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Performance Evaluation of Coolant Concentration When End Milling Hardened Steel Using Coated Carbide Tool

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Abstract. Cutting fluids having a significant role in machining operation and had great positive impact, especially on the tool life, tool wear and surface roughness of the workpiece. Investigation on end milling of hardened steel AISI 1045 using coated solid carbide cutting tool under different coolant conditions was carried out experimentally. Experimented work involved three different coolant concentrations which are 3%, 6%, and 9%, with a different cutting speed of 35m/min and 50m/min. The depth of cut and feed rate was kept constant at 4mm and 0.05mm/tooth, respectively. The machining performance was evaluated based on the effect of tool wear, tool life and surface roughness. Analysis of recorded data shows that tool performance during machining is dependent on coolant concentration and cutting speed. Coolant with 3% concentration gave the best overall performance as an effective combination of cooling and lubrication functions during machining. Longer tool life when machining at cutting at a higher cutting speed of 50mm/min, due to the reduced amount of the build-up edge (BUE) on the cutting tool.

INTRODUCTION

The machining process is an important part of manufacturing components such as mold and die. The most common form of machining for material removal process, which can create a variety of features on a part by cutting away the unwanted material is milling [1-3]. Milling can be classified as peripheral, face and end milling. The study will be focused on end milling, which is widely used in industry because of its versatility and efficiency. Applications of the end milling process can be found in many industries ranging from large manufactures to small tool and die shops [2].

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Therefore, the use of cutting fluids; coolants and lubricants are essential in a machining operation to increase manufacturing productivity. Cutting fluid is a liquid used in metalworking operations for reducing friction between the workpiece and the tool and for removal of the heat generated by the friction [3]. As that, coolant is very important in machining because it can reduce the cutting temperature and ease the removal of chips and metal debris from the tool and workpiece interface. Types and concentration of coolant used to depend on the machining method and type of material used [4]. In this study, the end milling machining using carbide tool is selected and the material used is hardened steel.

In several studies, they showed that coolant could be as cooling and lubrication effect and taking away formed chip from the cutting zone [1, 5]. The cooling effect of coolant is the most important parameter. It is necessary to decrease the effect of temperature on cutting tool and machined workpiece [6, 7]. Therefore, a longer life will be obtained due to less tool wear and dimensional accuracy of the machined workpiece will be improved. While for the lubrication effect would cause less built-up edge (BUE) when machining some materials because of the low friction coefficient [8-10]. As a result, a better surface finish would be observed in the machining process.

EXPERIMENTAL PROCEDURES

Machining experiments were conducted on hardened S45C steel, also known AISI 1045 steel with dimension 355mm × 36mm × 67mm using a five axes CNC milling machine, DMG MORI; DMU50. Titanium Aluminium Nitride (TiAlN) coated solid carbide tools with code K4EPEN 100C was used with finishing cutting condition. Cutting fluids and cutting speed are two parameters to be considered. The following cutting conditions were employed in this investigation:

i. Coolant concentration (%): 3, 6, 9
ii. Cutting speed (m/min): 35, 50
iii. Depth of cut (mm):
iv. Axial = 4
v. Radial = 0.5
vi. Feed rate (mm/tooth) = 0.05

Different coolant concentration was tested, and a refractometer was used to measure the coolant concentration. Cutting operation was stopped and change with a new cutting tool when any of the following criterion is met:

i. Average wear, $V_{B\,avg} \geq 0.2$mm
ii. Non-uniform wear, $V_{B\,max} \geq 0.4$mm
iii. Chipping ≥ 0.3mm
iv. Catastrophic failure

After the machining operation stop, the tool was observed under a digital optical microscope equipped with iSolution software to measure the tool wear. While Mitutoyo profilometer was used to measure the surface roughness of the machined surface of the workpiece. Surface roughness was measured at various intervals with a stylus-type instrument. Three readings were taken at different locations of the machined surface, and the average value was recorded.

RESULTS AND DISCUSSION

Table 1 is a summary of tool life when machining S45C hardened steel with TiAlN coated carbide tool at various coolant concentration with different cutting speeds.

