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Cryogenic Machining Performance of M303 at High Cutting Speeds

Nur Fadhilah Aimuni Mohd Ridzuan, Tahrin Othman, Afifah Zakiyyah Juri, Jaharah A. Ghani* & Che Hassan Che Haron

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

**Corresponding author: jaharahaghani@ukm.edu.my*

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ABSTRACTS

The material M303 is commonly used in the fabrication of machinery, automotive components, locomotive axle housings, and injection moulds. It is a stainless martensitic chromium steel known for its high strength, wear resistance, and corrosion resistance. The primary purpose of this study is to investigate the machinability of M303 under cryogenic conditions, specifically focusing on high cutting speeds. By exploring the effects of cryogenic machining on M303, the study aims to provide insights into the performance and characteristics of this material under extreme cutting conditions. This study investigates the influence of cutting parameters on the machinability of M303 in a cryogenic environment using liquid nitrogen (LN2) and coated carbide cutting tools in a high-speed turning process. The study focuses on high cutting speeds and examines essential machinability factors, including cutting forces, surface finish, and tool life. The experimental design utilises a Taguchi L4 orthogonal array to systematically study feed rates (0.1-0.2 mm/rev), depth of cut (0.2-0.6 mm), and high cutting speeds (260-340 m/min). Notably, at a low cutting speed of 260 m/min, coupled with low feed rates and depth of cut, the study reveals the longest tool life of 48.57 mintues was achieved. This condition is characterized by a good surface finish and low cutting forces with Ra of 0.9 µm and cutting force of 100 N respectively. The predominant wear occurs on the flank face, primarily due to fracturing and chipping, especially under high combinations of cutting parameters. Conversely, gradual wear is observed under low combinations of cutting parameters, resulting in an extended tool life. In conclusion, the application of LN2 proves effective under conditions of low cutting parameters. The study suggests that the risk of fracturing the cutting tool increases at higher feed rates and depths of cut, especially when combined with elevated cutting speeds. This research provides valuable insights into optimizing the machining of M303 for enhanced efficiency and tool longevity.

Keywords: M303, machinability, cryogenic, LN2, Taguchi Method

INTRODUCTION

The world is rapidly developing in line with technological advancements and the evolution of machining industries. In general, machining produces final component geometries using various physical effects, which can be broadly classified as mechanical, thermal, and chemical processes, as well as various combinations of these mechanisms (Liao et al. 2021). In the contemporary landscape of technological advancements, machining continues to be extensively employed as a subtractive process.

M303 is a stainless martensitic chromium steel with high hardness, wear and corrosion resistance, as well as enhanced polishability and machinability (Kriswanto et al. 2021; Othman et al. 2022; Zinner et al. 2010). Its primary application is in the manufacturing of moulds and dies (Kriswanto et al. 2021; Zinner et al. 2010). However, the use of M303 is increasingly prevalent in automotive and machinery components, tools, and as a shaft housing (Othman et al. 2022). The turning process of M303 at high cutting speeds under dry cutting conditions was studied by Othman et al. (2022). High cutting temperature is commonly the main problem in high speed. Therefore, in dry machining, high temperature is generated between the cutting tool's edge and the workpiece surface, as well as between the cutting tool and the chips (Natasha et al. 2016).

This accelerates tool wear, leading to a shorter tool life. The overall machining cost increases when tools need frequent replacement due to tool wear (Ghani et al. 2010). Tool replacement is essential because worn tools can affect surface quality, dimensional accuracy, and machining process profitability.

Cryogenic machining is a cutting-edge technology that involves the use of extremely cold temperatures during the machining process. Cryogenic cooling functions as a cooling agent and can produce excellent product quality, improve tool life, precision and accuracy, reduce cutting temperature, decrease surface roughness, and lower power consumption to enhance productivity, especially in high-speed machining (Jawahir et al. 2016; Yildiz & Nalbant 2008). Furthermore, sustainability considerations play a significant role in selecting machining conditions.

