Comparative assessment of hard turning under dry and minimum quantity lubrication

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Abstract. Hard turning with CBN and ceramic inserts is commonly regarded as a cost-effective alternative to grinding. However, there have been few studies comparing hard turning with low-cost carbide tools to high-cost CBN and ceramic cutting tools. When it comes to the usage of cutting coolant during severe turning, there are mixed outcomes. In this study, a PVD-coated TiSiN-TiAlN carbide tool was used to hard turn AISI 52100 steel in a dry and MQL environment. Through multi-objective optimization, a comparative assessment in terms of surface roughness, cutting force, and tool life under various cutting settings is provided. In terms of three components of cutting force, surface roughness, and tool life, mathematical models were constructed to forecast and improve machining performance. Under both dry and MQL conditions, the study discovered an optimal cutting speed of 108 m/min, a feed value of 0.09 mm/rev, and a depth of cut of 0.16 mm. Under MQL, hard turning produced optimal surface roughness and tool life of 0.88 m and 64 minutes, respectively. In comparison to hard turning under dry cutting, the optimal surface roughness was 1.07 m and the tool life was 49 minutes. Under MQL, tool life increased by over 31%, according to the findings of the experiments. Under dry and MQL conditions, however, no significant differences in cutting forces and surface roughness were identified.

Keywords. Machining performance, hard turning, dry and MQL quantity lubrication.

1. Introduction

Manufacturing is evolving fast nowadays as a result of environmental replenishment and new technology [1]. The use of CBN and ceramic inserts in hard turning is generally recognised as a low-cost alternative to the more expensive grinding procedure. Hard turning using a low-cost carbide tool vs high-cost ceramic and CBN cutting tools has been the subject of few research. However, when it comes to the usage of cutting coolant during severe turning, there are mixed outcomes. Cutting fluids constitute a severe concern for environmental preservation and human health, hence demand for dry or machining with a minimum quantity lubrication (MQL) is growing [2].

The majority of the researchers have put forth a lot of work to compare dry cutting, wet cutting, and MQL cutting. Shokrani et al. [3] found a variety of cooling strategies that can be used in conjunction to reduce or eliminate the need of traditional cutting fluids. During turning, Amrita et al. [4] found that MQL nano-graphite augmented cutting fluid performed better. However, it has been found that the
concentration of nanoparticles in the base fluid has a significant impact on torque and power consumption during the micro-drilling process under MQL [5].

During turning, a group of researchers [6-8] found that MQL performed better than dry and flood cooling. Yldrm et al. [9] found that turning Ni-based Inconel 625 with hBN nanofluid under the MQL reduced surface roughness and increased tool life compared to turning under dry circumstances. Bruni et al. [10], on the other hand, found no benefit in using the MQL to reduce tool wear. Furthermore, moist cutting resulted in increased surface roughness, according to their findings. MQL enhanced tool life, according to Liao and Lin [11], which they attribute to the formation of a protective oxide layer between the tool-chip contacts that acts as a diffusion barrier. Duc et al. [12] observed a decrease in cutting forces, friction coefficient, and tool wear during their experimental work on hard milling utilising aluminium oxide nanofluid under MQL. MQL increased tool life, according to Chinchanikar and Choudhury [13], due to improved lubrication and cooling. However, the efficiency of cooling is highly dependent on the choice of cutting speed, feed, and cut depth [14].

MQL reduced tool wear and surface roughness, according to Dhar et al. [15-16]. This could be due to a shift in tool-work and tool-chip interactions caused by a drop in cutting temperature. Hegab et al. [17-18] used multi-walled carbon nanotubes suspended in vegetable oil to test the MQL turning performance of Titanium alloy. The bonding between the workpiece and tool interface improved surface quality, tool life, and power consumption in their experiments using the nanofluid MQL. Chinchanikar et al. [19] found that while dry hard turning generated a superior surface finish, coconut oil as a cutting fluid produced a better surface finish at higher cutting speeds. MQL, according to Khan et al. [20], aids in reducing tool wear caused by abrasion, adhesion, and diffusion type wear. Under MQL conditions, Kilickap [21] noticed superior surface qualities than compressed air and dry drilling. MQL provides certain challenges for lubricants in reaching the exact cutting zone, according to Attanasio et al. [22].

According to the literature review, there are conflicting results on the usage of cutting fluids during severe turning. Furthermore, parametric optimization is frequently documented with ceramic and CBN tools during hard turning. However, just a few studies on multi-objective optimization of hard turning with a carbide tool have been published. In light of this, cutting parameters were optimised under dry and MQL conditions in order to discuss the use of coolants during hard turning in this study. Experimental observations were used to construct correlations between cutting parameters and performance indicators, specifically three components of cutting force, tool life, and surface roughness.

