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Research Article

Study of the Effect of Minimum Quantity Lubrication on the Surface Roughness of Incoloy 800 during Turning Operation

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Abstract

The motto of this project work is focused on the effect of Minimum Quantity Lubrication (MQL) on the surface roughness produced during turning Incoloy 800. Experiments were designed using Orthogonal array and nine experiments each under different conditions of lubrication viz. dry, MQL1(150ml/hr), MQL2(300ml/hr) and flood(600ml/hr) were conducted. Later Taguchi methodology was used to optimize the cutting parameters to have lowest surface roughness among different combinations of speed, feed and depth of cut. The results were analyzed using Analysis of Variance (ANOVA). It was shown that feed played a major role in producing lower surface roughness followed by speed whereas depth of cut has least significance in producing lower surface roughness. It was observed from the results that MQL1 showed least surface roughness compared to dry, MQL2 and flood condition. Regression Analysis was carried out for different cutting conditions using Minitab software and mathematical models were generated which established relation among cutting parameters and surface roughness. The models validation were checked using residuals normal probability plot, residual versus order run plot. Finally the accuracy of the developed models was checked using predicted versus actual surface roughness plot.

Keywords: *Minimum quantity lubrication, Surface roughness, Taguchi method, Regression analysis.*

1. Introduction

Incoloy 800 is a solid solution-strengthened iron–nickel base super-alloy which is extensively used in high temperature environments, such as steam generator tubes, reformer tubes, pyrolysis tubes in the refinery and petrochemical industries, nuclear power reaction tubes and gas turbines. The objective of the present research paper is to study the effect of minimum quantity lubrication on surface roughness produced on Incoloy 800 during turning. In metal cutting industry the use of coolant has become more problematic in terms of both employee‘s health and environmental pollution. It is said that the use of coolant forms approximately 8-16 % of the total production costs (Abhang, *et al*, 2010).

MQL (minimum quantity lubrication) is based on the principle that a drop of liquid is split by an air flow, and transported in the direction of flow of air. In MQL machining, a small amount of vegetable oil or biodegradable synthetic ester is sprayed to the tool tip with compressed air. Minimum quantity lubrication refers to the use of only a minute amount of cutting fluids typically at a flow rate of 50–500 ml/h.

Sometimes this concept of minimum quantity lubrication is referred to as near dry lubrication or micro-lubrication (Khan, *et al*, 2009). The Taguchi parameter design method is an efficient experimental method in which a response variable can be optimized, given various control and noise factors, and using fewer experimental runs than a factorial design (Kirby, *et al*, 2006).

2. Experimental Setup

The work piece material used was two cylindrical bars of Incoloy 800 of 200 mm length and 32 mm diameter. The surface of each of the work pieces was divided at steps of 20mm sample length and experiments were performed. The cutting inserts used for the experimental work was uncoated tungsten carbide with specification CNMG-120408 manufactured by SECO. Lubricant used was sunflower seed oil which is one of the vegetable-based oil. The tool holder used in the experiment work was PCLNR-2020-M12 (approach angle: 95°, back rake angle: -6° and inclination angle: -6°). Machine tool used was GEDEE WEILER LZ300G. Figure1 shows the experimental setup. The setup of MQL system consisted of a burette which had a capacity of 50ml to supply lubricant at controlled rate. The burette was fixed over the tool post so that it moved along with the tool. Compressor system with nozzle at one end with maximum working pressure of 4 kg/ cm² (approx 4Pa) was employed as an external source to supply air to impinge between tool and work piece during machining. The experiments were conducted with speed as 40, 50 and 60 m/min; feed as 0.033, 0.066 and 0.132 mm/rev; and depth of cut as 0.5, 0.75 and 1.0 mm.

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Fig.1 Experimental setup

After each experiment run surface roughness was measured using HANDY SURF E-35A. Average surface roughness (Ra) was obtained by taking average of three surface roughness readings for each experiment.

3. Results and Discussions

As we know that surface roughness is an important parameter in manufacturing engineering.