The primary problem this study aims to address is the adverse impact of high temperatures in dry machining, particularly during the turning process of M303 at high cutting speeds. High cutting temperatures, generated between the cutting tool's edge and the workpiece surface, as well as between the cutting tool and the chips, have been identified as a significant challenge (Othman et al. 2022; Natasha et al. 2016). This issue leads to accelerated tool wear, resulting in a shorter tool life and increased overall machining costs (Ghani et al. 2010). The motivation for exploring cryogenic cooling, specifically using LN2 as the cryogen, stems from the need to mitigate the negative effects of high temperatures during machining processes. Cryogenic cooling is expected to offer a solution by reducing cutting temperatures, extending tool life, improving precision and accuracy, and ultimately enhancing the overall machinability of M303, especially at high cutting. Additionally, the study recognizes sustainability considerations as a crucial factor in selecting machining conditions, further emphasizing the need for environmentally friendly and efficient solutions in the machining of materials like M303.

METHODOLOGY

The material used in this study is M303, which has material hardness of 30-32 HRC as supplied by the manufacturer. Prior to machining, this material is in the form of a cylindrical shape with dimensions of 150 mm in length and 60 mm in diameter. The composition of the material used is as shown in Table 1. Rhombus-coated carbide cutting tools are used in the machining experiment with a nose radius of 0.4 mm, and detailed properties and composition are shown in Figures 1 and 2, respectively. Table 2 shows the detailed specifications of the cutting tools.

Table 1. M303 chemical composition (KG 2019)

Type of material	C	Mn	Si	Cr	Ni	Mo
M303	0.27	0.65	0.30	14.50	0.85	1.00

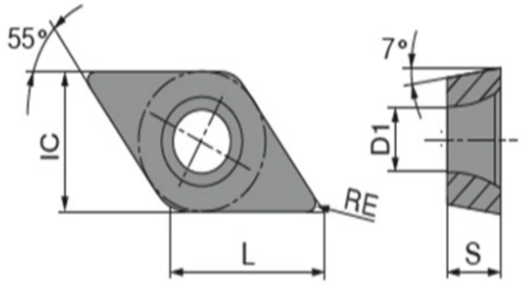

FIGURE 1. Schematic diagram of the cutting tool
Source: E-techstore (2021)

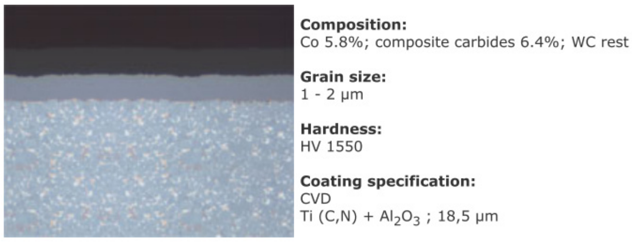

FIGURE 2. Tool composition and properties.
Source: E-techstore (2021)

TABLE 2. Detail specification of the cutting tool

Parameter	Specification
Cutting tool code	11T304EN, DCMT 11T304EN-SM CTC3110
Cutting tool type	Coated carbide 55 positive with hole
Nose radius, RE	0.4 mm
Side cutting length, L	11.6 mm
Cutting tool thickness, S	3.97 mm
Hole diameter, D1	4.4 mm
Circle diameter, IC	9.52

Source: E-techstore (2021)

Turning process were conducted using CNC machine (TORNADO T4) under high cutting speed subjected to cryogenic lubrication condition. The experiment was conducted in the laboratory environment at room temperature of 24 Deg C. Table 3 shows factors and levels used whereby Taguchi L4 method was applied to generate experimental design. The selection of this orthogonal array was based on its efficiency in requiring the least number of experimental runs while accommodating three factors at two levels each.

TABLE 3. Factors and levels used in the turning process.

