The effects of cutting environment on surface roughness and tool life in milling of AISI 4340

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Abstract. In this work, AISI 4340 alloy was machined using PVD tungsten multilayer TiAlN/AlCrN coated carbide inserts under two different cutting environments: cryogenic cooling using liquid nitrogen (LN) and dry cutting condition. The experiments were performed at varying cutting parameters of cutting speed: 200–300 m/min, feed rate: 0.15–0.30 mm/tooth, axial depth of cut: 0.3–0.5 mm, and radial depth of cut: 0.2–0.5 mm. Nine variations in tool life and surface roughness were observed when machining under different machining parameters of AISI 4340 at 32 HRC. The analysis includes the tool life and surface roughness as well as its relationship. Cryogenic LN showed significant improvement towards increasing the tool life to a maximum of 41.7% relative to dry cutting. The experiment showed that the cryogenic application was able to reduce the surface roughness by up to 43.9% when compared to dry machining. Thus application of cryogenic cooling reduces tool wear, reduces cutting temperature and produces good surface quality which is believed to be the main factor causing an improvement compared to dry cutting.

1. Introduction

Surface roughness is used to foretell the functional of an engineering parts as surface abnormalities may cause in the development of fractures or oxidization. The work material, geometrical factors, vibrations and machine tool factors have an effect on the surface roughness of a machined face [1].Machining parameters influences on surface roughness of a machined surface have brought about challenges for engineers and researchers. Therefore, necessary methods of predicting the surface roughness of a product before machining are needed to verify the suitability of machining parameters for a required surface roughness. Eq. 1, shown the higher feed rates result in machined surface that is rougher. This theoretical relation also shows that with the same feed, a wider nose range leads to a superior surface finish as a wider nose range makes the feed marks less prominent. The effect of cutting specifications on temperature and surface roughness are explored by [2]. The hardness of work
material was found to be the greatest substantial determining aspect. The researchers discovered that compared to dry machining, the advantage of a coolant jet with high-pressure reduces the roughness values (12.9%), cutting temperature (10.8%), and tool wear (29.4%) respectively.

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Ra \approx 0.032 \frac{f^2}{T}
\]  

Other than surface roughness, another subject matter, i.e. tool life, were explored by several researchers. In order to measure the performance of coated ceramic tools with AISI 4340 steel, Panda et al., [3] studied surface roughness, tool life as well as commercial viability. The outcome of this investigation revealed that 47 min of coated ceramic tool life is attained under optimum cutting conditions. The cut down of downtime and greater tool life also meant the total machining cost per piece lowered to only USD $0.29.

Research by Al-Ghamdi et al., [4] on an empirical investigation of the machining of AISI 4340 under cryogenic cooling environment using CO\(_2\) snow as coolant. Feed rate and machining speed were the predominant factors to achieve longer tool life. A lower combination of machining parameters affects the machining performance and life of the tool.

In this present work, the influences of machining conditions on surface roughness and tool life were evaluated in machining AISI 4340 steel (32 HRC) during cryogenic and dry conditions using a multilayer coated carbide (TiAlN/AlCrN). These findings may be utilized by the machining industry with the aims of improving the surface roughness and prolonging the tool life, which are related to achieving a sustainable environment.

2. Experimental procedures

Bars of AISI 4340 steel were end milled under cryogenic and dry machining conditions on a DMG-ECO vertical milling machine. The Taguchi L9 orthogonal array was adopted in designing the experiments for specific cutting scenarios based on the control elements (Table 1).

| Factors               | Level 1 | Level 2 | Level 3 |
|-----------------------|---------|---------|---------|
| Cutting speed (m/min) | 200     | 250     | 300     |
| Feed rate (mm/tooth)  | 0.15    | 0.20    | 0.30    |
| Axial depth of cut (mm)| 0.3     | 0.4     | 0.5     |
| Radial depth of cut (mm)| 0.20   | 0.35    | 0.50    |

The experimental tests were carried out using a PVD multi-coated TiAlN and AlCrN cemented carbide insert. A new cutting tool was used for each test, Liquid nitrogen (LN) at -197°C was applied in the middle of the freshly machined surface and tool flank front using a flexible hose and a copper pipe connected to the cylindrical liquid nitrogen (LN) tank as presents in Figure 1(a and b) during the machining process. A 20-mm diameter of tool holder was utilized to affix the insert and a spray distance of 50 mm and spray angle of 45° was applied.
In (Fig. 2a) a portable surface roughness profile meter was commissioned to quantify the arithmetic average roughness value (Ra) in micrometers (µm) of the first machining path. Measurements were captured thrice at three specific points: one in the middle and the other two on the edge. The average of these values were then determined to show the surface roughness.