TABLE 1. Tool life at various coolant concentration using different cutting speed

Feed Rate (mm/tooth)	0.05					
Coolant Concentration	3%		6%		9%	
Cutting Speed (m/min)	35	50	35	50	35	50
Tool Life (min)	15.54	24.06	3.28	10.46	14.38	17.49
Length of Cut (m)	5.005	7.605	0.7	3.325	4.655	5.685
V_b max (mm)	0.314	0.305	0.427	0.316	0.340	0.314
V_b avg (mm)	0.195	0.207	0.083	0.162	0.199	0.176

By referring to the data collected, graphs in Fig. 1 and Fig. 2 were plotted, which show the relationship of tool wear and cutting time at various coolant concentrations when using different cutting speed.

From Fig. 1, it can be seen that as cutting time increases, the average tool wear also increases. At cutting speed of 35m/min, the total cutting time to achieve the average tool wear of 0.2mm is around 16 minutes. At a low cutting speed of 35m/min at three different coolant concentrations, the wear increases and the tool failed due to chipping more than 0.3mm. Under 6% coolant concentration, the tool worn gradually from 0.066mm to 0.083mm before failure at about 3.28 minutes.

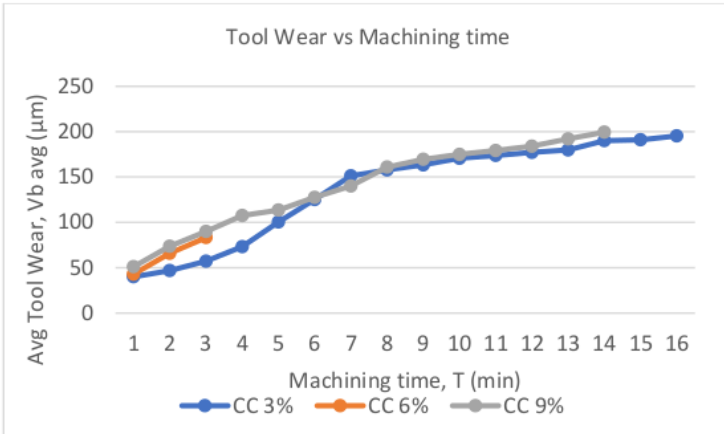


FIGURE 1. Tool wear curve when cutting speed 35m/min

Under coolant concentration of 3%, the tool wear increased from 0.04mm to 0.195mm after 16 minutes of cutting time. While at 9% of coolant concentration, the tool life criteria of 0.2mm wear is achieved when the total cutting time was 14.14 minutes as it increased from 0.051mm to 0.2mm. The tool worn reaches 0.083mm before failure due to chipping. Although the average tool wear was lower than 0.2mm, the size of chipping for one of the flutes exceeds 0.2mm. Hence the tool was considered failed.

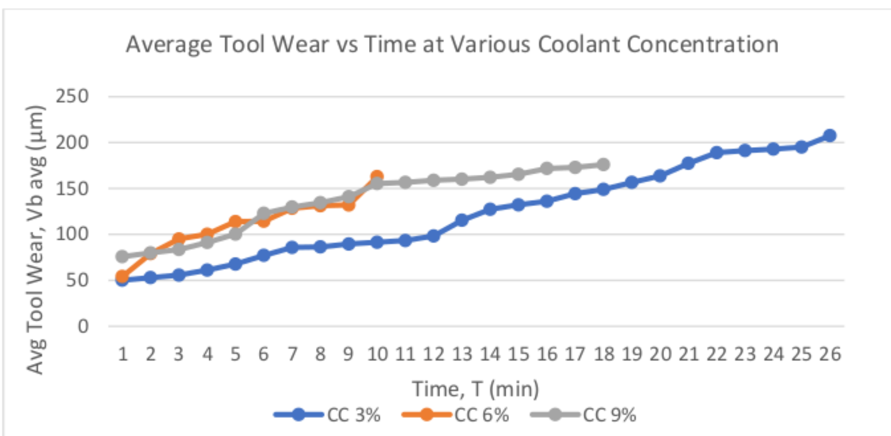


FIGURE 2. Tool wear curve when cutting speed 50m/min

From Fig. 2, at cutting speed 50m/min, it can be seen that as cutting time increases, the average tool wear also increases. The total cutting time to achieve the average tool wear when cutting speed at 50m/min was 24.55 minutes, with 3% of coolant concentration. Tool life at coolant concentration of 6%, and 9%, the total cutting time was 10.33 minutes and 17.43 minutes, respectively.

