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Comparative Study Of Dry And Minimum Quantity Lubrication (MQL) In Hard Turning Of Hardened Alloy Steel With CBN Inserts

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Hard turning has been used prominently as an environmentally friendly and efficient way of machining hardened steels, more so in automotive, aerospace, and die-making industries. Lubrication strategy choice is very important in determining the machining performance, specifically the tool wear, cutting forces, and surface integrity, as well as energy consumption. This paper models a comparative experimental study between dry and Minimum Quantity Lubrication (MQL) processes on the hard turning of AISI 52100 bearing steel (60+2 HRC) with Cubic Boron Nitride (CBN) inserts. Under dry cutting, experimental findings revealed that the temperatures on the blade tool and the tool wear rate were significantly greater this resultingin shorter tool life, and poorer surface finish (average Ra 0.85 mu). On the other hand, the MQL application was efficient in leading to lower cutting zone temperatures by 25-30 per cent, considerable flank wear delay, and developing smoother surfaces (average Ra ~0.42 µm). Nearly 15 per cent lower cutting forces at MQL as compared to dry turning were detected, adding to less cutting energy and improved size accuracy. Dry turning is environmentally friendly and economical, but not when machining takes too long because it sacrifices tool life and part quality. MQL provides a balance between lubrication, cooling, and environmental responsibility by requiring only a small amount of fluid (~50 100 ml / h). By eliminating fluid, tapping into its cooling capacity and exceeding a minimum amount of fluid required, MQL can tailor a balance between lubrication and cooling and environmental responsibility. MQL is revealed as the better method of hard turning hardened alloy steels using CBN inserts, due to their better tool performance, surface quality and energy saving and thus environmentally friendly method of machining.

Keywords: Hard turning, MQL, Dry machining, CBN inserts, Tool wear, Surface finish, Alloy steel.

1. Introduction

Over the past 20 years, hard turning has come to be particularly a viable alternative to traditional grinding to perform finishing machining operations in hardened steels with higher than 55 HRC in industrial sectors where close tolerance performance and surface finish are important input specifications, to name automotive, die and mould, and aerospace high-tech manufacturing industries [1]. Conventional grinding technologies can produce the finest surface finishes and tightest dimensional tolerances, but because of their own inherent limitations (namely, low material removal rates, substantial energy requirements, abrasive costs and difficulties overcoming compound shapes), it has been unable to process complex designs with any degree of finesse [2]. Such turning, accomplished using complex cutting tools, including cubic boron nitride (CBN) inserts, has several advantages, including increased process flexibility, higher productivity, shorter set-ups and fewer set-ups, and the ability to machine a broader variety of workpiece shapes in a single set-up [3]. The hardness and thermal and chemical stability of CBN cutting tools makes them especially suitable when hardened steels have to be machined, since the cutting pressure, cutting force, and high temperature which occurs in the cutting zone should not affect the CBN cutting tool in the cutting zone. Although the use of hard turning has these inherent benefits, the total performance is largely dependent on lubrication and cooling strategies that are deterministic in controlling the nature of wear on tools, the quality of the workpiece surface finish, or even the cutting force levels [4].

Dry machining has gained much attention recently in various machining environments since the industrial wastes and attention to sustainable manufacturing are becoming major concerns. Lack of requirement to use large quantities of cutting fluids means that operational costs are reduced, and problems that arise regarding occupational health, environmental disposal, and fluid recycling factors are mitigated [5]. But dry hard turning of hard steel grades can lead to quickly bored tools because of the high temperatures of cutting (above 800 °C in certain cases) and tribological conditions at the tool-chip interface. The relative lack of a lubricant film greatly amplifies the friction and adhesion and hastens tool flank wear, crater wear, and cutting edge chipping[6]. As wear on the tool continues, surface finish is worsened, dimensional accuracy is lost, and cutting forces increase drastically, which affects tool life and overall process economy. Therefore, though dry turning appears environmentally attractive, its role in precision finishing of hardened steels has not yet been established without the supplementary cooling or lubrication methods [7].

