EXPERIMENTAL INVESTIGATIONS AND REGRESSION ANALYSIS BASED MATHEMATICAL MODELLING FOR TOOL LIFE UNDER MINIMUM QUANTITY LUBRICATION

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ABSTRACT

Machining is a complex phenomenon that deals with challenging aspects. As the manufacturing sector is looking forward to profitability through productivity without compromising the quality of the product, it adds a burden on the entire system of the machining process under consideration. The heat generated at the machining zone results in a savior impact on the machining quality of the end product, which can be minimized using the cutting fluids appropriately. Tool life is an important aspect in every machining operation which does not only define the cost associated with the machining but also plays a vital role in defining the quality product. At the extreme temperature machining operation wear rate of the tool is faster which could be resulted in uneven surface integrity of the material under consideration. The additional attributes like coating, cutting fluid, and machining environment surely add life to the tool for a longer run. Considering the sustainable machining need, dry and near-dry machining are the most attributed techniques to explore. In the current research work, the experimental investigations into tool life are studied along-with the mathematical modeling using regression analysis. Under the application of minimum quantity lubrication and dry machining; the turning of the hardened AISI 4340 material is performed at varying cutting conditions. The vegetable oils are compared against the synthetic oil for better performance evaluation. The results are inferred that the canola oil gives superior performance in comparison to soybean and coconut oil under the category of vegetable oils. While comparing the overall performance; synthetic oil shows the better performance over the vegetable oils under consideration. The significant improvement in tool life is observed under minimum quantity lubrication as compared to the dry environment; attributed to the combined effect of cooling and lubrication by the virtue of compressed air and cutting fluid respectively.

KEYWORDS: *Machining environment, minimum quantity lubrication, near-dry machining, regression analysis, tool life, vegetable-based cutting fluids*

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1. INTRODUCTION

Machining is the key operation in every manufacturing house; caters to a lot of weightage entirely. Every machining operation is associated with certain input parameters like cutting conditions, application of cutting fluid, coating of tool material, machining environment, etc. which ultimately leads to deserving quality of the end product. Moreover, the associated dependent parameters like tool life, cutting forces, cutting temperature, chip morphology, surface roughness, etc. are responsibly shaping the true nature of productivity and profitability in the entire process which largely defines the success of the operation. The tool is the most significant parameter in the

machining operation under consideration and its life matters revealing most of the direct and indirect aspects thereof. The machining environment largely affects the tool life during the operation under consideration. Researchers have found the potential application of a few sustainable machining practices in the positive direction like dry machining and minimum quantity lubrication. The major concern associated with dry machining is its limitation at the higher cutting speed, limiting its application thoroughly for all the operations [1]. Minimum quantity lubrication is the innovative approach that uses a maximum of up to 150 ml/hr of the cutting fluid signifies the MQL as a near-dry machining or micro-lubrication approach; avoiding further challenges of wastage, disposal cost, direct exposure to the operator, etc. [2-5]. Though the cutting fluid application is useful to achieve the desired output product; the application of synthetic oil is a harmful and environmentally unfriendly approach as it causes several negative impacts on the environment and operator as well [6, 7].

Performance evaluation of MQL, dry, and flood has been revealed by past researchers for various cutting conditions. The improved surface finish and tool life under the MQL application was noted by Varadarajan et. al. 2002; [8] during the comparative evaluation of MQL, dry, and flood lubrication environment. On a similar line of study, Attanasio et. al, 2006; [9] has noted the superior results of MQL in terms of improved tool life in comparison to dry machining. They inferred that the improved tool life under MQL is attributed to the reduction in flank wear. MQL at high-speed machining found compatible, as studied by Liao et. al. 2007; [10] who has noted the better tool life during high-speed milling, under the application of MQL machining over the dry and flood lubrication. Eker et. al. 2014; [11] has also observed the improved tool life under MQL application over the dry machining technique.

