

Analysis of effect of Minimum Quantity Lubrication on different machining parameters Cutting Force, Surface Roughness and Tool Wear by Hard Turning of AISI-4340 Alloy Steel a Review

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ABSTRACT

This paper deals with the study of various machining process and show the effect of different cutting parameters on the properties of material. There are several important factors in the product quality which are surface finish, cutting temperature, tool life and coolant quality. The use of coolant generally causes life of tools and it also maintains work piece surface properties without damages. There are some negative effects and cutting fluid wastes in industries. In this paper, attention is focused on minimum quantity lubrication and recent work and some outcomes of machining factors from minimum quantity lubrication are presented. The review of the literature suggests that minimal fluid application provides several benefits in machining. It has been found that hardened alloy steel like AISI 4340 is known to be difficult to cut and a little knowledge is available in use of MQL for cooling. The main objective of the study of MQL is to reduce the surface roughness during machining and machining cost of cutting fluid. The minimum quantity lubrication also affects the surface finishing, reduce tool wear and reduce the cutting force. This paper provides a review of present work and some limitations of conventional cutting fluid machining and growing opportunities for development of the next generation MQL in machining operations.

Keywords: - Minimum Quantity Lubrication, Surface Roughness, Tool wear, Cutting force

1. INTRODUCTION

Dry machining is now of great interest and actually, they meet with success in the field of environmentally friendly manufacturing. however ,they are sometimes less effective when higher machining efficiently, better surface finish quality and severer cutting conditions are required .For these situations ,semi dry operations utilizing very small amounts of cutting lubricants are expected to become powerful tool ,in fact ,they already play a significant role in a number of practical applications.

Due to the multiplicity of being negative effects the cutting fluid wastes produce on mankind and our environment, in modern production there has been an increasing attention to carefully select efficient cutting fluids that would in addition to being efficient be also environment friendly. Therefore manufacturers as well as end users should find it in their common interest to develop new kinds of cutting fluids whose quality will be identifiable in terms of machinability parameters as well as ecological parameters.

For the companies, the costs related to cutting fluids represents large amount of the total machining costs. The review of the literature clears that the cost related to cutting fluids are frequently higher than those related to cutting tools. Consequently, elimination on the use of cutting fluids, if possible, can be significant economic incentive. Considering the high cost associated with the use of cutting fluids and projected escalating costs when the stricter environmental laws are enforced ,the seems obvious. Because of them some alternatives has been sought to minimize or even avoid the use of

cutting fluid in machining operations. Some of these alternatives are dry machining, machining with minimal fluid application and cryogenic cooling.

Minimal fluid application refers to the use of cutting fluids of only a minute amount typically of flow rate of 50 to 500 ml/hour. The concept of minimal fluid application sometimes referred to as near dry lubrication or micro lubrication.

The review of the literature suggests that minimum quantity lubrication is very effective in machining. The hardened alloy steel like AISI 4340 is known to be difficult to cut and a less knowledge is available in use of MQL for cooling [4]. Keeping this in mind the MQL for cooling is proposed to study the effect on surface roughness, cutting forces and cutting temperature. Present work deals with the comparative performance of CBN tool in machining hardened alloy steel in conventional dry turning and wet turning with minimal fluid application method by varying parameters such as speed and feed, depth of cut and tool geometry. The influence of different cutting and fluid application parameters for different tool geometry on machining performance such as cutting force, surface finish and cutting temperature is analyzed by Applying Taguchi Method.

In the next work the turning of AISI 4340, 50 mm bar on CNC Lathe is planned. The turning is carried with CBN insert and some cutting parameters changed with environmental conditions like dry, wet and MQL is planned.

2. REVIEW OF LITERATURE

In machining operation, the quality of surface finish is an important requirement of work pieces and parameter in manufacturing engineering. The main objective of the cutting fluid in hard turning is to serve as coolant as well as lubricant due to more heat generation in machining. Turning requires large quantities of coolants and lubricants that is why the total cost of production increases considerably. However, the advantages caused by the cutting fluids have been questioned lately, due to the several negative effects they cause. When inappropriately handled, cutting fluids may damage soil and water resources, causing serious loss to the environment. The operators may be affected by the bad effects of cutting fluids, such as by skin and breathing problems. Due to the multiplicity of being negative effects the cutting fluid wastes produce on mankind and our environment. Therefore in modern production there has been an increasing attention to carefully selection of efficient cutting fluids and its application method that would in addition to being efficient be also environment friendly. Therefore manufacturers as well as end users should find it in their common interest to develop new kinds of cutting fluids whose quality will be identifiable in terms of machinability parameters as well as ecological parameters.

It is found from literature that the various approaches have been tried by the researchers in this regard. It is known fact that a conventional application of flood coolant has limitations and hampers the machining productivity if the input parameters are not properly controlled and monitored. Thus the new technique that reduces the above draw backs are used by few authors. These approaches are Minimum Quantity Lubrication (MQL), cryogenic lubrication and coolant and water vapor as coolant. A study of performance in machining of different materials with dry, wet, MQL and cryogenic cooling is available in open literature.