Table 1 Observation of average roughness for dry

Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Avg. Ra (dry) (μm)	S/N Ratio
40	0.033	0.5	3.0	-9.5424
40	0.066	0.75	3.6	-11.126
40	0.132	1	4.1	-12.256
50	0.033	0.75	3.3	-10.37
50	0.066	1	3.8	-11.596
50	0.132	0.5	4.2	-12.465
60	0.033	1	2.8	-8.9432
60	0.066	0.5	3.26	-10.264
60	0.132	0.75	4.0	-12.041

Table 2 Observation of average roughness for MQL1

Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Avg. Ra (MQL1) (μm)	S/N Ratio
40	0.033	0.5	2.3	-7.2346
40	0.066	0.75	3.4	-10.6296
40	0.132	1	3.7	-11.3640
50	0.033	0.75	3.0	-9.5424
50	0.066	1	3.5	-10.8814
50	0.132	0.5	4.0	-12.0412
60	0.033	1	2.2	-6.8485
60	0.066	0.5	2.7	-8.6273
60	0.132	0.75	3.3	-10.3703

It is a characteristic that could influence the performance of mechanical parts and the production cost (Davim, 2001).

Thus, experiments were carried out to estimate the effect of process parameters (cutting speed, feed and depth of cut) on the output response i.e. surface roughness at different conditions of lubrication, viz. dry, MQL1(150ml/hr), MQL2(300ml/hr), and flood(600ml/hr). L9 orthogonal array was used for designing the experiments. The observations were recorded in the form of table as shown in table 1, table 2, table 3 and table 4 for dry, MQL1, MQL2 and flood conditions respectively. S/N ratio was calculated using Eq. (1).

Table 3 Observation of average roughness for MQL2

Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Avg. Ra (MQL2) (μm)	S/N Ratio
40	0.033	0.5	2.60	-8.2995
40	0.066	0.75	3.30	-10.3703
40	0.132	1	4.00	-12.0412
50	0.033	0.75	3.29	-10.3439
50	0.066	1	3.60	-11.1261
50	0.132	0.5	4.18	-12.4235
60	0.033	1	2.50	-7.9588
60	0.066	0.5	3.00	-9.5424
60	0.132	0.75	3.80	-11.5957

Table 4 Observation of average roughness for flood

Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Avg. Ra (flood) (μm)	S/N Ratio
40	0.033	0.5	2.82	-9.0050
40	0.066	0.75	3.40	-10.6296
40	0.132	1	4.10	-12.2557
50	0.033	0.75	3.40	-10.6296
50	0.066	1	3.60	-11.1261
50	0.132	0.5	4.30	-12.6694
60	0.033	1	2.76	-8.8182
60	0.066	0.5	3.20	-10.1030
60	0.132	0.75	4.00	-12.0412

3.1 Analysis of Variance

To obtain optimal machining performance, the smaller-the-better performance characteristic for surface roughness was taken (Nalbant, *et al*, 2007).
Smaller-is-the better (minimize):

$$\text{S/N ratio } (\eta) = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^{n} y^2 \right) \quad (1)$$

where y is observed data; n is the number of observations.

ANOVA was carried out to show the effect of process parameters that significantly affect the response. ANOVA table was generated using Minitab software.

3.2 Confirmation tests

The optimal levels of parameters were speed=60m/min, feed=0.033mm/rev and depth of cut=0.5mm. The predicted S/N ratios using these optimal levels of the parameters under different lubrication condition were calculated and corresponding surface roughness values were generated. The predicted values were compared with experimental values and % errors were obtained as shown in table 9.

Table 5 ANOVA for S/N ratio under dry condition

Source	DF	Seq SS	Adj SS	Adj MS	F	P	CSS	%ρ
Speed	2	1.6893	1.6893	0.8447	24.27	0.040	1.6197	13.00
Feed	2	10.4244	10.4244	5.2122	149.76	0.007	10.3548	83.15
Depth of cut	2	0.2697	0.2697	0.1349	3.87	0.205	0.2001	1.61
Error	2	0.0696	0.0696	0.0348				2.24
Total	8	12.4531						100.00

