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Analysis of Surface Roughness, Cutting Force and Cutting Fluid Consumption in Turning Operation with and Without Use of Cutting Fluid Optimizer

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Abstract

In the present work, cutting fluid consumption, surface roughness, component of forces and tool temperature were analyzed with and without online regulation cutting fluid. Cutting Fluid Optimizer (CFO) is a device that automatically regulates the supply of cutting fluid based on the temperature of the tool tip generated during the machining. Taguchi orthogonal L9 is employed for design of experiments using MINITAB-21. Every experiment was conducted on mild steel work material with use of a tungsten carbide tool insert on the conventional lathe. The best parameter is determined via grey relational analysis. Optimal condition of regulation of coolant with the Cutting Fluid Optimizer (CFO) and non-regulation of coolant with the cutting fluid optimizer are compared. Minimum surface roughness, machining forces, tool–work piece temperature was recorded in case of non-regulation of cutting fluid with the CFO at the cost of the consuming large amount cutting fluid. However, regulation of cutting fluid with the CFO was able to reduce coolant consumption by 15.3% but significantly resulting 3.3 % increase in component of forces, surface roughness and tool-work piece temperature.

Keywords: Coolant Regulation, Cutting Fluid Optimizer, Grey Relational Analysis, Taguchi

1.0 Introduction

Heat is produced at the tool-chip contact during metal-cutting processes as a result of friction. The heat produced during the operation of machining has an effect on dimensional precision, surface polish, cost of machining and tool life[1]. Various strategies have been employed to reduce this heat. In the beginning, water was employed as a medium for cooling, however this causes problems including the corrosion-related degradation of materials. Technology innovation has led to the development of new lubricating and cooling methods. The most popular technique for lubrication and cooling in commercial applications has been wet cooling. These techniques involve the recirculation of cutting fluid with a rate of flow up to 4–10 L/min[2-3]. Different cutting fluids and cooling techniques exist due to the several metal-cutting procedures. Cutting fluids are used as coolants to possibly lubricate and lower the temperature at the tool-to-chip contact. Along with improving machining efficiency, cutting fluids aid in chiph flushing. However, the use of typical metal working fluids causes some technical and environmental issues like pollution, health issues for workers, water contamination, and so on. Furthermore, cutting fluids has direct impact on overall manufacturing cost[4-6]. To address the previously stated issues, investigators are investigating several substitutes for standard cutting fluids. Other options include of use

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of high pressure coolants and dry cutting, coatings for tools, Lubricant with a minimum quantity (MQL), cutting fluids made from vegetable oils, and so on. Because cutting tool materials are developing so quickly, use of dry machining has attracted considerable interest in the realm of green manufacturing[7-9]. It loses its effectiveness, however, when increased machine productivity, improved surface quality, and harsh cutting circumstances are necessary. In this instances, MQL is a viable option, as it delivers a tiny amount of cutting lubricant at a high pressure via the nozzle over chip-tool interface region[10]. The combination of soluble oil and compressed air lessens cutting zone temperature and, to some extent, extends tool life[11]. MQL uses only 0.05% of the quantity of cutting lubrication required in wet machining, saving money on lubricant, recycling, and filtration, resulting in economic benefits[10-12]. The primary drawback, however, is the expensive expense of these cutting fluid supply systems. Khan and Dhar[11] examined the influence of MQL on tool wear, cutting temperature, dimensional deviation, and surface roughness in AISI 1060 steel turning. By comparing to dry machining, MQL lowered tool wear, cutting temperature surface roughness. A decrease in average cutting temperature of approximately 5% to 12% was observed when utilizing Minimum Quantity Lubrication (MQL) with vegetable oil compared to dry machining. The extent of this reduction depended on the levels of process parameters such as cutting speed and feed rate. Additionally, cutting forces experienced a reduction of about 5% to 15% when employing MQL with vegetable oil.

Haddad and Sadeghi[12]examined the impact of various cooling states on surface roughness and cutting forces in the turning of AISI 4140 alloy. They found that the two procedures (machining using the MQL technique and machining using flood cutting fluid) differ somewhat in cutting forces and surface roughness. As a result, cutting fluid consumption can be reduced.

Sreejith[9] researched the influence of lubrication conditions such as machining with minimum cutting fluid, dry machining, and machining utilizing flooding of coolant at the different parameters of aluminum alloy 6061. The findings reveal that while machining at higher cutting speeds, it is feasible to utilize very little coolant or even work in a dry machining state.

