

The influence of machining condition and cutting tool wear on surface roughness of AISI 4340 steel

A R Natasha¹, J A Ghani², C H Che Haron² and J Syarif³

¹Department of Manufacturing and Materials Engineering, International Islamic University Malaysia (IIUM), Jalan Gombak, 53100 Kuala Lumpur, Malaysia

²Department of Mechanical and Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor, Malaysia

³Department of Mechanical Engineering, College of Engineering, University of Sharjah, P.O.Box 27272, Sharjah, United Arab Emirates

Email: natashar@iium.edu.my

Abstract. Sustainable machining by using cryogenic coolant as the cutting fluid has been proven to enhance some machining outputs. The main objective of the current work was to investigate the influence of machining conditions; dry and cryogenic, as well as the cutting tool wear on the machined surface roughness of AISI 4340 steel. The experimental tests were performed using chemical vapor deposition (CVD) coated carbide inserts. The value of machined surface roughness were measured at 3 cutting intervals; beginning, middle, and end of the cutting based on the readings of the tool flank wear. The results revealed that cryogenic turning had the greatest influence on surface roughness when machined at lower cutting speed and higher feed rate. Meanwhile, the cutting tool wear was also found to influence the surface roughness, either improving it or deteriorating it, based on the severity and the mechanism of the flank wear.

1. Introduction

AISI 4340 steel is one of the most widely used materials in engineering products. The advantages of AISI 4340 steel such as high toughness and high strength make them dominant in various applications including automotive and machine tools industry. Among its applications include spindles, main shafts, axle shafts, gears and couplings [1]. AISI 4340 is a heat treatable alloy and the material usually undergo a heat treatment process like quenching and tempering in order for them to meet the required level of hardness, strength, and ductility [2]. It is usually machined in hardened state. According to Suresh et al. [1], the main problems associated with machining this type of steel are related to tool wear and surface quality.

Machined surface quality is one of the most important machining outputs and can be evaluated based on two categories; geometrical features, the texture of the surface and the metallurgical characteristics of the subsurface [3]. The texture of the surface includes the machined surface roughness. The value of surface roughness needs to be achieved depends on the requirement of the part's application [4]. During the turning operation, high heat generated during the process is said to improve the chip formation as well as the quality of the machined surface [5]. However, high cutting



temperature will also increase the tool wear rate during the cutting. Therefore, to control the amount of heat generated, cutting fluid is applied during the machining process.

Cryogenic application as a cutting fluid by using several types of cryogen such as liquid nitrogen (LN), oxygen, helium (LHe), methane, ethane, and argon to reduce the cutting temperature during machining is becoming more popular [6]. Extensive research on the effect of cryogenic application of numerous work materials on the machining outputs such as cutting temperature, tool wear, cutting forces, and surface quality have been conducted. Kaynak et al. [7] had reviewed some of these research in their comprehensive review paper and listed some of the work materials being studied, such as Inconel 718 [8–10], Ti-6Al-4V [10–15], various steels [16–20], shape memory alloys [21–23], magnesium alloys [24] and other engineering materials [25].

As the machining progresses, the cutting tool wear is also progresses. However, the effect of cryogenic coolant and the tool wear on machined surface roughness has not been fully explored yet. In this study, AISI 4340 steel was machined in dry and cryogenic conditions by using multilayer coated carbide cutting tool. The effects of machining conditions and cutting tool wear on machined surface roughness were evaluated.

2. Experimental procedures

AISI 4340 round bar with 100 mm initial diameter was turned in dry and cryogenic machining conditions on a TORNADO CNC lathe machine with the capability of 6000 rpm maximum spindle speed. The experimental tests were carried out using a Sumitomo flat face P10 carbide insert coated with $\text{TiC} + \text{Al}_2\text{O}_3$. Cylindrical liquid nitrogen (LN) tank was connected to a flexible hose and a copper pipe was used as a nozzle pointing to the cutting zone as shown in figure 1(a) and figure 1(b). The distance between the tip of the nozzle to the cutting point was fixed at 2 cm.

