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Research Article

Performing the optimization during hard turning of EN31 tool steel using eco-friendly cutting fluid under minimum quantity lubricant condition

Vaibhav CHANDRA[1,*], Praveen KUMAR[1], Varun KAUMAR PAL[1], Umesh KHANDEY[2]

[1]*Department of Tool and Production Engineering, Delhi Skill and Entrepreneurship University, New Delhi, 110077, India*
[2]*Department of Mechanical Engineering, National Institute of Advanced Manufacturing Technology, Ranchi, 834003, India*

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ABSTRACT

In current research work, several eco-friendly and biodegradable coolants were used such as distilled water, sunflower oil, and soyabean oil. These coolants along with dry run were implemented under minimum quantity lubrication (MQL) conditions to examine the machining performance of EN 31 tool steel under the hard turning condition. Therefore, the motive of the current work was to investigate the importance of environmentally friendly fluids such as sunflower oil, soyabean oil, and distilled water in order to prevent the metal cutting industry from using toxic and non-biodegradable cutting fluid. Additionally, examine the use of the MQL technique to reduce the amount of cutting fluids used in comparison to the conventional method of application. Nowadays, there is interest in using some vegetable oil in machining processes as a sustainable substitute for cutting oil made of minerals. Applying vegetable oil using the MQL method makes it more economical, sustainable, and environmentally friendly.
Sunflower oil was showed to be the most efficient cutting fluid among all of the others. It produces lowering cutting temperature among others coolants that are used under minimum quantity lubrication conditions. The experiments runs are based on the Central Composite Design having different input parametrs like cutting speed, depth of cut, and feed rate under different cutting environments. An ANOVA was also used to findout the dominancy of input parameters over output responses. Then, a regression-based model was also created for cutting temperature, during the validation it was found that the model was satisfactory with a 10% difference between prediction and actual value while conducting the validation test run. The desirability technique of response surface methodology was used to optimize the cutting temperature. An optimum condition of cutting temperature of 128 °Celsius was achieved by using the optimum machining settings, such as cutting speed of 125 m/min, depth of cut 0.5mm and feed rate of 0.15 mm/rev. In order to get insight into the features of tool wear under ideal circumstances, progressive tool wear was also evaluated at machining distances of 200 mm, 400 mm, and 800 mm using a stereo-zoom microscope. Around 80% of tool life was improved when compared with dry machining. The machining investigation of EN 31 tool steel under minimum quantity lubricant conditions while using various eco-friendly cutting fluids also assist in improving the tool life and machining efficiency. The cutting temperature was reduced up to 19%, 18%, and 17% for minimum quantity lubricant sunflower condition when compared with dry condition with the variation of cutting speed, feed, and depth of cut respectively.

***Corresponding author.**
*E-mail address: vaibhav.chandra@dseu.ac.in

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So this study promotes sustainability in the metal cutting industry and primarily focuses on ecofriendly fluid over synthetic or petroleum-based cutting fluids.

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INTRODUCTION

EN 31 Tool steel is a unique alloy that is often utilized in the production of dies, molds, etc. It is also employed in several other applications that call for qualities like high strength, high resistance to wear, and other attributes of a similar nature. It is a unique grade of technical material that is created when steel is subjected to several heat treatment procedures, such as quenching, annealing, and tempering. Hard turning is the method of directly machining steel pieces that have hardened, particularly those that have reached an HRC of greater than 45. In many situations, the hard turning technique exhibits significant advantages over the traditional production method. As a result, hard turning shows high attention to researchers and the manufacturing sector [1].

Nowadays EN 31 tool steel has extensive applications in tooling industries, such as in the manufacturing of forging dies, swaging dies, spinning tools, and beading rolls. Sometimes it is also used in making taps, gauges, etc. It also acts an important role in the making of injection molds, transfer molds, and compression molds used for plastic components. Such application makes EN 31 tool steel material very special.

A few benefits of hard turning include increased metal removal rate, cutting fluid elimination, energy savings, shorter machining times due to fewer heat treatments and grinding operations, inprove flexibility, and the capacity to produce intricate part geometries with tight tolerances in a single setup [2, 3].

The study investigates the effect of vegetable oil based MQL nozzle distance on cutting temperature while the turning of EN 31 tool steel. Further, ANOVA results reveal that cutting speed (68.44%) is the highly significant contributing factor, followed by nozzle distance (30.75%), highlighting their importance in controlling cutting temperature [4]. Table 1 displays the primary chemical constituents and Table 2 displays the mechanical properties of the selected workpiece [5, 6]. The classic Taguchi technique uses the S/N ratio to optimize the process parameters. However, it can only optimize a single response at a time and cannot optimize many responses at once. Therefore, the desirability approach is implemented to the current reseach work to optimize the multi-response variables.

Many researchers are now investigating the machinability behaviour of hard steel materials. Gupta et al. [7] developed indigenous carbon nano tubes coating to execute hard turning operation on EN 31 steel. They performed the optimization by using the Taguchi technique and ANOVA was used for data analysis. Mian et al. [8] inestigated that with the use of nano fluid assisted nearly dry turning, lower the surface roughness by 12% and 14% for EN8 and EN31 tool steel respectively, and lowerdown the cutting temperature by 7% for both the selected materials. Sen et al. [9] also performed some research experiments under MQL conditions, they used vegetable oil, nanoplatelets, and nanofluids as a cutting fluid and concluded that MQL provides better machining performance than other lubrication technology. Tuan et al. [10] performed the hard turning experiments under MQL as well as MQCL with use of nano cutting fluids and they found that MQCL shows promising results as compared to MQL in terms of surface quality due to good heat transfer capacity under MQCL cooling technique. The research work of Roy et al. [11] highlighted the work related to the chips study, surface topography, tool failure, while turning the AISI 4340 under novel pulsating MQL mode. Al_2O_3 coated tool is used to execute the hard turning operation. Tool wear (auxiliary and principal flank wear) was examined in thier study. Depth of cut and cutting speed are found to be dominating parameters for principal and

Table 1. EN 31 steel chemical compostion in wieght perentage [5]

Name of the Chemical	Percentage (%) by weight
Phosphorus (P)	0.04
Manganese (Mn)	0.30-0.75
Sulfur (S)	0.04
Carbon (C)	0.90-1.20
Chromium (Cr)	1.00-1.60
Silicon (Si)	0.10-0.35

Table 2. EN 31 steel mechanical properties with range value [6]

Mechanical Property	Range with units
Tensile strength	615 MPa
Hardness	40-45 HRC
Elastic modulus	197.37 GPa
Yield strength	528 MPa
Poisson's ratio	0.2

auxiliary flank wears. Das et al. [12] executed the study on MQL hard turning operation and they find out that with the use of nanofluid flank wear is reduces as compared to others cutting fluids. Zhao et al. [13] perfomed the turning operation on AISI 52100 and uses cBN tool with different edge radii of 40, 20, and 30 μm, they revealed that variations in edge radius can higly impacted on cutting force, tool life, and surface quality parameters. Karthik et al. [14] executed hard turning on EN 31 bearing steel, whose hardness is 60–62 HRC. They used cBN cutting tool and implemented Taguchi L_9 orthogonal design of the experiment along with ANOVA is used to find out the optimal value for output responses.