The machining test was paused on various intervals, at which point the tool was removed and the tool wear of the insert was calculated using Mitutoyo Toolmaker’s microscopes (Fig. 2b). Then, the tool was returned to the machine and the machining experiment was continued until the following tool wear measurement. In this experiment, the tool life criteria were set when the average flank wear achieved (VB_{avg} = 0.3mm) as mentioned in ISO 8688-2 (1989) [5]. Thus, machining time was used to represent tool life.

3. Results and Discussion
The surface roughness for both conditions were as shown in Table 2. The main effects analysis was used to study the trend of the effects of each of the factors. The main effects plot has been shown in Figures 3 and 4 for dry and cryogenic cooling respectively. The figures reveal that the feed rate significantly affects the surface roughness in both conditions. It was observed that the value of surface roughness increases with an increase of feed rate from 0.15 mm/tooth to 0.3 mm/tooth. This is in line with Bashiret al.,[6], who surmised that the increase in feed rate resulted in an increase in the surface roughness.

Figure 1. Nozzle orientation (a) The nozzle arrangement at the machine and (b) Schematic diagram.

Figure 2. (a) Surface roughness profile meter and (b) Toolmaker’s microscope for measuring tool life.
roughness. It was also observed that axial depth of cut is an insignificant factor on surface roughness in dry conditions, while speed is an insignificant factor in cryogenic conditions.

The surface roughness values attained were in the range of 0.114-0.319 µm for both cutting conditions (Figure 5). This made the process a match to manual grinding as the surface roughness values did not exceed 1.6 µm. The values of surface roughness were lower when machining with cryogenic coolant than those obtained during dry conditions. A lowest surface roughness of about 0.114 µm was observed for Experiment no 1 under cryogenic conditions. Meanwhile, the maximum surface roughness of 0.319 µm was achieved in Experiment no 2 under dry conditions. From Figure 5, the values showed that when under cryogenic conditions, an excellent surface finish was produced by as much as 43.9% as compared to surface finish under dry machining. This is due to the application of LN which lowered the surface roughness as the it reduces the coefficient of friction (CoF)[7-8]. According to Hong [8], LN generates a lubricating hydrodynamic film between the workpiece material and the cutting tool which yields a lessen coefficients of friction. Natasha et al., [9] had proved that the usage of LN lowers the CoF by up to 73% at the boundary of the chip and tool, which leads to lower surface roughness than that observed in dry machining.

Furthermore, effective penetration by the LN removes the chips from the cutting zones, which results in the just-machined surface not being subjected to friction, which in turn leaves no marks on the surface. Nonetheless, as cryogen is highly evaporable, the most appropriate approach is for the cryogen to seep into the cutting zone to improve the surface finish. Therefore, the use of cryogenic machininggenerates the best surface characteristic compared to the surface feature obtained by dry cutting.

**Table 2. Surface roughness under different cutting parameters.**

| Exp. No | $V_c$ (m/min) | $f_z$ (mm/tooth) | $a_p$ (mm) | $a_e$ (mm) | Ra (µm) (Dry) | Ra (µm) (Cryogenic) |
|---------|---------------|-----------------|-------------|-------------|---------------|-------------------|
| 1       | 200           | 0.15            | 0.3         | 0.20        | 0.181         | 0.114             |
| 2       | 200           | 0.20            | 0.4         | 0.35        | 0.319         | 0.179             |
| 3       | 200           | 0.30            | 0.5         | 0.50        | 0.176         | 0.229             |
| 4       | 250           | 0.15            | 0.5         | 0.35        | 0.204         | 0.166             |
| 5       | 250           | 0.20            | 0.3         | 0.50        | 0.216         | 0.135             |
| 6       | 250           | 0.30            | 0.4         | 0.20        | 0.220         | 0.227             |
| 7       | 300           | 0.15            | 0.4         | 0.50        | 0.163         | 0.149             |
| 8       | 300           | 0.20            | 0.5         | 0.20        | 0.284         | 0.195             |
| 9       | 300           | 0.30            | 0.3         | 0.35        | 0.278         | 0.184             |
Figure 3. Main effect plot for surface roughness under dry conditions.

Figure 4. Main effect plot for surface roughness under cryogenic conditions.