The review of the literature shows that minimum quantity lubrication provides more benefits in machining. The objective of the work is to experimentally detecting the role of minimum quantity lubrication (MQL) on surface roughness, cutting force, cutting temperature and tool wear in turning AISI-4340 steel at industrial speed-feed condition by coated carbide insert and compare the various parameters of MQL with that of dry and wet machining. Minimum quantity lubrication is an alternative to reduce the tool wear, friction and hence prevent the adherence of the material. The consumption of the cutting fluid in minimum quantity lubrication is generally less than 500 ml/hr.

2.1. Minimum Quantity Lubrication (MQL)

The function of the cutting fluid in the machining process is to provide lubrication and cooling and to minimize the heat produced between the surface of the part and tool. Cooling is required for the economically feasible service life of tools and the required service qualities. It cannot be eliminated completely particularly when tight tolerances are required or when the machining of difficult to cut materials is involved [5]. This makes the Minimum Quantity of Lubrication (MQL) is an alternative, to reduce the tools friction and to prevent the adherence of material. In MQL small amount of lubricant is pulverized in a compressed air stream. The fluid used nearly less than 300ml/hr. The advantages of MQL are less polluted, Labor costs are reduced while disposal, cycle time of cleaning of machine tool/work piece/ tool is less and during machining the working area is not flooded so if necessary the cutting operation can be observed easily. Lot of research work has been done on MQL to find the effect of feed, speed and depth of cut on surface

roughness, cutting forces, tool life and chip formation. Jitendra. M. Varma, Chirag. P. Patel (2013) [10], concluded that the application of solid lubricant in dry machining has proved to be a feasible alternative to cutting fluid, if it can be applied properly. There is a considerable improvement in surface roughness and quality of product produced. But this is cost consuming lubricant as compared to MQL. The surface roughness quality is better than solid lubricant.

2.2. Cutting Forces

The positive effect of the use of fluids in metal cutting was first reported in 1894 by F.Taylor, who noticed that by applying large amounts of water in cutting area, the cutting speed could be increased up to 33 % without reducing tool life. Since then, cutting fluid effect have been studied resulting in an extensive range of products covering most workpiece material and operations. However the costs associated mainly with fluid handling, recycling and disposal are leading to alternatives such as new tool material and coating which allows dry machining and application of small quantities of fluid as mist spray. Machado and Wallbank reported that the application of cutting fluid as spray mist at rates of 200-300 ml/hr when turning medium carbon steel at low cutting speeds and high feed rates resulted in lower cutting and feed forces and superior surface finish compared to overhead flooding. Machining cost is another relevant aspect to be considered. According to Kress, the costs associated with the use of cutting fluids represent approximately 17.5 of the finished workpiece cost against 4% spent with tooling.

The process parameters such as cutting speed, feed rate, depth of cut, tool geometry and work material have significant influence on the cutting forces during machining. Silva at al., (2005) dealt with the technical performance of the MQL in grinding using aluminum oxide and super abrasive CBN grinding wheel and the results produced by the MQL technique showed lower tangential cutting force values than those obtained with the conventional system.

N.R. Dhar at al.,(2007) [1] reported that the cutting performance of AISI 1060 by minimal quantity lubrication machining by vegetable oil is better than that of dry machining. An experimental investigation shows that MQL reduced the cutting forces are reduced by about 5% to 15%. The minimal lubrication reduced the cutting zone temperature and favorable changes in the chip-tool and work-tool interactions, which helped in reducing friction, built up edges formation, thermal distortion and wear of the cutting tool.

B. Ramamoorthy reported the overall performance of the cutting tools during minimal cutting fluid application was found to be superior to that compared to dry turning and conventional wet turning on the basis of parameters such as cutting force, temperature and surface finish. The influence of operating parameters in minimal fluid application was evaluated and it was observed that cutting performance mainly depends on fluid application parameters such as pressure and delivery rate. But these parameters are only effective to minimization of cutting fluid only, not the cutting parameters.

B. kumar, A.Sengole rayan Volume 11, Issue 3 Ver. III [2014] [9], investigated, when cutting velocity is high as 120 m/min, the chip makes fully plastic or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip- tool interface. This will results in high cutting force. When cutting velocity is less, feed and depth of cut is more, and then the cutting force will be more. So, when cutting velocity is 100m/min with feed as 0.1mm/rev and depth of cut at 0.8mm then the cutting force is low compared with other combination cutting parameters.

