Study on atomization characteristics of droplet of bio-degradable oil for end-milling of incoloy 925

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Presented in International Conference on Precision, Micro, Meso and Nano Engineering (COPEN - 12: 2022)
December 8 - 10, 2022 IIT Kanpur, India

ABSTRACT

KEYWORDS

MQL,
Coconut Oil,
Incoloy 925,
End-Milling,
RSM.

Minimum Quantity Lubrication (MQL) has been proved as an effective technique of lubrication and cooling in machining. However, evacuation of cutting temperature depends on the lubricant's droplet quality, which is highly influenced by MQL setup parameters. This paper aims to study the effects of nozzle angle, nozzle distance, flow rate, and air pressure on the end milling performance of Incoloy 925. Orthogonal array (L9) is used for the design of experiments, and the influence of MQL parameters is analysed by ANOVA. Response surface methodology (RSM) has been used for a linear regression model, and Composite Desirability function has been utilized for optimization of parameters. ANOVA shows that flow rate has highest influence on both cutting force and surface roughness. Nozzle angle is having lowest influence on cutting force, while stand-off distance has the lowest influence on the surface roughness.

1. Introduction

Superalloys have a prominent role in the manufacturing industry. One of the critical super alloys, Incoloy 925, is employed in the Oil and Gas industry due to its excellent resistance property towards sulfide stress cracking and stress-corrosion cracking in the “sour” natural gas and crude oil (INCOLOY Alloy 925, 2002). Machining of superalloy is difficult due to its indigent thermal conductivity, hot hardness, and chemical reaction with cutting tools (Hsiao et al., 2020). Heat generation is a big issue in the metal cutting process, so cutting fluid is required to reduce the cutting zone temperature. However, conventional cutting fluids adversely affect the environment and operators' health and are ineffective in heat transfer due to poor infiltration in the cutting zone. Further, its disposal is a challenge that leads to high costs. So, for sustainability point of view, approaching a new cooling and lubrication technique is highly required. Several researchers have seen that efficiency of cooling and lubrication in the cutting zone has been improved by using the MQL technique over the last few decades (Du et al., 2022). Khan et al. (2009) compared the turning performance of AISI 9310 steel in dry and MQL environments. It is found that cutting zone temperature, formation of chips,machined surface quality and tool lifewere improved in MQL conditions in comparison to that of dry machining. Sun et al. (2022) conducted the experiments on GH4099 with ceramic end mills in dry and MQL environments. It is found that in MQL environment cutting temperature, surface quality, tool life, and the degree of end mill wear were improved compared to dry machining. Nowadays, several researchers are adding nanoparticles to the base fluids to improve the efficiency of MQL. However, the efficiency of MQL has been characterized based on the quality of droplets that is highly influenced by the MQL setup parameters viz compressed air pressure, liquid flow rate, nozzle angle, and nozzle distance from the tool tip (Awale et al., 2020). Park et al., (2010)investigated the influence of nozzle stand-off distance and air pressure on the droplet distribution and size by sprayed on the silicon wafer and found that the quantity of droplets decreases as the nozzle stand-off distance increases; when air pressure increases, droplets size reduces but quantity increases. Tawakoli et al., (2010) conducted the experiments on MQL assisted grinding process of 100Cr6 hardened

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https://doi.org/10.58368/MTT.22.4.2023.45-51

Table 1
Main chemical compositions of Incoloy 925.

Elements	Ni	Fe	Cr	Mo	Ti	Cu	Al
%	38.78	32.19	20.12	2.78	2.18	2.04	0.344

Table 2
Cutting process and MQL parameters.

Parameters	**Value**
Cutting Parameters:	
Speed (v_c)	60 m/min
Feed (f_z)	0.035 mm/tooth
Axial depth of cut (a_p)	0.2 mm
Radial depth of cut (a_e)	5 mm
MQL Parameters:	
Cutting fluid	Coconut oil (commercially purchased)
Air pressure (P_r)	2, 4, 6 Kg/cm^2
Liquid flow rate (Q)	50, 100, 150 ml/hr
Nozzle angle (θ)	30°, 45°, 60 °
Nozzle distance (D)	30, 45, 60 mm

steel; and reported that air pressure, liquid flow rate, and nozzle position are highly influencing factors for grinding cutting force and surface quality.