Cutting fluids perform a key role in wider aspect during the machining under consideration. Biolubricants that are based on naturally available resources; mostly plant-based or vegetable-based are environment-friendly cutting fluids. Biolubricants are biodegradable up to the maximum extent than that of synthetic oils. Past researchers have evaluated the performance of bio-lubricants under the varying cutting conditions and have noted the potential application of the same over the traditional cutting fluids. Their excellent properties such as high viscosity, boiling point, and flash point, etc. provide the compatibility of their usage at higher temperature applications as well. It further reduces the chances of smoke formation or fire hazard to a larger extent [12, 13]. Vegetable-based cutting oils under the MQL application have shown prominent attributes of reduced tool wear, surface roughness, and minimum chip thickness resulting in improved quality of the end product under consideration [14, 15]. Agrawal et. al. 2014; [16] has developed the all-new biolubricants for the performance evaluation under the application of MQL in comparison to conventional oil. They found a significant improvement in tool life and surface finish comparatively. On a similar attempt by Gajrani et. al. 2019; [17] the results inferred the superior emulsion stability and anti-corrosion properties of the biolubricants under the application of MQL; leading to the sustainable machining approach. The improved tool life and reduced surface roughness, chip thickness, cutting forces, cutting temperature, etc. are noted by the various researchers during the usage of vegetable oils under the MQL application in comparison of dry and flood lubrication environment at varying cutting conditions, even at hard to cut materials like Inconel 718 material [18-22].

2. EXPERIMENTAL WORK

Hardened steel material; AISI 4340 (52-54 HRC) of dimension 90*250 mm is undertaken for the experimental investigation. Carbide inserts of AlTiN coating were used to evaluate the tool life during experimentation. Three different vegetable-based cutting oils namely canola, coconut, & soybean are compared against synthetic oil under MQL, and MQL further as compared with dry machining environment.

2.1 SETUP FOR MQL

Minimum quantity lubrication technique is the proven sustainable method of applying cutting fluids targeted to the machining zone. In the current study, the vegetable-based cutting fluid is used under MQL. The air pressure and oil flow rate for MQL were 6 bar and 50 ml/hr respectively, while the nozzle angle kept constant at 15° during the experimentation. The MQL set-up representation assisted to the CNC lathe machine is shown in figure 1 as below.

Figure 1: MQL application-the photographic view

2.2. DESIGN OF EXPERIMENT

The Taguchi L9 orthogonal array is used to design the experiments. Table 1 shows the values for experimental evaluation under consideration.

Table 1: Design of experiment

Sr. No.	Cutting speed V_c , m/min	Feed rate f , mm/rev	Depth of cut d , mm
1	200	0.1	0.15
2	200	0.15	0.2
3	200	0.2	0.25
4	220	0.1	0.2
5	220	0.15	0.25
6	220	0.2	0.15
7	240	0.1	0.25
8	240	0.15	0.15
9	240	0.2	0.2

Mathematical modeling for tool life under each machining environment and different cutting fluid application is presented using regression analysis.

3. RESULT AND DISCUSSIONS

Tool life is measured for the criteria of flank wear. For the current investigation, the tool wear criteria are attributed to 0.3 mm, and the respective tool life is noted for each machining environment under different cutting fluid applications. Figure 2 shows the Nikon measuring microscope for too wear measurement.

Figure 2: Tool wear measurement set-up

3.1 OBSERVATIONS

Table 2: Observations during tool life measurement under different machining environments

Sr. No.	Cutting speed Vc, m/min	Feed rate f, mm/rev	Depth of cut d, mm	Tool life, L _t , min				
				Canola oil, Cn	Coconut oil, Co	Soybean oil, So	Synthetic oil, Sy	Dry machining
1	200	0.1	0.15	8.82	6.39	5.53	22.42	3.17
2	200	0.15	0.2	8.67	6.17	5.24	21.23	2.85
3	200	0.2	0.25	8.12	5.82	4.23	20.67	2.23
4	220	0.1	0.2	5.9	3.53	2.66	14.28	1.64
5	220	0.15	0.25	5.63	3.15	2.52	14.12	1.5
6	220	0.2	0.15	5.95	3.65	2.67	14.36	1.67
7	240	0.1	0.25	2.36	2.29	2.23	6.47	1.1
8	240	0.15	0.15	2.37	2.35	2.26	6.67	1.15
9	240	0.2	0.2	2.37	2.32	2.25	6.5	1.12

Regression analysis based mathematical modeling is studied to validate the experimental investigations. Following are the equations are drawn based on regression analysis for each machining environment.

$$L_t, Cn = 40.52 - 0.15425V_c - 2.13f - 3.43d \quad 1.$$

$$L_t, Co = 25.86 - 0.0952V_c - 1.40f - 3.77d \quad 2.$$

$$L_t, So = 20.05 - 0.0688V_c - 4.23f - 4.93d \quad 3.$$

$$L_t, Sy = 98.27 - 0.37233V_c - 5.47f - 7.30d \quad 4.$$

$$L_t, Dry = 11.99 - 0.04067V_c - 2.97f - 3.87d \quad 5.$$

The Pred. R^2 , Adj. R^2 , and R^2 values for each environment are presented in table 3 as follows.