Figure 5. Difference of average surface roughness (Ra) in experimental testing of end milling for various parameters.
The flank face wear value exceeded the 0.3 mm criteria for both cutting conditions. The tool life for both conditions were as shown in Table 3. Figures 6 and 7 show the analysis of mean SN ratio plots for tool life obtained in both conditions. The analysis indicated that lower feed rate (0.15 mm/tooth) is more favorable when the tool life is of interest. The figures reveal that an increase in cutting speed leads to lower tool life. By increasing the cutting speed, the friction between cutting edge and workpiece surfaces increases and it may cause higher temperatures at the tool-workpiece interface. Therefore, the tool flank wear increases correspondingly. According to the work of Krahmer et al., [10], it was stated that the cutting speed plays an important role in cutting tool life of free-cutting steels (SAE 1212, SAE 12L14, and SAE 1215).

Figure 8 shows that the tool life which was obtained was in the range of 12.3-55.3 min for both cutting conditions. A minimum tool life of about 12.3 min was observed for Experiment no 1 under dry conditions. Meanwhile, the maximum tool life of 55.3 min was achieved in Experiment no 1 under dry conditions. The results indicate that in comparison to dry cutting, the use of cryogenic coolants greatly prolongs the lifespan of a tool by a maximum of 41.7%, which is in line with the results of literature [11-13]. This happens because cryogenic temperatures increase tool hardness and consequently lowers the rate of wear. Therefore, cryogenic cooling substantially improved the cutting tool performance. Therefore, the use of higher cutting speeds is suitable of machining AISI 4340 steel with 32 HRC with coated carbide tools. Yet the tool life increases with cutting speeds from 200 to 300 m/min without altering the surface roughness. This argument is supported from the study made by Halim et al.,[14] which shows that cryogenic CO₂ is able to reduce the flank wear rates, thus enhancing the life of a cutting tool.

| Exp. No | Vc (m/min) | fz (mm/tooth) | ap (mm) | ae (mm) | Tool life (mins) (Dry) | Tool life (mins) (Cryogenic) |
|---------|------------|---------------|---------|---------|------------------------|----------------------------|
| 1       | 200        | 0.15          | 0.3     | 0.20    | 55.3                   | 45.0                       |
| 2       | 200        | 0.20          | 0.4     | 0.35    | 44.5                   | 28.3                       |
| 3       | 200        | 0.30          | 0.5     | 0.50    | 29.8                   | 29.8                       |
| 4       | 250        | 0.15          | 0.5     | 0.35    | 39.7                   | 36.8                       |
| 5       | 250        | 0.20          | 0.3     | 0.50    | 31.2                   | 30.0                       |
| 6       | 250        | 0.30          | 0.4     | 0.20    | 30.8                   | 21.0                       |
| 7       | 300        | 0.15          | 0.4     | 0.50    | 35.0                   | 37.3                       |
| 8       | 300        | 0.20          | 0.5     | 0.20    | 26.1                   | 29.6                       |
| 9       | 300        | 0.30          | 0.3     | 0.35    | 12.3                   | 21.0                       |
Figure 6. Main effect plot for tool life under dry conditions.

Figure 7. Main effect plot for tool life under cryogenic conditions.

Figure 8. Difference of tool life in experimental testing of end milling for various parameters.
The applications of a cryogen can improve the removal of chips that have adhered in the tool-workpiece-chip area, which may then lead to lower wear and surface roughness. A good chip breaking mechanism at the tool-chip interface also leads to lower surface roughness. Panda et al., [3] stated that the intensity of surface roughness directly impacts the increase of flank wear of the tool. This may be due to the larger the area of flank wear, the higher the friction of the tool on the workpiece, resulting in high heat generation which will eventually result in the higher of surface roughness. This is in line with Kumar et al., [15], who claimed that the growth of flank wear increased with the surface roughness. From the various reported research, it was shown that the prolonged tool life and better surface roughness were because of reduction of flank wear of the tool when a cryogenic is properly applied. The application of cryogenics results in a good surface finish by reducing the temperature and tool wear.

4. Conclusion
This paper has discussed the effects of LN application on the end milling of AISI 4340 alloy steel. Tool life and surface roughness for both dry and cryogenic cutting conditions were compared experimentally. The following can be concluded:

- Cryogenic cooling could be employed as an effective alternative to dry milling, due to reasonably good performance within the range of parameters selected in this study.
- Under cryogenic conditions, excellent surface finish was reported, as compared to that under the dry conditions, by 43.9%.
- In terms of tool life, LN is more functioning in machining at high cutting speeds. Tool life is extended up to a maximum of 41.7% by cryogenic cutting as contrasted to dry cutting.
- Further studies are needed to verify whether the tool and surface hardness affect the surface roughness and tool life.

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