Zhang *et al*[13] investigated differences in cutting force and tool life while machining Inconel 718 in dry machining and minimal cutting fluid state. Their goal was to decrease or eliminate the use of cutting fluids to minimize environmental effect and expenses. The results demonstrate that in some circumstances, the cutting fluid cannot be entirely removed because there is insufficient cooling capacity in the air. Although it has been observed that utilizing biodegradable vegetable oil in MQL state may greatly increase machinability, such as tool life extension and cutting force reduction.

Sarikaya and Gullu[14] investigated the impact of machining settings on surface finish in AISI 1050 turning using the Taguchi technique and response surface approach. They discovered that the most beneficial criteria on surface finish are feed rate and cooling condition.

Devillez *et al*.[15] investigated the dry turning of Inconel 718 utilizing a coated and uncoated carbide tool. Their research found that applying a coating on carbide tools can remove the need for cutting fluid and reduce cutting forces when compared to using an uncoated tool with a flooding of cutting fluid. Furthermore, even while turning Inconel 718 in dry mode, tool wear may be managed, and tool coating can extend tool life.

Devillez *et al*.[16] studied the Inconel 718's surface quality during the turning operation. The primary goal of their research was to eliminate the coolant from the Inconel 718 turning process and analyses the impact of this elimination on the work piece's surface polish. The study's results indicated that removing coolant during the machining of Inconel 718 utilizing a coated carbide tool had no impact on the surface finish, similar to using the flooding of coolant application. This suggests that an acceptable surface finish can be achieved without the use of coolant after machining Inconel 718.

Xavior and Adithan[17] examined how different cutting fluids affect tool wear and surface roughness when turning AISI 304 stainless steel using carbide tools. The study compared three fluids: plain mineral oil, coconut oil, and an emulsion. The results indicated that coconut oil outperformed both plain oil and emulsion in terms of reducing wear and improving surface roughness.

Garca *et al*.[18] investigated how cutting settings and tool coating influences surface residual stresses created by turning of AISI 4340 steel. The results showed that when

the cutting temperature increased, the residual stresses grew more tensile, causing damage to the work piece's surface. In order to produce a superior surface polish, they recommended a lesser feed rate, a higher cutting speed, and non-coated tools with a reduced tool nose radius.

Garca *et al.*[19] investigated how cutting settings and tool coating influences surface residual stresses created by turning of AISI 4340 steel. The results showed that when the cutting temperature increased, the residual stresses grew more tensile, causing damage to the work piece's surface. In order to produce a superior surface polish, they recommended a lesser feed rate, a higher cutting speed, and non-coated tools with a reduced tool nose radius.

Ozcelik[20] conducted experimental research comparing the performance of canola and sunflower oil-based coolants with different percentages (8% and 12%) of extreme pressure additive, as well as two commercially available cutting fluids (semisynthetic and mineral-based), during the turning process of AISI 304L stainless steel. The study focused on evaluating various factors such as surface roughness, cutting force, feed force, and tool wear. Additionally, the experiments also included a dry cutting condition, which resulted in rapid tool wear and breakage. The tool life for dry cutting was below 200 seconds, while for semisynthetic cutting fluids, it was less than 1,000 seconds, and for mineral-based cutting fluids, it was less than 2,000 seconds.

According to literature survey it is found that online regulation of cutting fluid with the help of temperature generated during the machining is still least explored area and less effort has been done to regulate the supply of coolant during machining based on the machining temperature as the feedback control.

In the current study machining parameters were optimized in order to investigate the cutting fluid consumption, surface roughness, cutting forces and tool temperature. For design of experiment Taguchi orthogonal L9 array was used. Synthetic cutting oil was utilized as cutting fluid. The operational factors include cutting speed, depth of cut, air pressure and lubrication environments (regulation of cutting fluid with the CFO and non-regulation of cutting fluid with the CFO) were taken into account as the experimentation parameters. The experimentation was done on mild steel. Work material utilizing carbide tool insert on conventional lathe machine.