Table 3: The R^2 values for each machining environment

Factor	MQL environment				Dry environment
	Cn	Co	So	Sy	
R^2 (%)	99.36	94.51	83.69	99.84	92.70
Adj. R^2 (%)	98.98	91.21	73.91	99.74	88.32
Pred. R^2 (%)	97.65	82.96	52.37	99.46	77.08

The Pred. R^2 , Adj. R^2 , and R^2 values for each machining environment are in close agreement and shows minor variation due to unpredictable factors during experimentation.

3.2. PERFORMANCE EVALUATION OF TOOL LIFE

Tool life is noted for each machining environment concerning the criteria of average flank wear = 0.3 mm and the tool wear images are captured using a microscope. Comparing the dry and MQL and dry machining conditions; a significant improvement under MQL has been observed in comparison to the dry machining. The vegetable oils are compared with synthetic oil under an MQL environment.

(a) Combined effect of cutting speed & feed rate

(b) Combined effect of cutting speed & depth of cut

(c) Combined effect of feed rate & depth of cut

Figure 3: Performance evaluation under different machining environments and the combined effect on tool life

The tool life under varying machining environment and cutting conditions is illustrated in figure 3, as shown above.

Figure 4: Tool wear images at $V_c=240$ m/min; higher cutting speed

As expected, the tool life is significantly affected by the cutting speed for all environments under consideration. The tool life reduces sharply in direct proportionate to the higher cutting speed; which is in agreement with the previous researcher's work [23-25]. As shown in figure 4, the sudden tool failure has been observed at the $V_c=240$ m/min at all the machining conditions. This is attributed to an extreme temperature generated at the machining zone during higher cutting speed which results in the tool losing its strength to withstand the forces and temperature that occurred concerning the subsequent friction. For initial cutting speed of 200 & 220 m/min; the progressive wear pattern under all the cutting environments is noted. Comparing the MQL and dry machining environment; the results inferred that the MQL has better performance at the significant level due to the subsequent effect of compressed air and cutting fluid attributed to cooling and lubrication respectively. The average tool life was noted to be 6.73 and 1.83 min. under the application of MQL and dry environment respectively; which shows notable improvement comparatively.

The prospect of the current study is not only comparing the MQL and dry environment but also attributed to analyze the performance comparison of vegetable oils in comparison to synthetic oil. Three different vegetable oils; soybean, coconut, and canola are compared against the synthetic oil and with each other under an MQL environment. Considering the vegetable oils; canola oil has shown superior performance in comparison to soybean and coconut oil. This is attributed to the maximum heat transfer coefficient and higher density of the canola oil over the coconut and soybean oil leading to superior tool life concerning excellent cooling and lubrication [26, 27]. The average tool life was noted to be 5.58, 3.96, and 3.29 min. under canola, coconut, and soybean oil application respectively. The overall comparison of vegetable oils and synthetic oils under MQL reveals that the synthetic oil performs better than any of the vegetable-based cutting fluid. This can be attributed to its superior cooling properties eliminating the adverse impact of higher cutting speed. The average tool life under synthetic oil application is noted to be 14.08 min.

4. CONCLUSIONS

The current experimental research work is presented to study the tool life concerning the performance attributes of vegetable-based cutting fluids and synthetic oil under a dry and minimum quantity lubrication environment. Experimental study and regression analysis based mathematical modeling are presented. The R^2 values of the entire machining environment are in good agreement with the experimental findings. Following conclusions are drawn based on the present research study:

- The tool life was found superior under the MQL application environment to that of the dry machining environment.
- The average tool life under the MQL environment is noted to be 6.73 min, whereas for the dry environment it was 1.83 min.
- Canola oil shows superior performance in the vegetable oil category.
- The overall comparison between vegetable-based cutting fluids and synthetic oil inferred the better significant performance of synthetic oil over other machining environments.
- The highest tool life under different machining environment noted as follows:
MQL machining environment- (a) canola oil-8.82 min (b) coconut oil-6.39 min
(c) soybean oil-5.53 min (d) synthetic oil-22.42 min
Dry machining environment-3.17 min.

Aspiring for environment-friendly machining; vegetable-based cutting fluids are needed to be evaluated at varying machining environments. The prospective research attributed to mixing of cutting fluids, the addition of nanoparticles or certain additives, and relevant research work could result in the superior performance of environment-friendly cutting fluids in comparison to traditional practices of mineral or synthetic based cutting fluid application.

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