Factor / Level	1	2
Cutting Speed (m/min)	260	340
Feed rate (mm/rev)	0.1	0.2
Depth of cut (mm)	0.2	0.6

The progress of the tool wear on the flank face was measured using a microscope model Zeiss Stemi 2000-C. Passes for each experimental trial varied according to the tool wear progression measurements. The flank wear land (Vb) was measured until it reached 0.15 mm. This is due to the time constraint in conducting the experiment. The machining process was stopped at specific cutting intervals to measure tool wear progression. The cutting force was measured at the beginning of the cutting, i.e. the cutting tool still in good condition using a Neo-MoMac system that utilize a strain gauge based dynamometer. Surface roughness tester (SJ-210, Mitutoyo) was used to measure the mean surface roughness (R_a) at the initial machining. Machined surface roughness was measured by contact stylus across the feed direction taken at the beginning of cutting to prevent tool wear effect. Measurements were repeated five times for each run with the values then averaged for further analysis.

RESULTS AND DISCUSSIONS

Table 4 shows the results of tool life, cutting force and average surface roughness in machining M303 at high cutting speed regime.

TABLE 4. Machining results of M303 material on machining output

Exp.	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Tool Life (min)	Cutting Force (N)	Surface Roughness (µm)
	260	0.1	0.2	48.57	91.91	0.902
2	260	0.2	0.6	0.42	411.50	3.454
	340	0.1	0.6	1.20	264.39	1.383
4	340	0.2	0.2	3.42	151.01	3.229

Experiment 1 recorded the longest tool life at 47.75 minutes with a feed rate (Vb) of 0.15 mm. In contrast, experiments 2 and 3 showed very short tool life at the same feed rate. It becomes apparent that a high depth of cut (0.6 mm) is unsuitable for machining M303 under cryogenic conditions at high cutting speeds. The failure is attributed to catastrophic failure, where the cutting edge of the carbide tool fractured; a phenomenon observed by previous researchers (Ghani et al. 2010; Shah et al. 2021). This catastrophic failure was the primary reason for the exceedingly short tool life in experiments 2 and 3. Figure 3 visually illustrates the catastrophic failure in experiments 2 and 3, emphasizing that these cutting conditions are not recommended for machining M303 under cryogenic conditions. However, Experiment 4, while exhibiting a shorter tool life compared to the lower cutting speed of 260 m/min, could be considered if productivity is the primary concern.

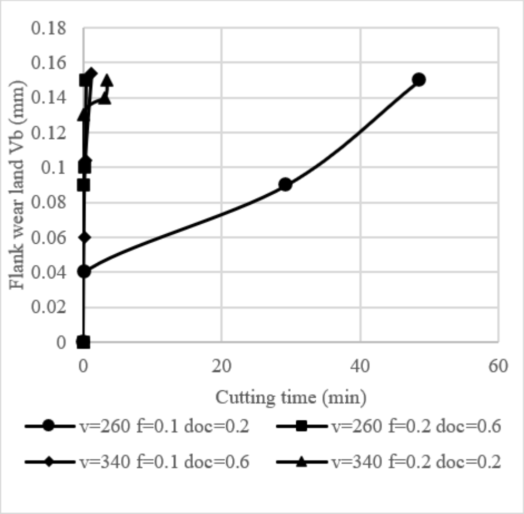

FIGURE 3. Vb (mm) against cutting time (min)

The cutting force measured in Experiment 1 yielded the lowest force, while Experiment 2, especially at the combination of high feed rate and depth of cut, resulted in high cutting force. This observation aligns with findings from Chen et al. (2018), who noted that higher feed rates led to increased cutting force during the turning of AD730 at high cutting speeds using PCBN tools. Minimizing or eliminating cutting force is essential to reduce vibration or chatter during the machining process, as these factors can significantly impact the quality of the machined surface. Figure 4 shows the average surface roughness and cutting force for this range of cutting condition.