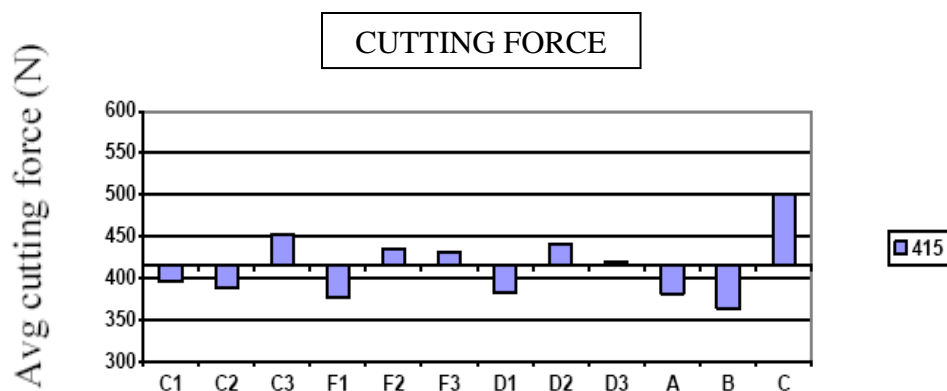


Fig.1 Cutting velocity (C), Feed (F), Depth of Cut (D), Application of Fluid (A, B, &C)

The form of chip produced is one of the major parameters influencing the productivity in the metal cutting industry, which is tightly prevalent during dry cutting. As water vapour is prone to reduce the main cutting force and improve the friction status of the rake face and chip, it can be an advantage in forming acceptable chips Dhar et al. (2007) [28] reported that in hard turning of AISI 4340 at low cutting speed the chip is a continuous type.

Aouici et al. [24] experimentally studied the effects, in hard turning, of cutting speed, feed rate, workpiece hardness, and depth of cut on surface roughness and cutting force components. AISI H11 steel had a hardness of 40, 45, and 50 HRC, machined using a CBN tool. Results showed that the cutting force components were influenced principally by the depth of cut and workpiece hardness.

Sahoo et al. [29] carried out some machinability studies on flank wear, surface roughness, chip morphology, and cutting forces in finish hard turning of AISI 4340 steel with a hardness of 47 HRC. The results indicated that a surface finish close to that of cylindrical grinding was produced by the best tool, type of chip, the components of the forces, and mixed alumina inserts. The surface roughness could be increase, but the use of this type of inserts could decrease the tool life.

2.3. Surface Roughness

The performance and service life of the machined/ground component are affected by its surface finish. Dhar et al., (2007) [1] MQL gives better surface finish than the dry and flood cutting irrespective of cutting velocity feed rate and length of cut.

The experimental study of Silva et al., (2005) results indicated that the MQL technique can be applied efficiently in plunge cylindrical grinding operation. The R_a value substantially reduced with use of MQL and the aluminum oxide grinding wheel provide a better surface finish than CBN wheel (Fig 2).

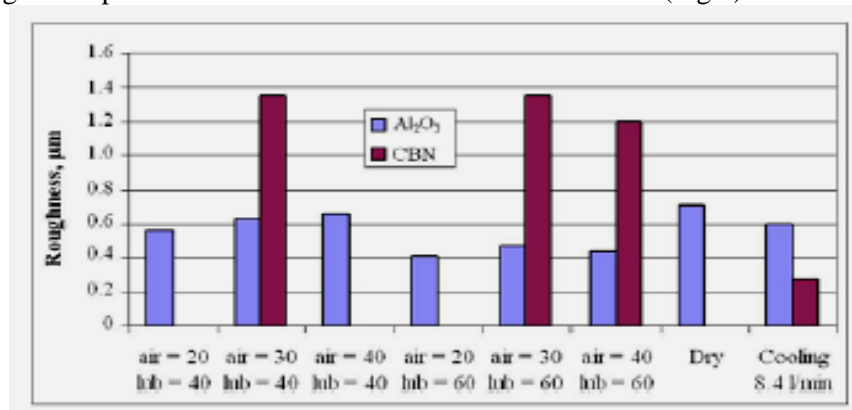


Fig.2. Roughness (R_a) after 90 cycles using Al_2O_3 and CBN grinding wheels ($V_{\text{air}} = \text{m/s}$; $V_{\text{lubri.}} = \text{ml/h}$; $V_s = 30\text{m/s}$; $V_f = 1\text{mm/min}$ and $a = 100\mu\text{m}$).

Machining with vegetable oil by MQL technique also gives good surface finish when compared to the dry machining (fig 3).

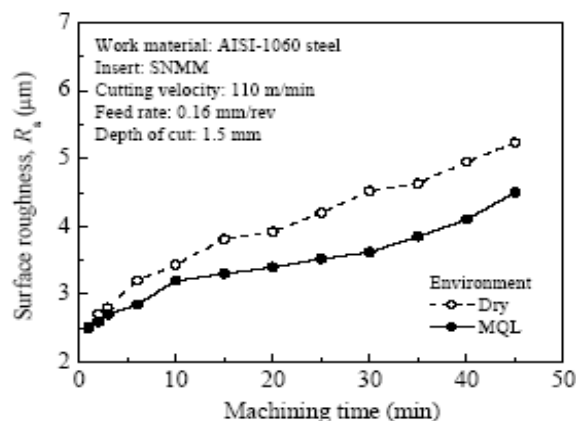


Fig.3 Surface roughness with progress of machining under dry and MQL by vegetable oil conditions

