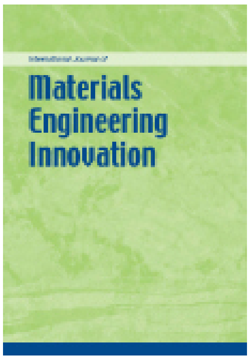

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A study on the sustainable machining of AISI 630 stainless steel under minimum quantity lubrication

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Abstract: In this study, experiments were performed by changing the cutting velocity, feed rate, depth of cut, and type of machining [flood, dry and minimum quantity lubrication (MQL)] to evaluate the MQL system's influence in turning AISI 630 (17-4 PH) stainless steel. Servocut 'S' is used as cutting fluid in flood and MQL turning. The optimum and most influencing process parameters on surface roughness were predicted through Taguchi L9 orthogonal array and analysis of variance, respectively. The lowest surface roughness, 0.185 μm, was obtained at the optimum process parameters (157.08 m/min, 0.15 mm/rev, 0.3 mm and MQL). The most influencing process parameter was found as the depth of cut with a 50.52% contribution. Furthermore, a good agreement was noted between the experimental findings and the predicted model. The utilisation of cutting fluid in MQL turning have, approximately 150% lower than the cutting fluid consumption in the flood turning. This significant reduction of cutting fluid can reduce the problems associated with ecological and economic and lead to a sustainable machining method. Further, it is recommended that the machining industries benefit when machining 17-4PH SS under predicted optimum process parameters to obtain better quality surface and less material waste.

Keywords: machining; steel; minimum quantity lubrication; MQL; sustainable machining; surface roughness; turning; optimisation; mineral oil; cutting fluid; AISI 630 steel; 17-4 PH steel.

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1 Introduction

In the machining or metal cutting process, cutting fluids are used extensively to perform two primary functions, namely cooling and lubrication. Machining a difficult-to-machine material uses a vast quantity of cutting fluid to obtain the required product quality. The use of cutting fluids in machining contributes to the total machining economics and leads to several environmental and health problems (Dosbaeva et al., 2008). On the one hand, the manufacturers are focusing on lowering the amount of cutting fluid in machining. In contrast, on the other hand, the environmental agencies are enforcing the manufacturers to minimise the usage of cutting fluids (Sivaiah and Chakradhar, 2019a).

A mechanical product is graded with many vital parameters. One such parameter is the surface integrity (i.e.) high surface finish and low surface roughness (Dhar et al., 2006). Achieving good surface integrity is by providing appropriate lubrication at the machining interface through cutting fluids. The types of machining by which the cutting fluids are supplied are flood machining, minimum quantity lubrication (MQL) machining and cryogenic machining. The flood machining method involves a flow of cutting fluids at the rate of 30 to 60 l/h. This high consumption of cutting fluids in flood machining accounts for a minimum of 7% and a maximum of 17% of overall manufacturing cost (Eltaggaz et al., 2020). Despite higher consumption of cutting fluids, flood machining has its limitations. The chip removed acts as a barrier for the cutting fluid to reach the machining interface, leading to increased friction and poor surface integrity. Also, the cutting fluid used in large quantities is stored and recycled, which involves maintenance and disposal issues leading to higher cost and increased environmental problems (Rozzi et al., 2010; Wichmann et al., 2013).

Dry machining, where not any cutting fluid is used, offers an alternate method. However, as no cutting fluid is used, the cutting fluid functions of cooling and lubricant are absent at the machining interface, increasing friction leading to a product with very low surface integrity. The absence of cutting fluids or cooling functions also increases the temperature at the machining interface. Overall, results of dry machining are rapid tool wear, dimensional inaccuracy, poor surface integrity, thermal damage on the product, increased force and power consumption during machining, when compared with flood machining (Tawakoli et al., 2009, 2010). Cryogenic machining uses CO_2, He, LN_2, Ar as a cutting fluid. The benefits are eco-friendly nature, rapid heat transfer and cooling and oil-free chips. However, the major limitation of cryogenic machining is that it is suitable only for low-speed machining as its lubrication becomes poor at high cutting speeds. Low-speed machining reduces productivity. Additionally, a cryogenic cooling system also increases the cutting force and increases power consumption (Gajrani and Sankar, 2020).

Stainless steel (SS) is often used in many engineering applications for its properties such as high strength, hardness, and corrosion resistance (Molaei et al., 2020; Saha et al., 2020). SS is difficult-to-machine material that needs higher force to carry out machining, resulting in higher friction. One of the most widely used materials in the stainless-steel group is AISI 630 SS (also known as 17-4 PH SS). SS 17-4 PH is a difficult-to-machine material by virtue of its composition and properties (Bressan et al., 2008). It is widely used in fasteners, reactor components, missile fittings, and jet engine parts (Sathyanath and Meena, 2020), safety valves, studs, and nuts (Coseglio, 2017), sailboat propeller shafts (Arisoy et al., 2003) and implantation (Mutlu and Oktay, 2013). All the above applications require a part made from AISI 630 (17-4 PH) SS with high surface integrity.