2.0 Experimentation

The experiments have been conducted on a standard Duo lathe (Duo Machine Corps, Rajkot, India) as shown in Figure 1. A cylindrical rod of mild steel 60 mm in diameter and of length 300 mm was utilized as material for work piece. WIDIA's tungsten carbide inserts (CCMT09T308-MRT2) were employed as a material for cutting tool that was mechanically fastened to the tool holder. The piezoelectric Kistler dynamometer (9257B) was utilized to measure the component of cutting forces. It includes a Type 5697A1 charge amplifier with hardware for data gathering and the Dyno Ware software (3.1.2.0) for operating and storing the average cutting force value. An instrument made by Mitutoyo, the SJ210 surface roughness tester, was utilized to measure the mean surface roughness (Ra). It comprises of a probe with a 2 μm radius diamond tip that explores the work piece. 0.08 mm is the cut off length, 0.25 mm/s is the measuring speed, and probe retraction speed is 1mm/s. The temperature was measured with a K-type thermocouple, one end of which was fixed in a carbide insert and the other end was connected to National Instruments' data gathering system, which captured the cutting temperature. The coolant is supplied under two conditions: regulation of cutting fluid with the CFO and non-regulation of cutting fluid with the CFO. Synthetic oil is used as the coolant during the experimental study.

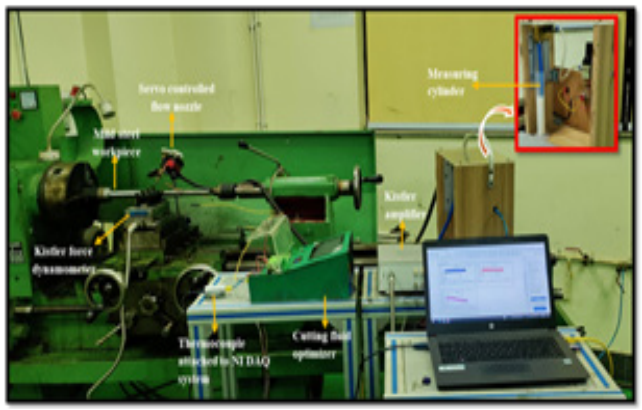


Figure 1. Experimental setup with cutting fluid optimizer and dynamometer

Table 1. Machining parameters and their level

Parameters Cutting velocity (m/min)	L 1 40	L 2 80	L 3 120
Depth of cut (mm)	0.25	0.50	0.75
Air pressure (bar)	2	3	4

Utilizing MINITAB-21 and the Taguchi design L9 technique, the experiment's design was created with three elements at three distinct levels, namely depth of cut, cutting velocity, and air pressure, as shown in Table 1. All nine of the combinations that produce the best outcomes for the response parameters are listed in Table 2.

2.1 Design of Experiments

In this current work, experiments are designed employing Taguchi's orthogonal L9, because Taguchi's is a useful tool for robust design and it focuses on a straight forward and methodical approach to enhance design for cost, quality, and performance L9. Correspondingly, 9 experiments are considered for three factors based on the Taguchi orthogonal L9 array design as displayed in Table 2.

2.2 Cutting Fluid Optimizer (CFO)

This device automatically regulates the supply of coolant fluid on the basis of temperature of the tool tip generated during machining as shown in Figure 2. The coolant is delivered directly on cutting tool and work piece through servo- controlled nozzle. The coolant supply is controlled by servo-controlled nozzle. It is programmed in such way that at a certain range of temperature, nozzle will remain open few percent by default and when temperature exceeds the range then further valve starts opening linearly according to temperature generation during machining. Tool tip temperature is measured using k type thermocouple. Servo-controlled valve consists of a servo motor which control the opening of the nozzle. The opening of nozzle is controlled by a gear knob that is attached to servo motor and when temperature increases or decreases then servo motor rotates the gear knob and the valve get open or closed respectively. A battery management system is employed to supply the needed voltage and current to run the system. Lithium iron phosphate (LiFePo4) type battery containing 3 cells each of 3.2V is used. Voltmeter and ammeter are used to display the voltage and current supplied by the battery. Arduino UNO is the microprocessor that runs the system. During machining when temperature of tool tip increases the valve starts opening and the cutting fluid supply increases and when temperature decreases its supply also decreases. It consists of solenoid valve for controlling air supply.