B. kumar, A. Sengole rayan Volume 11, Issue 3 Ver. III [2014] [9], investigated, when cutting velocity is high as 120 m/min, the chip makes fully plastic or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip- tool interface. When cutting velocity is low and feed is high, the chip- tool contact is partially elastic. So, when cutting velocity is 100m/min, feed 0.1mm/rev, depth of cut 0.8mm and with multiple jets gives good surface finish up to Ra value is nearly equal to 0.83. In the actual practice the Ra value at the depth of cut equal to 0.8mm could not be achieved, and the other factor involved is this value could be found up to 35HRC.

SURFACE FINISH

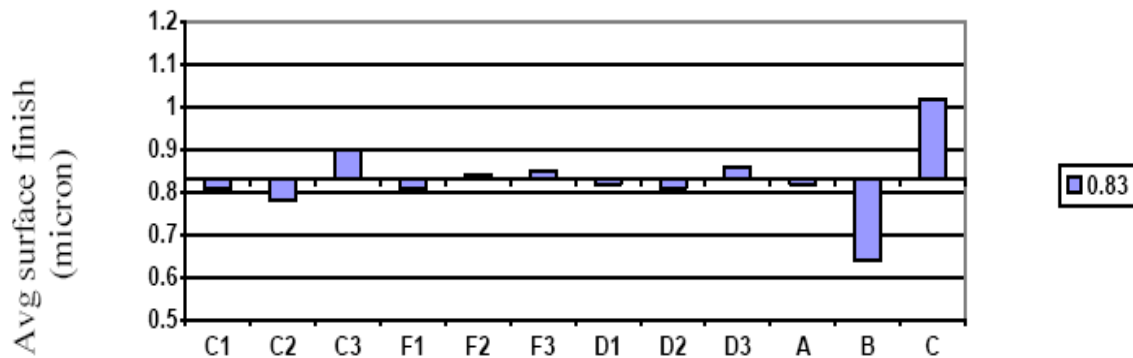


Fig.4 Cutting velocity (C), Feed (F), Depth of cut (D), Application of fluid (A, B & C)

S.R.Das, A. Kumar and D.Dhupal (2013) [7], they observed from the ANOVA that feed (60.85%) is the most significant parameter followed by cutting speed (24.6%) and the two level interactions were also found to be significant between cutting speed/feed (6.23%) and depth of cut-feed (2.62%) on surface roughness. From the experimentation it is found that, depth of cut did not impact the surface roughness in the studied range, significantly. The most optimal results for surface roughness were observed when cutting speed was set at 150 m/min and feed of 0.05 mm/rev. The present research work on turning of hardened AISI 4340 steel with CVD multilayer coated carbide insert will be useful for the advanced engineering industries those are working in the field of precision machining.

M.Z.A.Yazid, G.A.Ibrahim, A.Y.M. Said, C.H.CheHaron, J.A.Ghani [2], shows the experiments on the effects of dry and MQL conditions on finish turning Inconel 718 using PVD coated TiAlN carbide tool shows that MQL produces better surface roughness than dry condition. Surface roughness at 90 m/min is slightly lower when compared with 150 m/min and at lower cutting speed of 90 and 120 m/min, MQL 50 mL produces better surface roughness than dry and MQL 100 mL.

The result calculated for using MQL 0.2523 μm . Then the experiment result has shown 0.2546 μm . The percentage errors occur between calculated and experiment is 0.9 %.The result for wet get 0.3412 μm . Then the experiment result has shown 0.3720 μm . The percentage errors occur between calculated and experiment is 8.3 %.The percentage wet machining higher than percentage MQL machining. It can be conclude the some error more occurred during wet machining. The error perhaps occurred it vibration machine and etc.

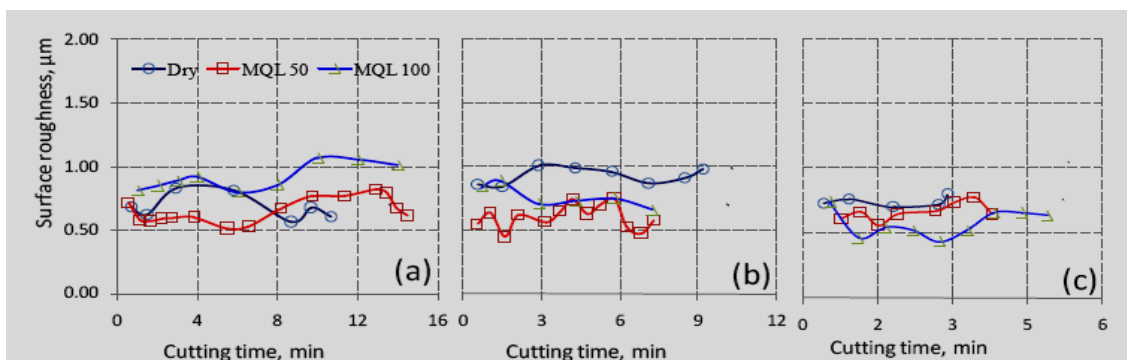


Fig. 5. Interaction of Surface roughness with cutting time under dry, wet and MQL ; Yazid, Ibrahim

A. Bhattacharya et al. (2009) [30] have investigated the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA. The result showed a significant effect of cutting speed on surface roughness and power consumption, while the other parameters have not substantially affected the response.