2. Experimental details

Experiments were carried out utilising a TiSiN-TiAlN coated carbide tool on AISI 52100 steel (62 HRC). The insert was mounted using a right-hand style tool holder defined by ISO as PCLNR 2525M12. Experiments were planned using a central composite rotatable design matrix [23]. Experiments were carried out with a mist made up of a minimum of 60 ml/hr of water-based cutting oil and 5 bar of compressed air. By combining compressed air and oil immediately beyond the nozzle, a minimum amount of fluid flow was obtained. The nozzle contains two inlets, one for the cutting fluid and the other for the air, which are 90 degrees apart.

| Parameters                  | Levels |
|-----------------------------|--------|
| Cutting speed (V) (m/min)   | 100    | 108 | 125 | 142 | 150 |
| Feed (f) (mm/rev)           | 0.081  | 0.088 | 0.113 | 0.142 | 0.15 |
| Depth of cut (d) (mm)       | 0.1    | 0.2   | 0.3   | 0.4   | 0.5  |

Table 1. Experimental conditions.
3. Results and discussion

A strain-gauge type dynamometer was used to measure the average values of the cutting force components. A Qualitest surface roughness tester was used to measure the roughness of the surface. Dino-Lite, a USB-powered portable digital microscope, was utilised to track flank wear and growth at regular intervals along the length of the cut. Hard turning studies on AISI were carried out on a CNC lathe with PVD-coated nano laminated TiSiN-TiAlN carbide inserts, changing feed, depth of cut, and speed. ISO has assigned the CNMG 120408 geometry to all of the insets (80° diamond shape with 0.8 mm nose radius). The inserts were mounted using a right-hand style tool holder defined by ISO as PCLNR 2525M12.

Twenty hard turning experiments were carried out, each with different cutting parameters under dry and MQL cutting circumstances. Experiments were carried out with a fluid flow rate of 60 ml/hr and a compressed air pressure of 5 bar. Table 1 shows the experimental matrix for dry and MQL cutting used in this work. Cutting parameters were chosen based on the manufacturer’s instructions and a review of the literature. Based on the experimental results, mathematical models are created to estimate three components of cutting force, surface roughness, and tool life under MQL and dry circumstances, taking into account the effect of feed (f), cutting speed (V), and depth of cut (d).

Cutting Force = f(V, f, and d) and can be written as:

\[ \text{Cutting force} = K V^a f^b d^c \]

where, the constant K and exponents a, b, and c are to be determined by substituting the experimental cutting force values at the given speed, feed, and depth of cut.

The R-Squared values of the developed models; equations (1) to (10) are in the range of 0.85 to 0.95, indicating that the developed models are valid and could be used to predict the investigated performance during AISI 52100 steel hard turning with PVD-applied nanocrystalline TiSiN-TiAlN coated carbide tool within the domain of the process parameters selected in this study.

### Table 2. Coefficients of force model under dry cutting.

| Performance index | Cutting environment | Experimental-based mathematical models | \( R^2 \) value | Equation no. |
|-------------------|---------------------|----------------------------------------|-----------------|--------------|
| Tangential cutting force (Fc) | Dry | \( F_c = 2974.1 V^{-0.2669} f^{0.7359} d^{0.0644} \) | 0.9 | (1) |
| Feed cutting force (Ff) | MQL | \( F_f = 4191.03 V^{-0.3376} f^{0.682} d^{0.1176} \) | 0.92 | (2) |
| Radial cutting force (Fr) | Dry | \( F_r = 4049.45 V^{-0.4531} f^{0.5305} d^{0.3347} \) | 0.97 | (3) |
| Surface roughness (Ra) | MQL | \( F_r = 4525.48 V^{-0.5232} f^{0.3897} d^{0.3187} \) | 0.95 | (4) |
| Tool life (T) | Dry | \( T = 512.613 V^{-0.0314} f^{0.2775} d^{0.2281} \) | 0.94 | (5) |
| | MQL | \( T = 543.34 V^{-0.0348} f^{0.2873} d^{0.1928} \) | 0.93 | (6) |
| | Dry | \( R_a = 33.508 V^{-0.3502} f^{0.6868} d^{0.0766} \) | 0.87 | (7) |
| | MQL | \( R_a = 12.445 V^{-0.0673} f^{0.845} d^{0.1547} \) | 0.95 | (8) |

A strain-gauge type three-component dynamometer was used to measure the tangential or primary cutting force (Fc), feed force (Ff), and radial cutting force (Fr) in this study. The least square error method was used to examine the experimental results. Data-Fit software was used to determine the unknown coefficients (Version 8.1).

The three components of cutting force, the tangential or main cutting force (Fc), feed force (Ff), and radial cutting force (Fr), tool life, and surface roughness, are generated using experimental data. The constant and exponent values for developed models are shown in Table 2. The R-Squared values of the developed models; equations (1) to (10) are in the range of 0.85 to 0.95, indicating that the developed models are valid and could be used to predict the investigated performance during AISI 52100 steel hard turning with PVD-applied nanocrystalline TiSiN-TiAlN coated carbide tool within the domain of the process parameters selected in this study.
Figure 1. Variation of cutting force components with (a) Cutting speed, (b) Feed, and (c) Depth of cut.