The optimized values of these parameters cannot be the same for all the machining processes like turning (Khan et al., 2009), milling (Sun et al., 2022) and grinding (Emami et al., 2013; Tawakoli et al 2010). The optimal parameters of MQL depend on the particular MQL system, the type of oil used, and the particular machining process used (Emami et al., 2013). Coconut oil, which mainly consist of saturated fatty acids (more than 90%), hashigh viscosity index, high lubricity, and high oxidative stability (Jayadas & Nair, 2006). However, research works on the optimization of bio-degradable oil-based MQL setup parameters for the end milling process are limited. So, atomization characteristics of the droplet of bio-degradable oil for end-milling performance on Incoloy 925 has been studied in the present work.

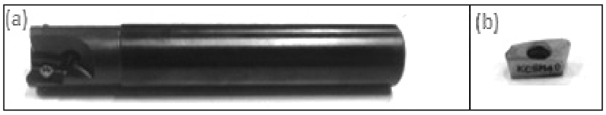

Fig. 1. (a) Inexable shoulder end mill, (b) Shape of insert.

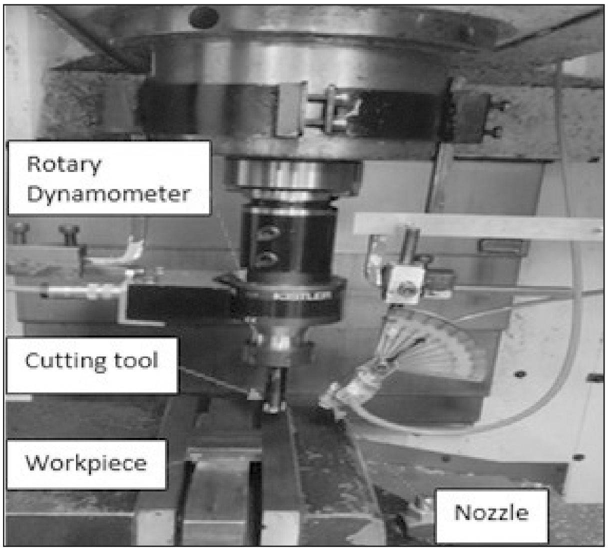

Fig. 2. Experimental setup for machining.

2. Experimental Methodology

Commercially purchased Incoloy 925 as a work material in dimensions of 50 x 50 x 15 mm^3 was used. The elemental compositions of the work material were obtained through Optical Emission Spectroscopy (OES) and listed in Table 1. Hardinge VMC 600 II as the Machine tool having spindle capacity of 8000 rpm and power capacity of 25KW, a shoulder end mill 1-10™ of 16 mm diameter tool (ISO 16A02R025A16ED10) and TiAlN/TiN PVD coated carbide inserts (ISO EDPT10T316PDERHD) manufactured by Kennametal were used. The indexable end mill is shown in Fig. 1(a), while the shape of insert is shown in Fig.1(b). The experimental set-up for machining is shown in Fig.2, whereas the cutting process and MQL parameters are presented in Table 2.

Kistler type of 9170A, rotating four component cutting force dynamometer (RCD), signal conditioning type of 5238B, and Dyno-Ware software was used for measuring the cutting force. For measuring surface roughness, Taylor Hobson precision, Model: Form Talysurf 50, and Taylor Hobson ultra 3.2.1 software were used. For viewing the microstructure of machined layer, cross-section of samples was polished up to mirror finish, and then etched using HCL (30 ml)

Table 3
Design of experiments with responses of machining.

S. No.	P_r (kg/cm^2)	Q (ml/hr)	θ (°)	D (mm)	F_c (N)	R_a (μm)
1	2	50	30	30	93.58	0.3579
2	2	100	45	45	91.81	0.3437
3	2	150	60	60	102.05	0.3295
4	4	50	45	60	106.41	0.3641
5	4	100	60	30	89.10	0.3418
6	4	150	30	45	82.13	0.2522
7	6	50	60	45	97.69	0.3622
8	6	100	30	60	86.72	0.2907
9	6	150	45	30	68.41	0.2733

and H_2O_2 (2 ml), while for viewing the size and distribution of atomized droplets of oil, samples were collected on glass slides, and LEICA optical microscope was used for this purpose. 3D topography of machined surface was captured using 3D optical profilometer (Zeta Instrument, Model: Zeta-20). Design of Experiments (DOE) is used to reduce the experimental cost and time. In this work, L9 orthogonal array design (as shown in Table 3) was used to minimize the number of experiments. To establish a linear relationship between MQL parameters and machining response, the first-order model of RSM was used. To analyse the impact of MQL parameters on cutting force (Fc) and surface roughness (Ra), ANOVA was performed. To optimize the MQL parameters Composite Desirability function, by giving equal weightage to machining responses, has been used.