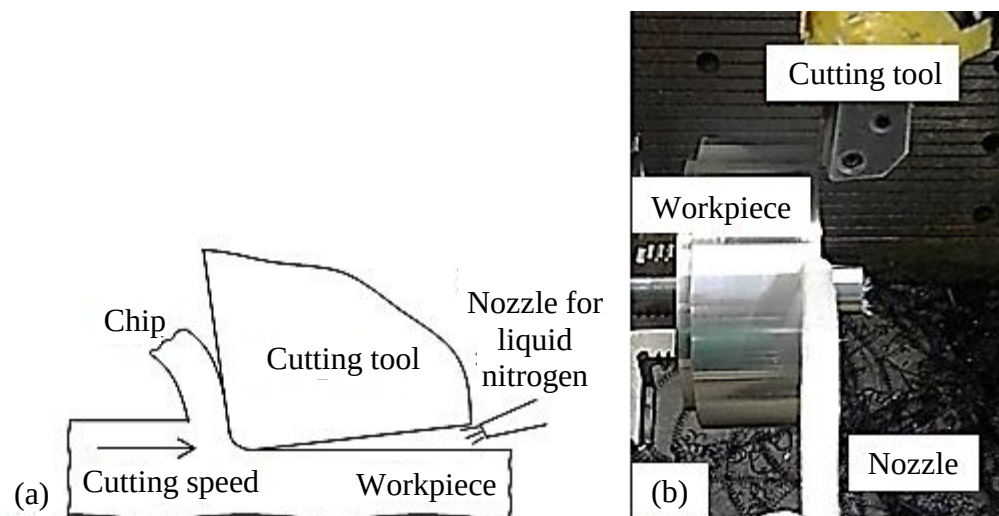


Figure 1. Nozzle orientation at the clearance face of the tool (a) Schematic diagram and (b) Photograph of the nozzle setup at CNC lathe machine.

Machining tests were carried out at cutting speeds of 160, 200 and 240 m/min. The feed was varied at 0.3 and 0.4 mm/rev and the depth of cut employed was 1.0 mm. Machining was interrupted at regular intervals to measure the tool flank wear using an Olympus SZ61 stereo microscope. The machining operation was stopped when the tool flank wear measurement reached one of the tool failure criteria as mentioned in ISO 3685 [26]; that is when average flank wear (V_B) ≥ 0.3 mm or the maximum flank wear (V_{Bmax}) ≥ 0.6 mm.

The surface roughness of the machined part were measured using a Mitutoyo Surftest SJ-310 portable surface roughness tester. The arithmetic average roughness value (R_a) in micrometer (μm) was taken at every first, middle, and end of the run of each experimental test. This was done as to compare the effect of tool wear on the roughness of the machined surfaces. The measurement was performed five times at five different spots, then the average value was calculated to represent the value of surface roughness.

3. Results and Discussion

The results of machined surface roughness of the work material AISI 4340 alloy steel when cutting using a new multilayer coated carbide tool are presented in figure 2. The value of the surface roughness, R_a reported for each experimental run was the average value of five roughness readings. Figure 2 shows the comparison of R_a of the machined surface using a new cutting tool in dry and cryogenic condition for various values of cutting speed and feed rate.

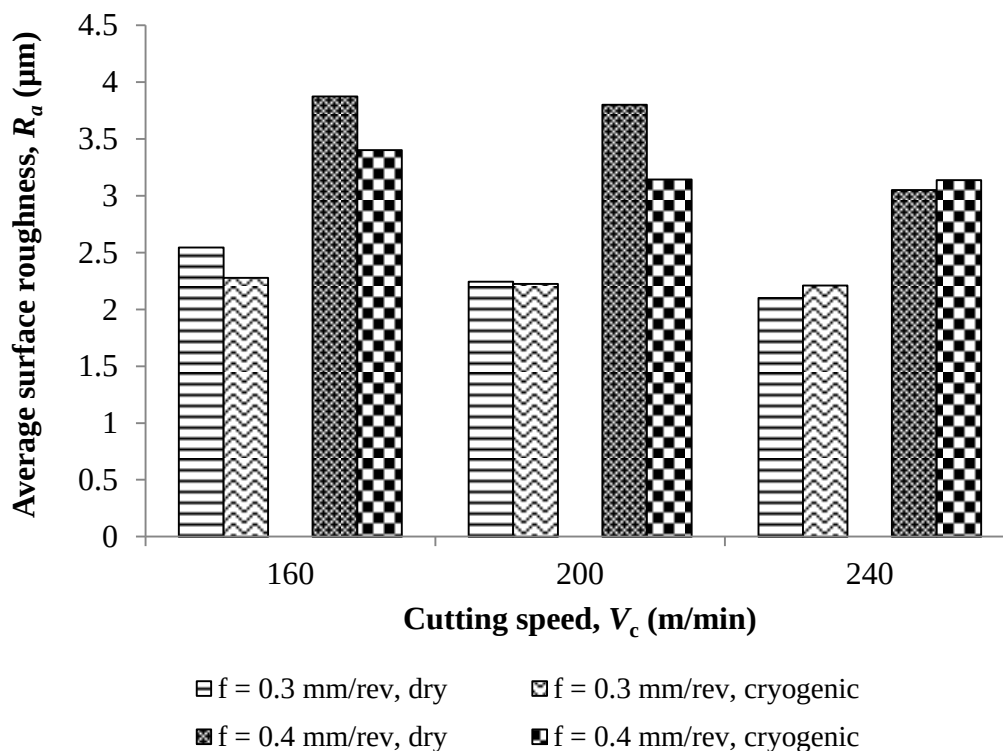


Figure 2. Comparison of average surface roughness (R_a) in experimental test of turning AISI 4340 alloy steel in dry and cryogenic condition for various cutting speeds and feed rate (doc = 1.0 mm).