AISI 630 SS becomes difficult to machine material due to distinctive properties like higher thermal resistance and high strength. 17-4 PH steel has superior corrosion resistance than 304 and 316L SS. Its lower thermal conductivity nature retains the temperature at the machining interface. Such higher generated temperature affects the quality of the machined surface and tool life, which leads to lower machinability and, thereby, lower productivity and high production costs (Leksycki et al., 2020; Fernando et al., 2020). So far, very few researchers have carried out investigations on the machining of AISI 630 SS. Based on the literature review, it was found that few studies were carried out in the machining of the AISI 630 SS.

During machining of AISI 630 (17-4 PH) SS, the maximum heat is generated and retained at the machining interface resulting in reduced surface quality and lesser tool life. These problems are mitigated by the selection of suitable cutting fluid and cooling techniques. In recent research, various cooling strategies such as flood, cryogenic and MQL were used to improve the machinability of AISI 630 (17-4 PH) SS (Sivaiah and Chakradhar, 2017, 2018). The flood cooling system improved the machining performance by reducing cutting temperature and friction using a high amount of cutting fluid in AISI 630 (17-4 PH) SS. It also causes adverse environmental effects due to disposal problems (Kuram et al., 2013). On the other hand, utilisation of the cryogenic cooling system is a threat to ecology, and its installation also involves high capital and operational cost (Duchosal et al., 2016).

In recent times, machining researchers and practitioners are showing keen interest in implementing MQL as a means of sustainable machining, which reduces the quantity of cutting fluid and thereby reduces the harmful effects on the environment and cost of machining. One such high effective, sustainable method is the MQL (Abbas et al., 2020).

MQL is widely being adopted, particularly for machining difficult-to-machine materials. In the MQL system, a small quantity of cutting fluid is released through the nozzle and pressurised air, decreasing the friction between tool and chip, cooling the machining interfaces, and removing the chips produced during machining (Bedi et al., 2020; Selvam and Sivaram, 2018). An outlook of papers on the benefits of MQL machining from the literature is provided in Table 1. Also, a brief literature review on MQL machining on steels is presented in Table 2.

Table 1 Outlook of papers on the benefits of MQL machining from the literature

Paper	*Machining operation and material*	*Cutting fluid*	*Inferences/benefits*
De Lacalle et al. (2006)	Milling, Al 5083-H112	Mineral oil	Lower tool flank wear of 0.09 mm was obtained with the MQL system compared to flood machining (0.16 mm). Cutting fluid consumption was reduced by 95% with the MQL system (3.6 ml/h). MQL system with nozzle angle 135° assists the cutting fluid to reach the tool edges.
Duchosal et al. (2016)	Milling	Polyol's ester	Difficult-to-machine material required 20–30% less quantity cutting fluid using MQL. The decrease in cutting fluid usage reduces the total cost of machining.
Mane et al. (2019)	Turning, Ti-6Al-4V	Balscout 4000	Lubrication by cutting fluid is predominant when machining at low cutting speed, whereas it is significant at high speeds. Low viscous oil at a lower cutting speed reduced the cutting temperature significantly, whereas high viscous oil at higher speed enhanced the cooling effect.
Moretti et al. (2020)	Grinding, ductile cast iron DIN GGG70	Semisynthetic, Biocut 9000	A large quantity of cutting fluid used in flood machining enhanced the grinding performance. Sustainable machining was achieved by the MQL system, which consumed only 150 ml/h of cutting fluid. It reduced the consumption of cutting fluid by 113 times than flood machining. MQL machining resulted in surface roughness of up to 1.6 μm which is acceptable as per grinding standards.
Gaurav et al. (2020)	Turning, Ti-6Al-4V	LRT 30 oil, Jojoba oil	Compared to dry machining, lower cutting force, surface roughness and tool wear were observed as 78.3 N, 0.1498 μm, and 0.13 mm, respectively, with MQL machining.
Bhowmick et al. (2020)	Drilling, Ti-6Al-4V	Vegetable oil	MQL machining obtained lower machined surface temperature (~200°C) and roughness (3.28 ± 0.17 μm) than flood machining (~230°C, 5.85 ± 0.15 μm). No significant tool wear was observed for both flood and MQL machining.

From the literature review, it is known that MQL machining is a very effective technique for minimising cutting fluid usage. Also, MQL machining is very much suitable for machining the various grades of steel. Optimisation of machining parameters on the machining responses was performed enormously for various materials under different machining environments. Few investigations have been identified for optimising the machining parameters such as cutting velocity, feed rate and depth of cut on the surface roughness in turning AISI 630 (17-4 PH) SS under the MQL machining. A very few studies discussed the machining environment as an influencing parameter on surface roughness. To the authors' knowledge, no papers reported Servocut 'S' as a cutting fluid in the machining of AISI 630 (17-4 PH) SS under MQL.