3. Results and Discussion

For each experiment, three reading was recorded and the average observed values of cutting force (F_c) and surface roughness (R_a) are presented in Table 3. After the collection of data, further analysis has been done.

3.1. Mathematical model

The developed first-order models for cutting force (F_c) and surface roughness (R_a) using the RSM technique (Khidhir et al., 2015)with the help of Minitab 17, have been presented in Eq. (1) and Eq. (2), respectively.

$$Fc=82.19 - 2.884\, Pr - 0.1503\, Q + 0.2933\, \theta + 0.4899\, D \quad \text{..................(1)}$$

$$Ra = 0.3633 - 0.00874\, Pr - 0.000764Q + 0.001474\, \theta + 0.000126\, D \quad \text{..................(2)}$$

The model of cutting force, Eq. (1), and the model of surface roughness, Eq. (2), explain the data behavior with (R^2) 95.74% and 98.25%, respectively.

3.2 Analysis of variance (ANOVA)

ANOVA has the capability to show the efficiency of the developed mathematical model and the impact of the parameters on the machining responses (Cardoso et al., 2021). The results of ANOVA for the cutting force (Fc) and the surface roughness (Ra) have been listed in Table 4 and Table 5, respectively.

The percentage contribution of each parameter shows the degree of influence on the machining responses (Cardoso et al., 2021). At a confidence level of 95%, it can be concluded that cutting force model and surface roughness model are significant, with 95.74% and 98.25 %, respectively, for explaining the behavior of MQL parameters on machining responses. Oil flow rate (Q) is identified as the highest influencing factor on both cutting force and surface roughness, which explains 33.14 % and 63.49 %, respectively. Safiei et al. (2018) also found similar results during the end milling of AA6061-T6.

For checking the adequacy of models, residual plots have been used (Cardoso et al., 2021). Residual is the difference between experimental and predicted values. Fig. 3 and Fig.4 reveal that residuals are distributed normally, there are no particular trends, and errors are within the acceptable range.

Table 4
ANOVA for Fc.

Source	DF	Adj. (SS)	Adj. (MS)	F value	P value	Cont. %
Model	4	978.41	244.60	22.49	0.005	95.74
Pr	1	199.57	199.57	18.35	0.013	19.5
Q	1	338.70	338.70	31.14	0.005	33.14
θ	1	116.16	116.16	10.68	0.031	11.37
D	1	323.99	323.99	29.79	0.005	31.70
Error	4	43.50	10.88			4.26
Total	8	1021.91				

Table 5
ANOVA for Ra.

Source	DF	Adj. (SS)	Adj. (MS)	F-Value	P-Value	Cont. (%)
Model	4	0.01354	0.00339	56.12	0.001	98.25
Pr	1	0.00183	0.00183	30.41	0.005	13.28
Q	1	0.00875	0.00875	145.11	0.000	63.49
θ	1	0.00293	0.00293	48.61	0.002	21.26
D	1	0.00002	0.00002	0.35	0.584	0.15
Error	4	0.00024	0.00006			1.74
Total	8	0.01378				

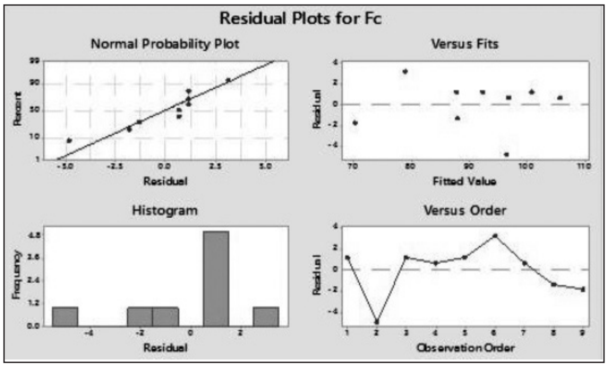

Fig. 3. Residual plots for Fc.

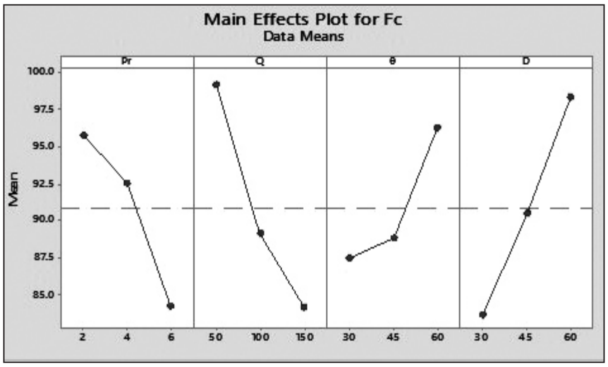

Fig. 5. Main effects plot for Fc.