The experimental result shows that the surface roughness values ranging from 2.10 μm to 3.88 μm were recorded during the turning process of AISI 4340 alloy steel under dry and cryogenic condition using a new cutting tool. The lowest value of machined surface roughness was measured at cutting speed of 240 m/min, feed rate 0.3 mm/rev, machined in dry condition, while the highest value of surface roughness was obtained at cutting speed 160 m/min, feed rate 0.4 mm/rev, machined in dry condition.

It was observed that the value of surface roughness decreased as the cutting speed increases both in dry and cryogenic condition, at both feed rate of 0.3 mm/rev and 0.4 mm/rev. This might be due to the higher temperature generated at higher cutting speed, hence increasing the thermal softening effect of the work material. Therefore, lower forces needed to cut the workpiece hence resulted in better

roughness compared to those obtained at lower cutting speed [27]. In addition, the high temperature may also lead to the adhesion of the work material onto the tool nose, consequently smoothening the nose profile, thus contributing to the better surface finish [28]. However, the differences in the roughness values at different cutting speeds were not that significant and apparent in cryogenic turning.

The effect of feed rate on surface roughness was observed to be more significant compared to the cutting speed. As shown in figure 2, the values of machined surface roughness increased tremendously as the feed rate was increased from 0.3 mm/rev to 0.4 mm/rev. This increment pattern was observed in both dry and cryogenic conditions at all values of cutting speed. These results are in agreement with equation (3.1) where high feed rates will produce a rougher machined surface. On the other hand, low feed rate will improve the machined surface finish when cutting using the same value of tool nose radius. With the increase of the feed rate, higher cutting forces are needed for the cutting tool to cut the work material, which resulted in higher cutting temperature. This may lead to a worse tool wear condition and deteriorate the surface finish [29]. However, despite a better surface finish when cutting at the lower feed, the rate of material removed will be decreased too.

$$R_a = \frac{f^2}{32r} \quad (3.1)$$

This result is consistent with some other previous researches [1,28,30,31]. According to Thakur et al. [32], at the higher feed rate, the friction between the tool and the workpiece increases. As the cutting progresses, the temperature will increase and result in reduction of material shear strength. The chips of the work material that stick to the tool edge will cause the surface roughness escalated.

From figure 2 as well, it can be said that the application of liquid nitrogen during the turning process produced slightly better surface roughness compared to dry turning at cutting speed of 160 m/min and 200 m/min. At cutting speed of 240 m/min, the cryogenic application, however resulted in slightly rougher machined surface than dry turning. This might be due to the lower temperature generated in cryogenic turning, hence reducing the tendency of sticky work material at the cutting edge which leads to improved surface finish. Besides, the application of LN during machining reduces the coefficient of friction at the interfaces and this can be another factor that contribute to the better surface roughness [33].

The influence of cutting tool wear on the machined surface roughness was also investigated in this study. Figure 3 shows the readings of average surface roughness as a function of cutting tool condition. The R_a values were measured at flank wear, $V_B = 0 \mu\text{m}$ (new tool), $V_B \geq 0.15 \mu\text{m}$ (medium wear), and $V_B \geq 0.3 \mu\text{m}$ (wear). It was observed that there were a few patterns of the graph relation between surface roughness and tool wear. Several machining conditions produced better surface roughness when cutting using a worn tool. This is most probably due to the effective flattening of the tool nose resulted from the increase in the worn flat on the flank of the tool [34], which increases the tool nose radius as shown in figure 4, thus contributing to better machined surface quality. A significant decrement of the roughness value when cutting using a worn tool at cutting speed of 240 m/min in cryogenic condition might be due to the combined benefits of higher speed and cryogenic application to the surface roughness improvement as discussed previously.

