A105 Work-Material Turning Experimentation using L9 Orthogonal Array Runs with Dry, MQL and Nano-\text{Al}_2\text{O}_3 Assisted MQL Machining Conditions

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Abstract. A105 carbon structural steel material exhibits high strength and hence pose machining difficulties such as excessive tool wear due to high cutting temperatures. Abrupt cutting actions due to improper selection of feed rates have posed to bad surface finish of work-pieces. These materials find best applications in flanges and pipe fittings and generally turning operations are conventional methods to change its dimensions and attaining accuracy levels. An attempt is made to experiment on A105 work material using lubricant vegetable coconut oil under minimum quantity lubrication (MQL) assisted by nano-particles such as Al$_2$O$_3$ in order to find suitable combinations of working environments, to compare with dry cutting, and also to decide suitable feed rates and cutting speeds combinations.

Keywords: MQL, \text{Al}_2\text{O}_3, nano-material, Turning, A105 work-material

1. INTRODUCTION

MQL lubrication and cooling in machining is exercised to reduce the tool chip cutting temperatures during high speed machining eg. turning. MQL acts as a film between the tool and chip contact thereby reducing friction and cutting temperature to a large extent which is quite common in dry cutting operations. The use of vegetable oils such as coconut oil in the present experimental study is to ensure better biodegradability of the oils which otherwise is least in mineral oils. New researches on use of lesser lubricating oils and coolant oils in machining led to use of forced vented spraying nozzle setups which are named as minimum quantity lubrication or near dry lubrication which works under 10 bar pressures and at fluid flow rates of upto 50 ml/hr. Nano-materials assisted in MQL lubrication also have profound effects on the responses. Alumina, Molybdenum Disulphide, Graphene are some of the few nano materials (nano-size in the range of 10-30 nm) which are employed in lubricant with proper mixing and homogenizing of the mixture by a technique called as Ultra-sonication [1-3].

2. BRIEF LITERATURE INVESTIGATIONS:

1. Vasu (2011) [4] experimented turning process and indicated that feed rate and depth of cut are major parameters that affects the surface quality in machining Inconel 600 alloy.
2. Padmini et al.(2016) [5] found in his experimental investigation of nano MoS2 based Coconut oil lubricant on AISI 1040 steel during turning operation that, there is decrease in parameters of surface roughness and tool wear by 39% and 44%.
3. AISI 1040 work material was turned under dry, wet, mist and nano fluid mist by Sharma et al.(2016) [6] and found that Nano-cutting fluid reduces tool wear and improves surface roughness by 63.9% and 48.6% respectively.
4. Effect of nAl$_2$O$_3$ in lubricant for machining AISI 1050 steel improves tool life since it flushes away heat from the cutting zone effectively than dry and wet machining as experimented by Khalil et al. (2015) [7].

5. Ali M. et al. (2016) [8] found that MQL with nano fluid and surfactant added in nanofluid has a profound effect in reducing tool wear and improving surface finish.

6. A reduction of 30% in chip thickness is observed in machining process with nano cutting fluid. The chip morphology characteristics such as less burning, long smooth chip ribbons are obtained in nano cutting fluid machining as experimented by Anburaj et al [9].

7. For good surface finish, Ramakrishnan et al. (2019) [10] recommends 1% of Al2O3 Nano lubrication for better result as compared to 0.5% nano lubrication and dry machining conditions.

8. When comparing with different vegetable oils, canola vegetable oil gives better tool life than coconut oil and soybean oil. Surface finish is found to be constant under varying cutting speeds as depicted by Gunjal et al. (2018) [11].

3. RESEARCH METHODOLOGY

ASTM A105 steel workpiece material of 50 mm diameter and length 200 mm was taken for experimental study whose chemical composition is as shown in Table 1. Kirloskar Lathe was used to turn the work material. P type uncoated CNMG120408 geometry Carbide tool insert is employed as tool material. Depth of cut is 0.5 mm which is maintained constant throughout the experimentation. Minimum Quantity Lubrication (MQL) cooling using Coconut Oil is delivered by KencoMist Lubrication System. 5 mm distance gap is maintained between nozzle and tool-chip interface with a flow rate of 50 ml/hr. Surface roughness in microns were measured along three positions on the 200 mm work-piece on every cut using Talysurf Surface meter, Tool wear is measured in microns using inverted microscope with digital camera setup connected to computer via proprietary software module. The chip thickness is measured accurately after every length of cut using digital vernier caliper.