Table 6 ANOVA for S/N ratio under MQL1 condition

Source	DF	Seq SS	Adj SS	Adj MS	F	P	CSS	%ρ
Speed	2	7.3030	7.3030	3.6515	30.36	0.032	7.0624	26.81
Feed	2	17.6300	17.6300	8.8150	73.30	0.013	17.3894	66.02
Depth of cut	2	1.1646	1.1646	0.5823	4.84	0.171	0.9240	3.51
Error	2	0.2405	0.2045	0.1203				3.66
Total	8	26.3382						100.00

Table 7 ANOVA for S/N ratio under MQL2 condition

Source	DF	Seq SS	Adj SS	Adj MS	F	P	CSS	%ρ
Speed	2	3.9712	3.9712	1.9856	15.72	0.060	3.7186	18.73
Feed	2	14.9286	14.9286	7.4643	59.08	0.017	14.6760	73.92
Depth of cut	2	0.7024	0.7024	0.3512	2.78	0.265	0.4498	2.27
Error	2	0.2527	0.2527	0.1263				5.08
Total	8	19.8550						100.00

Table 8 ANOVA for S/N ratio under flood condition

Source	DF	Seq SS	Adj SS	Adj MS	F	P	CSS	%ρ
Speed	2	2.1417	2.1417	1.0709	13.50	0.069	1.9831	13.26
Feed	2	12.2408	12.2408	6.1204	77.16	0.013	12.0822	80.80
Depth of cut	2	0.4121	0.4121	0.2061	2.60	0.278	0.2535	1.69
Error	2	0.1586	0.1586	0.0793				4.25
Total	8	14.9533						100.00

3.3 Regression analysis

Multiple regression analysis was implemented to develop prediction models using the predictors viz. cutting speed, feed and depth of cut under different conditions of machining. In general the second order response surface model (Montgomery, 2001) is represented by Eq. (2).

$$y=\beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<j} \sum_{j=2}^{k} \beta_{ij}\ x_i x_j \qquad (2)$$

where y is the response;

β_j, j=0,1,2….,k. are called the regression coefficients;
x represents control factors.

Minitab software was used for the analysis of the experimental work. The Minitab software utilizes the specified data to develop predictive models for surface roughness under dry, MQL1, MQL2 and flood conditions. The models generated were reduced by eliminating insignificant factors. The generated models are as follows:

Avg. Ra (Dry)= -4.58+0.296 Speed+23.2323 Feed -0.00306667 Speed*Speed -75.5025 Feed*Feed

Avg. Ra (MQL1)= -11.3+0.546667 Speed+35.3535 Feed -0.00566667 Speed*Speed-142.843 Feed*Feed

Avg. Ra (MQL2)= -8.97333+0.48 Speed+11.8615 Feed-0.0049 Speed*Speed

Avg. Ra (Flood)= -6.48222+0.380667 Speed +11.4574 Feed -0.0038667 Speed*Speed

The summary of the model illustrates the effectiveness of the models developed as shown in table 10.

Table 9 Comparison of predicted and experimental Ra

Cutting condition	Predicted S/N Ratio	Predicted Avg. Ra (μm)	Exp. Avg. Ra (μm)	% Error
Dry	-8.88016	2.78	2.63	-5.70
MQL1	-6.33834	2.07	1.93	-7.25
MQL2	-7.83231	2.46	2.53	2.76
Flood	-8.78024	2.75	2.82	2.48

Table 10 Summary of the model

Condition	S	R-Sq %	R-Sq (adj) %	PRESS	R-Sq (pred) %
Dry	0.09922	98.03	96.07	0.19935	90.05
MQL1	0.17638	95.95	91.91	0.63000	79.52
MQL2	0.14365	96.30	94.08	0.36695	86.84
Flood	0.10703	97.59	96.15	0.20078	91.56

3.4 Validation of regression models

The residual is the difference between an observed value (y) and its corresponding fitted value (ŷ). The residual plots are used to check the goodness of the model fit (Mamun, *et al*, 2012).