Air pressure is varied by solenoid valve. Coolant is filled in measuring cylinder (100 ml) and during each experiment its consumption is being recorded (20 min). All the experiments are conducted on a same experimental setup using Cutting Fluid Optimizer (CFO) and responses are recoded in terms of surface roughness, cutting temperature, cutting forces, and cutting fluid consumption as shown in the Table 3 and Table 4 non-regulation of cutting fluid and regulation of cutting using CFO respectively.

Table 2. Design of experiment

Serial No	Cutting velocity (m/min)	Depth of cut (mm)	Air pressure (bar)
1	40	0.25	2
2	40	0.50	3
3	40	0.75	4
4	80	0.25	3
5	80	0.50	4
6	80	0.75	2
7	120	0.25	4
8	120	0.50	2
9	120	0.75	3

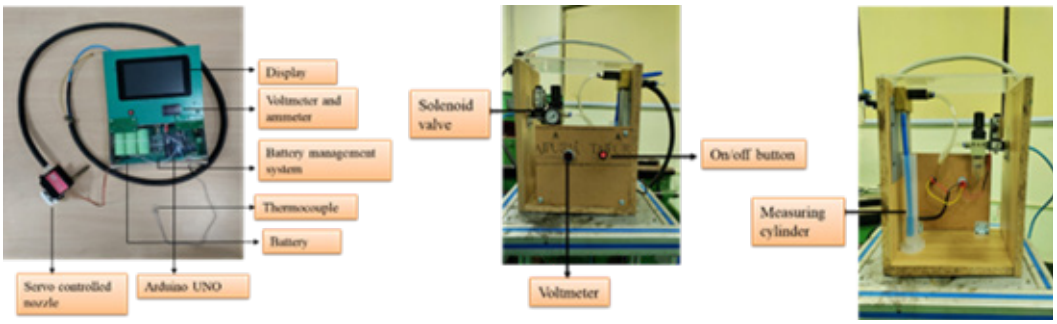


Figure 2. Cutting fluid optimizer and its components

Table 3. Output responses in non-regulation of cutting fluid with using CFO

Cutting velocity (Vc)(m/min)	Depth of cut (doc) (mm)	Air pressure (p) (bar)	Surface roughness Ra (μm)	Feed force Fx (N)	Thrust force Fy (N)	Cutting force Fz (N)	Temperature T(° C)	Coolant consumption (CC) (ml/min)
40	0.25	2	2.514	309.7	195.08	401.7	50.1	47
40	0.5	3	2.704	340.3	219.6	415.7	48.5	53
40	0.75	4	3.775	489.1	240.9	690.1	46.3	64
80	0.25	3	1.584	255.19	184.62	393.3	52.5	53
80	0.5	4	1.973	302.7	199.3	417.7	54.5	64
80	0.75	2	3.491	411.1	235.7	614.5	56.5	47
120	0.25	4	1.643	208.2	183.47	305.6	57.6	64
120	0.5	2	1.797	300.92	200.13	425.3	58.2	47
120	0.75	3	2.631	386.7	215.6	584.3	63.1	53

Table 4. Output responses in regulation of cutting fluid with the use of CFO

Cutting velocity (Vc)(m/min)	Depth of cut (doc) (mm)	Air pressure (p) (bar)	Surface roughness Ra (μm)	Feed force Fx (N)	Thrust force Fy (N)	Cutting force Fz (N)	Temperature T(° C)	Coolant consumption (CC) (ml/min)
40	0.25	2	2.68	314.8	221.3	408.9	53.3	29
40	0.5	3	2.859	350.9	229.9	426.81	52.1	37
40	0.75	4	4.101	495	244.01	702.6	50.2	46
80	0.25	3	1.819	264.1	203.8	402.1	55.9	41
80	0.5	4	2.238	313.5	222.4	428.2	58.1	50
80	0.75	2	3.806	417.75	231.5	626.07	61.2	37
120	0.25	4	1.791	215	191.2	314.2	60.9	54
120	0.5	2	2.158	308.4	212.5	433.2	61.6	42
120	0.75	3	3.063	397.9	219.7	596.8	66.5	49

3.0 Result and Discussion

In this work, there are six responses, namely, component of cutting forces (feed force, thrust force, cutting force), cutting temperature, surface roughness, and coolant consumption, which are measured in two conditions of coolant supply (regulation of cutting fluid using CFO and non-regulation of cutting fluid using CFO). After experimentation the testing results are compiled, and it is found that during the non-regulation of cutting fluid with the CFO, at the same input parameters, coolant consumption is found more than that of regulation of cutting fluid with CFO but at the same time it is producing less cutting temperature, reduced value of components of forces and better surface roughness as compared to regulation of cutting fluid with the CFO, displayed in Table 3 and Table 4 respectively.