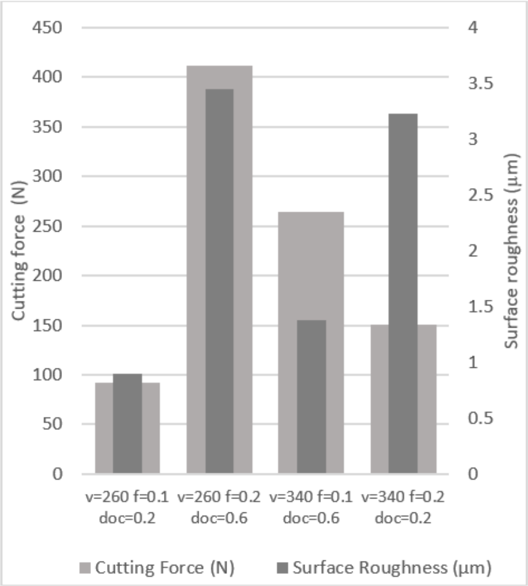

FIGURE 4. Average surface roughness and cutting force in turning M303

The average surface roughness measured ranges from 0.902 µm to 3.454 µm, corresponding to the N7 to N9 grade range according to ISO 1302:2002. This Ra range aligns with typical values for the turning process, as noted by Grzesik et al. (2010). When compared to a previous study investigating the impact of surface roughness on M303 using a carbide tool in dry conditions, it was observed that the Ra value produced in cryogenic conditions was higher than that achieved in dry conditions (Othman et al. 2022). This finding contradicts earlier studies that asserted cryogenics could result in smoother surface roughness (Ali Khan et al. 2019; Baig et al. 2023; Dhar & Kamruzzaman 2007; Muhamad et al. 2019). The likely reason for this contradiction is the chips tangling around the machined surface in this experiment, as depicted in Figure 4. Notably, a high feed rate of 0.2 mm/rev resulted in rougher surface values. The feed rate is a significant factor influencing surface roughness, as similarly found by Othman et al. (2022) and Carou et al. (2014).

The utilization of liquid nitrogen, which generates an extremely low temperature of -197 °C, has led to thermal shock on the carbide tip, as noted by Abdul Halim et al. (2020). This thermal shock accelerates fatigue on the cutting tool edge during machining in cryogenic LN2 conditions compared to dry conditions due to the drastic change in temperature. A noticeable change in the color of the carbide tip, from a golden to a metallic blue, indicates the removal of the coating material on the surface of the carbide tool. This removal of the coated material has expedited wear on the cutting tool edge. Flank wear was found to predominantly control the tool life in these experiments, as illustrated in Figure 4. At high depths of cut, chipping and fracturing on the cutting edge were clearly observed in Figure 4 (b) and (c). In contrast, uniform wear on the flank face was observed in Figure 4 (a) and (d) at low depths of cut, even though an adherence of chips was noted in Figure 4 (d).

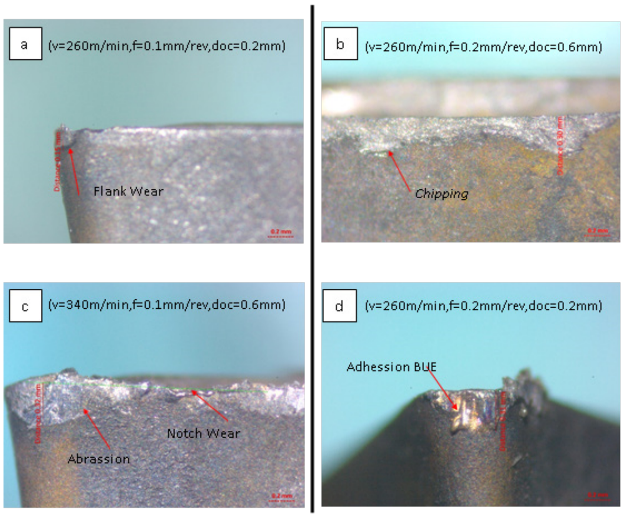

FIGURE 4. Carbide tool wear; (a) experiment 1 (b) experiment 2, (c) experiment 3, and (d) experiment 4

The adherence of chips results in the formation of a build-up edge (BUE). As explained by Musfirah et al. (2017), the disposal of BUE at the edge of the cutting tool leads to adhesive wear. This is caused by the chemical bond between the substrate of the cutting tool material and the workpiece, resulting in the formation of BUE at the cutting tool's edge. The wear mechanism observed aligns with findings from Halim et al. (2023) in their study on wear mechanisms at the cutting tool edge in cryogenic conditions.