The lower surface roughness attained under optimum conditions which is 0.1492μm. Bartarya et al. [15] also perfomed the hard turning operation and used a cBN cutting insert to study the impact of tool wear on surface integrity. They found that when cutting speed increased and flank wear increased, stress profiles were less compressive, or more tensile. Thangarasu et al. [16] selected TiN coated carbide tool with ISO geometry as a CNMG 120408 grade and inspected tool wear while doing hard turning on EN 8 steel. They came to the assumption that the cutting force was frequently affected by the depth of cut and just slightly by the cutting speed. Alam et al. [17] applied the Taguchi DOE to analyze surface roughness and tool wear. They executed turning operation on EN 31 tool steel and found that the best combination for reducing tool wear is 60 m/min cutting speed, 0.10 mm/rev feed rate, and 0.50 mm deep cut. Allu et al. [18] employed a response surface optimizer to optimize the settings when machining AISI 52100 steel. The results showed that a wiper insert with a 1.2 mm nose radius, 0.05 mm/rev feed, 70 mm cutting speed, and 0.2 mm cutting depth would provide an optimal roughness of 1.69μm. The RSM and face centred central composite design (FCCD) based optimization was performed by Azizi et al. [19] and second order regression model was also constructed. The tool's radial vibration was discovered to be impacting the surface roughness throughout the hard turning process. Singh et al. [20] turned the EN 31 steel, they employed a dry and MQL cutting environment. Later, they used the TOPSIS approach to optimize the parameters and discovered that, when compared to other machining systems, less heat generation was observed during MQL conditions because of the excellent cooling and lubricating capabilities of the air-oil mixed jet directed towards the tool chip area.

Nas et al. [21] performed the combined approach of Taguchi with GRA to optimize the parameters, it was exposed that cutting tool wear decreased with increasing feed rate and that flank wear amplified with increased cutting speed. Elsadek et al. [22] demonstrated in their study that the workpiece hardness has the utmost influence on the cutting temperature. They implemented the Cuttlefish Algorithm to optimize the parameter when machining AISI H13. Deshpande et al. [23] assessed many eco-friendly cutting fluids to substitute with mineral oils that are used in industry. The study that a lesser number of vegetable oils had the potentials of good cutting fluids, including viscosity, thermal absorption capacity, and non-toxicity. Singh [24] used biodegradable cutting fluid and nanosolid lubricants to machined the materials which are considered to be difficult-to-cut materials, are utilized. The selected ecofriendly cutting fluids have a higher flash point, and high viscosity index, and bio-based oils are non-toxic and biodegradable in nature. Marichelvam et al. [25] established an eco-friendly cutting fluid by addition of HNO_3 in various amounts to neem seed oil and it can be used in turning operation on AISI Tool seel. They revealed that using the recommended cutting fluids lower down the flank wear up to by 30%. Gatade et al. [26] investigated the MQL based milling operation on SS304 workpiece material, they also found that under MQL conditions surface quality and tool wear rate was got upgraded. Likewise, Gupta et al. [27] MQL showed suitable results over dry and wet condition when EN 31 tool steel was turned. Singh et al. [28] focus on lowering the use of cutting fluids in terms of volume, they put an effort into other substitute cooling techniques like hybrid cooling, cryogenic cooling, and nominal lubricant used. Kumar et al. [29]. Performed the optimization and modeling while turning of AA6061 composite material. In their study feed parameter emerged to be the dominating parameter for surface value. Seeman et al. [30] find the effect of important input parameters on machining responses while machining Al/10%SiC Metal Matrix Composite.

Talvinder Singh et al. [31] achieved optimization and modeling process for cutting process while machining EN 31 tool steel. The optimum settings for the optimization are found to be 2% nanoparticle percentage, cutting speed of 600 rpm cutting, and depth of 0.1 mm under MQL condition

Kazeem et al. [32] examine the milling machining performance under palm kernel oil and conventional mineral oilm on the seleceted workpiece. They perfomed the milling operation on AISI 1081 steel under MQL method. Due to use of palm kernal oil, the cutting temperature is lower down which thereby results into the high tool life, stable machinability and further, surface roughness is also improved by 15% over the conventional oil. Adesusi et al. [33] studied machnaibilty, with the use of different vegetable based cutting fluid like Jatropha seeds oil, sed oil, and neem oil under MQL technique for carbon steel.

Ganesh et al. [34] observed the machining performance of Inconel 718 using eco-friendly nanofluid and found a significant improvement in cutting temperature by 34% 56%, and 32% and surface roughness by 45%,47%, and 38% in contrast to dry, flood, and MQL conditions Tazehkandi et al. [35] Performed the machining and observed that under the cryo-MQL eco-friendly condition, the cutting forces, tool wear rate, cutting zone temperature and residual stresses are reduced. Similarly, another study by Tazehkandi et al.

[36] was executed on clean turning operation. They performed the experiments under MQL conditions using PCD and PCBN cutting tools. The machinability was improved under MQL conditions for Inconel 686. Subramani et al. [37] optimize the machining parameters under minimum quantity lubricant machining using different vegetable oils (Calophyllum Inophyllum, Azadirachta Indica, and Ceiba Pentandra). The use of such cutting oils thereby results in enhancing the machining sustainability by reducing temperature, surface roughness, and cutting fluid usage. Ghuge et al. [38] examined the machnaibilty under MQL condiction using AISI 4130 steel using Blasocut oils, sunflower oil, coconut oil, soyabean oil and, groundnut oil. The feed of 0.35mmm/rev, 0.5mm depth of cut and 75.38m/min are the optimum condition.

According to the literature, it was concluded that a limited number of reseach work is conducted for dry and MQL turning of EN31 tool steel using soybean oil, sunflower oil, and distilled water. Therfore the potential of these eco friendly cutting fluids with regard to improve the machining performance is yet to expolored.

MATERIALS AND METHODS

The complete details of the experiments are mentioned in Table 3. To conduct the current reseach work , EN 31 steel having 48 HRC, dimension of 300mm length with 60 mm diameter is selected. Initially, the work material was soft and no hardness was induced in it. Now to induce hardness in the workpiece, some heat treatment processes were performed such as pre-heating at 550°C for 1.5 hours, hardening for 1050°C for 2 hours, followed by oil quenching, and then tempering at 250°C for 2 hours. After attaining the desired hardness of 48 HRC, all the experiment runs were conducted. The experiment was performed on conventional lathe machine, using various selected cutting fluids under minimum quality lubricant condition, having nozzle angle 45°, applied at 3 bar and at the rate of 200ml/hr and in dry condition using coated carbide TNMG 16040855, SK 15 grade insert.

The MJNL25X25 tool holder is utilized for the current work. The input parameters and their corresponding levels are shown in Table 3. The levels of process parameters are selected on the basis of various factors such as literature review, considering the physical nature of the workpiece and cutting insert, and other machining conditions. The experiments' strategy is based on the Central Composite Design, which is displayed in Table 4. There is an 8 mm turning length. Cutting temperature (T) produced at the tool-workpiece contact point in degrees Celsius (°C) and progressive tool chip contact area in μm^2 are measured with the help of a stereo zoom microscope. The actual images were captured and thereafter the images were processed with the customized software Toup View to measure the tool wear. Even the progressive tool wear is measured with the same stereo zoom microscope, a thermal image camera (Make Flir C5) was used to detect the cutting temperature during the conduction of experiments. Thermal Imager Flir C5 is a powerful and versatile camera that is designed to help professionals in various industries to detect accurate temperatures. The instrumemt is having high resolution thermal imaging sensor. Due to such a feature, the images of the real time machining were captured of all experiments and accordingly, the processing was done to find out the actual cutting temperature. The flowchart is also shown in Figure 1 to give the overall information about the sequencing of the current work in the form of a flowchart. Figure 2 showed the MQL based experimental setup and thermal image camera which is used to capture the cutting temperature.