In their experimental research work, Benga and Abrao et al. (2003) [12] underlined that feed rate is most significant factor affecting surface finish than cutting speed for both CBN and ceramic inserts. Latter Ozel et al. (2005) [19] conducted a set of ANOVA and performed a detailed experimental investigation on the surface roughness and cutting forces in the finish hard turning of AISI H13 steel. Their results indicated that the effects of workpiece hardness, cutting edge geometry, feed rate and cutting speed on surface roughness are statistically significant.

The present study is to investigate the influence of machining parameters under the surface roughness in dry turning of hardened AISI 4340 steel with CVD (TiN/TiCN/Al₂O₃/ZrCN) multilayer coated carbide tool and determine the optimal levels of machining parameters for optimizing the surface roughness (Ra) by employing Taguchi's orthogonal array design and utilizing analysis of variance (ANOVA). The relationship between the machining parameters (depth of cut, feed and cutting speed) and the performance measures i.e. surface roughness (Ra) has been developed by using multiple second order regression models.

Davim and Figueira et al. (2007) [18] [25] investigate the machinability of cold work tool steel D2 heat treated to a hardness of 60 HRC. They concluded that with an appropriate choice of cutting parameters it is possible to obtain a surface roughness with Ra < 0.8 µm. This implies that hard machining is an alternative competitive process, which allows eliminating cylindrical grinding operation solutions.

An investigation by Kumar et al. (2006) [11] gives an idea about the comparative performance of different coated tools in conventional dry turning and wet turning process with the MQL method by varying speed and feed; keeping the depth of cut as constant. Overall performance of the cutting tool during the MQL application found superior over the dry turning and conventional wet turning based on the parameters such as cutting force, temperature and surface finish. By carefully choosing these parameters, it is possible to produce high quality components with the MQL.

M. Kaladhar et al. [27] determined the best levels of machining parameters such as cutting speed, feed, depth of cut and nose radius to obtain the minimum surface roughness during turning of AISI 202 austenitic stainless steel using full factorial design of experiment.

J.S. Senthikumar et al. [26] conducted the experiments as per full factorial design of experiments under dry cutting condition in machining i.e. finish turning and facing of Inconel 718, and optimized the machining parameters on surface roughness & flank wear using Taguchi technique.

Chavoshi et al. [16] studied, using a CBN tool, the influence of hardness and spindle speed on surface roughness in hard turning of AISI 4140 steel with a hardness of 55 HRC. The results indicated hardness has a significant effect on the surface roughness; the surface roughness dropped as the hardness increased up to 55 HRC.

Cakir et al. [31] investigated how surface roughness was affected by cutting parameters (cutting speed, feed rate, and depth of cut) and two coating layers. Results indicated that feed rate had the greatest influence on surface roughness followed by cutting speed.

Oliviera et al. [22] investigated the hard turning of AISI 4340 steel (56 HRC) in continuous and interrupted cuts with PCBN and whisker reinforced cutting tools. The results indicated that the longest tool life could be achieved in continuous turning by PCBN tool. On the other hand, similar tool life values were obtained during interrupted turning using both the PCBN and ceramic tools. However, PCBN showed better results in terms of surface roughness.

Lima et al. [15] evaluated the machinability of hardened AISI 4340 and D2 grade steels at different levels of hardness by using various cutting tool materials. The AISI 4340 steels were hardened to 42 and 48 HRC and then turned by using coated carbide and CBN inserts. The higher cutting forces were recorded when AISI 4340 steel was turned using low feed rates and depth of cut and lower surface roughness values were observed for softer workpiece materials as cutting speed was elevated and they deteriorated with feed rate.

Jiang et al. [21] addressed the surface morphology, surface roughness, coating cross-section, chemical composition, crystal structure, micro hardness, adhesion and wear life issues of CBN-based coating deposition on carbide inserts (SNMG 120408) for finish hard turning of hardened AISI 4340 steel. The surface quality of machined work pieces in terms of surface roughness and white layer formation was also analyzed.

Yallase et al. [17] experimentally investigated the behavior of CBN tools during hard turning of AISI 52100-tempered steel. The surface quality obtained with the CBN tool was found to be significantly better than grinding. A relationship between flank wear and surface roughness was also established based on an extensive experimental data.

Yahya Isik (2010) [13] The results of the present work indicated that cutting fluid did not show a significant improvement on surface roughness particularly when cutting tests with 0.8 mm nose radius were considered. In fact, the roughness similarly deteriorated under wet machining in some of tests.