3.1 Grey Relational Analysis (GRA)

Grey system theory is utilized to calculate the most influential process variables from various experiment results[21]. Several scholars have utilized GRA to improve control settings for many-response systems using grey relational grade[22]. This approach obtains the interconnection between the comparability sequences and reference, after which ranks them based on this correlation. The measured values of the experimental data were initially Normalized to a value between 0 and 1[23]. Following that, the Grey Relational Coefficient (GRC), which depicts the connection between ideal and real normalization values, is then calculated using the normalized data. The Grey Relational Coefficient (GRG) is then determined by using the mean of the GRCs for every experiment. As a result, a numerous response process improvisation challenge is reduced to a one response improvisation problem. The optimum parameter setting is regarded to the factor setting that results in the highest GRG[24].

If the initial sequence's target value is limitless, it has the property of "Greater is better." Following is a normalization of the original sequence:

$$B_a^{\circ}(j) = \frac{b_a^*(j) - \min b_a^*(j)}{\max b_a^*(j) - \min b_a^*(j)} \quad (1)$$

When the original sequence has the "lesser is better" feature, the primary sequence ought to be normalized as follows.

$$B_u^{\circ}(j) = \frac{\max b_a^*(j) - b_a^*(j)}{\max b_a^*(j) - \min b_a^*(j)} \quad (2)$$

Where, $B_a^{\circ}(j)$ and $B_u^{\circ}(j)$ are the values following Grey Relational Generation for higher is better and lower is better criterion.. Max $b_a^{\circ}(j)$is the greatest value of $B_a^{*}(j)$ for jth response and min b_a^{*} (j) is the smallest value of $B_a^{*}(j)$ for the jth response. The GRC $\xi_i(j)$ may be computed as:

$$\xi_a(j) = \frac{\Delta\min - \psi\,\Delta\max}{\Delta P_a(j) + \psi\,\Delta\max} \quad (3)$$

$$\Delta P_a = \| b_o(j) - b_a(j) \| \quad (4)$$

$$\gamma_a = \frac{1}{n}\sum_{k=1}^{n} \xi_a(j) \quad (5)$$

3.1.1 Analysis of Grey Relational Results in Case of Non-Regulation of Cutting Fluid with the CFO

All the output parameters are normalized using "Lower is Better" equation. The GRC is computed utilizing equation 3. The distinguishing coefficient is assumed to be 0.5. Equation 5 is used to compute the value of GRG. The combination which has maximum value of GRG is considered as optimum parameter. As shown in Table 3 the optimum parameter in non-regulation of cutting fluid with the CFO is Vc = 120 m/min, doc = 0.25 mm and air pressure = 4. Table 5 displays the value of rank and grey relational grade.

Response table for grade is used to calculate which factor has most significant impact on GRG. In non-regulation of cutting fluid with the CFO, depth of cut has most effect on GRG, followed by cutting velocity. Air pressure has least effect on GRG, shown in Table 6.

3.1.2 Analysis of Grey Relational Result in Case of Regulation of Cutting Fluid with the CFO

All the output parameters are normalized using "Lower is Better" equation. The GRC is computed utilizing equation 3. The distinguishing coefficient is assumed

Table 5. Grey relational grade and rank

Ra (μm)	Fx (N)	Fy (N)	Fz (N)	T(◦ C)	CC (ml/m)		
0.5409	0.5805	0.7121	0.6667	0.6885	0.9048	0.6822	3
0.4945	0.5153	0.4428	0.6359	0.7925	0.5758	0.5761	5
0.3333	0.3333	0.3333	0.3333	1.0000	0.3333	0.4444	9
1.0000	0.7493	0.9615	0.6867	0.5753	0.5429	0.7526	2
0.7380	0.5978	0.6446	0.6317	0.5060	0.3333	0.5752	6
0.3649	0.4091	0.3547	0.3836	0.4516	1.0000	0.4940	7
0.9489	1.0000	1.0000	1.0000	0.4264	0.3455	0.7868	1
0.8372	0.6024	0.6328	0.6163	0.4138	0.9048	0.6679	4
0.5113	0.4404	0.4719	0.4082	0.3333	0.5135	0.4464	8