RESULTS

Effects of Process Parameters

Following the completion of the experiments based on the CCD varying with selected input parametrs, the

Table 3. Overall details of machining experiments

Details	Parameters
Machine Tool.	Conventional lathe machine, Make (Panther 2050)
Cutting Insert	ISO Geometry- TNMG 16040855, Coated carbide, with SK 15 grade Insert.
Specification of tool holder	MJNL25×25 tool holder
Machining conditions	Dry machining
	MQL: Sunflower oil, nozzle angle 45°, applied at 3 bar and at the rate of 200 ml/hr
	MQL: Soyabean oil, nozzle angle 45°, applied at 3 bar and at the rate of 200ml/hr
	MQL: Distilled water, nozzle angle 45°, applied at 3 bar and at the rate of 200ml/hr
Feed rate (mm/rev)	0.1, 0.15, 0.2, 0.3, 0.4
Cutting Speed (m/min)	50, 75, 100, 125, 150
Depth of cut(mm)	0.25, 0.5, 0.75, 1.0, 1.25

Table 4. Central Composite Design for input parameters

S.No	Cutting Speed (s) in m/min	Feed Rate (f) in mm/rev	Depth of Cut (d) in mm
1	150	0.2	0.75
2	125	0.3	1
3	75	0.15	0.5
4	100	0.2	0.75
5	125	0.3	0.5
6	75	0.15	1
7	100	0.2	0.75
8	100	0.2	0.75
9	100	0.2	0.25
10	50	0.2	0.75
11	100	0.2	0.75
12	100	0.4	0.75
13	125	0.3	0.5
14	100	0.2	0.75
15	75	0.3	1
16	75	0.3	0.5
17	100	0.2	0.75
18	125	0.15	1
19	100	0.1	0.75
20	100	0.2	1.25

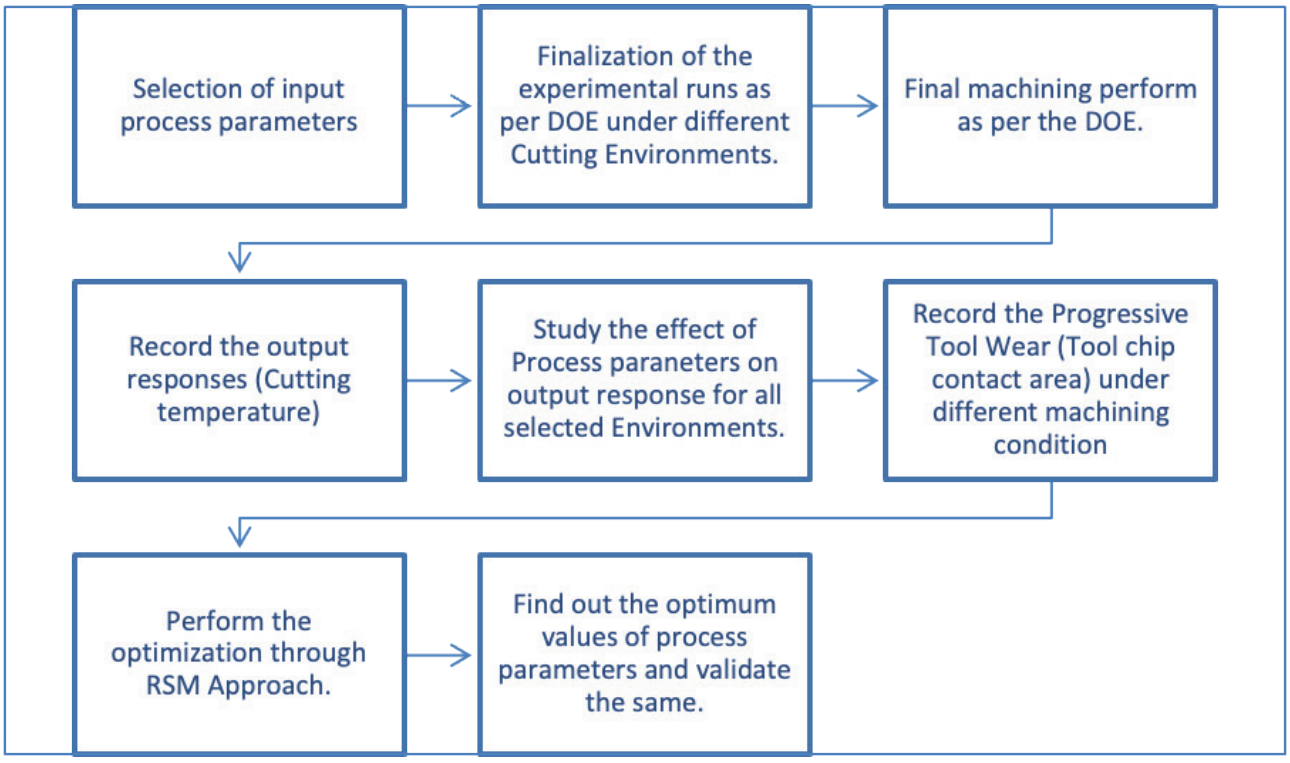


Figure 1. Flowchart for the overall experiments.

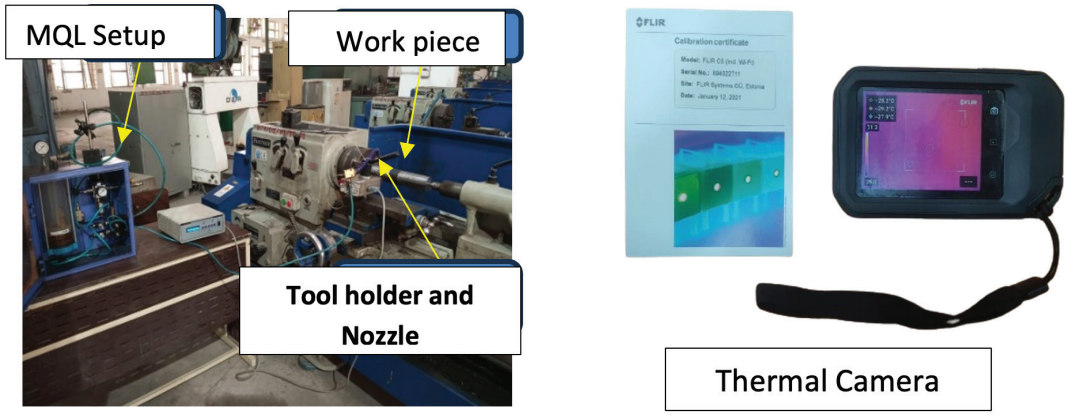


Figure 2. Experimental setup (MQL setup using sunflower oil as a cutting fluid) and thermal image camera.

recorded values of the output parameters were noted and shown in Table 5. Figure 3, Figure 4 and Figure 5 illustrate the trend of the cutting temperature with regard to variations of the input parameters such as cutting speed, feed rate, and depth of cut. According to Figure 3 the cutting temperature is increases in all the cutting environments with the increase in cutting speed. However, the increases in cutting temperature are found to be marginally increased except under dry machining. Around 66% of the increase was found under dry conditions for cutting temperature and 50% of the increase was found for MQL sunflower conditions. Under all the cutting environments, sunflower oil under MQL conditions shows a lower cutting temperature due to efficient cooling.

Table 5. Generation of cutting temperature under different cutting environment

Design of Experiments (DOE)				Generation of Cutting Temperature (T) in °Celsius.			
S.no.	**Cutting Speed (m/min)**	**Feed (mm/rev.)**	**Depth of Cut (mm)**	**MQL Soyabean oil**	**MQL Sunflower oil**	**MQL Distilled water**	**Dry run**
1	150	0.2	0.75	160	148	165	179
2	125	0.3	1	169	161	176	190
3	75	0.15	0.5	138	130	147	160
4	100	0.2	0.75	156	145	169	184
5	125	0.3	0.5	147	135	155	166
6	75	0.15	1	157	143	163	177
7	100	0.2	0.75	152	144	162	175
8	100	0.2	0.75	151	143	160	173
9	100	0.2	0.25	134	120	143	159
10	50	0.2	0.75	154	142	167	181
11	100	0.2	0.75	160	147	171	185
12	100	0.4	0.75	168	155	176	190
13	125	0.3	0.5	150	138	160	175
14	100	0.2	0.75	160	148	173	188
15	75	0.3	1	162	154	173	187
16	75	0.3	0.5	152	141	164	177
17	100	0.2	0.75	156	146	166	179
18	125	0.15	1	155	145	167	180
19	100	0.1	0.75	142	131	153	165
20	100	0.2	1.25	164	153	175	189