R. Suresh, S. Basavarajappa, (2012) [3] investigates the surface roughness is sensitive to variations in feed rate at lower values of cutting speed as compared to higher cutting speed values. The surface roughness is highly sensitive to variations in depth cut at lower values of cutting speed as compared to higher cutting speed values. But the surface roughness is found to be insensitive to variations in machining time irrespective of the cutting speed specified.

2.4. Tool Wear

Fig 6 clearly shows that rate of growth of flank wear decreased by MQL. The cause behind the reduction is observed by Dhar at al.,(2007) [1] that the reduction in the flank temperature by MQL which helped in reducing abrasion wear by retaining tool hardness and also adhesion and diffusion type wear, which are highly sensitive to temperature. Because of such reduction in rate of growth of flank wear, the tool life would be much higher if MQL is properly applied.

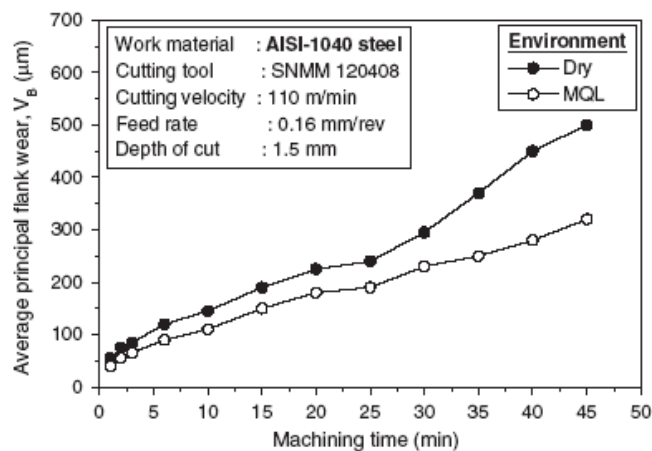


Fig. 6 Growth in average flank wear on the main cutting edge while machining AISI-1040 steel using carbide insert under both dry and MQL conditions (Dhar at al., 2007)

The growths of the average flank wear with machining time of the steel under dry and MQL by vegetable oil conditions are shown fig 2.8. The application of the MQL by vegetable oil reduces flank wear. The SEM views of the worn out inserts after being used for about 45min of machining under dry and MQL by vegetable oil conditions shows abrasive scratch marks in the flank. Severe groove wear and notch wear at the flank surfaces were found in the insert under dry condition. Effective temperature control by MQL by vegetable oil almost reduced the growth of the notch and groove wear on the main cutting edge. It clearly shows that MQL by vegetable oil reduces average flank wear and crater wear.

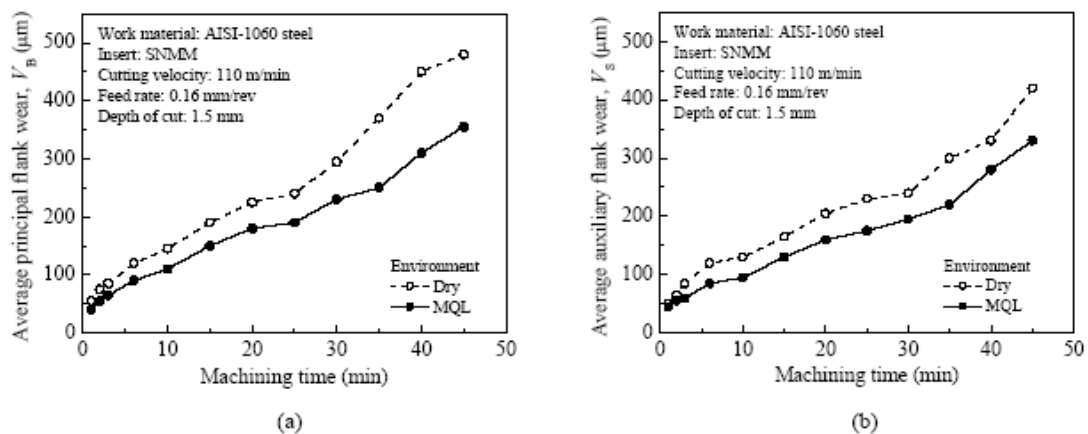


Fig.7 Growth of average principal flank wear V_B (a) and average auxiliary flank wear V_S (b) with machining time under dry and MQL by vegetable oil conditions

High speed grooving of carbon steel was carried out by Toshiyuki at al., (2006) under dry, MQL and wet conditions to investigate the performance of MQL. In high speed grooving with the P35 coated tool and P25 uncoated tool, MQL reduced both the corner and flank wears more effectively. Fig. 2.10 shows that the corner and flank wears in MQL decreased drastically. Fig 5 shows that MQL reduced the wears to a large extent even at a very high speed of 5m/sec.

