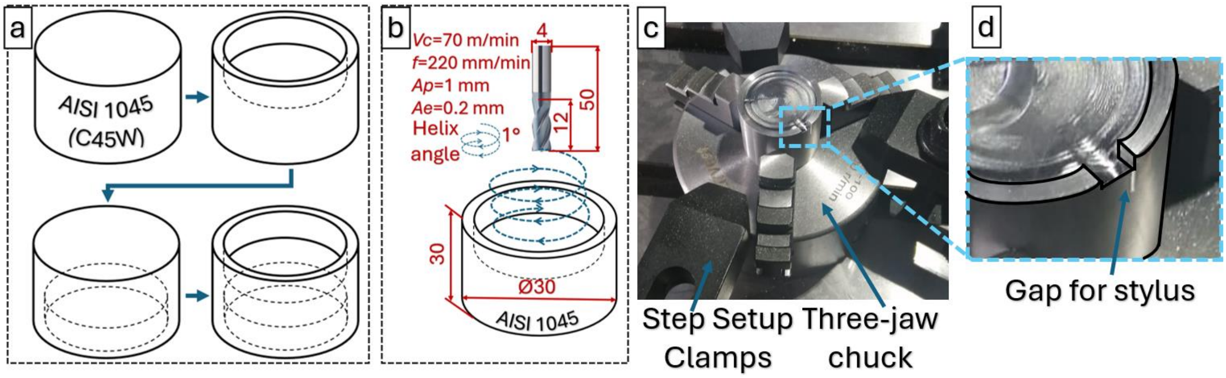


Figure 1. *The experimental setup*

A 4 mm diameter, four-flute AlCrN-coated carbide end mill (HPMT, Malaysia) was used in the experiments. The total length of the tool was 50 mm, and the cutting length was 12 mm (Figure 1b). The same end mill was used to observe the progression of the wear and perform eight passes on both sides of the workpiece. The axial depth of cut (ap) was set to 1 mm for these passes. All the cutting conditions are provided in Table 3.

Table 3. *The mechanical properties of AISI 1045 material*

Cutting Speed (*Vc*)	Feed rate (*f*)	Radial depth of cut (*ae*)	Axial depth of cut (*ap*)	Helix angle
70 m/min	220 mm/min	0.2 mm	1 mm	1°

The cutting tool was attached to the tool holder with a collet tool holder, and the workpiece was clamped to the machine table with a three-jaw chuck, as shown in Figure 1c. At each pass, the surface roughness of the machined surface was measured using a 2D stylus profilometer. A small opening was left unmachined to provide access to the machined surface (Figure 1d).

Surface roughness measurements were recorded using a Mahr Marsurf M300 evaluation unit and a Mahr Marsurf RD18 drive unit via Bluetooth connection. The average of these measurements was taken as the workpiece surface roughness value (Figure 2). In the experiments, both the arithmetic mean deviation of the profile (Ra) and the maximum height of the profile (Rz) were obtained.