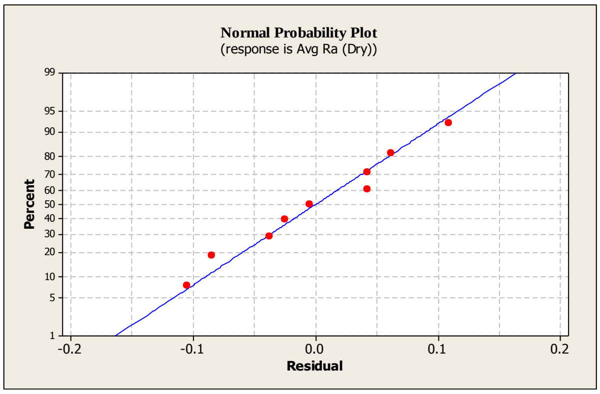

Fig.2 Normal probability plot (dry condition)

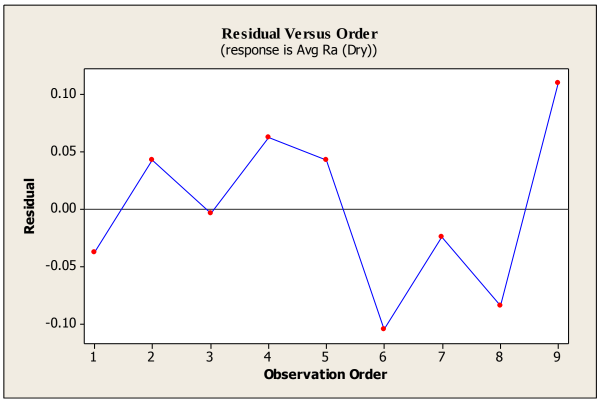

Fig.3 Residual vs. order plot (dry condition)

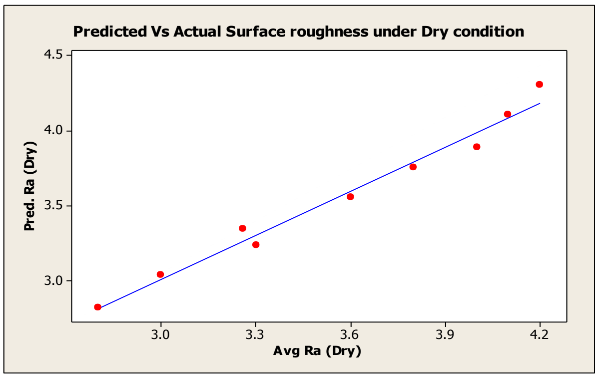

Fig.4 Predicted vs. actual Ra (dry condition)

In the normal probability plot the data points were fairly close to the fitted line. The predicted versus actual surface roughness was obtained through scatter plots and a good agreement between predicted values from the model and actual experimental values were seen by the closeness of the points to the line.

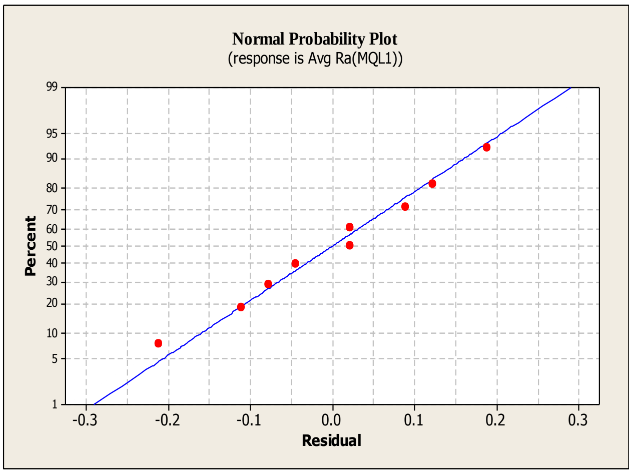

Fig.5 Normal probability plot (MQL1 condition)

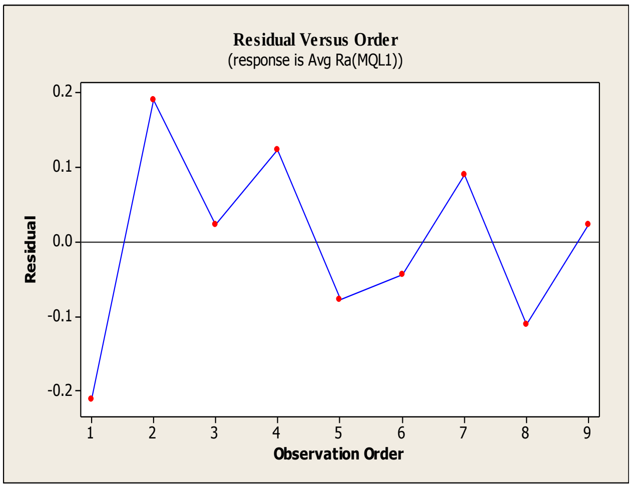

Fig.6 Residual vs. order plot (MQL1 condition)