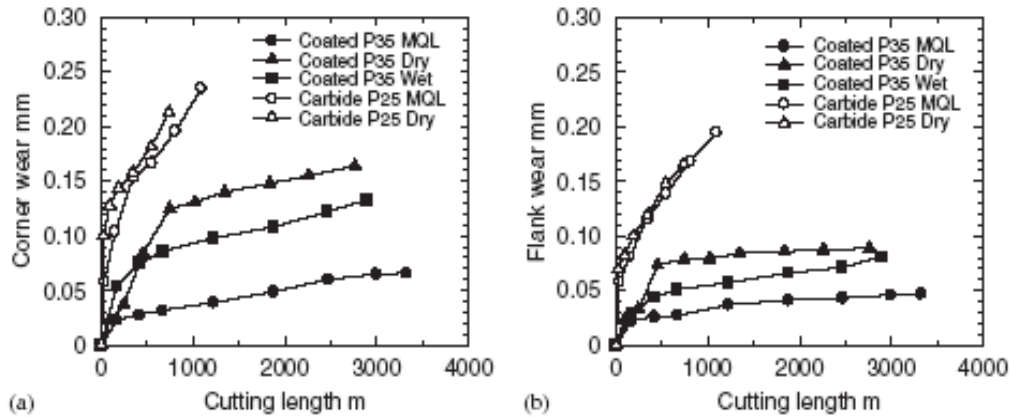


Fig. 8. Wear development under MQL, dry and wet conditions. (a) Corner wear and (b) Flank wear. Cutting conditions—tool, P35-coated carbide and P25 carbide; cutting speed, 4.0 m/s; feed rate, 0.12 mm/rev; width of cut, 5.1 mm; air pressure of MQL, 0.70 MPa.(Toshiyuki at al.,2006)

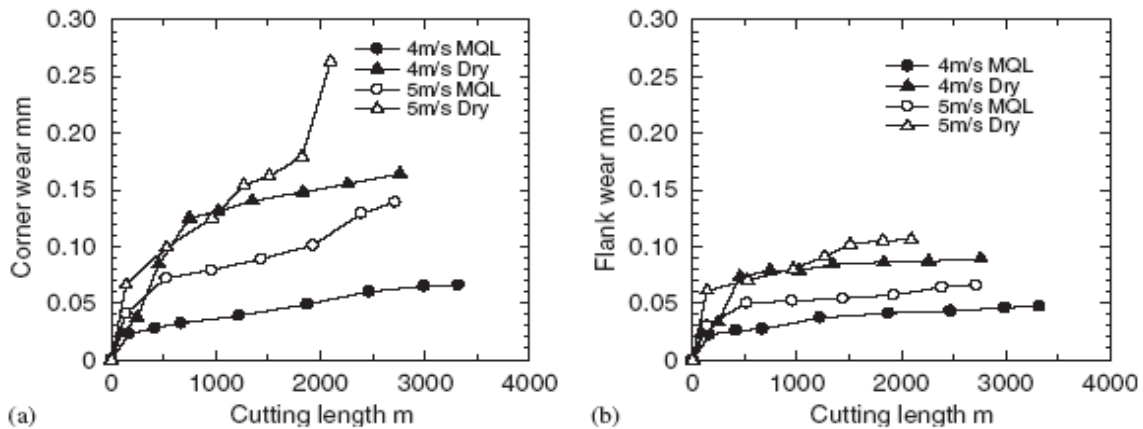


Fig.9. Wear development at different cutting speeds. (a) Corner wear and (b) flank wear. Cutting conditions—tool, P35-coated carbide; cutting speed, 4.0, 5.0 m/s; other conditions are the same as in Fig. 2.10.

The effect of MQL on the tool life of small twist drills in deep hole drilling was studied by Heinemann at al. (2006). A continuous MQL supply is beneficial in terms of tool life for small diameter twist drills in deep-hole drilling, whereas interrupting the MQL-supply leads to a substantial drop in tool life.

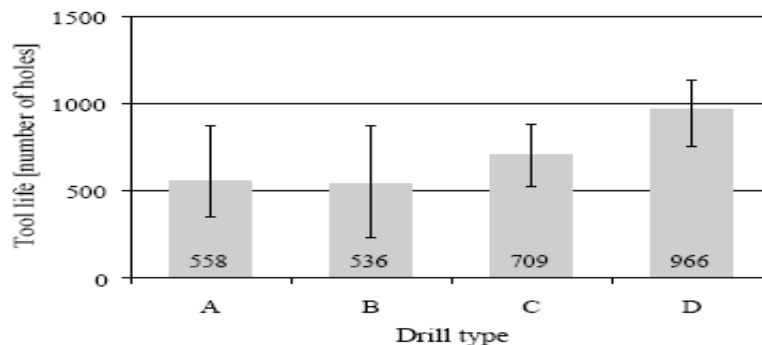


Fig.10. Tool life achieved with a continuous supply of minimum quantity Lubricant at 18 ml/h. A=HSS uncoated, B=Co-HSS uncoated, C=Co-HSS coated with TiN, D=Co-HSS coated with TiAlN (Heinemann at al., 2006)