| Carbon% | Silicon% | Manganese% | Sulphur% | Phosphorus% | Niobium% |
|---------|----------|------------|----------|-------------|----------|
| 0.223   | 0.186    | 0.690      | 0.013    | 0.018       | 0.011    |
| Cerium% | Cobalt%  | Titanium%  | Tungsten% | Aluminium%  | Lead%    |
| 0.001   | 0.00     | 0.005      | 0.051    | 0.045       | 0.019    |
| Nickel% | Molybdenum% | Copper%     | Chromium% | Iron%       |
| 0.018   | 0.012    | 0.003      | 0.149    | 98.495      |

4. EXPERIMENTAL DESIGN

Turning Experimentation is carried out with three factors viz. parameters mainly machining conditions, cutting speed and feed rate with depth of cut keeping constant as 0.5 mm in all run conditions. 3 levels for each factor is selected which is shown in the Table 2. MQL fluid with nano material – Al$_2$O$_3$ is mixed with technique called as ultra-sonication method using an ultra-sonicator which is run for 1 hour continuously to create fine dispersion of nano-particles in the base fluid (Coconut oil). Agglomeration of particles is so far not avoided and for every 3 hours of rest time, 30 minutes of ultra-sonication is done to get homogenous mix just before using it in the MQL unit for experimentation.
Fractional factorial experiment using L₉ Orthogonal Array Design is employed as shown in Table 3. Full factorial will take 27 runs for 3 factors and 3 levels which is time consuming and our main aim here is to understand the significance of MQL and nano material in responses and to find the trend analysis keeping in view avoiding biases of experiment by selecting Orthogonal Array. The levels of the factors especially for Cutting speeds and feed rates are selected based on the Turning machine capability to machine A105 work-piece with good degree of surface finish, lower tool wear rates and better chip characteristics.

### Table 3. L₉ Orthogonal Array Design runs

| Experimental Run | A (machining conditions) | B (cutting speed in rpm) | C (feed rate in mm/rev) |
|------------------|--------------------------|--------------------------|-------------------------|
| 1                | Dry                      | 630                      | 0.25                    |
| 2                | Dry                      | 1000                     | 0.28                    |
| 3                | Dry                      | 1600                     | 0.315                   |
| 4                | MQL                      | 630                      | 0.28                    |
| 5                | MQL                      | 1000                     | 0.315                   |
| 6                | MQL                      | 1600                     | 0.25                    |
| 7                | MQL + n Al₂O₃            | 630                      | 0.315                   |
| 8                | MQL + n Al₂O₃            | 1000                     | 0.25                    |
| 9                | MQL + n Al₂O₃            | 1600                     | 0.28                    |

5. EXPERIMENTAL RESULTS  
For the 9-Run experiment, each run data related to surface roughness, tool wear and chip thickness was measured. Referring to Figure 1, Surface roughness values were measured along the work-piece length in 3 locations i.e extreme ends and middle. Distance between the two measurements approximated to 50 mm. So, a cumulative length scale in X-axis is taken in graph with respective measured surface roughness values in each step is measured. After every 3 readings on the length of cut of 200 mm, next 0.5 mm depth of cut is taken and same set of conditions for the run is continued till the cumulative length of 1200 is covered. Total 24 data points were collected for each experimental run and hence plotted in Figure 1.
Figure 1 Surface Roughness (microns) versus length of cut for different experimental runs

Referring to the Figure 1, it is evident that minimum surface roughness curves exist for the RUN 6 which depicts MQL condition, high rpm of 1600 with feed rate of 0.25 mm/rev which is lowest. The next experimental run found to give minimal good readings in lower surface roughness seems to be nano-MQL at 1000 rpm with feed rate at 0.25 mm/rev which is RUN 7. The other remaining curves seem to follow near same patterns within surface roughness band of 2.1 microns to 3 microns. Hence, we can conclude, that for better surface finish of workpiece A105, for both MQL and nano assisted MQL, a lower feed rate of 0.25 is favourable. Nano assisted MQL helps to leverage down the speed selection from 1600 rpm to 1000 rpm and shows that nanoaluminium oxide particles (Al₂O₃) has an effect on surface finish qualities.

Figure 2 Average Surface Roughness (microns) versus different experimental runs

The average surface roughness values of each experimental run across 1200 mm cumulative length is taken on graph as shown in Figure 2. It is clearly evident that MQL and nano assisted MQL dominate with better surface finish values i.e lower surface roughness at all speeds and feed ranges. The
preferred speed ranges as per the graph is between 1000 to 1600 rpm, a lower rpm of 1000 is advisable for economic savings of energy. In that case, for 1000 rpm cutting speed step, nano-MQL at 0.25 mm/rev feed rates are advisable. This will result in better surface quality of work material during turning and also lesser power losses during turning. Hence, Run 7 is optimal for lower energy consumption during metal cutting and better surface finish.