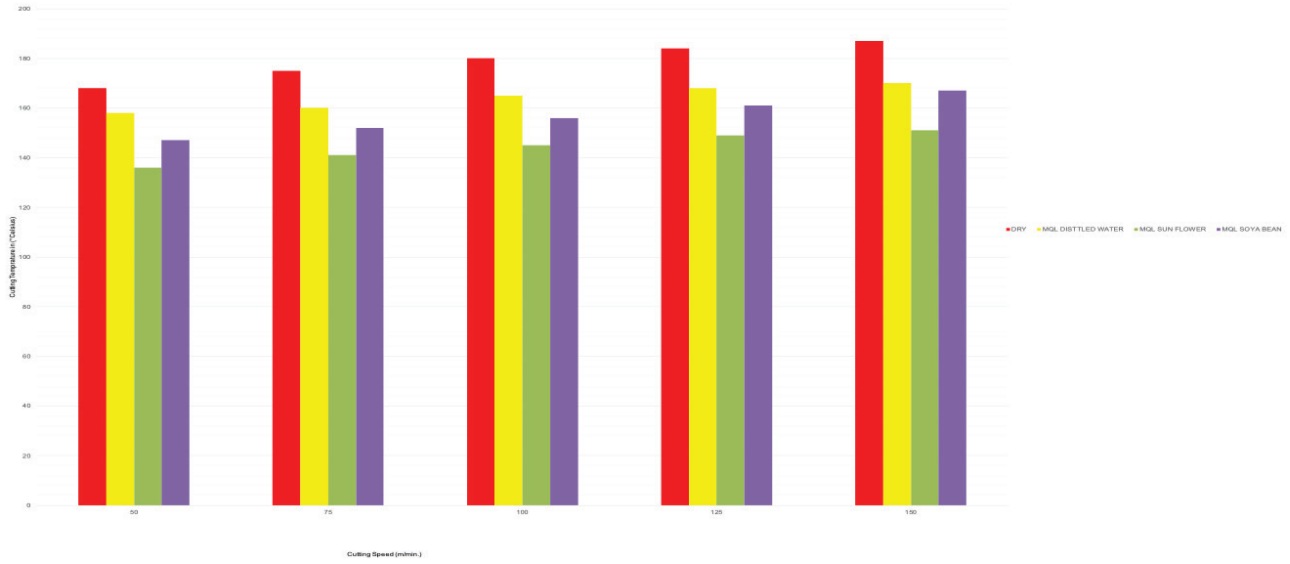


Figure 3. Variation of cutting speed under different environments for evaluation of cutting temperature at feed (f) 0.2mm/rev. and depth of cut(t) 0.75mm.

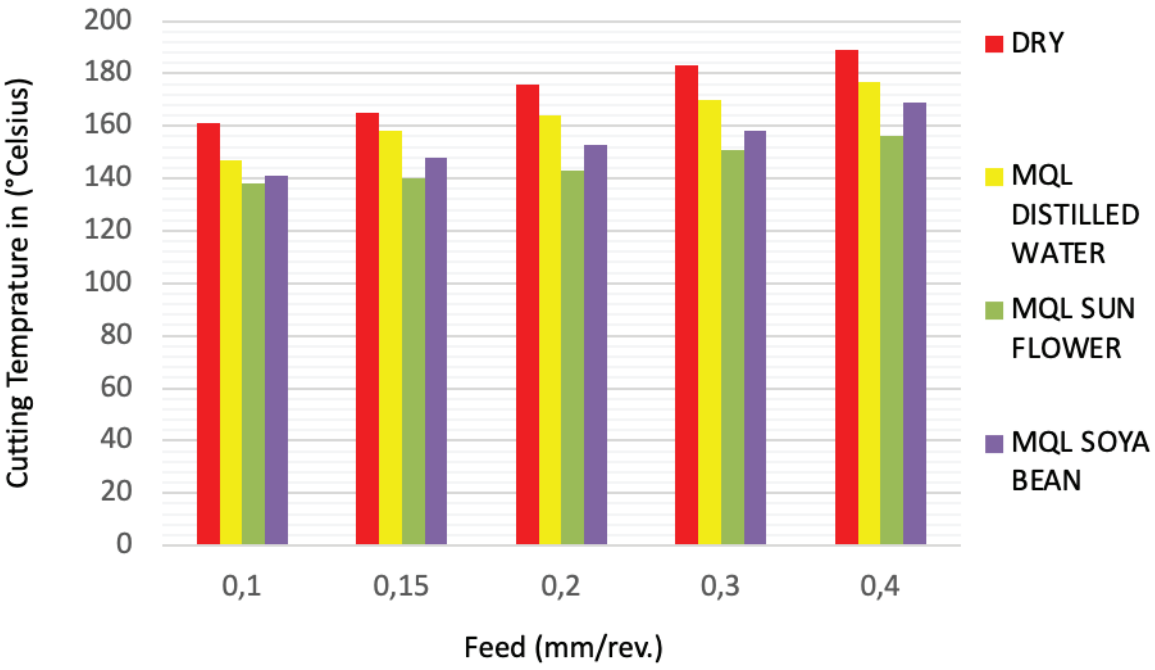


Figure 4. Variation of feed under different environments for evaluation of cutting temperature at cutting speed 100mm/min and depth of cut(t) 0.75mm.

This may be because the cutting fluid mist of sunflower oil discharged from the nozzle of MQL setup reaches the tool rake face by lifting the chips which in turn decreases the tool chip contact area and thereby decreases the friction between the chip and tool rake surface. Due to these phenomena, the generation of cutting temperatures is reduced. Similarly, Figure 4 shows the generation of cutting temperature at the cutting speed as 100 m/min with a depth of cut of 0.75 mm and with the feed rate variation.

It was concluded that the low cutting temperature was recorded for sunflower oil when it was used under MQL conditions at high pressure. Figure 5 shows the cutting speed as 100 m/min with a feed rate of 0.2 mm/rev throughout the depth of cut variation. Among the

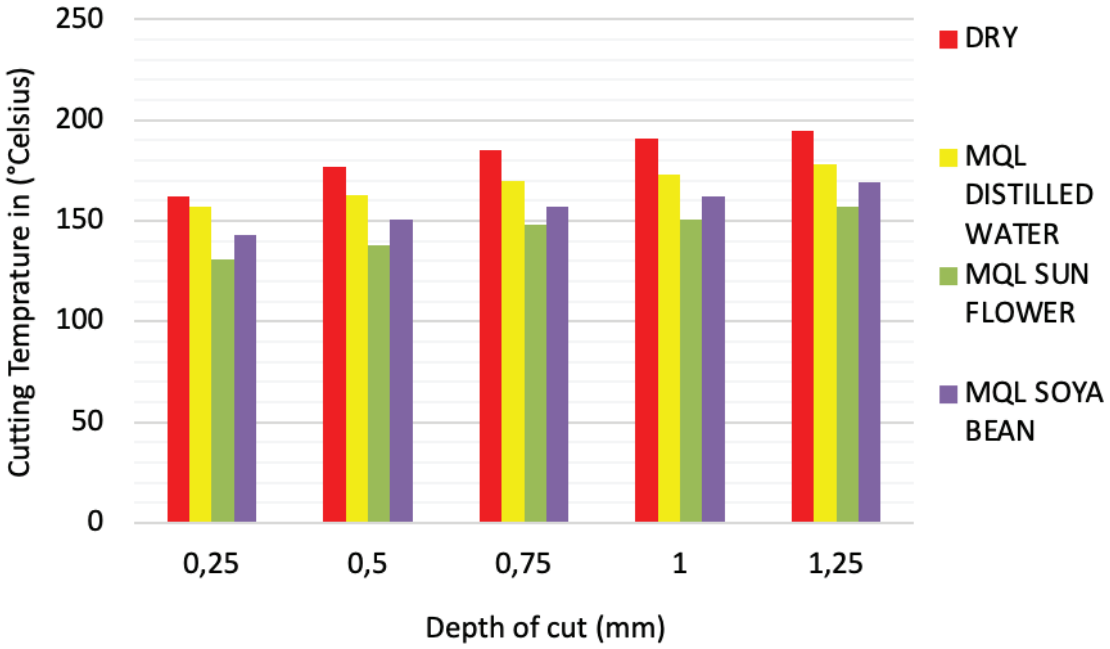


Figure 5. Variation of depth of cut under different environments for evaluation of cutting temperature at cutting speed 100m/min and feed(f) 0.2mm/rev.

selected environmentally friendly cutting fluids, sunflower oil under MQL conditions was shown to be the most effective. Heat is produced at the primary deformation zone during machining as a result of shear and plastic distortion. The temperature rises as a result of friction between the tool and the job. In MQL method, finer droplets of lubricant provide a larger surface area, due to which enhancment of heat transfer and reduction of cutting temperature results. However, the extent of this effect depends on droplet evaporation, lubricant properties, and other cutting conditions as well. Compared to oil made from minerals, sunflower oil has a greater viscosity index. At higher temperatures, a high viscosity index indicates improved performance. As the cutting temperature rises, the viscosity of sunflower oil reduces more gradually than that of petroleum based oil.