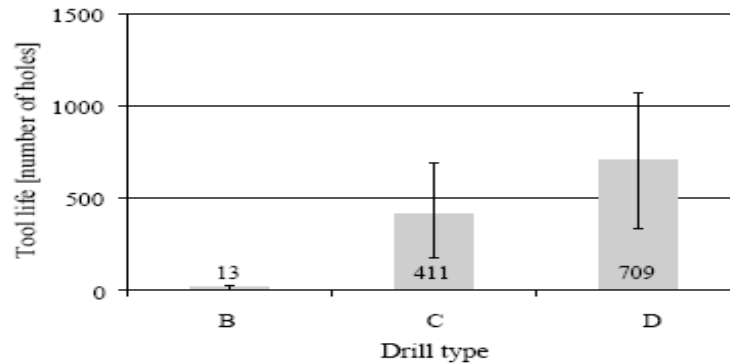


Fig.11. Tool life achieved with a discontinuous supply of minimum quantity Lubricant supply terminated at a depth of 5 mm. (Heinemann et al., 2006)

B. kumar, A.Sengole rayan [9], investigated that when cutting velocity is high as 120 m/min, the chip makes fully plastic or bulk contact with the tool rake surface and prevents any fluid from entering into the hot chip- tool interface. This will results in high cutting force. When cutting force increases the tool wear will also increases and tool life will be reduced. When cutting velocity is less, feed and depth of cut is more, and then the cutting force will be more. So, when cutting velocity is 100m/min with feed as 0.1mm/rev and depth of cut at 0.8mm then the tool wear is low compared with other combination cutting parameters.

TOOL WEAR

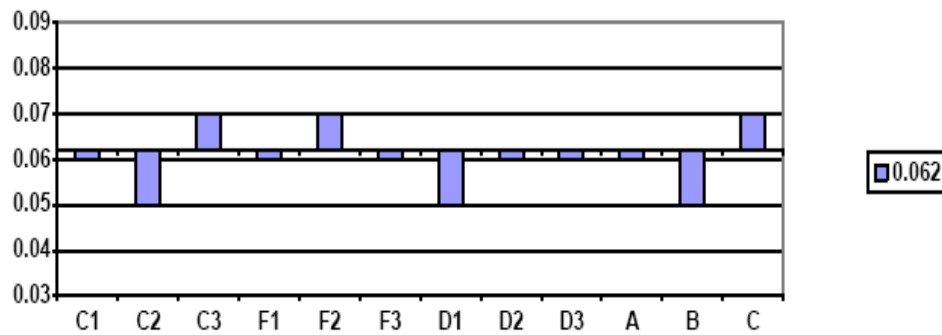


Fig.12. Cutting velocity (C), Feed (F), Depth of cut (D), Application of fluid (A, B & C)

Lugscheider et al. [8] used this technique in reaming process of gray cast iron and aluminum alloy with coated carbide tools and concluded that it caused a reduction of tool wear when compared with the completely dry process and, consequently, an improvement in the surface quality of the holes.

Yaltese et al. [14] investigated experimentally the behavior of a CBN tool during hard turning of 100Cr6 tempered steel. The results showed that a CBN tool offers good wear resistance despite the aggressiveness of the 100Cr6 with hardness of 60 HRC.

Bouchelaghem et al. [17] described wear tests on CBN tool behavior during hard turning of AISI D3 steel with a hardness of 60 HRC. Results showed that the CBN tool is wear resistant.

Ramesh and Melkote [20] presented a study on white layer formation in orthogonal machining of hardened AISI52100 steel with a hardness of 62 HRC. The results show that white layer formation does have a significant impact on the magnitude of surface residual stress and on the location of the peak compressive surface residual stress. Fig. 3 shows the results of a search, using scientific resource items indexed within all databases: ISI Web of Knowledge (Thomson Reuterse), (17/12/2012). The figure indicates the growing interest in this subject.

3. CONCLUSIONS

From the recent experimental investigations based on various analyses considering the limits of the variables employed, the following conclusions are drawn:-

- a. The cutting performance of MQL machining is better than that of dry and conventional machining.
- b. MQL improved tool life and also gives better finished surface.
- c. Some arrangements used by end users such as CVD multilayer tool are costly.
- d. Cutting fluid wastage is reduced to large extent.
- e. Use of coating layers is cost consumption.
- f. Cutting force could be reduced if cutting velocity is less.
- g. CBN tool is less wear resistant in comparison of conventional tool.
- h. Taguchi method proved to be efficient tools for controlling the effect on surface roughness and tool wear.
- i. It was found that, the Ra value for MQL condition is less than that Ra value for dry and wet turning.
- j. The solid lubricant is not so effective as compared to MQL. It is not cost effective also.
- k. The minimum surface roughness value could be achieved at hardness value up to 45HRC.

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