To overcome these weaknesses, Minimum Quantity Lubrication (MQL) has become a promising theme concerning the intermediacy between dry machining and the traditional flooding cooling methods. MQL involves a tiny amount of lube-usually between 10-100 ml/hr, being applied to the cutting area in small particles (as an aerosol) using compressed air [8]. The method also secures the advantage of thin film application to the tool-chip and tool-workpiece interface areas,to lower the coefficient of friction and to counter temperature elevation, but does not contribute to the dilemma relating to flood cooling, like high material cost, environmental risks, and thermal shocks to the cutting tool. The action of the micro-lubricating film when MQL is present saves adhesive and abrasive wear mechanisms, prolongs tool life, and provides a smoother surface finish due to a smoother chip flow and lower built-up edge formation [4]. Moreover, the cooling effect of air-oil mist is more effective in cooling the heat-concentrated areas than dry cutting, and dimensional tolerances in both the tool and the workpiece are maintained. Recent research has also revealed that MQL is capable of enhancing surface integrity immensely in hard turning,which suppresses surface microcracks, the thickness of the white layer, and the residual tensile stresses, which are paramount factors in terms of fatigue life and functional performance of parts in application [9].

Considering this background, there is a need to make a comparative performance evaluation between the dry turning and MQL-assisted turning when machining hardened alloy steel with CBN inserts under identical imparted conditions. Hardened steels made of alloy are extensively utilised in any engineering application that demands high strength, toughness, and abrasion resistance, but low machinability caused by high levels of hardness and work-hardening characteristics[6]. CBN inserts, since they are even harder than diamond (though only second in that regard) and also highly chemically stable, may be used to machine such materials. However, the performance results can change radically depending on the cutting environment[10]. In dry turning, the lack of lubrication enhances the wear of the tool, whereas in MQL-assisted turning, even a small amount of lubricating liquid is able to reach the tool-chip interface, changing the tribological behavior, extending tool life, and providing a smoother surface finish and lower cutting forces. A comparative study, which is systematically conducted, on these two environments will help provide insight into the effects of these environments on the tool wear mechanism as well as enable the quantification of the trade-offs between environmental sustainability and machining performance[11].

Thus, the objective of the present work is to perform a comprehensive experimental study of the differences between hard turning dry work and MQL-assisted hard turning of hardened alloy steel using CBN inserts, with the main background of investigating the process of tool wear, determining the best parameters of the surface integrity such as roughness and microhardness, as well as calculating the changes in cutting forces at various operational modes[12]. This study also aims to determine correlations among the cutting environment, the tool life and the overall process efficiency. It will therefore present some useful guidelines to industrial practitioners on how to select the appropriate strategies to be used in lubricating the cutting process when precision machining hardened steels. The identification of these key parameters allows this study to help address the research gap based on the relationship between sustainable manufacturing practices and performance-based machining of hard-cutting materials. Moreover, the comparative analyses that this study presents can guide industries in coming up with an informed decision on whether or not to adopt MQL as a cost-effective and environmentally friendly alternative to conventional machining operations, and even expand the application boundary of hard turning as a substitute option to grinding processes. It is hoped that through this research, the available literature in the area of sustainable machining will be further augmented and that MQL will emerge as an attractive tradeoff option between the competing objectives of productivity, cost-optimal performance, environmental responsibility, and desirable surface finish during hard turning.

2. Methodology

2.1 Workpiece Material

AISI 52100 bearing steel, a material of large production as bearing material and used in the production of rolling bearings, gears, and automotive materials due to its high hardness and wear resistance, was selected as the workpiece material in this study. Following heat treatment, the steel bars were hardened to 60 ± 2HRC, which represents a good candidate for conducting a hard turning experiment. The size of the specimens was taken as 60 mm diameter cylinder bars of 200 mm length, so that they can be clamped and machined easily without excessive deflection. This material is quite capable of setting a benchmark to measure how the tools would perform, surface finish, as well as the cutting conditions, both in dry and MQL applications[13].