Tool wear was measured in microns using Dixel Software coupled to Camera attached to Inverted microscope. A sample photograph of tool wear at Run 3 during completion of 150 mm cutting is as shown in Figure 3.

![Figure 3](image)

**Figure 3** Tool Wear @ Dry cutting, cutting speed = 1600 rpm, feed rate = 0.315 mm/rev at cutting length = 150 mm

Tool wear measurements were taken similarly till length of 1200 mm for all 9 runs with the data as shown in Table 4. It is seen that as the length of cut progresses, consecutively the tool wear also progresses. To understand the data analysis better, a graph of Tool wear (microns) versus step wise length of cut upto 1200 mm is plotted as shown in Figure 4.

**Table 4.** Tool Wear values for different Experimental runs upto 1200 mm length of cut.

| Cumulative length of cut (mm) | 150  | 300  | 450  | 600  | 750  | 900  | 1050 | 1200 |
|-----------------------------|------|------|------|------|------|------|------|------|
| DRY, 630 rev, 0.25 mm/rev.  | 25   | 34   | 54   | 68   | 98   | 116  | 130  | 154  |
| DRY, 1000 rev, 0.28 mm/rev. | 26   | 63   | 80   | 96   | 105  | 127  | 145  | 186  |
| DRY, 1500 rev, 0.315 mm/rev.| 39   | 52   | 84   | 122  | 155  | 178  | 203  | 217  |
| MQL, 630 rev, 0.28 mm/rev.  | 12   | 21   | 29   | 37   | 52   | 66   | 81   | 101  |
| MQL, 1000 rev, 0.315 mm/rev.| 14   | 22   | 32   | 42   | 56   | 63   | 72   | 92   |
| MQL, 1500 rev, 0.25 mm/rev. | 19   | 31   | 48   | 62   | 74   | 86   | 91   | 106  |
| nMQL, 630 rev, 0.315 mm/rev.| 5    | 12   | 14   | 15   | 18   | 19   | 21   | 24   |
| nMQL, 1000 rev, 0.25 mm/rev.| 6    | 9    | 12   | 13   | 15   | 18   | 19   | 22   |
| nMQL, 1500 rev, 0.28 mm/rev.| 11   | 14   | 18   | 21   | 23   | 27   | 28   | 29   |
It is evident from the Figure 4 that for minimal tool wear, nano-particle assisted MQL surpasses other machining conditions i.e. Dry and MQL. The Tool wear in nano assisted MQL are far below microns and shows good indication of tool life. The best run for tool wear works out to be nano MQL at 1000 rpm cutting speed, 0.25 mm/rev which is true for better surface finish as proved in earlier section. It is evident that, cutting speeds have lesser prominence on tool wear w.r.t nano MQL. Cutting and plain MQL has lesser tool life as is evident that tool wear is 200 microns max. and 100 microns max. respectively. Nano MQL has better prospects for improvement in tool life and hence good savings in tool material. The main reason of this advantage over Dry and MQL condition is that nano particles i.e. Al2O3 exhibit good wear resistance qualities that acts between the tool and work material when actual cutting action takes place. It reduces the friction at the tool chip interface and hence lesser temperature gradients which maintains tool strengths at higher speeds and feed rates.

The average chip thickness for each run of experimentation is plotted as shown in Figure 5. It is clearly evident that nano MQL at 1000 rpm cutting speed and at 0.25 mm/rev feed rates exhibit lesser chip thickness. It is recommended that lesser chip thickness helps to reduce cutting temperatures due to less contact area zone. It was also found that Dry machining conditions had burnt chips with sharp and hard edges. MQL and nano MQL delivered smooth cutting of chips which helped in long bright ribbon chips which were easier to collect and dispose off. The edges of the chips from MQL and
6. CONCLUSIONS

1. From the experiments, it is evident that A105 work material which is carbon structural steel material can be machined effectively for better surface finish, lower tool wear rates and minimal chip thickness at conditions of 1000 rpm speed range, lower feed rates of 0.25 mm/rev. and assisted by nano-MQL (3% Al₂O₃ in coconut Oil).

2. Since the nano lubricant mixture was homogenous and evenly spread throughout, the experimental results had fairly proved that nano-particles have a profound effect on the improved response values. Proper mixing of nano particles demands for proper ultrasonication time, method and accurate MQL injection system at the tool chip interface.

3. Dry machining is not advisable since it deteriorates the surface finish to a large extent as is evident from the surface roughness values, it has a drastic effect on tool life and the chips are occasionally burnt due to high feed rates. MQL with or without Nano particles are always better methodology and hence proved correct for A105 material.

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