Table 2 A brief literature review on MQL machining on steels

Paper	*Machining operation and material*	*Cutting fluid*	*Inferences/ benefits*
Attanasio et al. (2006)	Turning, 100Cr6 steel	COUPEX EP46 oil	MQL machining resulted in higher tool life of 11.44 mins for 0.2 mm/rev and 200 mm cutting length than dry machining.
Junior et al. (2009)	Milling, SS 15-5PH	Vegetable oil	MQL machining improved the wear mechanism by offering better lubrication and cooling at the machining interface, thus resulting in longer tool life.
Yan et al. (2012)	Milling, 50CrMnMo steel	Esters of lubricant oil	Lower friction and higher tool life were found in MQL machining in comparison with dry and flood machining. Machinability remained the same when varying the oil flow rate by 43.8–58.4 ml/h.
Rahim et al. (2015)	Turning, AISI 1045 steel	Synthetic ester	MQL machining at higher cutting speed and lower feed rate reduced the cutting temperature, cutting force and chip thickness to ~300°C, 350 N, and 0.2372 mm, respectively when compared to dry machining.
Mia et al. (2018)	Turning, AISI 1060 steel	Olive oil, graphite (solid)	MQL system penetrated the machining interface sufficiently to get a lower cutting temperature of 425°C. Both dry and MQL system machining decreased the tool life. However, considering increased productivity, MQL machining was found better.
Abd Rahim and Dorairaju (2018)	Turning, AISI 1045 steel	Synthetic ester	MQL machining effectively reduced the cutting force and temperature by providing cutting fluid in the form of a mist of size 20–30 μm. Moreover, a nozzle size of 3 mm in the MQL system resulted in a higher cooling rate as it generated a large spray angle, high droplet velocity and smaller droplets.
Selvam and Sivaram (2018)	Turning, AISI 4340 steel	Servocut 'S' oil	Surface roughness by MQL machining was obtained as 0.9343 μm which is slightly higher than flood machining, i.e., 0.9144 μm, whereas significantly lower than dry machining, i.e., 1.0535 μm. However, the tool life in MQL machining was more compared to flood and dry machining.

Table 2 A brief literature review on MQL machining on steels (continued)

Paper	*Machining operation and material*	*Cutting fluid*	*Inferences/benefits*
Babu et al. (2019)	Milling, AISI 304 steel	MAX Sherol B oil, olive oil	Surface roughness and tool wear by MQL machining was observed to be 0.2 μm and 0.12 mm, respectively, compared to flood machining resulted in 0.6 μm and 0.4 mm. MQL machining is a better substitute to dry and flood machining due to its better lubrication capability by generating a smaller oil droplet that penetrates the machining interface more efficiently.
Tomaz et al. (2019)	Milling, maraging 300 steel	Vegetable oil	Flood and MQL machining resulted in similar milling performances. However, in terms of economics and environment, the MQL system used a lesser amount of cutting fluid of 80 ml/h.
Bedi et al. (2020)	Turning, AISI 304 steel	Rice bran oil and coconut oil	Rice bran oil in MQL machining resulted in lower cutting force, cutting temperature, and surface roughness of ~140 N, ~82°C, and ~0.58 μm, respectively. Compared to coconut oil, rice bran oil in MQL machining reduced the tool wear.
Lai et al. (2020)	Turning, 316L steel	Biodegradable oil and gas	The MQL system of machining assisted in reducing the surface roughness and cost of the process compared to other cutting fluid supply techniques. Sustainability of the machining can be retained when machining 316L SS with coated cutting tool under MQL system. Effective penetration of the oil mist by the MQL system reduced the surface roughness and cutting force significantly compared to other cooling techniques.
Rajaparthiban et al. (2020)	Turning, AISI 316 steel	-	The experiment was designed using Taguchi L9 orthogonal array method for the machining responses such as surface roughness and material removal rate. The most dominating process parameters on machining responses were obtained using ANOVA. Also found the process parameter such as depth of cut and feed rate were caused a significant effect on the surface roughness.
Satynarayana et al. (2020)	Turning, EN 18 steel	Divyol ST cut 54 oil	The surface roughness of the machined surface in MQL machining was 1.162 μm, and in dry machining was 1.482 μm at the same cutting speed (100 m/min), feed (0.05 mm/rev), and depth of cut (0.4 mm).
Mustafa et al. (2021)	Turning, AISI 52100 steel	Palm, peanut, sunflower, coconut, and castor oil	Compared to other oils, palm oil in MQL machining reduced the cutting temperature and surface roughness to ~50°C and ~2.1 μm, respectively. It was also found that low viscous oil was more contributing in cooling, whereas higher viscous oil is in lubrication.

In the present study, the influence of machining parameters and machining environment was analysed in turning of AISI 630 (17-4 PH) SS using mineral oil Servocut ‘S’ in the MQL system. The reason for choosing mineral oil is that they are readily available and economical compared to vegetable oils. The overall cost of the cutting fluid can be significantly reduced while utilising mineral oil in MQL machining as in the flood cooling machining (Mustafa et al., 2017). Optimum process parameters and the most influencing parameter were determined for the surface roughness using Taguchi’s technique and analysis of variance (ANOVA). Furthermore, regression analysis was utilised to develop a model for predicting the machining performance.