Meanwhile, several other machining conditions produced rougher machined surface when cutting using a worn tool. As machining time increases, tool sharpness deteriorates and leads to a degraded surface roughness [34]. Besides, the adhesion of the work material on the tool edge and the tool flank face may also be a factor contributing to a bad surface finish. A significant increment of the roughness value was observed when cutting using a worn tool at cutting speed 200 m/min in cryogenic condition. Closer observation of the cutting tool used in this machining condition showed that the cutting tool experienced fracture wear on the tool flank face. This might deteriorate the machined surface even more compared to other machining conditions.

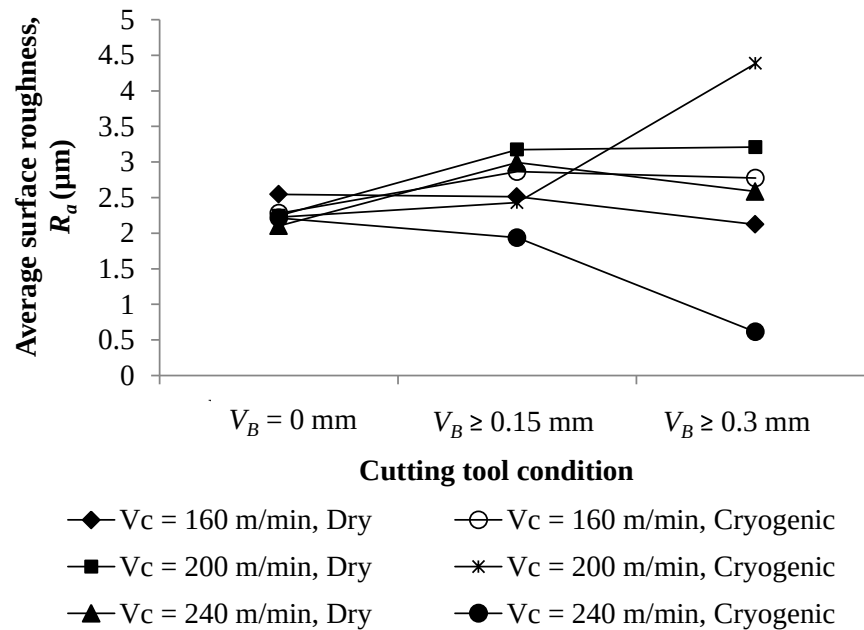


Figure 3. Effect of cutting tool condition on the average surface roughness (R_a) of AISI 4340 alloy steel machined at different cutting speed under dry and cryogenic environment ($f = 0.3 \text{ mm/rev}$).

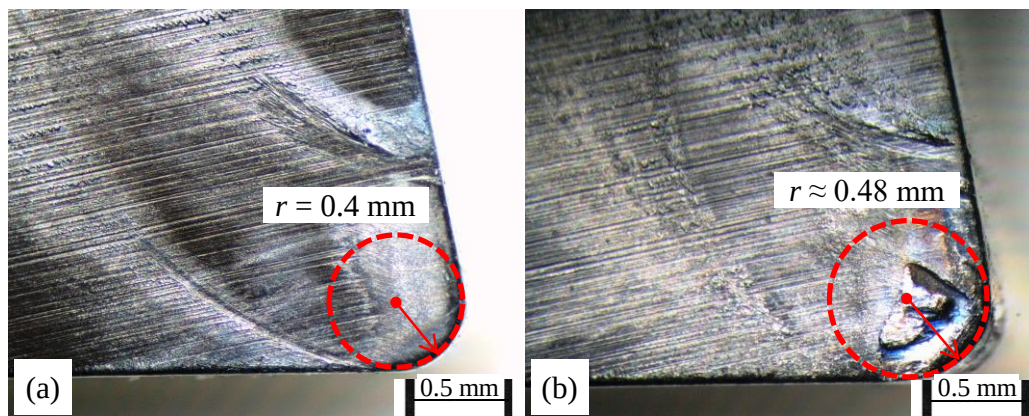


Figure 4. Comparison of tool nose radius in (a) new tool, and (b) worn tool.

4. Conclusion

In this work, AISI 4340 steel was turned using coated carbide insert in order to assess the effect of machining conditions and cutting tool wear on the machined surface roughness. It was found that higher cutting speed and lower feed rate produced better surface finish both in dry and cryogenic cutting conditions. However, the differences between the roughness values were not apparent in cryogenic turning as the cutting speed varied. Cryogenic cutting improved the machined surface roughness, except at cutting speed 240 m/min. For the effect of cutting tool wear on the surface roughness, several machining conditions produced better surface roughness when cutting using a worn tool with cutting at 240 m/min speed in cryogenic condition showed the most significant decrement of roughness value. On the other hand, several other machining conditions produced rougher machined surface when cutting using a worn tool especially when machined at cutting speed of 200 m/min in cryogenic condition.