Progressive Tool Wear

Progressive tool wear was evaluated using stereo zoom microscope in terms of tool chip contact area at regular intervals of machining length during each test for all the selected cutting environments. Figure 6 shows the measured value of tool chip contact length measured to 800 mm of machining length. Due to the penetration of cutting fluid in the form of mist at the tool chip interface, there is effective cooling and lubrication which results in reduction of the friction force. Accordingly, the cutting temperature is also reduced which thereby results into low wear of cutting insert. However, under dry conditions, the cutting edge of the tool is blunt at 400 mm machining length. And tool under sunflower oil showed good results in terms of chip tool contact area. Some of the tool wear images of the coated tool under different cutting conditions at various machining lengths are shown in Figure 7 and Figure 8.

Figure 8 shows the cutting insert's blunt state when the tool's chip contact area value reached 817090.90 μm^2. As per the Figure 6, tool chip contact area value enlarged to a maximum of 1015008.79 μm^2 when machining with distilled water under the influence of MQL up to the length of 800 mm and tool became blunt eventually. In contrast, the lowest tool chip contact area value of 174402.77 μm^2 was discovered when machining was done with sunflower oil under the influence of MQL. The graph validates that machining in a dry condition originally produces unfavorable results and ultimately becomes blunt up to a 400 mm machining length. However, machining up to 800 mm causes an extreme change in tool wear that is detected with distilled water under the influence of MQL. When machined up to a length of 800 mm, sunflower oil had the lowest tool-chip contact area (174402 μm^2) among all cutting fluids.

Regression Modelling of Cutting Temperature Using RSM for Improved Cutting Environment (Sunflower)

To developed the predictive model of the slected output responses, RSM techinique is used and implemented on the recorded expermnetal results. Further for perfoming

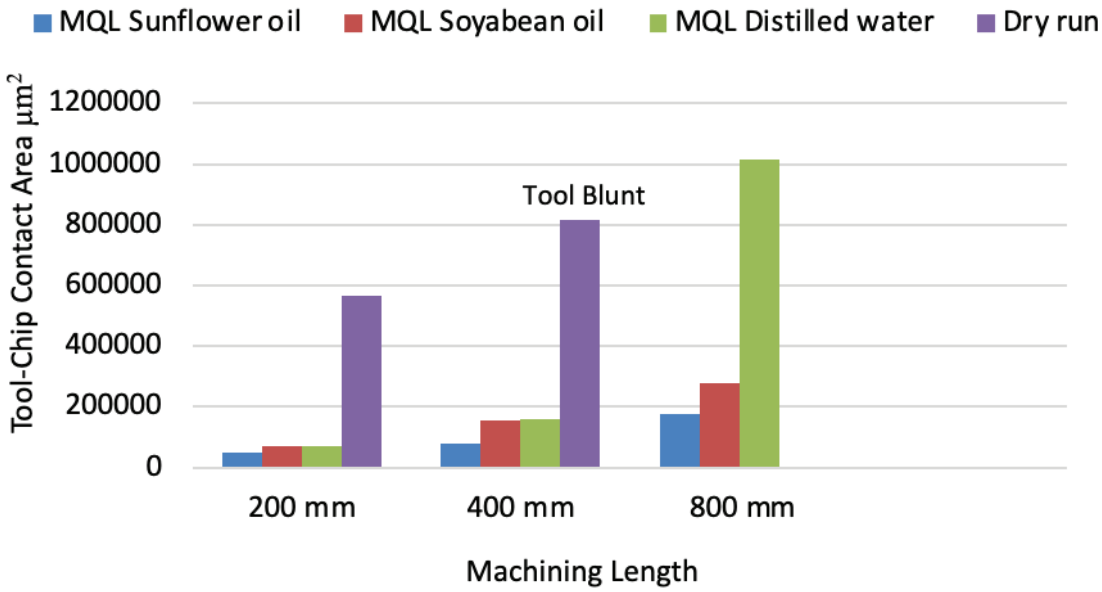
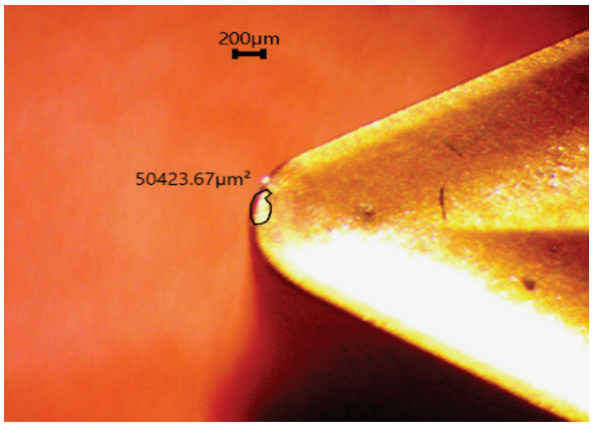
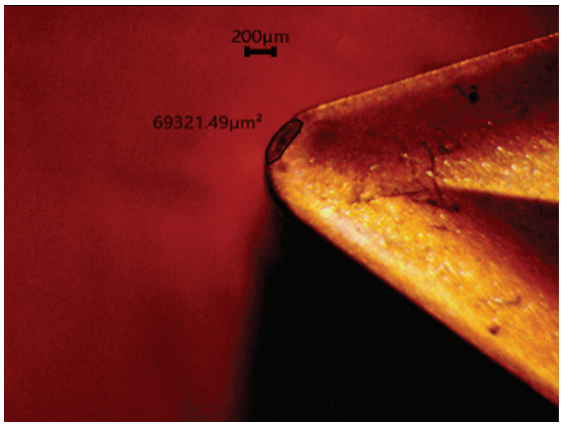


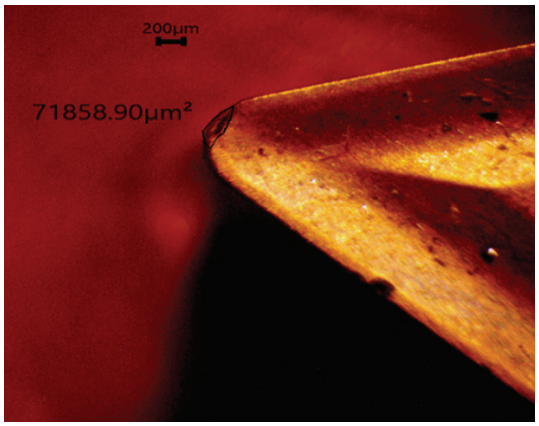
Figure 6. Tool-chip contact area vs. machining length under various cutting environments: cutting speed 75 m/min, DOC 1 mm, feed 0.2 mm/rev.