2 Materials and methods

In the present study, the turning process was carried out using a centre lathe with varying speed and feed. A cylindrical bar of 50 mm diameter and 140 mm length AISI 630 (17-4 PH) SS was chosen as the workpiece material. The turning parameters and conditions considered are provided in Table 3. The cutting tool was coated tungsten carbide inserts (Ceratizit make) having an ISO designation CNMG 120408EN-M70 with a nose radius of 0.8 mm for all sets of experiments. A new cutting edge was used for each level of process parameters and mounted on a tool holder with ISO designation PSBNR2525-M15. From the tool manufacturer guidelines and the existing literature, the turning process was conducted for different process parameters, including cutting velocity (94.25, 125.66 and 157.08 m/min), feed rate (0.05, 0.1 and 0.15 mm/rev), depth of cut (0.3, 0.6 and 0.9 mm) and coolant type (flood, dry and MQL). The turning process under the above three conditions is illustrated in Figure 1. According to the tool manufacturer guidelines, the selected level of each process parameter used in the turning process is given in Table 4. The tabulated range of level of turning parameters was performed by Sivaiah and Chakradhar (2019b) and Rajbongshi and Sarma (2019). Dry turning was performed without cutting fluid. Servocut ‘S’ oil was utilised as cutting fluid in MQL as well as flood turning. The cutting fluid emulsion was made by mixing both oil and water in the proportion of 1:10 for use in flood turning of AISI 630 SS. The flow rate of the cutting fluid emulsion during flood machining was kept as 60 l/h. However, the oil of 5.4 l/h was used during machining.

Table 3 Turning conditions

Workpiece material	*AISI 630 cylindrical rod*
Dimensions	Ø50 mm × 140 mm
Cutting tool insert	Coated carbide cutting tool inserts (CNMG 120408 EN-M70 as per ISO designation); manufacturer – Ceratizit
Tool holder	ISO specification of PSBNR 2525-M15
Tool nomenclature	Rake angle: – 6°; inclination angle: – 6°; clearance angle: 6°; primary cutting-edge angle: 75°; nose radius: 0.8 mm
Machining conditions and cutting fluid used	MQL turning (Servocut ‘S’); flood turning (Servocut ‘S’) emulsion-based cutting fluid at 1:10 soluble oil; dry turning (no cutting fluid)
Supply of cutting fluid	MQL turning: flow rate – 36 ml/h (through an external nozzle); compressed air pressure – 5 kg/cm^2; flood turning: flow rate – 1 litre/min

In this study, cutting fluid was supplied in the form of mist by a self-fabricated MQL system, including a piston pump, oil reservoir, mixing chamber, and pressure regulators. MQL turning was achieved with the help of an MQL unit, an air compressor, a filtre-regulator-lubricator (FRL) unit, and a nozzle. Pressurised air from the air compressor was passed to the MQL unit through the FRL unit. Pressurised air actuated the piston pump, carried the pump's discharged oil, and generated the mist through the nozzle. A schematic drawing of the MQL system is indicated in Figure 2. Approximately 105 US dollars was spent for fabricating the MQL system, and this includes the cost of components, labour, and miscellaneous during fabrication. Servocut 'S' (neat oil) was supplied as the cutting fluid at a flow rate of 36 ml/h and pressure of 5 bar through a 2 mm nozzle in the MQL turning. The utilisation of cutting fluid in MQL turning is much lower than coolant used in flood turning. The distance between the cutting tool and nozzle exit was maintained at 50 mm throughout the experiment. Surface roughness was determined using a portable contact-type profilometer roughness tester following the procedure stated in ISO 2488:1997 standard.

Figure 1 Different turning environments, (a) flood turning (b) dry turning (c) MQL turning (see online version for colours)

(a) (b) (c)

Figure 2 Schematic diagram of MQL system (see online version for colours)

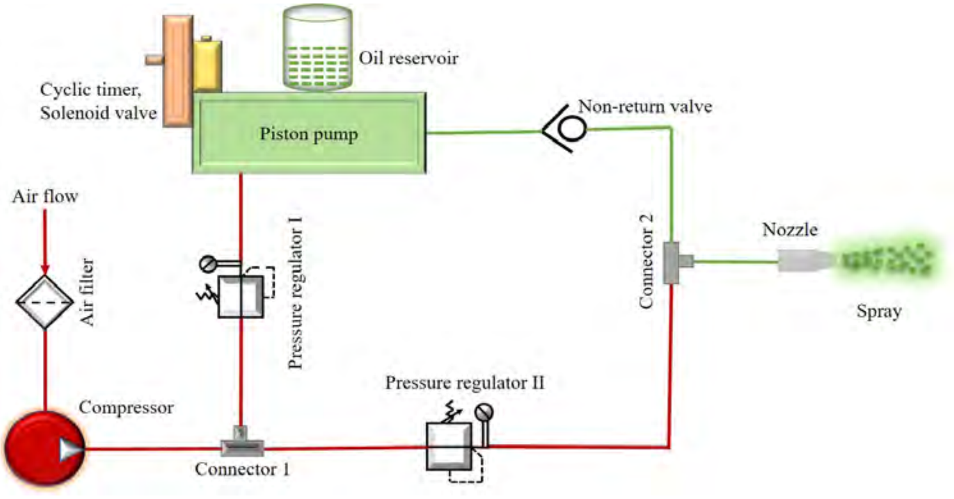


Table 4 Turning parameters and corresponding levels

Turning parameter		*Cutting velocity*	*Feed rate*	*Depth of cut*	*Type of machining (turning environment)*
Unit		*(m/min)*	*(mm/rev)*	*(mm)*	
Notation		*v*	*f*	*d*	*TE*
Levels	1	94.25	0.05	0.3	MQL
	2	125.66	0.1	0.6	Flood
	3	157.08	0.15	0.9	Dry

Mitutoyo SJ-210 model was used for surface roughness measurement with a measuring speed of 0.25 mm/s. The machined surfaces under all turning conditions were measured with a cut-off length (λ_c) of 0.08 mm along the feed direction of the turning process. Surface roughness was determined by the arithmetic mean of three sampling readings measured.