References

- [1] Suresh R, Basavarajappa S, Gaitonde V N and Samuel G L 2012 *Int. J. Refract. Met. Hard Mater.* **33** 75–86
- [2] Al-Ghamdi K A, Iqbal A and Hussain G 2014 *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 1–21
- [3] Davim J P 2010 *Surface Integrity in Machining* vol 53 (London: Springer-Verlag London)
- [4] Petropoulos G P, Pandazaras C N and Davim J P 2010 *Surface Integrity in Machining* ed J P Davim (Springer) 37–66
- [5] Klocke F, Settineri L, Lung D, Claudio Priarone P and Arft M 2013 *Wear* **302** 1136–44
- [6] Shokrani A, Dhokia V and Newman S T 2012 *Int. J. Mach. Tools Manuf.* **57** 83–101
- [7] Kaynak Y, Lu T and Jawahir I S 2014 *Mach. Sci. Technol.* **18** 149–98
- [8] Courbon C, Pusavec F, Dumont F, Rech J and Kopac J 2013 *Tribol. Int.* **66** 72–82
- [9] Kaynak Y 2014 *Int. J. Adv. Manuf. Technol.* **72** 919–33
- [10] Wang Z Y and Rajurkar K P 2000 *Wear* **239** 168–75
- [11] Bermingham M J, Kirsch J, Sun S, Palanisamy S and Dargusch M S 2011 *Int. J. Mach. Tools Manuf.* **51** 500–11
- [12] Hong S Y, Ding Y and Jeong W 2001 *Int. J. Mach. Tools Manuf.* **41** 2271–85
- [13] Hong S Y, Markus I and Jeong W cheol 2001 *Int. J. Mach. Tools Manuf.* **41** 2245–60
- [14] Strano M, Chiappini E, Tirelli S, Albertelli P and Monno M 2013 *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **227** 1403–8
- [15] Yasa E, Pilatin S and Çolak O 2012 *J. Prod. Eng.* **2** 1–9
- [16] Dhar N R, Paul S and Chattopadhyay A B 2001 *Wear* **249** 932–42
- [17] Paul S and Chattopadhyay A B 1996 *Int. J. Mach. Tools Manuf.* **36** 63–72
- [18] Venugopal K a., Paul S and Chattopadhyay a. B 2007 *Wear* **262** 1071–8
- [19] Pušavec F, Govekar E, Kopač J and Jawahir I S 2011 *CIRP Ann. - Manuf. Technol.* **60** 101–4
- [20] Rotella G, Umbrello D, Dillon O W and Jawahir I S 2012 *J. Adv. Mech. Des. Syst. Manuf.* **6** 989–98
- [21] Kaynak Y, Karaca H E and Jawahir I S 2011 *6th International Conference and Exhibition on Design and Production of Machines and Dies/Molds* pp 123–8
- [22] Kaynak Y, Karaca H E, Noebe R D and Jawahir I S 2013 *Procedia CIRP* **8** 498–503
- [23] Kaynak Y, Karaca H E, Noebe R D and Jawahir I S 2013 *Wear* **306** 51–63
- [24] Pu Z 2012 *Cryogenic machining and burnishing of AZ31B Magnesium alloy for enhanced surface integrity and functional performance*
- [25] Wang Z and Rajurkar K 1997 *Int. J. Mach. Tools Manuf.* **37** 319–26
- [26] ISO 3685 1993 *Tool-life testing with single-point turning tools* (Geneva: International Organization for Standardization (ISO))
- [27] Pawade R S, Joshi S S, Brahmanekar P K and Rahman M 2007 *J. Mater. Process. Technol.* **192–193** 139–46
- [28] Dhar N R and Kamruzzaman M 2007 *Int. J. Mach. Tools Manuf.* **47** 754–9
- [29] Arunachalam R M, Mannan M A and Spowage A C 2004 *Int. J. Mach. Tools Manuf.* **44** 1481–91
- [30] Lima J G, Ávila R F, Abrão a. M, Faustino M and Davim J P 2005 *J. Mater. Process. Technol.* **169** 388–95
- [31] Suresh R, Basavarajappa S and Samuel G L 2012 *Measurement* **45** 1872–84
- [32] Thakur D G, Ramamoorthy B and Vijayaraghavan L 2009 *Mater. Des.* **30** 1718–25
- [33] Natasha A R, Ghani J A, Syarif J, Haron C H C and Hadi M A 2014 *Appl. Mech. Mater.* **554** 7–11
- [34] More A S, Jiang W, Brown W D and Malshe A P 2006 *J. Mater. Process. Technol.* **180** 253–262