International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 8 (2015) pp. 21549-21563

http://www.ripublication.com

A Study on Effect of Sub Zero Temperature Cooling on Surface Roughness of Turned EN8 Steel Rod

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Abstract

Achieving ideal surface roughness is always a challenge in machining industry. An experimental study was conducted on dry turning of EN8 (AISI 1040) steel rod in two different turning environments namely pre cooling to Sub Zero temperature up to-45^{o}Cand room temperature in dry condition using four different cutting speeds 30, 49, 78, 123 metres/minute and feeds 0.18,0.315,0.4& 0.5 mm/revolution respectively at 1.5mm depth of cut. Dry ice was used for pre cooling the steel rod. The various aspects of surface roughness are studied and a regression model is created for predicting the surface roughness.

Keywords— Sub Zero Temperature; Cooling; Cryogenic; Dry ice; Surface roughness; Predcition model; Dry turning; EN8; AISI 1040; Steel; Anova; Cutting speed; Feed; Depth of cut.

INTRODUCTION

Many researchers already worked on finding out optimum cutting parameters under different machining environments. Cutting fluids reduces surface roughness values to the requirement but the disposal, health hazards and higher cost of cutting fluid makes researchers to think on various other solutions like cryogenic machining[1], Minimum quantity lubrication (MQL)[2] etc. Solid lubricants mixed with acid or oil proved to be effective than dry machining in EN8 steel but flow of lubricant fluid is difficult to control [3]. Vishal. S.Sharma et al[4] reported that mixing of air/vapor with different lubricants to reduce heat and in turn to reduce surface roughness. This method calls for a specially designed nozzle for mixing of lubrication oil with air vapor. W.Grzesik et al [5] used a pre cooling method for hard turning of 41Cr4 steel using a chamber.

Another way of pre cooling is supplying cryogenic cooling agent thru pipe and sending it over the work piece just before machining. Y.Ding et al [6] used this method to pre cool low carbon steel using liquid nitrogen. Yildiz and Nalbant [7] reviewed that over a period of 20 minutes there is substantial reduction in surface roughness while turning AISI 4037 with cryogenic jet cooling. However all this methods has its own advantages along with certain complexities such as special design of nozzle, need of special arrangements for using a cryogenic cooling agent and higher cost involved over using it. This work uses dry ice as a cooling agent and proposes a cooling chamber to pre cool the EN8 steel rod. This paper reports about benefits of pre cooling EN8 steel rod in a chamber before turning over room temperature turning in terms of surface roughness parameters. C.X. (Jack) Feng et al [8] reported how investigators created various empirical models for surface roughness prediction based on various factors and using different materials. In this paper a statistical prediction model is created using fit regression model using speed, feed and turning environment as varying factors.

Experiment

A. Set up

The experiment was conducted in Kirloskar make TURN MASTER 35 centre lathe.EN8 steel rod of diameter 35mm was cut into 150mm long pieces. It was held in 3 jaw chuck at one end and supported by live centre at another end. The depth of cut is kept constant at 1.5 mm. The experiment is based on single pass. TheTable.1listsspecifications, experiment conditions and its parameters.

TABLE.1 List of specifications

SLNO	SPECIFICATION	PARAMETER	
1	Material	EN8 (AISI 1040)	
2	Tool Holder	PCLNR 2525 M12	
3	Cutting Insert	CNMG 120408 MP TT 5100	
4	Environment	-45^{o}C using dry ice	Room Temperature
5	Cutting Speed (m/min)	30, 49, 78, 123	
6	Cutting Feed (mm/rev)	0.18, 0.315, 0.4, 0.5	

The chemical composition of EN8 (AISI 1040) steel rod is given in the Table.2

TABLE.2 Chemical composition of EN8 Steel rod.

C	Mn	Si	S	P
.35-.45	.60 –1.0	.05-.35	0.06 Max	0.06 Max

Dry ice is solid form of carbon dioxide and it directly evaporates as gas from solid state when it is heated. Dry ice has temperature as low as -78 degree Celsius [9]. It is easy to procure, use and dispose. It is also cheaper than any other cryogenic cooling agent. The steel rods are kept in dry ice as shown in Fig.1 for 16 hours before machining. The temperature of dry ice and cooled steel rod is confirmed using a "K" type thermo couple and a digital read out. Due to setting time taken in centre lathe the temperature of steel rod drops down from -78^{o}Cto -45^{o}C +/- 2^{o}C after taking out from cooling chamber and just before turning. The steel has ductile to brittle transition temperature (DBTT) between -50^{o}Cand-120^{o}C[10]. Hence this experiment happens at very low ductility of steel rod rather than semi ductility by means of dry ice cooling.