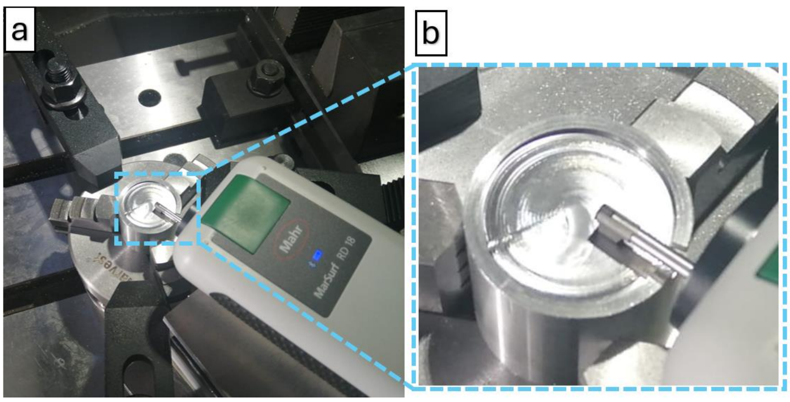


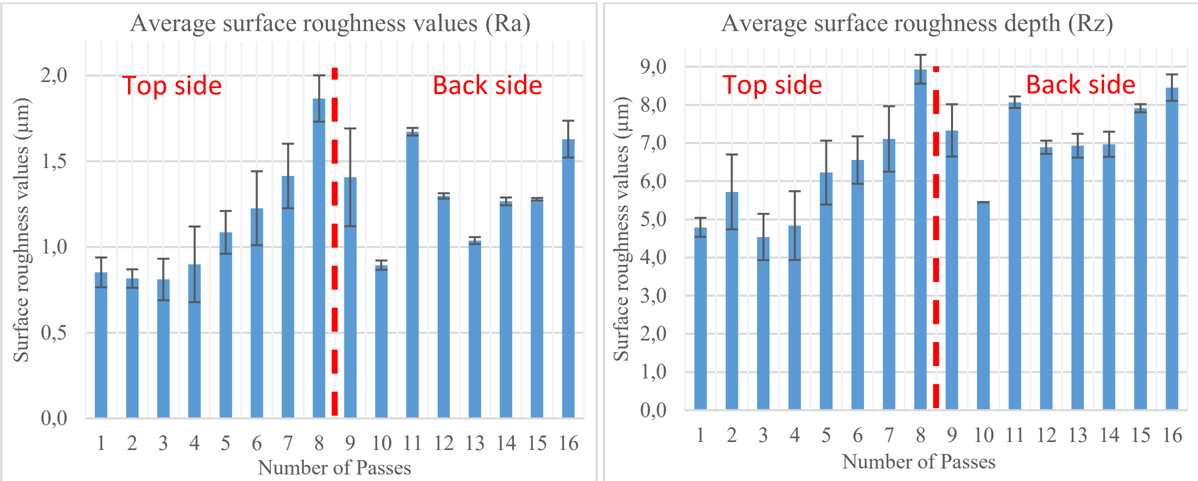
Figure 2. *The surface roughness measurements*

In addition to the surface roughness measurements, the tool wear was evaluated by scanning electron microscopy (SEM) after the experiments. An Energy-dispersive X-ray (EDX) analysis was also carried out to detect the formation of a built-up edge (BUE) on the surface.

3. THE RESEARCH FINDINGS AND DISCUSSION

3.1. Surface Roughness

Surface roughness is one of the most important aspects of machining. In general, the lower the surface roughness, the higher the quality of the machined part. For this reason, surface roughness is the focus of many investigations. In this study, after each machining operation, the plots generated using the values obtained from the surface roughness measurements are shown in Figure 3.



(a) (b)

Figure 3. *The surface roughness values a) Ra b) Rz*

Figure 3 clearly illustrates the change in surface roughness in both Ra (Figure 3a) and Rz (Figure 3b). The surface roughness values increase with each pass at the top of the workpiece. The rate of increase is almost the same for both Ra and Rz. This can be explained by tool wear. Generally, as the tool wear increases, the surface quality decreases, and the surface roughness increases. Interestingly, however, the surface roughness values of the back side of the workpiece are controversial. Figure 3a shows that lower surface roughness values can be seen. In particular, in the 10th and 13th passes in Figure 3a, the surface roughness values (Ra) were observed to be low. Rz values are also meaningful when evaluating the surface roughness values of the workpiece. Compared with the Ra values, the Rz values become more reasonable. These controversial results can be explained in several ways. First, after machining the top side, the thermal and dynamic conditions on the back side may have become more stable [19]. Second, tool wear may have caused the sharp corner of the cutting tool to dull and the cutting edge to round, which could result in improved surface roughness [20]. Third, even though the same clamping method was used, slight variations in orientation may have led to reduced vibration or deflection during cutting [21]. Fourth, BUE formations were observed during the experiments. As the tool continues to cut, the BUE may either break off or stabilize, potentially resulting in smoother cuts on the backside [22].