3 Results and discussion

3.1 Taguchi's technique

Taguchi's technique is an excellent tool for the optimising the parameters of any process. In this study, L9 orthogonal array was selected for designing the experiments to optimise the surface roughness. The surface roughness is a function of four variables, i.e., cutting velocity, feed rate, depth of cut and type of machining (turning environment). The control parameters for the process and its resultant surface roughness are given in Table 5. The ratio between mean and standard deviation is the signal to noise (S/N) ratio. In any machining process, the process is considered good when the surface roughness is lower. The mean S/N ratio was evaluated by considering the 'lower the better' response.

$$\text{S/N ration lower the better} = -10\log\frac{1}{n}\sum(R)^2 \tag{1}$$

where

n number of observed data

R observed data for each response.

The values of the S/N ratio for the response were calculated by means of equation (1), and the same is shown in Table 5. Minitab 19.1 is the statistical analysis tool utilised for performing the Taguchi technique.

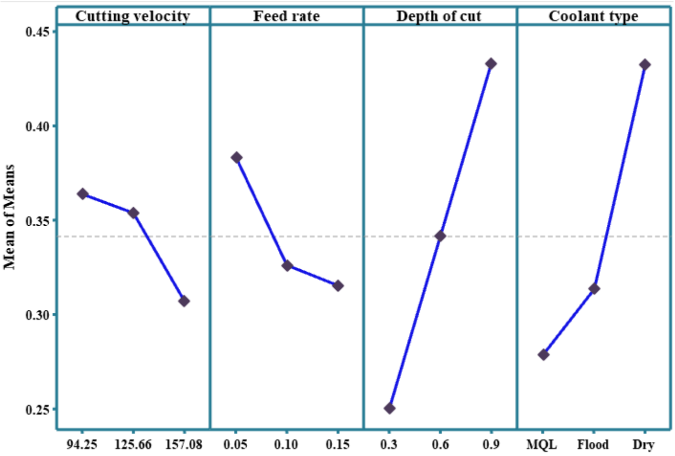
3.2 Influence of process parameters on surface roughness

In this study, the surface roughness of the turned workpiece was measured for different turning parameters. Variations in surface roughness on the workpiece by cutting velocity, feed rate, depth of cut and type of machining (turning environment) are depicted in Figure 3. It was noticed that the surface roughness of the workpiece decreased as increasing cutting velocity. The surface of the workpiece becomes softer due to the heat produced at the machining interface and consequently reduced the material smear on the machined surface. Therefore, lower surface roughness was achieved (Sivaiah and Chakradhar, 2019a). It is seen from Figure 3 that the value of surface roughness was decreased as feed rate increased; and increased as depth of cut increased. Surface roughness is also increased due to a built-up edge (BUE) on the cutting tool. Movement of the cutting tool is resisted by the workpiece when increasing the depth of cut, resulting in a more BUE formation. Thus, the surface roughness of the machined workpiece increased as depth of cut increased. The trends obtained from this study for surface roughness at different turning parameters concurred with the machining theory (Sivaiah and Chakradhar, 2018, 2019a).

Table 5 Design of experiment and the experimental results

Run	*Controllable process parameters*				*Experimental results*	*S/N ratio of result*
	v (m/min)	*f (mm/rev)*	*d (mm)*	*TE*	*Average surface roughness (Ra) (μm)*	
1	94.25	0.05	0.3	MQL	0.251	12.0065
2	94.25	0.1	0.6	Flood	0.320	9.8970
3	94.25	0.15	0.9	Dry	0.520	5.6799
4	125.66	0.05	0.6	Dry	0.486	6.2673
5	125.66	0.1	0.9	MQL	0.367	8.7067
6	125.66	0.15	0.3	Flood	0.208	13.6387
7	156.08	0.05	0.9	Flood	0.412	7.7021
8	156.08	0.1	0.3	Dry	0.291	10.7221
9	156.08	0.15	0.6	MQL	0.218	13.2309

Figure 3 Effect of turning parameters on surface roughness (see online version for colours)