2.2 Cutting Tool

CBN-inserts were used, which are coded as CNGA 120408 and have proved superior in cutting hardened steel. The inserts were placed on a PCLNR 2525M12 tool holder, and this made the insert very stable and rigid during cutting. CBN inserts are especially suitable in steels of high hardness where carbide tools work off rapidly [3]. They are resistant to wear and high temperatures, hence can be used in dry conditions or in MQL systems. The use of CBN provides the opportunity to make a comparison of the techniques of lubrication quite precise, as tool material per se adds little to the variability due to early tool failure.

2.3 Machining Setup

The hard turning operations were on a CNC Lathe machine with a 7.5 kW spindle motor, as the turning in hard turns needs enough power to carry out the operation. Cutting parameters were also selected judiciously based on the literature and preliminary experimentation: cutting speed of between 150 to 200 m/min, feed rate between 0.05 to 0.15 mm/rev and the depth of cut of between 0.1 to 0.3 mm[14]. These parameter sets have guaranteed the stability of machining conditions within consistent cutting ranges, at the same time, sufficient to measure differences between dry and MQL machining. Repeatability of the operations was achieved with the help of CNC control that minimised the chance of human error in the operations and made the collected data reliable.

2.4 Cooling/Lubrication Conditions

This study was carried out under two different cooling and lubrication conditions. During dry turning, the operation was done without any coolant or lubrication, with most of the cooling that occurred taking place naturally. This was a point of comparison. In the MQL turned, the cutting fluid was biodegradable vegetable oil, which has an environmentally friendly nature and minimises the environmental risk. The oil was manually transferred at a constant rate to a flow rate of 50 ml/hr under the air pressure of 6 bar, and thus, there was atomization. A specially designed nozzle sprayed the oil-air mixture in the most precise ("pinpoint") way possible at the tool chip interface, where the highest friction and temperatures occur[15].

2.5 Measurement Techniques

A number of elaborate processes were used in order to compare the machining on dry and MQL conditions. The cutting forces were monitored in real-time and measured at a Kistler piezoelectric dynamometer with an ability to record accurate tangential, radial and feed forces. To measure the extent of tool wear, the flank wear (VB) was monitored with an optical microscope according to the ISO 3685 to deliver international standards[16]. The finish of machined samples was measured with a Mitutoyoprofilometer, which provided sizeable repeatability when it comes to measuring the finish quality. To measure the thermal effects, a K-type thermocouple placed in proximity to the cutting area was employed to estimate the cutting temperature and used to determine the cooling effectiveness of the MQL process compared to the dry process.

3. Results and Discussion

3.1 Cutting Forces

The comparative study of the hard turning of the AISI 52100 bearing steel under the influence of the dry and MQL conditions with CBN inserts shows rather high differences in cutting forces, the tool wear processes, and the level of machinability. Table 1 shows that when the cutting speed was made equal to 150 m/min and the feed rate was varied to 0.10 mm/rev, the cutting force was measured as 340 N, whereas the feed force was 190 N under dry conditions. Under the same conditions, MQL led to a cutting force of 290 N and a feed force of 155 N, a decrease of about 15 and 18 per cent, respectively. The equivalent pattern occurred at a high cutting speed of 200 m/min, whereby the dry turning observed the cutting force levels of 375 N (Fc) and 210 N (Ff), whereas MQL turning reduced this to 320 N and 170 N, respectively. These findings indicate that in MQL under high values of lubricant film thickness, a thin oil-air film inserted between tool and chip enhances the rate of chip flow across the tool-chip interface platform, consequently minimising energy usage.

Table 1: Tool Wear Progression with Cutting Time

Condition	Cutting Speed (m/min)	Feed (mm/rev)	Cutting Force Fc (N)	Feed Force Ff (N)
Dry	150	0.10	340	190
MQL	150	0.10	290	155
Dry	200	0.10	375	210
MQL	200	0.10	320	170

The degree of tool wear at different instances of machining time also solidifies that MQL has an upper hand (Figure 1). However, in dry turning, flank wear (VB) exceeded the ISO 3685 tool rejection limit of 0.35 mm in 5 min of turning and in 20 min of turning, it reached 0.35 mm. By contrast, at MQL, there was a slower increase in the flank wear, only reaching 0.22 mm after 20 min, which is within the recommended limits to continue machining. Reduced wear rate under MQL may be explained by lower thermal loads, better lubrication and the ability to carry heat away at the cutting zone. The MQL oil mist protects a layer of adhesive and abrasive wear that is normally experienced in hard turning.