The Ra/Rz ratio can provide another useful metric for machining. The consistency of the Ra/Rz ratio reflects the stability of the machining process [23-25]. In the experiments, the Ra/Rz ratio was consistent, and it was calculated to be between five and seven.

3.2. SEM and EDX Analysis

Cutting tools are affected by numerous factors during machining. These factors influence affect tool wear. In order to understand the wear mechanism on the tool, the tool wear was examined by scanning electron microscopy (SEM) analysis using a ZEISS GeminiSEM 500 device. Although the cutting tool has four cutting edges, the wear characteristics were depicted similarly, and even though the cutting tool has four cutting edges only two cutting edges were examined. These cutting edges are shown in Figure 4.

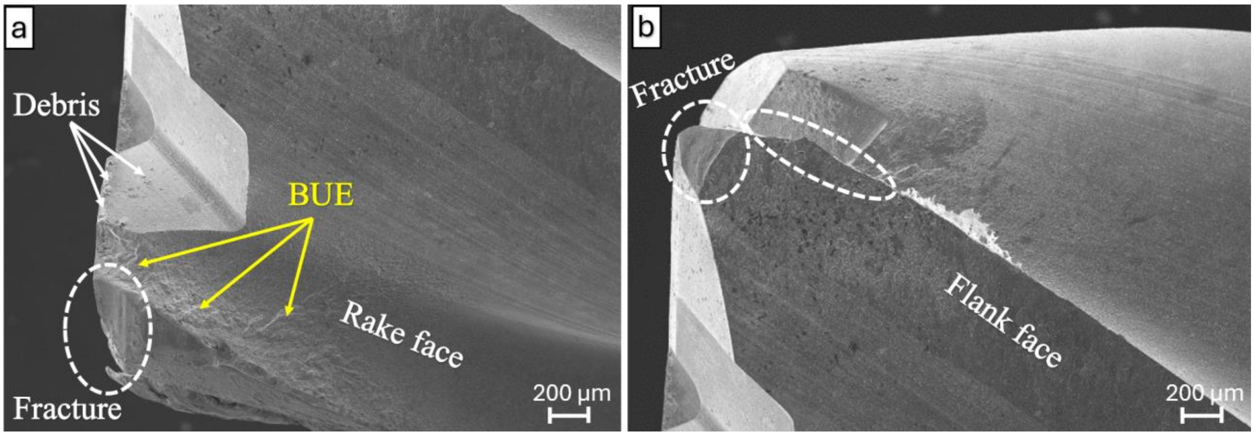


Figure 4. *The SEM Analysis of cutting corner of the tool*

In both Figure 4a and Figure 4b, the fracture was observed at the corner of the tool. It is a well-known fact that flat-end mills are generally worn at their corners. As no cutting fluid or lubricant was applied, the tool wear was obvious. Both the rake and flank surfaces were observed to be relatively clean. The detail from Figure 4b is shown in Figure 5.