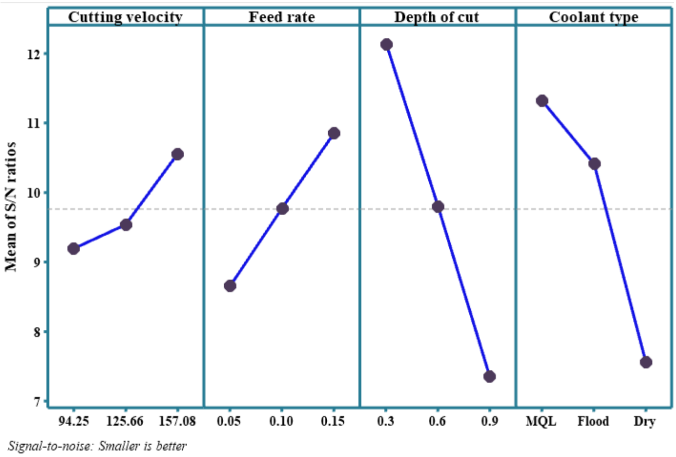


Furthermore, the influence of various cooling strategies (turning environment) on surface roughness was analysed during the turning of AISI 630 (17-4 PH) SS, and its results are depicted in Figure 3. Surface roughness was increased in the order of MQL, flood and dry turning. It is clearly seen that turning environment influences the surface roughness, and MQL turning has a lower surface roughness than flood and dry turning. MQL system supplies the cutting fluid in the form of mist or micro-sized droplet at the machining interface, leading to improved cooling and lubrication. MQL system penetrated the cutting fluid as fine droplets between tool and workpiece. Therefore, the friction and cutting temperature were reduced significantly. The reduction of these parameters made sense in the machining response and reduced the surface roughness of the material compared to other turning environments.

Table 6 Response for surface roughness – mean S/N ratio

Parameter		*Cutting velocity*	*Feed rate*	*Depth of cut*	*Type of machining*
Unit		(m/min)	(mm/rev)	(mm)	
Notation		*v*	*f*	*d*	*TE*
Mean S/N ratio at each level	1	9.194	8.659	*12.122*	*11.315*
	2	9.538	9.775	9.798	10.413
	3	*10.552*	*10.850*	7.363	7.556
Difference between maximum and minimum		1.357	2.191	4.760	3.758
Rank		4	3	1	2

Figure 4 Mean S/N ratio of surface roughness (see online version for colours)



Minitab 19.1 was utilised for examining the surface roughness for various turning conditions. The results of the mean S/N ratio for the surface roughness at all levels of process parameters are tabulated and presented in Table 6. A higher value of the S/N ratio denotes the minimum changes in the difference between expected and measured output of the process. A higher S/N ratio for the responses at each level of turning process parameters is highlighted. The highest S/N ratio was observed for depth of cut, and it decreased in the order of coolant type, feed rate and cutting velocity. Also, the rank for the process parameters was given based on the difference between the maximum and minimum value of the S/N ratio. The rank preference was awarded for the process parameter having a higher difference in the S/N ratio value. The mean S/N ratio for the

surface roughness at various levels of process parameters is shown in Figure 4. It is clearly seen that cutting velocity of 150.08 m/min, feed rate of 0.15 mm/rev, depth of cut of 0.3 mm and MQL system are found as the level of process parameters where maximum S/N ratio was obtained.

A higher mean S/N ratio for the process parameter represents a lower machining response. Based on that, the process parameter levels with a higher mean S/N ratio were selected for the lower surface roughness. Therefore, the levels of process parameters $v_3 - f_3 - d_1 - TE_1$ were chosen as predicted optimum process parameters on the surface roughness.

3.3 *Confirmation test*

The optimum process parameters obtained by Taguchi's technique are to be validated by conducting a confirmation test. Surface roughness at the predicted optimum process parameter was estimated using equation (2) and verified by using the predicted S/N ratio (Sivaiah and Chakradhar, 2019a).

$$\varepsilon_p = \varepsilon_t + \sum_{i=1}^{x} \left(\varepsilon_{op} - \varepsilon_t \right) \tag{2}$$

where

ε_p predicted optimum mean S/N ratio

ε_t total mean S/N ratio

ε_{op} mean S/N ratio at optimum level

x number of input machining parameters.

Table 7 Confirmation test for surface roughness

	Level	*Ra*	*S/N ratio*	*Improvement in S/N ratio*	*Reduction of Ra*
		μm	*dB*	*dB*	*%*
Initial process parameter	$v_3 - f_3 - d_3 - TE_2$	0.277	11.150	3.5065	33.21
Optimal process parameter by experiment	$v_3 - f_3 - d_1 - TE_1$		15.555		
	$v_3 - f_3 - d_1 - TE_1$	0.185	14.656		

The confirmation test was performed for surface roughness at Taguchi's predicted optimum process parameters, and obtained results are indicated in Table 7. It is clearly seen that the results of the S/N ratio obtained from optimum process parameters of both experimental and Taguchi have a close agreement. The difference between the S/N ratio of initial and optimal process parameters was found as 3.5065 dB. The result shows that predicted optimum process parameters improved the S/N ratio significantly compared to the initial condition. From the confirmation test, optimum process parameters obtained by Taguchi's technique has given better results than the initial condition. Furthermore, optimum process parameters predicted by Taguchi's technique reduced the surface roughness by 33.21% from the initial condition. It is concluded that the combination of process parameters $v_3 - f_3 - d_1 - TE_1$ was found as optimum process parameters, which substantially decreased the surface roughness in the turning of AISI 630 (17-4 PH) SS.

3.4 ANOVA for surface roughness

ANOVA was performed to determine the process parameter that causes a substantial impact on the machining response. The results obtained from the ANOVA for surface roughness are shown in Table 7.