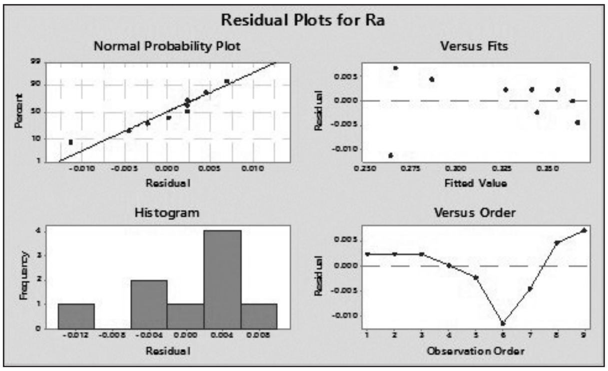

Fig. 4. Residual plots for Ra.

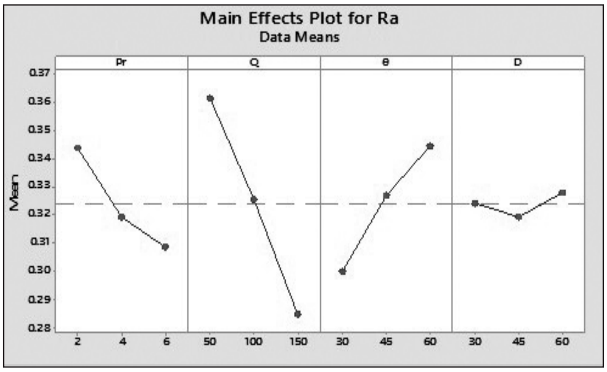

Fig. 6. Main effects plot for Ra.

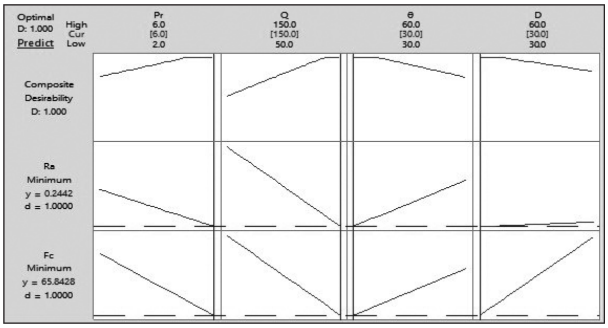

Fig. 7. Optimization plot.

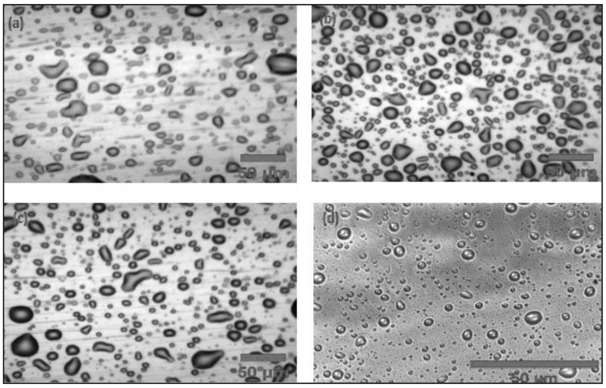

Fig. 8. Droplet shape, size, and distribution: (a) at low level, (b) at medium level, (c) at high level, (d) at optimal level of MQL parameters.

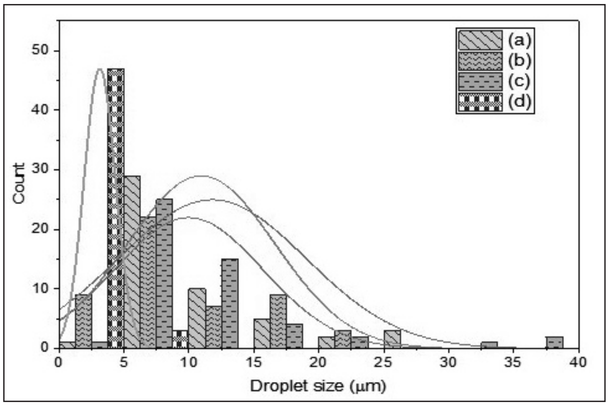

Fig. 9. Histogram of size distribution: (a) at low level, (b) at medium level, (c) at high level, (d) at optimal level of MQL parameters.

