Comparison of surface roughness and chip characteristics obtained under different modes of lubrication during hard turning of AISI H13 tool work steel.

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Abstract. Surface roughness is one of the important parameters, which not only affects the service life of a component but also serves as a good index of machinability. Near Dry Machining, methods (NDM) are considered as sustainable alternative for workshops trying to bring down their dependence on cutting fluids and the hazards associated with their indiscriminate usage. The present work presents a comparison of the surface roughness and chip characteristics during hard turning of AISI H13 tool work steel using hard metal inserts under two popular NDM techniques namely the minimal fluid application and the Minimum Quantity Lubrication technique (MQL) using an experiment designed based on Taguchi’s techniques. The statistical method of analysis of variance (ANOVA) was used to determine the relative significance of input parameters consisting of cutting speed, feed and depth of cut on the attainable surface finish and the chip characteristics. It was observed that the performance during minimal fluid application was better than that during MQL application.

Keywords—Minimal cutting fluid application, Minimum quantity lubrication, Near dry machining, Hard turning.

1. Introduction

Metal cutting involves the use of mechanical force to deform and ultimately fail a material. This is characterised by the severe cutting conditions such as high cutting temperatures and vibrations. The cutting conditions will greatly affect the resulting surface finish. To obtain the lowest possible surface roughness, the tool will need to remain at its state of minimum wear. This forces the machinist to sharpen the tool or change the tool insert frequently adding to the machining time and cost. When the material being machined is of the hardened classes of metals (hardness greater than 45 HRC), the tool wears even more rapidly and hence a time dependent rise in surface roughness can be expected. Hard machining became viable, thanks to the introduction of CBN, ceramic and other tools of high hot hardness [1]. These came as a substitute to a time and labour intensive machining process that involved machining to near net shape first, hardening by heat treatment followed by finish grinding to achieve the tolerances requirements. Hard turning allows for machining the steel blank to its final dimension in the hardened state resulting in significant time and cost savings.

Tool softness due to excessive temperature, high rates of tool wear, high surface roughness are found to be countered by the usage of cutting fluids [2]. Use of cutting fluid also reduces the friction at tool chip interface reducing the cutting forces and preventing the adherence of chip onto the tool [3]. The most common method of application of cutting fluid is flood or deluge cooling which involves the bulk application of cutting fluids in the cutting zone [2]. The elevated cutting zone temperature during hard turning will instantly boil and vaporize the cutting fluids not only causing thermal distortions but also harmful fumes which cause adverse effects to operator health [4]. Flood cooling delivers a quantity of about 20 litres/min of cutting fluid at the cutting zone and is then filtered and re-pumped. This continuous pump cycle accounts for up to 30% of total machining costs [5]. Prolonged exposure to cutting fluid vapours may lead to irritant contact dermatitis, occupational acne, tracheitis,
esophagitis, bronchitis, asthma etc. [6]. Given the recent trend of adopting more eco-friendly policies, it is in the interest of manufacturers to upgrade to a more sustainable and less toxic substitute to flood cooling while not compromising on the surface finish. Hence the recent interest in the field of NDM methods.

Majority of the research work in the field of NDM methods use MQL. MQL relies on a source of compressed air and atomizer to create a jet of aerosol in which tiny droplets of the cutting fluid are dispersed. This jet delivers the cutting fluid at high pressure to the cutting zone, which not only aids the cooling but also serves in chip removal ensuring better penetration of the cutting zone [7]. Vardarajan et al [8] developed a system called Machining with Minimal Fluid Application (MFA). Instead of the compressed air system used for MQL, MFA uses fluid applicator that propels the cutting fluid in high velocity pulses with controllable frequency of pulsing and rate of application. The system provided very good performance in terms of reduction in cutting forces, cutting temperature, tool life, surface finish, cutting ratio and tool–chip contact length.

The largest energy consumptions in wet CNC machines are cutting process (~25%), metal working fluid (MWF) system (30 - 40%), and compressed air (15 - 20%). For MQL, however, the MWF related energy no longer practically exists, which automatically results in saving in energy. However, MQL requires increased compressed air usage compared to wet machining [5]. The air samples were collected from machining zone, filtered exhaust, and plant air for examination. Total airborne particulate concentrations in the plant air was found at least an order of magnitude less than the lowest Occupational Exposure Limit (OEL) (1 mg/m\(^3\)) and US Occupational Safety and Health Administration (OSHA) Permission Exposure Limit (5 mg /m\(^3\)).

According to Tai [5] Ford Motor Company has demonstrated the use of MQL in machining of automotive power train, valve bodies, torque converter housings, and transmission cases, and currently has a total of over 400 MQL CNC machining centres in numerous global transmission and engine plants running MQL operations, with further implementation planned for new programs globally. By comparing two identical transmission modules for a 10-year cycle analysis including downtime cost, maintenance, operating cost, and floor space, study shows over 15% savings on a dedicated MQL machine tool.