Table 8 Analysis of variance for surface roughness

Process parameter	*Notation*	*Degree of freedom*	*Sum of squares*	*Mean squares*	*Percentage contribution*
Cutting velocity (m/min)	v	2	2.9882	1.4941	4.44
Feed rate (mm/rev)	f	2	7.2031	3.6015	10.71
Depth of cut (mm)	d	2	33.9866	16.9933	50.52
Type of machining	TE	2	23.0957	11.5479	34.33
Total		8	67.2736		100.00

It was noticed from Table 8 that among all process parameters, the depth of cut was observed as the most influencing parameter on the surface roughness. The type of turning environment also has a considerable effect on surface roughness. Further, the depth of cut was involved in the reduction of surface roughness with the highest contribution of 50.52%, followed by the type of machining (turning environment), which contributed 34.33%. The influence of other process parameters such as cutting velocity and feed rate on the surface roughness is insignificant with contributions of 10.71% and 4.44%, respectively. Hence, it is confirmed from the outcomes of ANOVA that the depth of cut was the highly influenced process parameter for the surface roughness during turning of AISI 630 (17-4 PH) SS.

3.5 Mathematical model

The dependent variable and independent variables form the structure of the mathematical model. In a mathematical model, the independent variables evaluate the dependent variable. In this study, a mathematical model for the response was developed with the help of linear regression analysis in Minitab 19.1. The surface roughness as a function of the process parameters (cutting velocity, feed rate, and depth of cut) was evaluated using the mathematical model. The predictive mathematical model for the surface roughness developed by regression analysis is represented as equation (3).

$$Ra = 0.1858 - 0.000902\,v + 0.677\,f + 0.3050\,d - 0.0768\,T\ \left(R^2 = 94.83\%\right) \tag{3}$$

The coefficient of determination (R^2) verified the accuracy of the predictive mathematical model. The range of R^2 values varies from 0 to 1. The independent and dependent variables have a good fit when the R^2 value lies close to unity. In the present study, it was noticed that the value of R^2 was obtained as 0.9483 for the predicted model. The obtained R^2 value is close to unity, and variables have a good fit with each other. The implication of the coefficients in the predicted model was verified by using a residual plot. The straight-line residual plot represents the residue errors in the predicted model follow normal distribution, and coefficients are significant. The residual plot for surface roughness is depicted in Figure 5. It is noticed from the plot that residuals are accumulated near the straight line in the plot for surface roughness. Hence, the coefficients in the mathematical model are valid for corresponding process parameters.

Figure 5 Residual plot for surface roughness (see online version for colours)

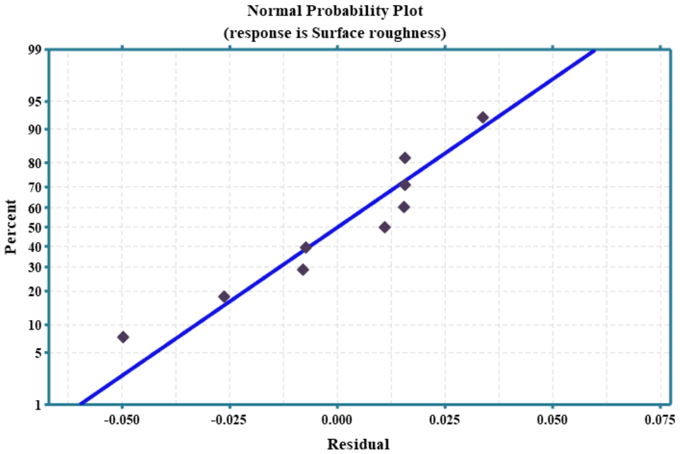


Table 9 Confirmation test results for the developed models

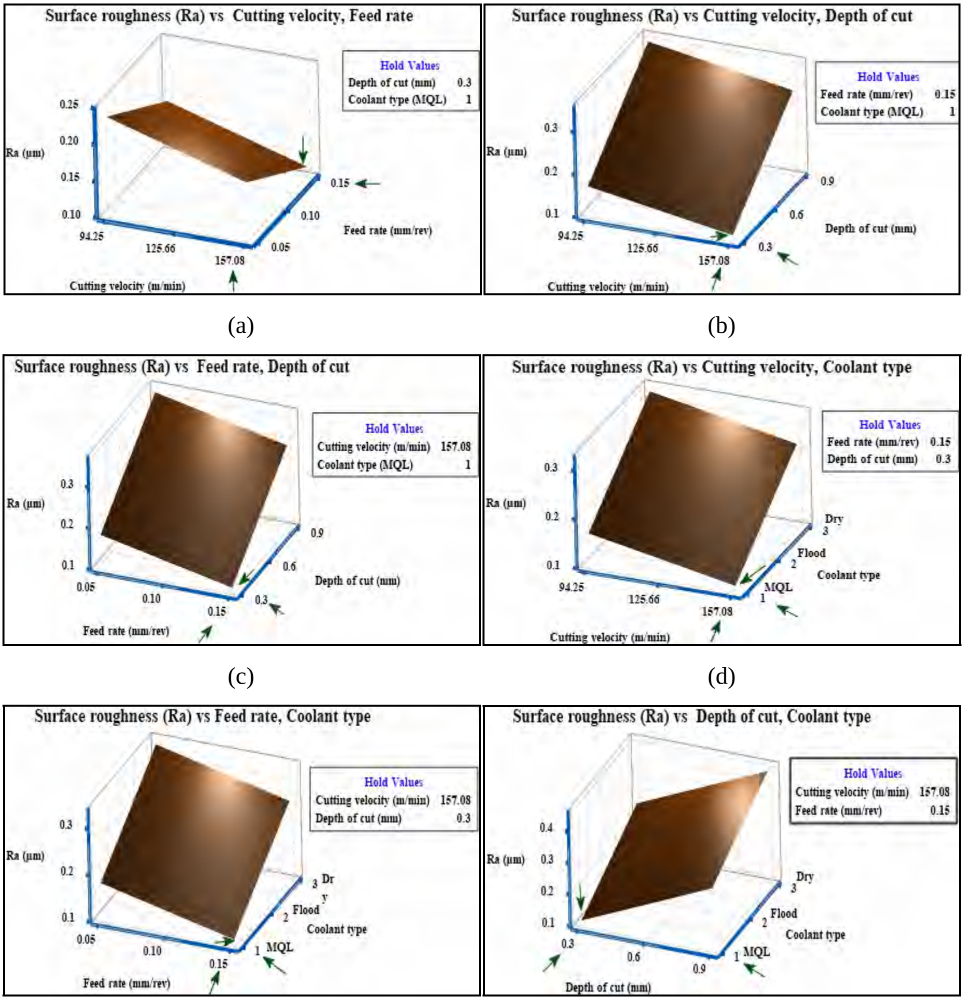
Run	*Surface roughness (μm)*			*Error %*
	Experimental	*Predicted*	*Residuals*	
3	0.520	0.504	0.0157	3.02
5	0.367	0.356	0.0109	2.97
6	0.208	0.216	–0.0081	3.90
8	0.291	0.298	–0.0074	2.56