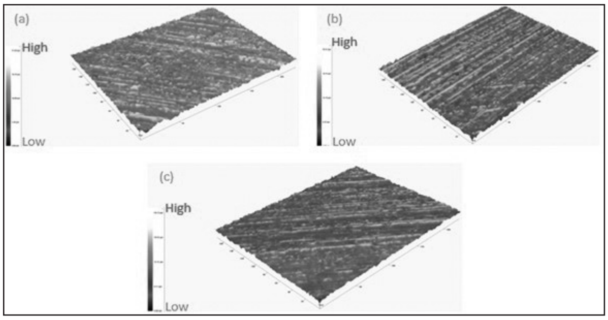

Fig. 10. 3D topography of machined surface: (a) at dry condition, (b) at high level, (c) at optimized level of MQL parameters.

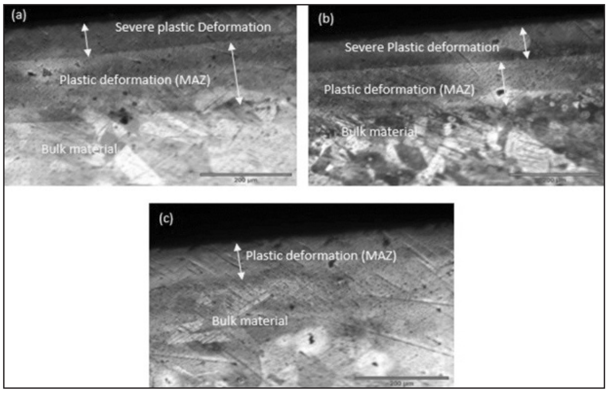

Fig. 11. Microstructure of machined surface layer: (a) at dry condition, (b) at high level, (c) at optimized level of MQL parameters.

3.3. Influence of parameters on machining responses

Fig. 5 and Fig. 6 clearly show that when oil flow rate and air pressure are increased, cutting force and roughness are decreased due to better atomization of oil droplets, and thus improved lubrication and cooling in the cutting zone. While, as the nozzle angle and nozzle distance from tool tip are increased, cutting force and surface roughness also increase. Several other researchers (Awale et al., 2020; Du et al., 2022; Safiei et al., 2018) have also studied the impact of MQL parameters on machining responses and found similar type of trends.

3.4. Optimization of MQL parameters

Optimization plot of MQL parameters using composite desirability function(Cardoso et al., 2021) is illustrated in Fig. 7. Droplet shape, size, and distribution at low, medium, high, and optimized level of MQL parameters have been shown in Fig. 8, while histogram of size distribution is shown in Fig. 9. 3D topography of machined surface, and microstructure of machined surface layer at dry, maximum level, and optimized value of MQL parameters have been shown in Fig. 10 and Fig. 11, respectively. Further, at the optimized value of MQL parameters viz Pressure of 6kg/cm^2, flow rate of 150 ml/hr, nozzle angle of 30°, and stand-off distance of 30 mm, an additional experiment for confirmation was conducted with repetition of three times and the average values of responses were taken; and it is compared with the prediction models of RSM as shown in Table 6. Errors of 4.91% with cutting force and 8.22% with surface roughness have been found that are acceptable.

Table 6
Responses at optimal set of parameters.

Source	Optimal set of parameters				Responses	
	P_r(kg/cm$^{2)}$	Q(ml/hr)	Θ (°)	D(mm)	F_c(N)	R_a(μm)
Experimental	6	150	30	30	62.76	0.2661
Predicted	6	150	30	30	65.84	0.2442
Error %					4.91	8.22

4. Conclusion

From these experiments the following conclusions can be drawn:

1. 150 ml/hr (flow rate), 6 kg/cm^2 (Pressure), 30° (nozzle angle), and 30 mm (nozzle distance) are the optimized values of the MQL parameters.
2. Cutting force (F_c) and surface roughness (R_a) have been reduced at optimized values of the MQL parameters due to better atomization of oil which caused better distribution of droplets and the reduction of coefficient of friction between workpiece and cutting tool.
3. Plastically deformed surface layer has been reduced at optimized value of MQL parameters due to effective lubrication and cooling.

Acknowledgments

We would like to thank Sri Subhash Chand for helping in preparation of the MQL set-up, and Sri Pankaj Sansanwal for assisting in the milling machine operation.

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