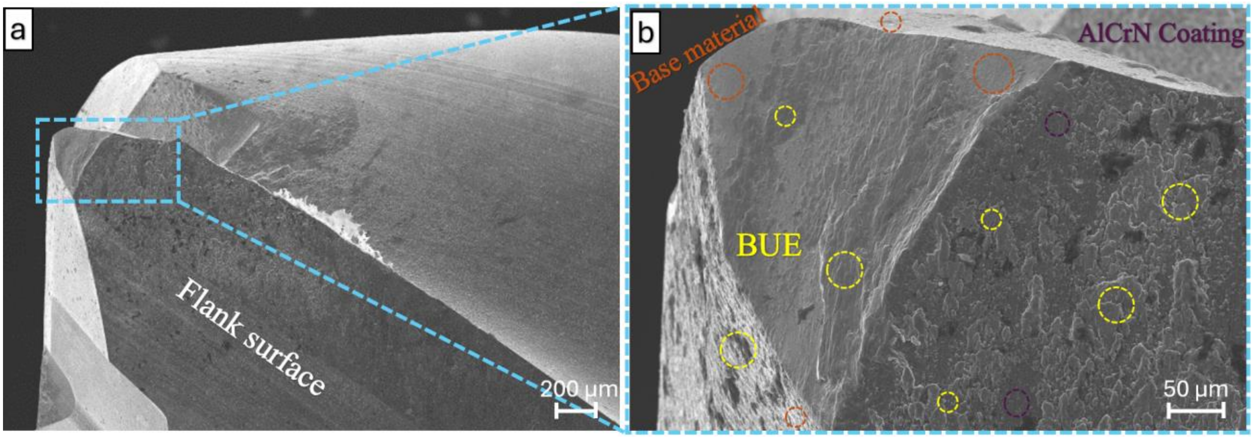


Figure 5. *The detailed SEM Analysis of the cutting corner of the tool*

As shown in Figure 5a and its detailed view in Figure 5b, the fracture is apparently visible. There are also some visible marks on the flank surface. During machining, three-element (three-body) abrasive wear causes flank wear [8-18], and excessive forces in challenging cutting circumstances can accelerate this wear [14]. The interaction between the cutting tool and the workpiece (friction, heat, and pressure) also may cause BUE formation [14]. In these experiments residual particles can be easily detected on the flank surface of the tool (Figure 5b). The cutting tools also exhibited delamination of the coating layer due to abrasive wear in many cases [8-14]. Since a coated tool was utilized in the experiments, it can be concluded that some parts of the coatings were peeled off. An energy-dispersive X-ray spectroscopy (EDX) analysis was also performed to confirm this (Figure 6). Two EDX analyses were performed to understand the fractured surface, and two additional EDX analyses were performed on other regions of the tool.