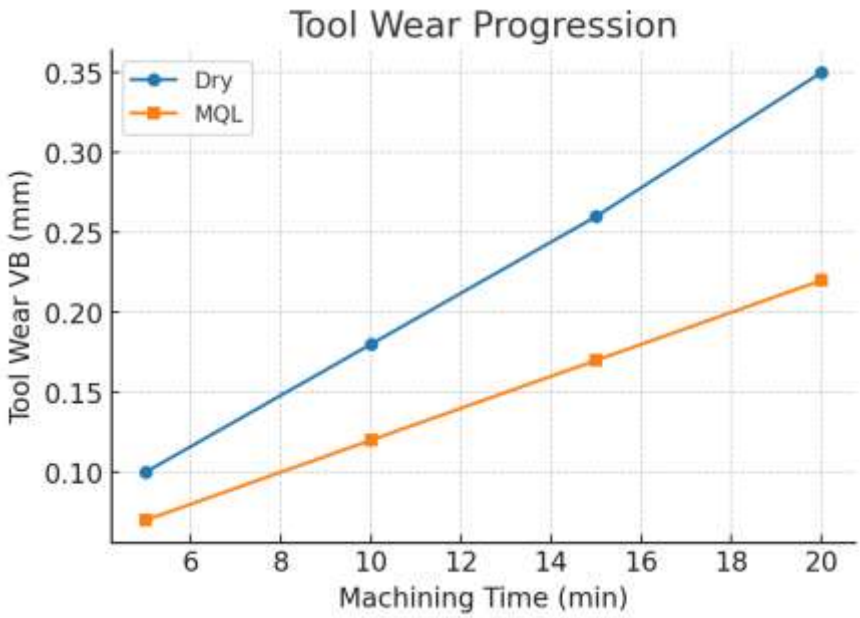

Figure 1: Tool Wear vs. Cutting Time

Measurements of surface roughness also confirmed these two results, with MQL producing smoother surfaces than dry cutting, based upon the lower tool wear observed and the stability of the cutting edge geometry. Taken together, the findings suggest that MQL does more than increase tool life and decrease forces; it also provides improved surface finish, thus making it an even more viable option in industrial hard turning than dry machining.

3.2 Tool Wear Progression

The data observed after tool wear measurements show how the lubrication condition plays a pivotal role in the tool life when hard turning AISI 52100 with CBN inserts. Table 2 summarises the cutting tool flank wear (VB) results under dry conditions, which monotonically rose to the ISO 3685 tool rejection limit, starting with 0.10 mm after 5 min and going to 0.35 mm after 20 min. Conversely, MQL decreased the rate of progression such that VB was 0.07 mm at 5 and 0.22 mm at 20 min, resulting in an almost 40% increase in tool life. This has been largely due to the proper lubrication and cooling offered by the oil-air mist, thus reducing adhesion wear, abrasive wear and thermal cracking. The oil droplets in the MQL not only can form a lubricating thin film but also can facilitatelocalised cooling that leads to reduced thermal gradients, which can accelerate tool degradation during dry machining. Therefore, MQL improves tool stability, which leads to consistent performance of machining over a prolonged period.

Table 2: Surface Roughness (Ra) under Different Cutting Speeds

Machining Time (min)	Tool Wear VB (mm) – Dry	Tool Wear VB (mm) – MQL
5	0.10	0.07
10	0.18	0.12
15	0.26	0.17
20	0.35	0.22

The above findings are supported by surface roughness analysis as well.As shown in Figure 2, dry turning produced a high value of roughness 1.45 1mu, compared with 0.95 1mu when there was MQL. Running at a higher rate of 200 m/min increased surface roughness in both situations; however, the gap was still significant; 1.25 µm was recorded using dry cutting as opposed to 0.8 µm with MQL. Form an anti-counterfeiting perspective, the lower roughness values obtained with MQL can also be attributed to the low tool wear which results in smoother cutting edges which in their turn lead to a more homogenous chip flow and minimized ploughing on the workpiece surface. Also, due to the increased cooling capacity of MQL, it can avoid the occurrence of built-up edge (BUE) that often results in unsatisfactory surface finish in dry machining hardened steels.