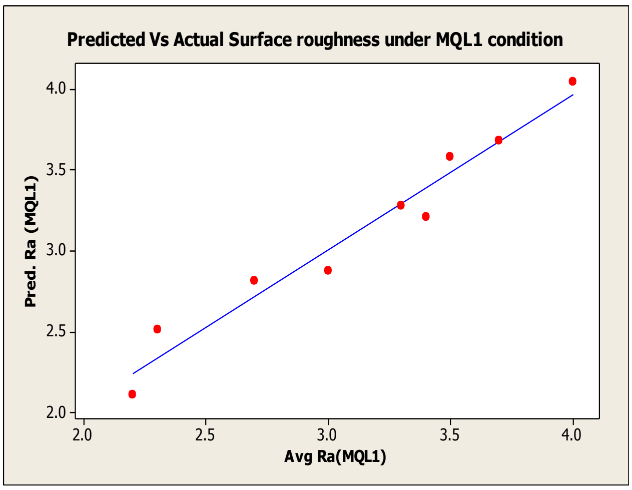

Fig.7 Predicted vs. actual Ra (MQL1 condition)

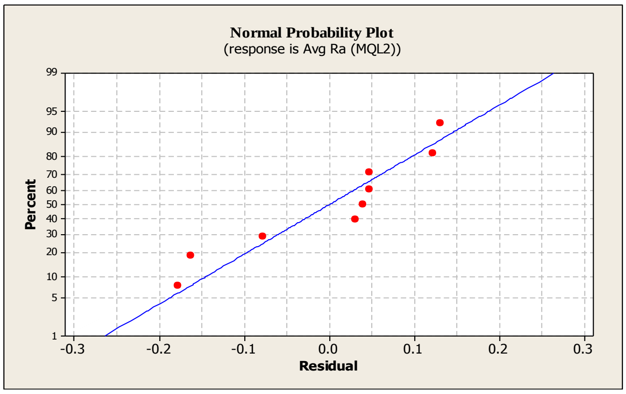

Fig.8 Normal probability plot (MQL2 condition)

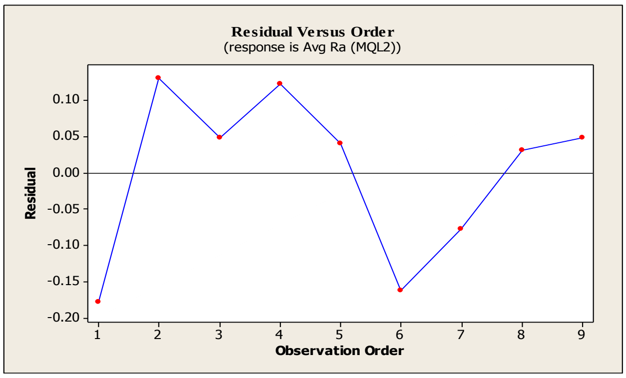

Fig.9 Residual vs. order plot (MQL2 condition)

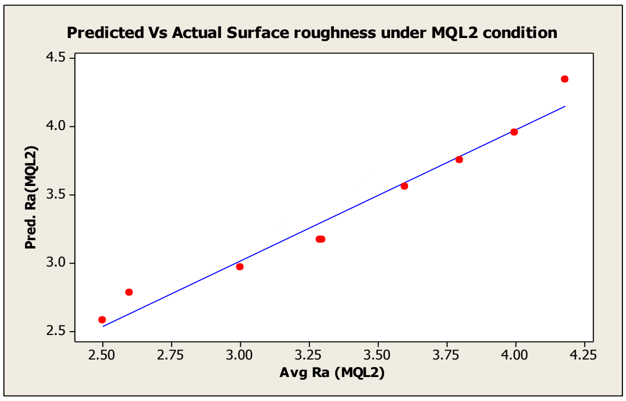

Fig.10 Predicted vs. actual Ra (MQL2 condition)