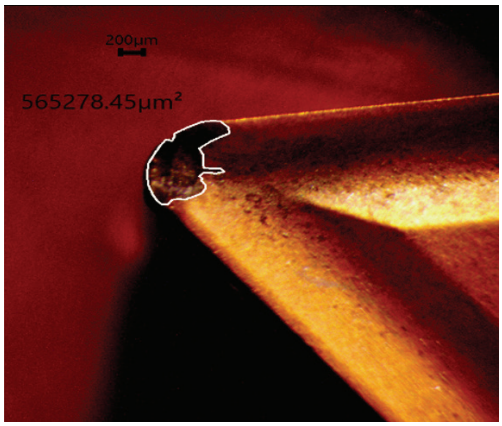
MQL Sunflower oil



MQL Soyabean oil



MQL Distilled water



Dry Run

Figure 7. Progressive wear of EN 31 tool steel material at cutting length 200mm, feed rate 0.2mm/rev, depth of cut 1mm and cutting speed 75m/min.

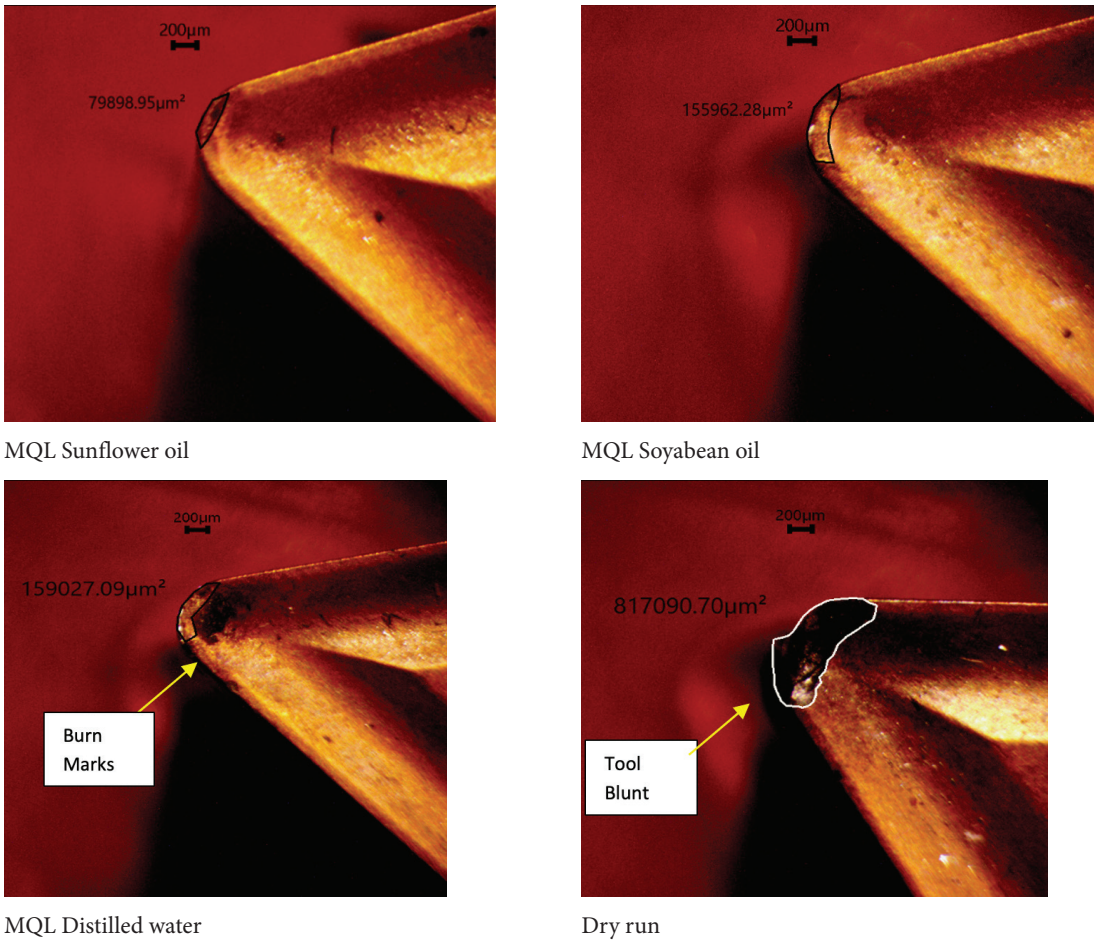


Figure 8. Progressive wear of EN 31 tool steel material at cutting length 800mm, feed rate 0.2mm/rev., depth of cut 1mm and cutting speed 75m/min.

the optimization these models would be of great use. The experimental results obtained were used by response surface methodology (RSM) to develop these mathematical models. A commercially available software namely Design Expert has been used to calculate the constants and other desired parameters of the regression modeling. Cutting temperature also helps in understanding the machinability of the material. The cutting temperature is influenced by a large number of machining parameters such as cutting speed, feed, and depth of cut. So, there is a need to investigate the combined effect of the cutting conditions during the machining of EN 31 tool steel under different cutting environments. The most favorable cutting environment was found to be sunflower oil as a coolant. A regression-based model for cutting temperature has been developed using the experimental results for the improved cutting environment (Sunflower oil). A quadratic-based model for cutting temperature has been developed which is as under.

$$\begin{aligned} Cutting\ Temperature = {} & 94.761 - 0.134\ x\ Cutting\ speed \\ & + 169.79\ x\ Feed\ rate + 43.279\ x\ Depth\ of\ cut - 0.068 \\ & x\ Cutting\ speed\ x\ feed\ rate + 0.336\ x\ Cutting\ speed \\ & x\ depth\ of\ cut + 61.618\ x\ Feed\ rate\ x\ Depth\ of\ cut \\ & - 0.0003\ x\ Cutting\ speed.^2 - 281.32\ x\ Feed\ rate.^2 \\ & - 37.527\ x\ Depth\ of\ cut.^2 \end{aligned} \quad (1)$$

The multiple regression coefficient, R^2 of the second order model is estimated at 0.9672. ANOVA analysis is shown in Table 6. The model for cutting temperature under sunflower oil condition has been found to be significant as the p-value is less than 0.05, considering at 95% confidence level. From ANOVA it can also be concluded that individual effect of feed rate and depth of cut is found to be most signifcant for cuttimg temperature as it has the lowest p-value <0.05 (Highest F-ratio value).

With the use of design expert software 3D graphs was created to study the effect of input parameters on output response. The 3D graphs are shown at Figure 9. It is evident that, in the three-dimensional graph, as cutting speed increases, so does cutting temperature but at very

Table 6. ANOVA for cutting temperature (under Sunflower oil condition)

Source	Sum of Squares	df	Mean Square	F-value	p-value	Model
Model	1649.08	9	183.23	32.80	<0.0001	significant
A-Cutting Speed	9.76	1	9.76	1.75	0.2157	
B-Feed	477.12	1	477.12	85.41	<0.0001	
C-Depth of Cut	1124.48	1	1124.48	201.29	<0.0001	
AB	0.1299	1	0.1299	0.0232	0.8819	
AC	29.57	1	29.57	5.29	0.0442	
BC	10.41	1	10.41	1.86	0.2022	
A^2	1.21	1	1.21	0.2158	0.6522	
B^2	54.23	1	54.23	9.71	0.0110	
C^2	136.44	1	136.44	24.42	0.0006	
Residual	55.87	10	5.59			
Lack of Fit	33.87	4	8.47	2.31	0.1721	Not significant
Pure Error	22.00	6	3.67			
Cor Total	1704.95	19				