The standard RSM technique was used to analyse the experimental findings in order to study the effect of cutting parameters on performance measures and to identify the region of interest where
performance measures attained their optimum or near optimum value. Using the derived equations, the cutting force varies with process parameters.

Figure 1(a) displays the cutting force components as a function of cutting speed and depth of cut of 0.113 mm/rev and 0.3 mm, respectively. Figure 1(b) displays the cutting force as it varies with feed, whereas Figure 1(c) depicts the cutting force as it varies with depth of cut. Figure 1(b) depicts the results obtained at \( V = 125 \text{ m/min} \) and \( d = 0.3 \text{ mm} \). Figure 1(c) shows the cutting force components measured at \( V = 125 \text{ m/min} \) and \( f = 0.2 \text{ mm/rev} \).

Figure (1) shows that cutting forces are larger under MQL and decrease with increasing cutting speed while increasing with increasing \( d \) and \( f \). It is also clear that the radial component of force has a higher value than the tangential and feed forces. Cutting forces were seen to be greatly reduced at higher values of \( V \) when paired with higher values of feed, which may be attributed to a shear strength reduction of the workpiece due to greater temperature generation, particularly during dry cutting conditions [24-25].

Figures (2) and (3) show the variance in surface roughness and tool life under various cutting conditions. Table 3 shows the cutting condition matrix for figures 2 and 3.

**Table 3. Cutting condition matrix**

| Cutting condition | Cutting speed (m/min) | Feed (mm/rev) | Depth of cut (mm) |
|-------------------|-----------------------|---------------|------------------|
| 1                 | 100                   | 0.113         | 0.3              |
| 2                 | 125                   | 0.113         | 0.3              |
| 3                 | 150                   | 0.113         | 0.3              |
| 4                 | 100                   | 0.081         | 0.3              |
| 5                 | 150                   | 0.15          | 0.3              |
| 6                 | 100                   | 0.113         | 0.1              |
| 7                 | 150                   | 0.113         | 0.5              |

**Figure 2.** Surface roughness at different cutting conditions.
From figure (2), it can be seen that superior surface polish is obtained under MQL cutting and at higher V, lower f, and d values. However, with higher cutting parameters, this result is not as noticeable. The improved surface finish under MQL circumstances could be due to improved chip breaking and chip control over dry cutting. However, the improvement in surface smoothness under MQL was not as considerable since the greater cutting pressures used in MQL caused more vibrations and thus chatter marks on the completed workpiece. In conclusion, there was no substantial benefit to employing MQL during hard turning in terms of improving surface smoothness and lowering cutting force.

Figure 3 demonstrates increased tool life when MQL cutting is used and process parameters are kept to a minimum. However, at higher cutting parameters, there is no discernible improvement in tool life. The values of the exponents and constants ((9) and (10) show that V is the most influential parameter on tool life. However, this outcome is more noticeable while dry machining. The low tool life found under dry conditions was due to crater wear causing a rapid fracture of the tool. However, at greater V, this effect was severe.

4. Multi-objective optimization
Furthermore, for various cooling settings, the optimum process parameters that result in greater tool life, surface finish, and minimum cutting force were established. To determine the best cutting parameters, the Design-Expert software was employed. The optimal option is the one with the maximum desirability. Under both the dry and MQL circumstances, V = 108 m/min, d = 0.16 mm, and f = 0.09 mm/rev are shown to be optimal. Hard turning with MQL produced the best tool life and surface roughness of 64 min and 0.88 m, respectively. In comparison to dry cutting, we achieved an optimal surface roughness of 1.07 m and a tool life of 49 minutes. Under MQL, experimental results reveal a considerable increase in tool life, nearly by 31%. However, there was no discernible change in surface smoothness or force between chilling strategies. The increased tool life under MQL can be attributed to the generation of a minimal cutting temperature and, as a result, a minimum tool wear due to adhesion wear.

5. Conclusion
A comparative study of machining performance during hard turning with MQL and dry conditions is addressed in this paper. Experiments on AISI 52100 steel (6-62 HRC) were carried out with a coated TiSiN-TiAlN carbide tool. For installing the insert, an ISO PCLNR 2525M12 right-hand style tool holder was employed. The trials were conducted with a MQL of 60 ml/hr at 5 bar air pressure. When compared to dry cutting, the MQL condition produced a considerable increase in tool life of over 31 percent. However, in MQL conditions, no substantial benefit in terms of obtaining a superior surface finish or lowering the force has been noted. This study found that a cutting speed of 108 m/min, a depth of cut of 0.16 mm, and a feed rate of 0.09 mm/rev are the best parameters for both dry and MQL
conditions. Hard turning with MQL produced the best tool life and surface roughness of 64 min and 0.88 m, respectively. In comparison to dry cutting, an optimum surface roughness of 1.07 m and tool life of 49 minutes were recorded. As dominant wear forms, nose wear, chipping off at the nose, and clearance face were noticed.

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