The shape and size of the chips formed during the machining process exhibited variation, as observed by previous researchers (Muhamad et al. 2018). Figure 5 (a)-(d) illustrates diverse chip shapes, including continuous tubular, spiral, and ribbon-like shapes as shown in Figure 5(a) and (d). Elemental chips were also noted, as depicted in Figure 5 (b) and (c). Cutting parameters with a low depth of cut produced discontinuous and tubular chips, while those with a high depth of cut resulted in elemental, serrated, and arc-shaped chips, consistent with observations made by Dhar et al. (2002). According to Dhar et al. (2002), the color of the chips becomes brighter, exhibiting a metallic or golden hue due to the low cutting temperature in cryogenic conditions.

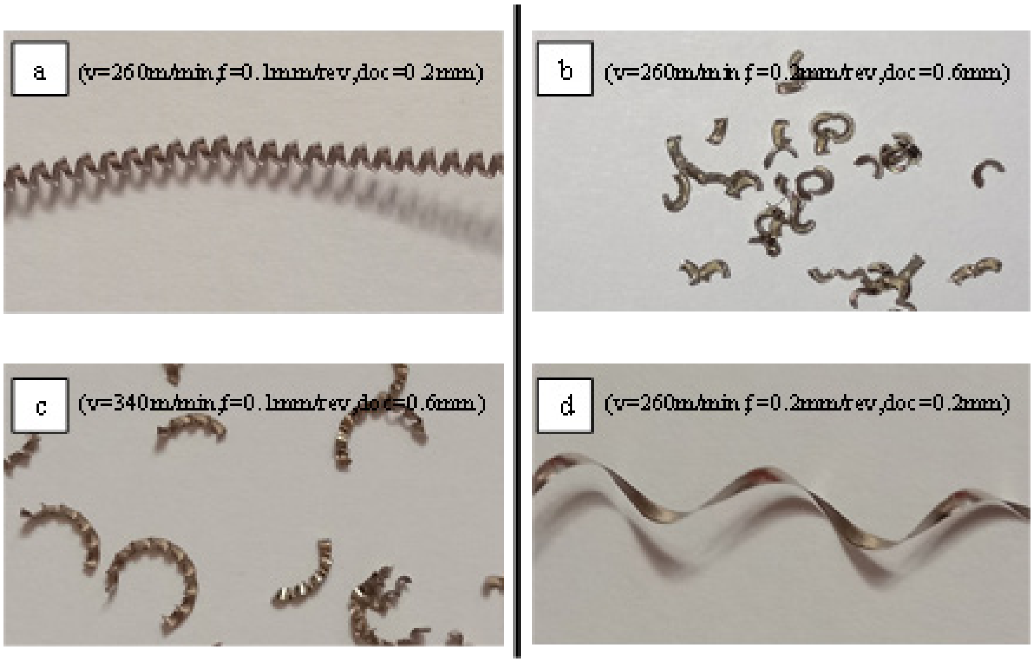

FIGURE 5. Chip formation; (a) experiment 1 (b) experiment 2, (c) experiment 3, and (d) experiment 4.

CONCLUSION

At a low cutting speed of 260 m/min and with low feed rate and depth of cut, the study observed the longest tool life, reaching 48.57 minutes. This cutting condition also yielded a good surface finish of 0.9 µm and a low cutting force of 100 N. The dominant wear occurred on the flank face, primarily due to fracturing and chipping, especially at high combinations of cutting parameters. Gradual wear was only observed at the low combination of cutting parameters, resulting in an extended tool life. The study concludes that the application of LN2 is suitable under conditions of low cutting speed, feed rate, and depth of cut. Fracturing of the cutting tool is induced at high feed rates and depths of cut, and this effect is exacerbated when combined with high cutting speeds.

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DECLARATION OF COMPETING INTEREST

None

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