At coolant concentration of 3%, the tool wear increased from 0.05mm to 0.207mm after machining almost 24.55 minutes. While at 6% and 9% of coolant concentration, the tool wear increases from 0.054mm to 0.163mm and from 0.076mm to 0.176mm, respectively. Although the average tool wear was lower than 0.2mm, the tool failed due to chipping in wear, the size of chip one of the flute, which was quite large with greater size more than 0.2mm, hence the tool was considered failed for both conditions of coolant concentration.

Based on the result obtained, when end milling at cutting speed of 35m/min and 50m/min at various coolant concentration, indicates that the 3% of coolant concentration produces longer cutting time in order to achieve the average tool wear before failure due to chipping in one of the flutes of the cutting tool. In a nutshell, Figs. 1 and 2 suggest that machining with 3% of coolant concentration gives a better result in terms of average tool wear for the longest cutting time than 6% and 9% of coolant concentration.

The tool life for two different cutting speed with various coolant concentration is plotted and illustrated in Fig. 3. Based on the chart, it shows that at highest cutting speed of 50m/min with 3% of coolant concentration have the longest tool life of 24.6 minutes, whereas at coolant concentration 6% with lowest cutting speed of 35m/min have the shorter tool life of 3.28 minutes was recorded.

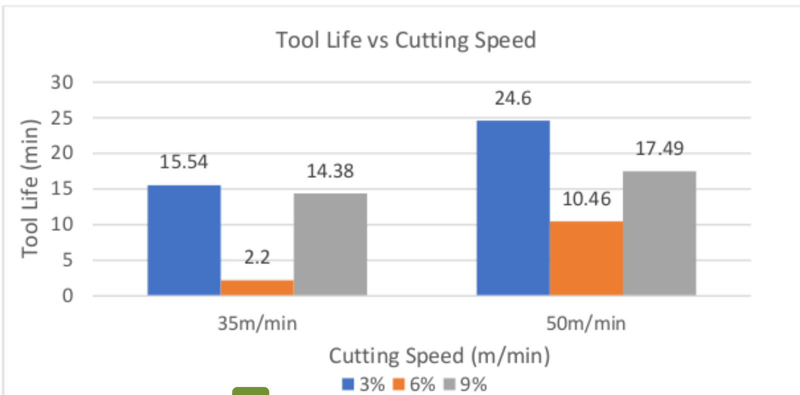


FIGURE 3. Tool life at different cutting speed and concentration

At cutting speed of 50m/min, the most extended tool life recorded under 3% coolant concentration was 24.06 minutes, followed by 9% of coolant concentration with 17.49 minutes and lastly, 6% of coolant concentration with 10.46 minutes. A similar trend was observed that cutting speed of 35m/min under coolant concentration of 3%, and the tool life was 15.54 minutes, then decrease to 14.38 minutes with 9% coolant concentration and lastly under 6% of coolant concentration the lowest tool life obtained was only 3.28 minutes.

As cutting speed increases from 35m/min to 50m/min, the tool life increases from 15.54 minutes to 24.6 minutes under 3% of coolant concentration. Similarly, with 6% and 9% of coolant concentration, the tool life increases with increase in cutting speed.

Fig. 3 also shows the effect of increasing coolant concentration on tool life from 3% to 6 and 9% resulted in reduction and increment in tool life, respectively, at the cutting speed of 35m/min and 50m/min. Generally, it can be deduced from Fig. 3 that machining with 3% coolant concentration exhibited better overall performance in terms of tool life than with 6% and 9% of coolant concentration.