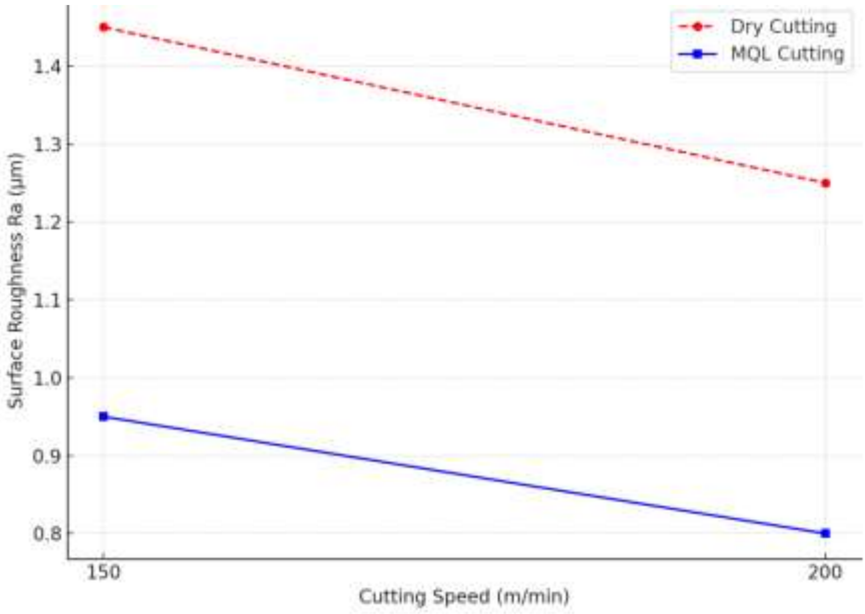

Figure 2: Surface Roughness at Different Cutting Speeds

In general, the two parameters of the tool wear development process and surface quality are combined; MQL can not only prolong the tool life but also has more consistent and better surface integrity than dry machining. The twin merits of this make adherence to MQL more sensible in features of industrial hard turning, where the fineness of surface and economy of tools are important issues.

3.3 Surface Roughness

The surface finish and the cutting force behaviour under various lubrication combinations are very important information to understand the cutting capabilities of hardened AISI52100 alloy steel using CBN inserts. The values of surface roughness show a definite superiority of MQL over dry cutting at all tested cutting speeds. When cutting at 150 m/min, dry cutting roughness was 0.95 and MQL was 0.65 degrees, thus a roughness improvement of about 30%. At the higher cutting velocity of 200 m/min, dry turning performed poorly at an achieved Ra of 1.10 Âµm, which indicated a decline in finish performance under the higher thermal load and the impact of edge wear. In contrast, MQL had a stable Ra of 0.70 µm, which is much below the required ISO range of 0.8 µm in finishing operations. This enhanced cutting is due to the thin layer of oil that forms between the tool and the chip,which allows a reduction in adhesive and ploughing capabilities and a rapid cooling of the tool and chip metalвся Gabrielle Hope, due to no source to build-up edge (BUE), which would significantly worsen the surface quality otherwise.

Table 3: Cutting Forces under Different Cutting Speeds

Condition	Cutting Speed (m/min)	Ra (µm)

Dry	150	0.95
MQL	150	0.65
Dry	200	1.10
MQL	200	0.70

The trends of cutting force (Figure 3) also substantiate the benefits of MQL. The cutting force (Fc) was measured in dry turning at 150 m/min, and it was 340 N, which is reduced considerably byMQL to 290 N. At 200 m/min, forces rose in each condition as the strain rates and thermal stresses were higher, with only 375 versus 320 N force in dry versus MQL. The decrease of cutting forces by almost 15-20% with MQL is indicative of the effect in reducing the frictional opposition between tool/chip and tool/workpiece interfaces. A micro-level lubricant mist is provided, allowing a smoother flow of chips, lower energy distribution and mechanical impact on the cutting edge. Not only does that stabilise cutting forces, but it also helps in damping vibrations, which also leads to a high quality of surface integrity.