Table 6. Response table for grade

Factors	L1	L2	L3	Max-Min	Rank	
Vc	0.5676	0.6073	0.6337	0.0661	2	
DOC	0.7406	0.6064	0.4616	0.2789	1	
P	0.6147	0.5917	0.6022	0.0230	3	
Average value of GRG	0.6029					

Table 7. Grey relational grade and rank

Ra (μm)	Fx (N)	Fy (N)	Fz (N)	T(◦ C)	CC (ml/m)		
0.5651	0.5838	0.4673	0.6722	0.7244	1.0000	0.6688	3
0.5196	0.5074	0.4056	0.6330	0.8109	0.6098	0.5810	4
0.3333	0.3333	0.3333	0.3333	1.0000	0.4237	0.4595	7
0.9763	0.7403	0.6770	0.6884	0.5884	0.5102	0.6968	2
0.7210	0.5870	0.4584	0.6301	0.5078	0.3731	0.5462	6
0.3644	0.4085	0.3958	0.3837	0.4256	0.6098	0.4313	8
1.0000	1.0000	1.0000	1.0000	0.4324	0.3333	0.7943	1
0.7589	0.5998	0.5535	0.6201	0.4169	0.4902	0.5732	5
0.4759	0.4336	0.4809	0.4073	0.3333	0.3846	0.4193	9

Table 8. Response table for grade

Factors	L1	L2	L3	Max-Min	Rank
Vc	0.5698	0.5581	0.5956	0.0375	3
DOC	0.7200	0.5668	0.4367	0.2833	1
P	0.5578	0.5657	0.6000	0.0422	2
Average value of GRG	0.5745				

to be 0.5. Equation 5 is utilized to calculate the value of GRG. The combination which has maximum value of GRG is considered as optimum parameter. So optimum parameter in regulation of cutting fluid with the CFO is Vc = 120 m/min, doc = 0.25 mm and air pressure = 4.0, displayed in Table 4. Table 7 displays the value of rank and GRG.

Response table for grade is used to calculate which factor has most effect on grey relation grade. In regulation of cutting fluid with the CFO, DOC has most impact on GRG, followed by Air pressure, cutting velocity has least effect on GRG as displayed in Table 8.

Comparison between the optimum parameters of non-regulation of cutting fluid with the CFO and regulation of cutting fluid with the CFO

The optimum parameter in between the regulation and non-regulation of cutting fluid with CFO is find out with the help of GRA. The best combination from the process variables is chosen on the basis of highest Grey relational grade. At optimum parameter, Output response in both condition (regulation and non-regulation of cutting fluid with CFO) are compared.

The mean of summation of components of forces is taken and then compared, it is found that at the time of during the regulation of cutting fluid with CFO forces are being increased by 3.3%. The value of cutting temperature during the non-regulation of cutting fluid is 57.6◦C which is increased to 60.9◦C at the time of regulation of cutting fluid with CFO. Surface roughness value is found to be 1.643 at the time of non-regulation of cutting fluid with CFO, which gets increased to 1.791 during the regulation of cutting fluid with CFO. At the time of regulation of cutting fluid with CFO Coolant consumption is found to be lowered by 15% from the non-regulation of cutting fluid with CFO.

4.0 Conclusions

In this current work, optimization of parameters and cutting fluid consumption without and with use of cutting fluid optimizer and the effect of regulation of cutting fluid using CFO over non-regulation of cutting fluid with CFO is studied in terms of surface roughness, cutting temperature, and machining forces. From experimental results and analysis flowing conclusion has been drawn. The optimum parameter at which all the response is at their minimum value in regulation of cutting fluid with CFO and non-regulation of cutting fluid with CFO is vc=120m/min, doc= 0.25mm and air pressure= 4 bar. During the non-regulation of cutting fluid with the CFO the coolant is supplied uncontrollably resulting in lower value of surface roughness, components of forces and less cutting temperature then the regulation of cutting fluid with CFO. While the Regulation of cutting fluid with CFO, the coolant consumption is controlled on the basis of temperature which causes in cutting off of the excess coolant supply and the optimization of coolant supply is being achieved. However, when the coolant supply is regulated with CFO the other responses namely, surface roughness, component of forces, and mean cutting temperature are slightly increased.

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