The predicted model is to be examined by performing a confirmation test. The results of surface roughness obtained during the confirmation test are given in Table 9. The test was conducted by choosing the response randomly from the design of experiments. It is clearly seen from Table 9. That variation in the percentage of residual error among the experimental and predicted model was observed within 5%. Furthermore, the surface roughness obtained from experiments had good agreement with the results determined by the predicted model.

Surface plots examine the consequences of various levels of process parameters such as cutting velocity, feed rate, depth of cut and turning environment on surface roughness. The relation between the turning process parameters and surface roughness are depicted in Figure 6. Taguchi technique's predicted optimum process parameters are used as constant continuous variables in the surface plot setting. Low surface roughness is noticed from Figure 6(a) when turning AISI 630 (17-4 PH) SS at high cutting velocity (157.08 m/min) and feed rate (0.15 mm/rev). It is seen from Figure 6(b) that high cutting velocity (157.08 m/min) and low depth of cut (0.3 mm) resulted in lower surface roughness.

Similarly, a high feed rate and low depth of cut generated low surface roughness, as shown in Figure 6(c). The effect of the turning environment on surface roughness concerning cutting velocity, feed rate and depth of cut is shown in Figures 6(d)–6(f). Low surface roughness was obtained with the MQL turning with high cutting velocity, high feed rate and low depth of cut, respectively, and it can be noticed from Figure 6(d), 6(e) and 6(f). The MQL turning of AISI 630 (17-4 PH) SS decreased the surface roughness significantly in comparison with flood and dry turning.

Figure 6 Surface plot depicting the relationship – surface roughness (vs.), (a) cutting velocity and feed rate (b) cutting velocity and depth of cut (c) cutting velocity and turning environment (d) feed rate and depth of cut (e) feed rate and turning environment (f) depth of cut and turning environment (see online version for colours)



(a) (b)

(c) (d)

(e) (f)

4 Conclusions

The study aimed to evaluate the influence of machining parameters on surface roughness during turning of AISI 630 (17-4 PH) SS in various environments namely dry, flood and MQL. Taguchi technique and ANOVA were implemented to assess the optimum process parameters on the surface roughness. The predicted optimum parameters were verified by performing a confirmation test. The following conclusions were made by results obtained from experimental and statistical methods.

- Investigation of machining response was carried out during turning of AISI 630 (17-4 PH) SS under various process parameters (cutting velocity, feed rate and depth of cut) and different turning environments (dry, flood and MQL).
- The lowest surface roughness was observed at the optimum process parameters (cutting velocity of 156.08 m/min, feed rate of 0.15 mm/rev, depth of cut of 0.3 mm, and MQL turning environment) predicted by Taguchi's technique.
- Turning of 17-4PH SS under the MQL system reduced the surface roughness by 33.21% compared to flood turning environment.
- The most influencing parameter on surface roughness was estimated using ANOVA among all process parameters. Depth of cut influences the surface roughness significantly with 50.52%, followed by MQL turning contributing 34.33%.
- The developed mathematical model for surface roughness has shown good agreement between experimental and predicted optimum conditions. A series of experiments can be avoided by choosing the appropriate process parameters with the help of a predicted model for improving the surface quality of the material.
- The prominent finding from this study is that Taguchi's predicted optimum condition for MQL turning has improved the surface roughness significantly than flood turning during machining of 17-4PH SS.
- MQL system consumed little quantity of cutting fluid (36 ml/h) to cool and lubricate the machining zone during the turning process, whereas the flood cooling system utilised 5.6 L/h. Thus, the cost of cutting fluid will be reduced by 150% compared to the flood system.
- The machining industry can use the predicted optimum process parameters to improve surface quality with low material waste when machining 17-4PH SS.

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