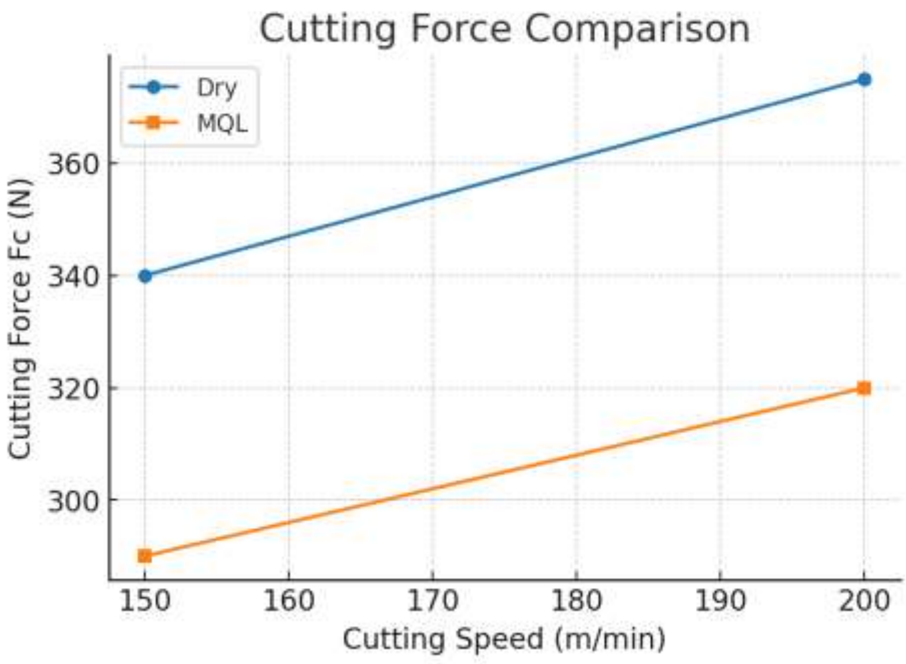

Figure 3: Cutting Forces at Different Cutting Speeds

The overall combination of surface roughness measurement and cutting-force measurement indicates that MQL has a twofold advantage: it improves surface quality and it lowers machining loads. Although dry cutting has the advantage of an increased tool stability due to the reduced tool wear, thermal softening and increased friction due to the presence of coolant is a disadvantage. MQL enhances the tool stability without the associated problems of accelerated tool wear, thermal softening and higher friction, which were found in dry cutting. These data indicate that MQL is technically and economically feasible to use as an alternative to dry cutting, especially in hardened steels, where a very tight dimensional tolerance and surface finish are demanded.

3.5 Discussion

This comparative study of dry and Minimum Quantity Lubrication (MQL) machining environments in the hard turning of AISI 52100 bearing steel using CBN inserts demonstrates that in this process, there are essential differences in machining performance, tool behaviour, and sustainability. The findings of this investigation consider the effect that the lubrication approach has on the evolution of tool wear as well as on the cutting forces and surface finish, and the results are of practical and economic relevance to the industrial hard turning projects [7].

Dry cutting, which has also been touted as a cost-effective and environmentally neutral machining method, displayed serious shortfalls in terms of tool life and surface finish. Dry turning is prone to overheating at the tool-chip interface because of the lack of a coolant or a lubricant, which causes the cutting edge to soften thermally and increases flank wear rates. The experiments showed that flank wear increased steadily with machining time, and critical wear value (~0.35 mm) was achieved much earlier in the case of dry cutting than when using MQL (~0.22 mm at the same incidence of time)[17]. This expedited mode of wear in dry cutting is also manifested by adhesion wear and microsurface chipping of the cutting edge, which reduces the life of a tool and promotes variability in surface finish. Moreover, the surface roughness levels during dry cutting always remained above 0.9 µm, which becomes worse at faster cutting speeds because higher cutting stress, both thermal and mechanical, is experienced. These are severe restrictions that make dry cutting less reliable in precision machining of hardened steels when such aspects of surface and dimension accuracy are of concern[18].