The surface finish of the machined surface was observed and analyzed on the phenomena of tool wear and tool life at different cutting speeds under various coolant concentration. Based on the graphical result shown in Fig. 4, it is observed that the surface roughness fluctuated as cutting time increases at cutting speed of 35m/min. Fig. 4 shows the average value of surface roughness measured at three different positions on the machined surface.

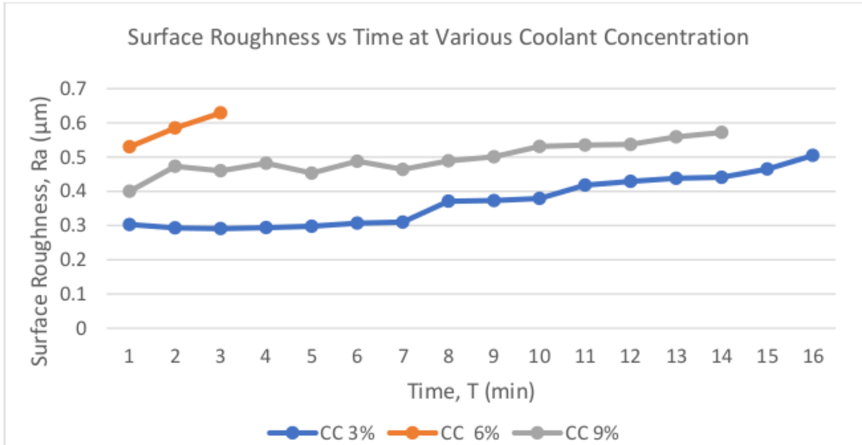


FIGURE 4. Surface roughness when cutting speed 35m/min

On the other hand, it was observed that at 6% of coolant concentration, the surface roughness was relatively high and reduced at coolant concentration of 9% and 3%, respectively. Results showed that the lower coolant concentration, the better the surface finish. This may occur due to the fact that low coolant concentration during machining provided a better lubricating effect that reduces friction between the cutting tool and workpiece and results from the failure mode of the flute on the tools also can affect the surface roughness of workpiece.