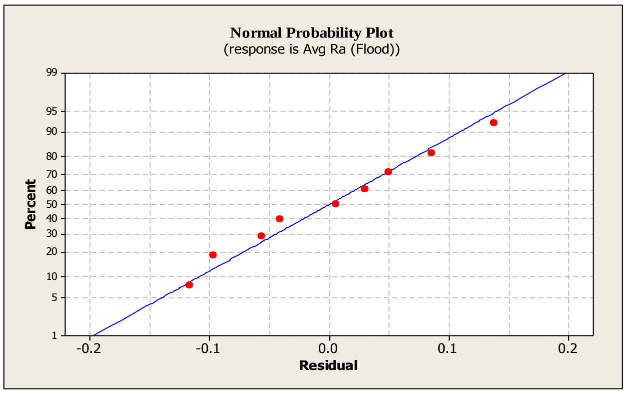

Fig.11 Normal probability plot (flood condition)

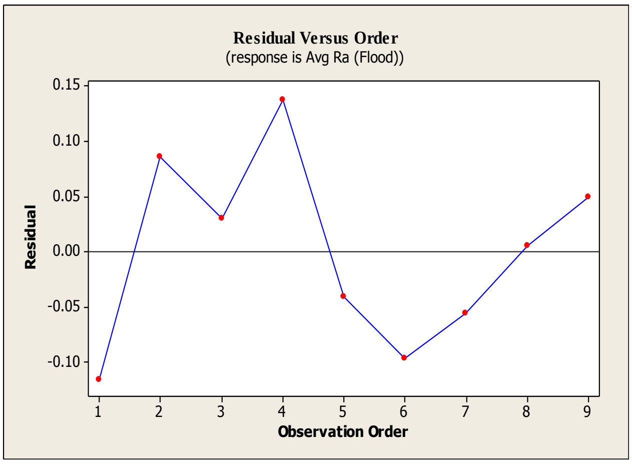

Fig.12 Residual vs. order plot (flood condition)

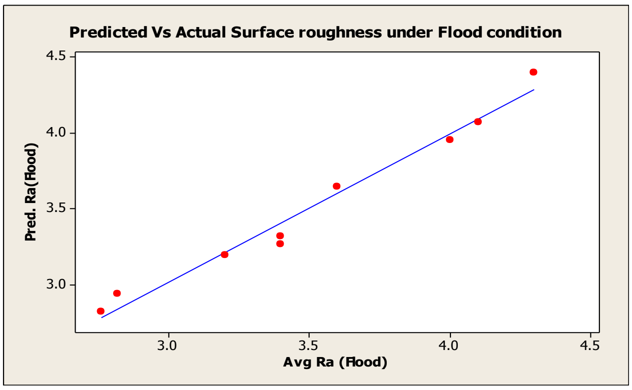

Fig.13 Predicted vs. actual Ra (flood condition)

Conclusions

The aim in this work was to take advantage of the Taguchi method to perform optimization with a small number of experiments and utilization of multiple regression analysis to obtain mathematical models which are a powerful tool to predict response for any of input parameters values within the experimental domain.

1) Through ANOVA it was confirmed that feed was the major significant factor followed by speed whereas depth of cut played an insignificant role in affecting surface roughness. This was true for all conditions of lubrication viz. dry, MQL1 (150ml/hr), MQL2 (300ml/hr) and flood (600 ml/hr).
2) Through Taguchi robust design methodology; the optimum levels of speed, feed and depth of cut is obtained as 60m/min, 0.033mm/rev, 0.5mm respectively. The % error between the predicted and experimental surface roughness at the optimum levels, in all conditions of lubrication, were below ± 10%.
3) Experimental and predicted surface roughness at optimal condition for MQL1 (150ml/hr) is 1.93µm and 2.07µm respectively which were below other dry, MQL2 and flood conditions' values at the same optimal condition.
4) By the regression model it was seen that under dry and MQL1 condition the surface roughness was influenced by speed, feed, speed^2 and feed^2 factors

and under MQL2 condition and flood condition surface roughness was influenced by speed, feed and speed^2 factors.

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