Research work by Boubekri [9] on dry turning of AISI 1060 steel using vegetable oil based MQL fluid indicate that the cutting force, cutting zone temperature, tool wear and surface roughness were reduced by the application of MQL as compared to dry cutting. In the case of AISI 1045 steel, a low viscous type MQL lubricant with high cooling capability gave rise to a notably prolonged tool life. In the case of Ti6Al4V, it was observed that the cutting temperature with application of MQL internally through the tool recorded a 50% reduction in cutting temperature compared to MQL applied with an external nozzle. Application of MQL also improved the dimensional accuracy as compared to dry cutting. It was also observed that the characteristics of machining using MQL are yet to be determined for a whole class of materials and machining processes under varying machining conditions.

Gerald et al [10] developed an artificial neural network model which can predict the response during the MFA assisted machining of AISI H13 tool steel. Good overall cutting performance when compared to dry cutting was reported. The method of MFA assisted milling was studied by Thepsonthi et al. [11] claims that performance of MFA was superior to the other methods in terms of surface finish and tool wear. Three fold reduction of flank wear was observed during pulsed jet application of cutting fluid. Anil et al [12] reviewed publications on the research work employing MFA for the operations of hard milling and hard turning. MFA was found to give better cutting performance apart from promoting a green atmosphere on the shop floor. The current study aims at comparing the performance during MFA technique with that during MQL technique during hard turning of AISI H13 tool steel using hard metal inserts.
2. Selection of work material
AISI H13 tool steel was selected as work material in the present investigation. This material is of good hardenability, enjoys wide usage in applications such as pressure die casting tools, extrusion tools, forging dies, hot shear blades, stamping dies and plastic moulds. The material was hardened to 45 HRC. The AISI H13 steel is chemically composed of the following elements as shown in Table 1. A cylindrical workpiece of length 360 mm and diameter 70 mm was used in this investigation.

| Table 1. Composition of work piece material |
|--------------------------------------------|
| C  | Cr  | Mn  | V   | Si  | Mn  | Fe  |
| 0.39 | 5.15 | 1.25 | 1.1  | 1.0  | 0.5  | Balance |

3. Selection of cutting tool
SNMG 120408 MT TT 5100 hard metal inserts manufactured by TaeguTecPvt. Ltd. were used. The cutting tool had an orthogonal rake angle of 6° and a nose radius of 0.8 mm. The tool holder used was PSBNR 2525 M12.

4. Experimental setup

The MFA system shown in figure 1 was developed in house at Karunya University by Varadarajan et al [8]. It consists of a P-4 Bosch fuel pump coupled to an infinitely variable electric drive. The system uses fluid nozzles to generate and direct high velocity pulsing jet of cutting fluid at both the chip-tool and the work-tool interfaces. The MFA apparatus allowed independent variation of pressure at the fluid injector, frequency of pulsing and the rate of application of cutting fluid. An MQL fluid application system (figure 2) was also developed to supply cutting fluid in which the cutting fluid was propelled by a stream of compressed air. The pressure at the outlet was adjusted by varying the cone angle [13, 14]. The MQL setup parameters were kept constant at 10 bar pressure and 8 ml/min of cutting fluid delivery quantity. An emulsion of 20% synthetic cutting oil in water was used for all the experiments. The MFA parameters were kept constant at an injector pressure of 100 bar, frequency of 600 pulses/min and rate of delivery of 8 ml/min.
5. Experimental procedure

5.1 Design of experiment

A nine run, three factors, three level orthogonal array was designed by following Taguchi’s design of experiments to conduct the experiments. The design matrix is shown in Table 2 and the response tabulation in Table 3 (show the design matrix also).

5.2 Selection of parameters and levels

The cutting speed, feed rate and depth of cut are the three main control parameters in turning operations. For the experimental runs, cutting parameters were varied at three levels. The object function was to minimise surface roughness.

Table 2. Cutting parameters and their levels

| Parameter        | Level 1 | Level 2 | Level 3 |
|------------------|---------|---------|---------|
| Cutting speed (m/min) | 75      | 0.5     | 0.05    |
| Feed rate (mm/rev)  | 95      | 0.75    | 0.075   |
| Depth of cut (mm)   | 115     | 1       | 0.1     |

5.3 Measurement of surface finish

Surface finish was measured using a Mitutoyo surface roughness tester (SJ210).

6. Results and discussion

The surface roughness observed during each experimental trial is recorded in Table 3.
Table 3. Results of the 9 run experiment

| Run order | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) | Surface roughness during MFA (Ra) (µm) | Surface roughness during MQL (Ra) (µm) |
|-----------|----------------------|--------------------|------------------|----------------------------------------|---------------------------------------|
| 1         | 75                   | 0.05               | 0.5              | 0.62                                   | 0.7                                   |
| 2         | 75                   | 0.075              | 0.75             | 0.94                                   | 1.19                                  |
| 3         | 75                   | 0.1                | 1                | 1.12                                   | 1.65                                  |
| 4         | 95                   | 0.05               | 0.75             | 0.89                                   | 1.21                                  |
| 5         | 95                   | 0.075              | 1                | 1.08                                   | 1.47                                  |
| 6         | 95                   | 0.1                | 0.5              | 0.97                                   | 1.53                                  |
| 7         | 115                  | 0.05               | 1                | 0.99                                   | 1.34                                  |
| 8         | 115                  | 0.075              | 0.5              | 1.02                                   | 1.39                                  |
| 9         | 115                  | 0.1                | 0.75             | 1.26                                   | 1.75                                  |

6.1 A Relative significance charts for surface roughness obtained during MCFA and MQL assisted machining.

The relative significance of each cutting parameter on the surface roughness is as shown in the column effects charts shown in Fig. 3 and Fig. 4.