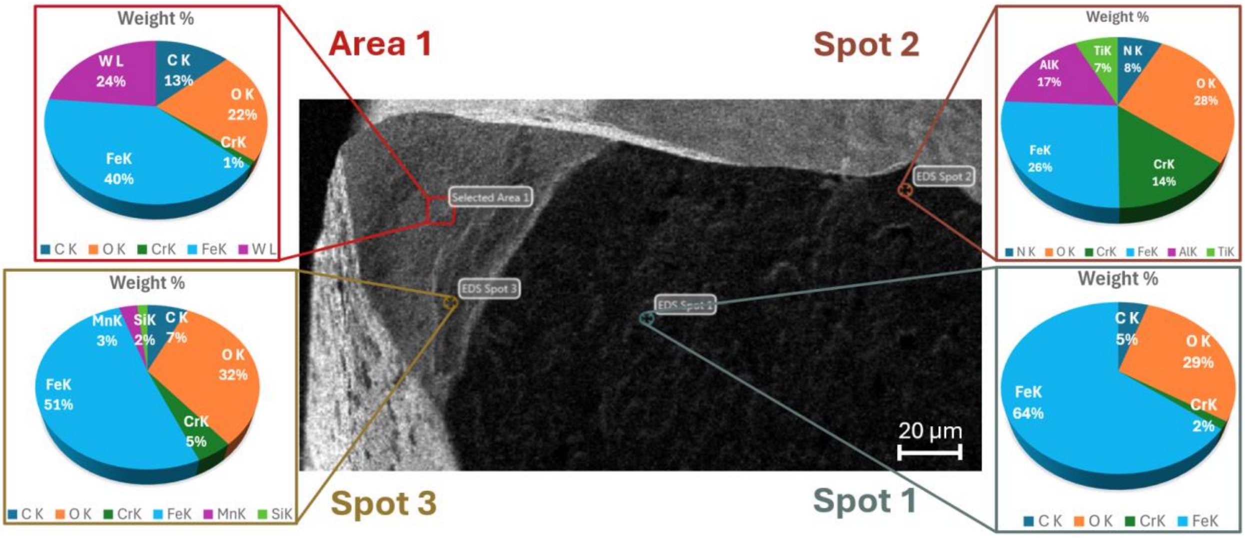


Figure 6. *The SEM-EDX analysis of the cutting tool*

According to the EDX analysis in Figure 6, the elements Fe, W, C, O, and Cr were detected in the measurements of area 1 (red square box). Tungsten (W) and carbon (C) are typically used as the primary materials in cutting tool manufacturing. It can be noted that the high content of W and C indicates the main chemical structure of the tool, and the intense presence of O elements shows oxidation in area 1. The workpiece's chemical composition also includes high carbon; therefore, it has been claimed that the presence of Fe is directly related to the workpiece. Cutting tools typically contain Co or Ni as a binder in their chemical formulation. However, it is significant to note that Co or Ni were not detected in area 1.

Similar to area 1, the measurements in spot 3 revealed almost identical elements, except for W. Some insignificant amounts of Mn and Si can be related to the chemical composition of the workpiece. It is claimed that built-up edge (BUE) formation was detected in this spot. In spot 1, the high presence of Fe and C shows BUE formation and the presence of O shows oxidation on this spot.

Cutting tools are often coated to enhance their mechanical and chemical resistance. An AlCrN-coated tool was used in the experiments. Measurements of spot 2 detected Al, Cr, and N, indicating that the coated layer is still unworn in the spot. The presence of O in spot 2 indicates oxidation, and the presence of Fe likely indicates debris from the workpiece.

Although spots 1 and 2 are both on the same surface (flank face) of the cutting tool, the SEM-EDX analyses of the two spots differ. The absence of Al in spot 1 can be explained by the complete or partial wear of the cutting tool's coating. The low-level presence of Fe indicates BUE formation; however, the presence of Al, Cr, and N is directly related to the tool's coating layer. Therefore, it can be concluded that the slightly worn cutting tool coatings were detected in spot 3.

4. RESULTS

In this study, AISI 1045 steel material was subjected to pocket milling operations using helical interpolation; the material was machined with 16 passes. The workpiece was subjected to eight passes on one side and eight passes on the other side, utilizing two separate machine setups. After each pass, the surface roughness of the workpiece was evaluated using both Ra and Rz. At the end of the experiments, SEM and SEM&EDX analyses were performed to analyze tool wear. The machining operations were completed successfully without any defects with both setups. In conclusion, the following results were obtained after these experiments.

From the surface roughness measurements taken after each pass, it is clear that the surface roughness values increase with each pass. However, during the final eight passes in the second setup, some surface roughness values (both Ra and Rz values) were measured that were inconsistent with those from the first eight passes.

These unexpected surface roughness values could possibly be the result of a change in the vibration behavior of the workpiece, the breaking and re-stabilization of the built-up edge (BUE), or the dulling and rounding of the cutting tool's sharp corner. The Rz/Ra ratio was found to be consistent and in the range of five to seven.

After tool wear measurements were performed using SEM and SEM&EDX, significant tool wear was detected on the cutting tool. The sharp corners of the tool were broken, and visible fractures were observed after the experiments. Although the cutting surface of the tool remained relatively clean. However, some BUE formations were observed on the tool, particularly close to the fractured areas. In addition, the coated layer on the cutting surfaces of the tool was found to have peeled off.

In this study, the vibration values weren't recorded, which was considered as a limitation of the study. Future research can address this by evaluating vibration behavior during machining. Furthermore, since the cutting fluid or lubricant was not used in the current study, future work could explore the effects of various coolant/lubricant environments to evaluate surface roughness and tool wear.

CONFLICTS OF INTEREST

No conflict of interest was declared by the author.

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