Fig.1 Dry Ice cooling chamber shown in unsealed condition.

B. **Measurement and Tabulation**

Totally 32 experiments were conducted in different cutting speed and feed combinations as listed in Table 3 out of which 16 are conducted in -45˚C using dry ice and another 16 are conducted in room temperature in dry condition. MIUTOYO make SURFTEST ST-301 surface roughness tester was used for measuring surface roughness Ra in µm. The length of measurement and cut off length was set as 4mm and 0.8mm respectively. The measurement has been taken in five places over the length of machining. Surface roughness Ra in microns is listed in Table 3. To avoid corrosion the turned steel rods are applied with corrosive resistant oil.

TABLE.3 Experiment combinations and Surface roughness Ra (µm)

Experiment No	Turning Environment	Speed (RPM)	Feed (mm/rev)	Surface roughness Ra (µm)
1	Dry Ice cooled	280	0.180	3.20
2	Dry Ice cooled	280	0.315	5.40
3	Dry Ice cooled	280	0.400	7.60
4	Dry Ice cooled	280	0.500	10.30
5	Dry Ice cooled	450	0.180	3.21
6	Dry Ice cooled	450	0.315	4.36
7	Dry Ice cooled	450	0.400	6.93
8	Dry Ice cooled	450	0.500	9.10
9	Dry Ice cooled	710	0.180	2.28
10	Dry Ice cooled	710	0.315	4.21
11	Dry Ice cooled	710	0.400	6.93
12	Dry Ice cooled	710	0.500	8.32
13	Dry Ice cooled	1120	0.180	1.70
14	Dry Ice cooled	1120	0.315	4.36
15	Dry Ice cooled	1120	0.400	6.80
16	Dry Ice cooled	1120	0.500	9.50
17	Room Temperature	280	0.180	4.30
18	Room Temperature	280	0.315	6.00
19	Room Temperature	280	0.400	9.30
20	Room Temperature	280	0.500	13.50
21	Room Temperature	450	0.180	4.50
22	Room Temperature	450	0.315	6.20
23	Room Temperature	450	0.400	8.05
24	Room Temperature	450	0.500	11.15
25	Room Temperature	710	0.180	2.60
26	Room Temperature	710	0.315	5.02
27	Room Temperature	710	0.400	7.50
28	Room Temperature	710	0.500	9.70
29	Room Temperature	1120	0.180	1.80
30	Room Temperature	1120	0.315	4.41
31	Room Temperature	1120	0.400	6.70
32	Room Temperature	1120	0.500	9.60

RESULTS AND DISCUSIONS

A. Surface roughness under various conditions.

The theoretical surface roughness Ra value is calculated using equation (1), where 'f^2' is feed rate in inches/revolution and 'r'is tool nose radius in inches [11].

$$\text{Theoretical Surface Roughness Ra} = \frac{0.0321\, f^2}{r} \quad (1).$$

The graph for surface roughness values Ra (µm) Vs feed (mm/rev) are plotted for each cutting speed 30, 49, 78& 123 m/min as shown in Fig 2 to Fig 5. It is found that a) surface roughness values are always lesser in case of dry ice cooled turning than room temperature dry turning for any speed and feed until cutting speed is 78 m/min. b) In all the cases, surface roughness Ra value in -45˚C turning environment using dry ice is closer to theoretical values which can be understood from Fig 2 to Fig 5. C) As feed rate approaches from 0.4mm/rev to 0.5mm/rev surface roughness in dry ice cooled turning either reaches theoretical value or drops down below theoretical value. All above said phenomenon is due to heat produced during dry ice cooled turning is far lesser than room temperature dry turning. This can be confirmed from the Fig 7a & 7b which compares the chip color between two cutting environments for same speed and feed of 123 m/min and 0.315mm/rev respectively. Blue color chips are produced under higher temperature interface between chip and work piece in room temperature dry turning where as golden metallic color in dry ice cooled turning. However dry ice cooing is not much effective while working at higher cutting speed say 123m/min. It can be understood from Fig 5 & 6 that there is no significant difference between dry ice cooled turning and room temperature dry turning at higher cutting speeds. Another phenomenon is that surface roughness values reaches theoretical value for any feed rate when cutting speed is 123m/min. The Fig 8 shows surface roughness values for different cutting speeds at a feed rate of 0.315mm/rev. It is evident from the Fig 8 that surface roughness value reaches theoretical value around 123 m/min. This phenomenon agrees with experimental data given by Boothrayd et al[12].