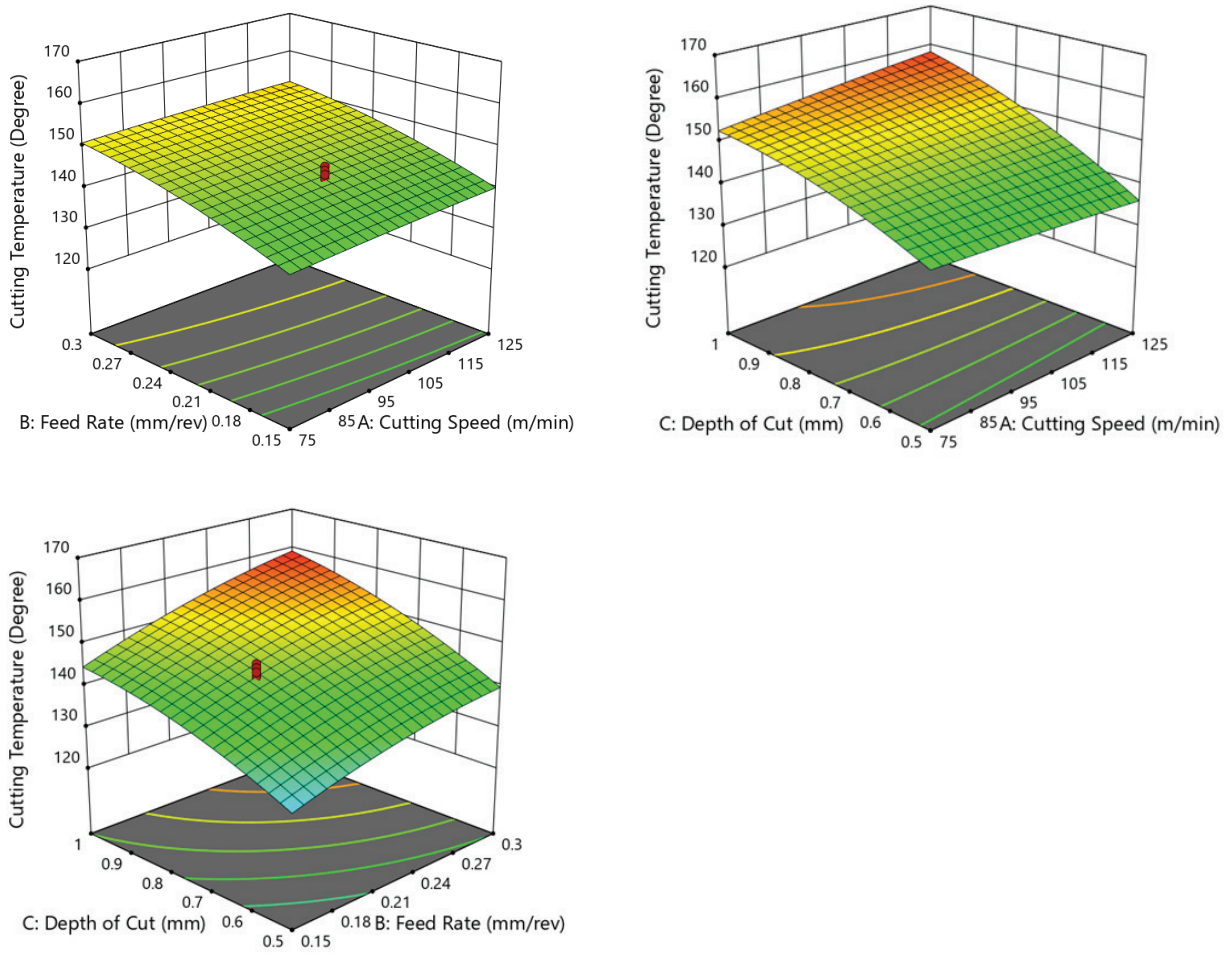


Figure 9. 3D Graphs to see the effects of process parametrs.

marignally scale. Similarly, when feed rate and depth of cut incrases the cutting temperature also increases with very high rate, further, compared to cutting speed, the feed rate and depth of cut is a more dominanat.

Optimization Using the Desirability Function

With the help of design expert 12 software optimization of cutting temperature is performed.

The desirability based optimization using RSM indentied the optimal machining condition such as depth of cut of 0.5 mm, feed of 0.15mm/rev and cutting speed of 125 m/min, and the optimum values for cutting temperature is 128 °C with desirability value of 1 as shown at Figure 10 and Figure 11. The optimum results are validated with the actual experiments which shows the percentage of error

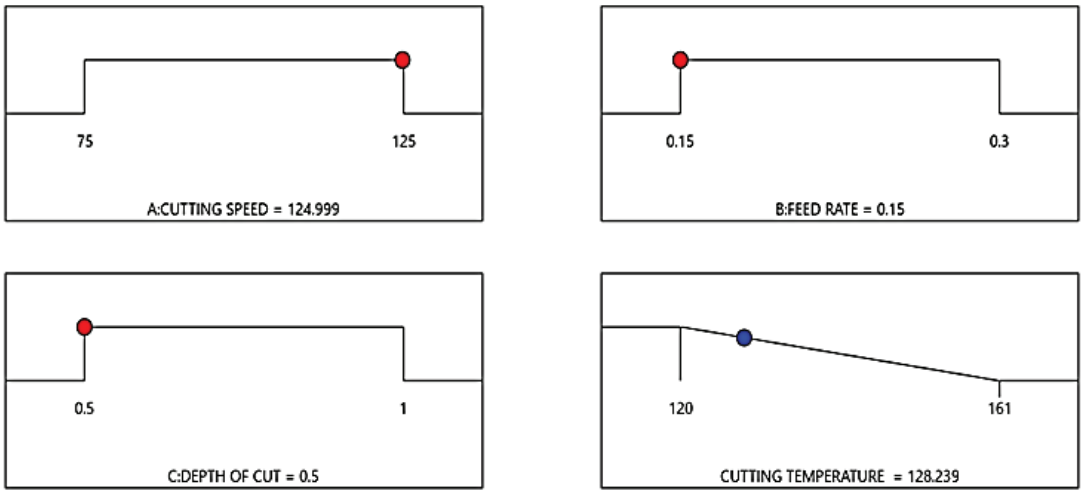


Figure 10. Ramp graph showing desirability for cutting temperature where input parameters are cutting feed, speed and depth of cut.

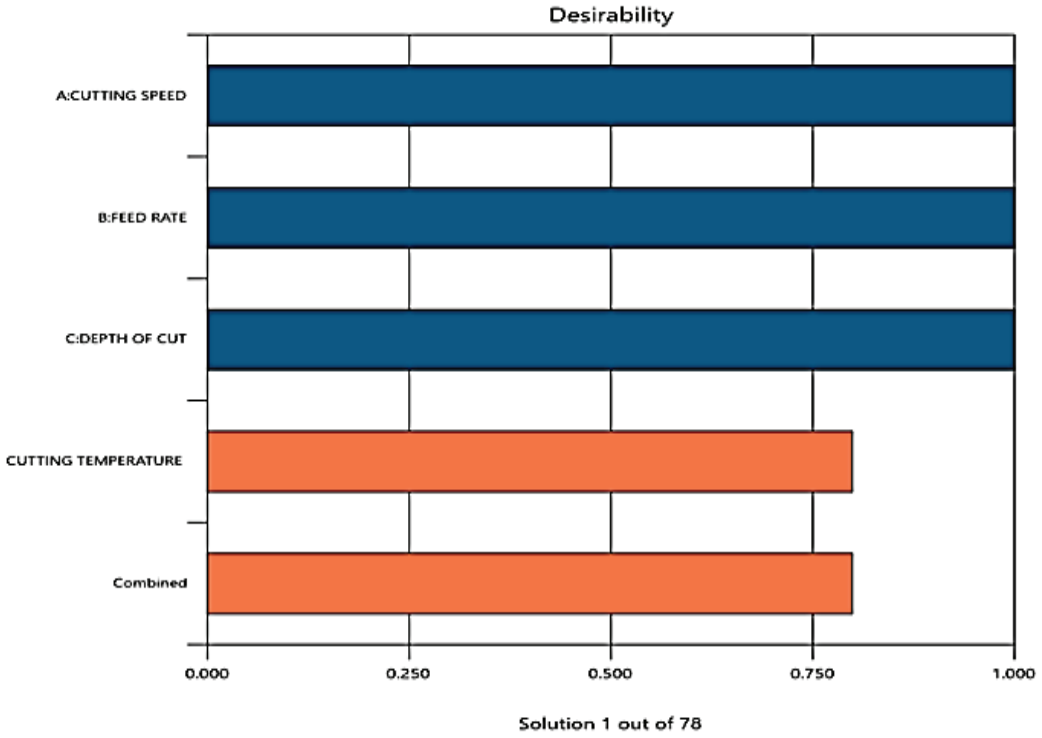


Figure 11. Bar graph illustrating the desirability values for cutting temperature.