**Figure 3.** Chart indicating relative significance of cutting parameters on surface roughness during MFA (v - cutting speed, f - feed rate, d - depth of cut).
Figure 4. Column effects chart for surface roughness during MQL (v-cutting speed, f-feed rate, d-depth of cut).

As seen in the Figures 3 and 4, the cutting velocity, the feed rate and the depth of cut are to be maintained at the lower level to minimise surface roughness in both MFA and MQL.

6.2 ANOVA for surface roughness obtained during MFA and MQL assisted machining.

The analysis of variance is a widely used statistical methods commonly used to study the effects or relation between the input and output parameters in machining operations. ANOVA uses a combination of statistical methods that compare the means and variances to check for significance between sets of data. ANOVA for the two cases of NDM (Tables 4 and 5) shows highest significant effects for feed rate with 50.13% and 59.10% of significance for MFA and MQL respectively.

Table 4. ANOVA summary for MFA assisted turning

| Factors         | DOF | Sum Of Squares | Variance | F-Ratio | Pure Sum | Percent contribution (%) |
|-----------------|-----|----------------|----------|---------|----------|--------------------------|
| Cutting speed   | 2   | .044           | .022     | 10.968  | .04      | 19.744                   |
| Feed rate       | 2   | .1             | .05      | 24.608  | .096     | 50.13                    |
| Depth of cut    | 2   | .046           | .023     | 11.476  | .042     | 21.801                   |
| Error           | 2   | .003           | .001     |         |          |                          |
| Total           | 8   | .195           |          |         |          | 100.00%                  |

Table 5. ANOVA summary for MQL assisted turning

| Factors         | DOF | Sum Of Squares | Variance | F-Ratio | Pure Sum | Percent contribution (%) |
|-----------------|-----|----------------|----------|---------|----------|--------------------------|
| Cutting speed   | 2   | .156           | .078     | 8.537   | .137     | 18.009                   |
| Feed rate       | 2   | .47            | .235     | 25.738  | .452     | 59.108                   |
| Depth of cut    | 2   | .12            | .06      | 6.576   | .101     | 13.324                   |
| Error           | 2   | .017           | .008     |         |          | 9.559                    |
| Total           | 8   | .765           |          |         |          | 100.00%                  |

The cutting speed and depth of cut during MFA assisted machining was found to have a significance of 19.7% and 21.80% respectively while that during MQL assisted machining was 18.0% and 13.32%.

6.3 Comparison of surface roughness

Fig. 5 presents the average surface roughness during each trial for the MFA and MQL application. It is observed that lower Ra values were observed during MFA when compared to MQL application.
6.4 Comparison of performance during Dry turning, turning with flood application, turning with MFA and MQL at optimal levels of cutting parameters.

The surface roughness was minimum when the cutting parameters were kept as cutting speed as 75 m/min., feed as 0.05 mm/rev and depth of cut as 0.5 mm as in trial no.1 as in Table 3. Cutting experiments were carried out at this condition for dry turning, conventional wet turning, turning with MFA and turning with MQL. The surface roughness values obtained during each trial are as recorded in Table 6. It is observed that turning with MFA gave the minimum surface roughness followed by MQL and flood cooled turning.

| Surface roughness $R_a$ ($\mu m$) |
|----------------------------------|
| Dry | Flood | MCFA | MQL |
| 3.04 | 1.37 | 0.62 | 0.7 |

6.5 Comparison of chip characteristics

Physical nature of the chips is characteristic of the cutting conditions undergone by the chip. It is therefore helpful to compare the chips obtained under different modes of cutting fluid application and study their physical appearance. Chips with severe serrations were observed during dry turning and turning with flood application. MFA gave tightly coiled chips with minimum serrations allowing easy handling and disposal. This is attributed to the better rake face lubrication and superior heat removal during MFA which is predominantly in the evaporative mode compared to the other methods. Chips produced during dry and flood application were dark purple in colour whereas no prominent colour change was observed during turning with MFA and MQL. This may be attributed to the lower cutting temperatures encountered than is possible during flood application and pure dry turning. This is made possible by the better rake face lubrication as available during MFA and MQL applications [8]. The best Cutting performance was obtained during turning with MFA.
7. Conclusions

The comparative investigation led to the following conclusions:

- Feed rate was found to be the factor accounting for the highest variations in the surface roughness followed by cutting speed and depth of cut.
- MFA assisted turning was found to outperform other lubrication techniques in achieving better surface finish.
- Surface roughness obtained during turning with MFA was 35% lower than that can be achieved during MQL assisted turning.
- The chip characteristics during turning with MFA was better than that during MQL application and conventional flood application under the same cutting conditions.

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