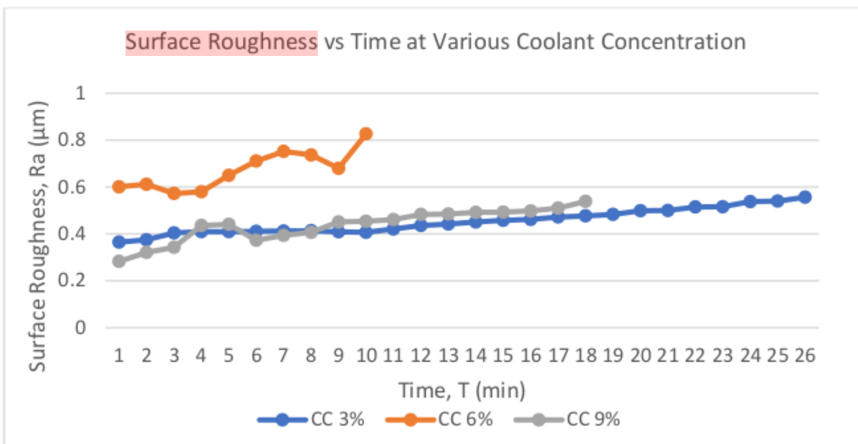


FIGURE 5. Surface roughness when cutting speed 50m/min

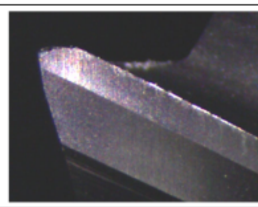
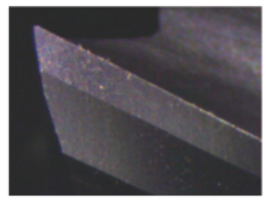
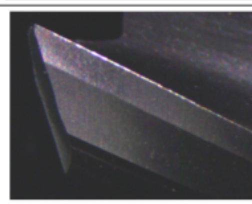
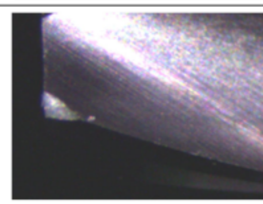
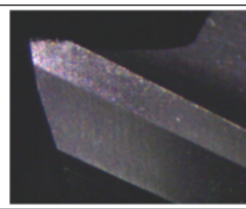
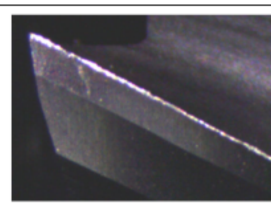
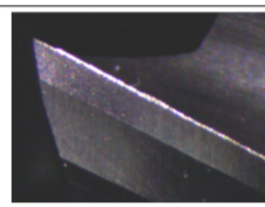
From the graph in Fig. 5, it is observed that the curve of surface roughness at cutting speed 50m/min also fluctuated when cutting time increases. However, the results recorded is the average value measurement of surface roughness at three different points on the machined surface. The surface roughness showed a marginal upward trend against cutting time.

Meanwhile, it was observed that at 3% of coolant concentration, better surface roughness results were obtained as compared with 6% and 9% of coolant concentration. This implies that machining under higher coolant concentration produces more elevated surface roughness values and vice versa. The reason why the 3% coolant concentration gives the better surface finish because with the more extended tool life and prolonged machining at 3% coolant concentration resulted in rounding up of the cutting edges of the tool, which tends to increase the nose radius hence improve the surface finish.

Generally, both graphs indicated that at cutting speeds 35m/min and 50m/min with 3% of coolant concentration, better surface finish was attained. However, cutting speed of 50m/min gives a better surface finish than 35m/min with higher tool life of 24.55 minutes. This is due to the effect of decrease in build-up-edge (BUE) at high cutting speed, as reported by other researchers [10-14]. Further, with prolonged machining, the surface roughness improved due to the round-up of the cutting edge. Therefore to produce better surface finish, machining should be done at higher speed with low coolant concentration avoiding BUE and lubrication effect at low cutting speed.

The cutting tool used in the experiment was considered failed when the average tool wear, $V_{avg} \geq 0.2mm$ or maximum tool wear, $V_b \geq 0.4mm$ or chipping ≥ 0.3mm. By observing Table 2, with coolant concentration 3% at cutting speed 35m/min and after 15.54 minutes, it was found that the tool failed due to chipping on two of the flute of the cutting tool. While at cutting speed of 50m/min, it was found that the tool failed due to chipping and catastrophic failure on the flutes of the cutting tool after 24.06 minutes of machining.

TABLE 2. Tool failure when machining at 3% of coolant concentration

Flute No	Cutting Speed = 35m/min	Cutting Speed = 50m/min
1		
2		
3		
4		

CONCLUSION

In conclusion, higher cutting speed 50m/min at 3% of lower coolant concentration exhibits the most extended tool life and better surface finish. This may be due to the fact that when cutting at high speed, the size of the build-up edge (BUE) decreases or being eliminated, and the effect of nose radius under prolonged machining contributed to the low surface finish. Besides, coolant at low concentration provides better cooling effect that cools the cutting zone and cutting tool from overheat. It also reduces the friction between the cutting tool and workpiece as the function of coolant is to improve tool life and surface finish. It as found that chipping was the dominant tool failure mode under almost all conditions due to mechanical shock and thermal fatigue as a result of interrupted cutting and the effect of vibration during machining. Based on the results and observation of the present experimental investigation, the following conclusion can be drawn:

i. Most extended tool life was generally obtained when machining the S45C hardened steel with 3% coolant concentration at the higher cutting speed of 50m/min.
ii. Better surface finish was obtained when machining S45C hardened steel with 3% coolant concentration at the higher cutting speed of 50m/min.
iii. Higher coolant concentration with 6% and 9% decrease tool life due to higher compressive stresses generated by the reduction of the tool-chip and tool-workpiece contact area.
iv. Coolant concentration of 3% with cutting speed 50m/min exhibits the best performance in terms of tool life and surface finish when end milling S45C hardened steel using TiAlN coated carbide tool.

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