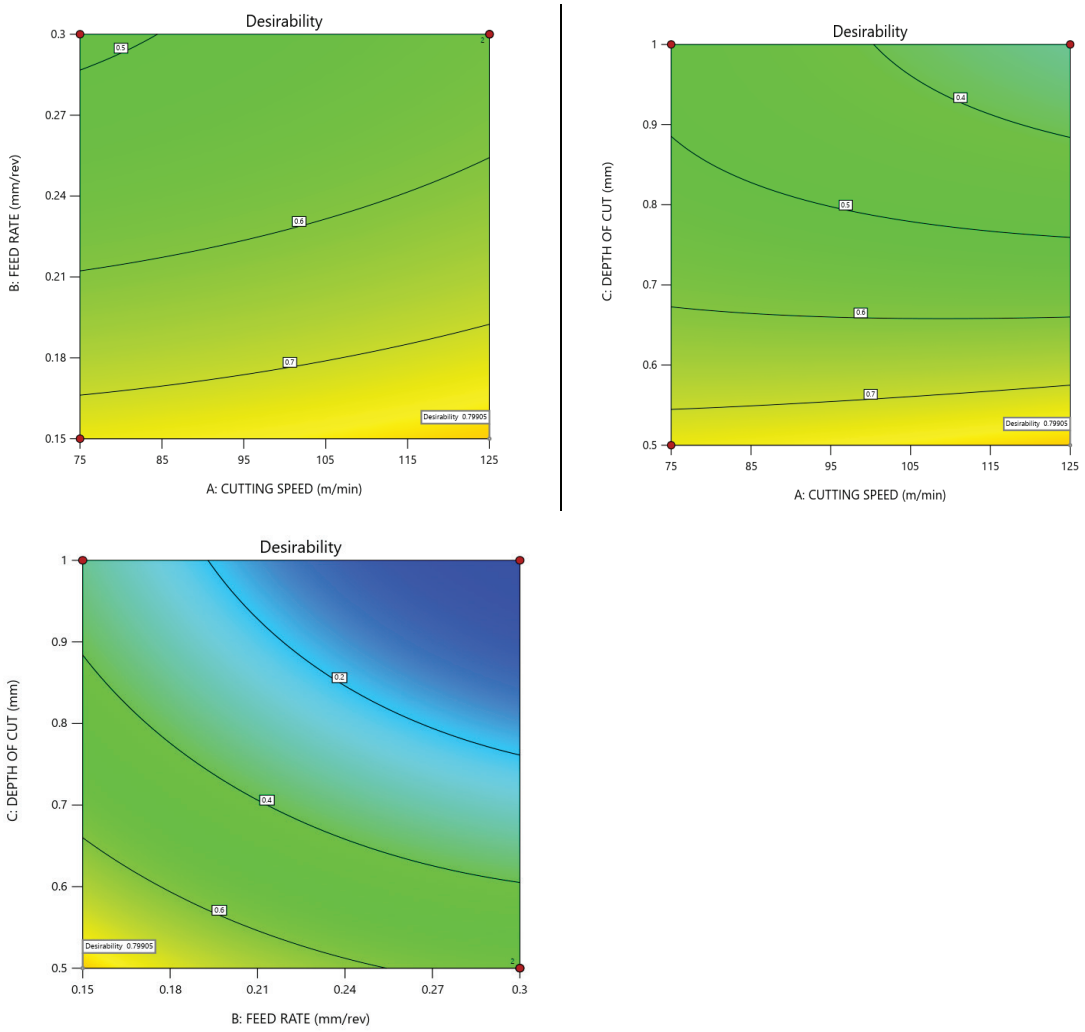


Figure 12. Graph between Cutting speed, Feed rate and depth of cut for desirability.

with in less than 10%. Figure 12 shows the desirability graphs with different rate of process parameters.

CONCLUSION

The current paper implemented the Response Surface Methodology to analysis of the factors related to cutting temperature and their optimization with the help of design expert software. The primary takeaway drawn from the present investigation is that promising results can be obtained under minimum quantity lubricant conditions when eco-friendly cutting fluid is used. Moreover, using environmentally friendly sunflower oil cutting fluid improves overall machinability. Such a study may also help to replace the harmful coolants that have adverse effects on the environment and are tough to dispose of with alternative eco-friendly cutting fluid °C such as sunflower oil, etc. As per the results some conclusions are made.

1. The implementation of the minimum quantity lubricant technique showed promising results for the generation of cutting temperature for all the selected cutting environments. The reduction in cutting temperature was found in the range of 15% to 20% under minimum quantity lubricant conditions. With high pressure generated in minimum quantity lubricant technique thereby results in the cutting fluid to reach upto the main primary zone and therefore effective cooling was done. A similar trend of results was also found in existing literature.
2. Among all the selected environments, minimum quantity lubricant under sunflower cutting conditions showed better results for the generation of cutting temperature. The average temperature was reduced up to 19%, 18%, and 17% for minimum quantity lubricant while using sunflower oil, when compared with dry conditions respectively with the variation of input parameters. This is due to the physical properties of

selected cutting fluids such as oxidation stability, viscosity, lubricity, and melting point are reported low values as compared to conventional fluids. The literature also confirms that cutting fluids using vegetable oils generated low cutting forces during machining.

3. Lesser progressive tool wear rate was observed under minimum quantity lubricant condition while using sunflower oil as a coolant. Around 80% tool life was improved when compared with dry machining.
4. With the application of minimum quantity lubricant method and with the use of ecofriendly cutting fluid (Sunflower oil) is one of the good option for promoting the sustainable machining solution which save the large volume of toxic cutting fluid. Further study also examine the comparison of machining performance for other ecofriendly cutting fluid.
5. Under dry machining, the tool cutting edge got completely blunt at 400 mm of machining length. It is due to generation of extremely high cutting temperature at the main shear zone. Such heat exposure to the tool cutting edge causes excessive tool wear and weakens the cutting edge.
6. At higher cutting speed cutting temperature also increasing and found out to be the most dominating factor.
7. It was observed that cutting speed = 125 m/min., feed = 0.15 mm, and depth of cut = 0.5 mm were the optimum factors and the optimum value for cutting temperature is 128 °Celsius with desirability of 1.
8. The multiple regression coefficient, R^2 of the second order model is estimated at 0.9672. According to the ANOVA analysis. The model for the cutting temperature under sunflower oil condition found to be significant as the P value is less than 0.05, considering at 95% confidence level. From the ANOVA is observed that feed rate and depth of cut is found to be most significant for cutting temperature as it has the lowest P-value < 0.05 (Highest F-ratio value).
9. Regression based second order model found to be suitable and same model have been validated for cutting temperature. The variation between predicted and experimental value is observed less than 10 %. Such model can be used to predict the output response without performing the actual experiments.

Future Scope of Work and Some Limitations

The current paper also highlights various gaps, areas for future research, and solutions to improve modern eco friendly machining.

1. Exploring other Eco-Friendly cutting fluids: In order to find out the working efficiency, the studies can be counducted under various machining situations, these studies can be extended to various bio-degradable cuuting fluids like castor oil, neem oil, or coconut oil.
2. Some more studies can be executed to investigate the effects of eco-friendly cutting fluids on surface integrity, including surface roughness, microhardness, and residual stresses.
3. To increase productivity the use of machine learning models could be done and explored optimize parameters and forecast machining results.
4. Some more extended versions of the tool wear study can be explored under different cutting fluids that are sustainable in nature.
5. Future studies may be explored to enhanced ecofriendly cutting fluids to improve lubrication and thermal conductivity. The current study is limited to narrow range of cutting fluids and process parameters, and a restricted only to tool wear investigation.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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