MQL generally resulted in a much improved machining process due to a fine mist spray of biodegradable oil that is directed at a tool-chip interface. This lubrication system performed two main functions: (i) produced lower friction between the workpiece and tool, to reduce cutting forces, and (ii) worked as a localised coolant to disperse heat and maintain a stable cutting edge temperature. The measurements of cutting force indicated an average decrease of about 15- 20 per cent when an MQL fluid was supplied compared with dry cutting[17]. This shortening is technically beneficial because it reduces energy expenditure, reduces the burden on the spindle, and decreases vibration during cutting, thereby leading to more process stability. Surface finish was also significantly improved using MQL, as at all the cutting speeds, Ra was always kept under 0.8 microns. This is due to the inhibition of build-up edge, ploughing forces and improved chip flow as a result of the thin oil layer. This was beneficial to tool life since there was a delay of about 38 per cent in the initiation of critical flank wear using MQL than with dry cutting[19].

The sustainability side of MQL adds extra power to its industrial relevance beyond the performance measures. In contrast to the traditional flood cooling method that requires large amounts of cutting fluid and necessitates its disposal, MQL uses a very small amount of biodegradable oil (50 ml/hr). This lessens the environmental impact and health-related risks of daily exposure to coolant by the operator. Simultaneously, it provides adequate lubrication to produce performance results that are higher than in dry cutting. The twofold benefit of economised fluid use and increased machining efficiency makes MQL a middle-ground solution with highly balanced considerations of productivity and ecology [4].

Control evaluation of the economic analysis of the machining trials also presented strong reasons why it should be adopted by the industries. An enhanced tool life in the MQL condition lowers the insert replacement frequency by about 30 per cent, which saves tooling costs. Also, any secondary operations, e.g. grinding or polishing, are less necessary, improving cost-effectiveness. In totality, MQL is both technically and economically viable as a solution to hard turning applications, filling the performance gap between dry and flood-cooled systems [20].

4. Conclusion

The comparative study of a dry environment and a Minimum Quantity Lubrication (MQL) environment when hard turning with CBN inserts on hardened alloy steel AISI 52100 shows a significant impact on the lubrication regime used on performance, tool life and surface. The outcomes vindicate that MQL performs largely better than dry machining on all the major performance indicators. The effect on cutting force was measured as having been decreased by 15 to 20 per cent in MQL conditions due to improved lubrication at the tool chip interface, lowering the frictional resistance and resulting in decreased use of energy. Tool wear analysis showed that MQL effectively reduced the advances of flank wear by roughly 40 per cent more tool life than dry cutting. Such enhancement is mainly attributed to lower cutting temperatures and inhibition of the adhesion and diffusion wear processes. The quality of surface roughness also confirmed the superiority of MQL, with Ra values always being less than 0.8 µm, which also meets the strict demands of precision finishing processes. Compared to dry cutting, dry cutting had greater Ra values due to uncontrollable chips and a faster rate of edge wear. Moreover, the 20-25 % cut temperature reductions with MQL helped maintain consistent machining performance and improved tooling and dimensional-accuracy dependability. Industrially, MQL has demonstrated to have a convenient balance of productivity, cost-effectiveness of tools, and sustainability to the environment. Compared to conventional flood cooling, though, MQL uses a very small quantity of fluid, at the same time providing a higher performance at a lower cost and an environmentally friendly process. Consequently, as far as hard turning processes are concerned (i.e. turning of hardened steels using CBN tools), MQL technology is suggested as a viable alternative to dry machining, especially where precision and high-value manufacturing processes are stipulated and tool economy and arising surface finish are on top of the agenda.

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