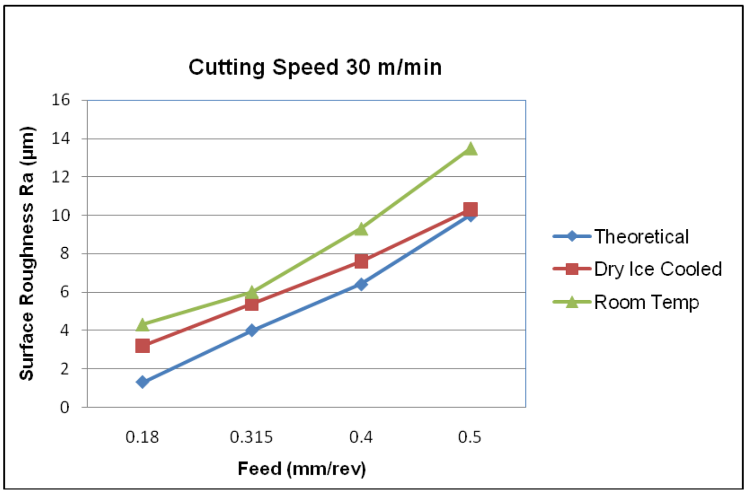


Fig.2 Surface roughness Ra (µm) vs. Feed (mm/rev) at cutting speed of 30metres/minutes.

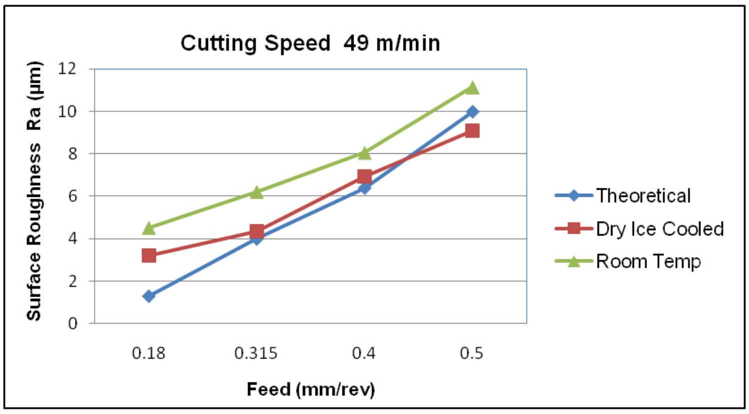


Fig.3 Surface roughness Ra (µm) vs. Feed (mm/rev) at cutting speed of 49metres/minutes.

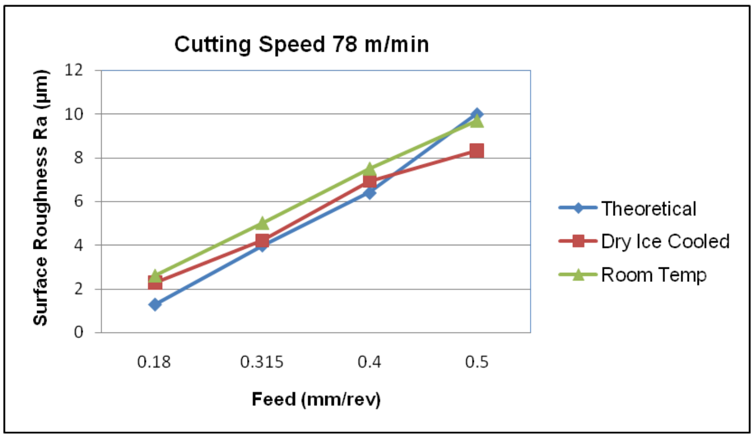


Fig.4 Surface roughness Ra (µm) vs.Feed (mm/rev) at cutting speed of 78metres/minutes.

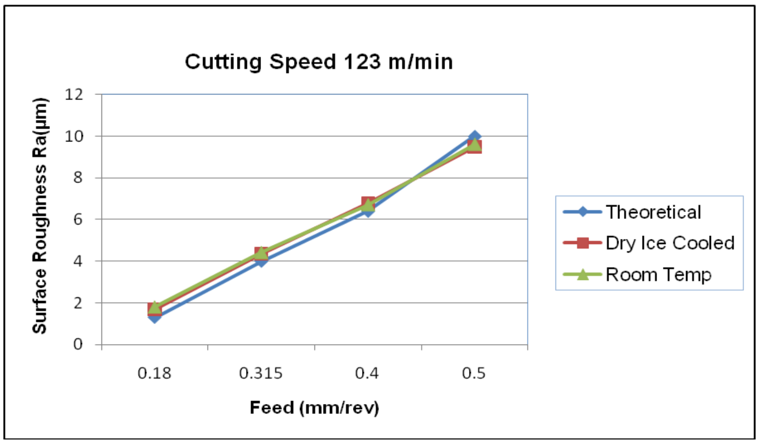


Fig.5 Surface roughness Ra (µm) vs. Feed (mm/rev) at cutting speed of 123metres/minutes.

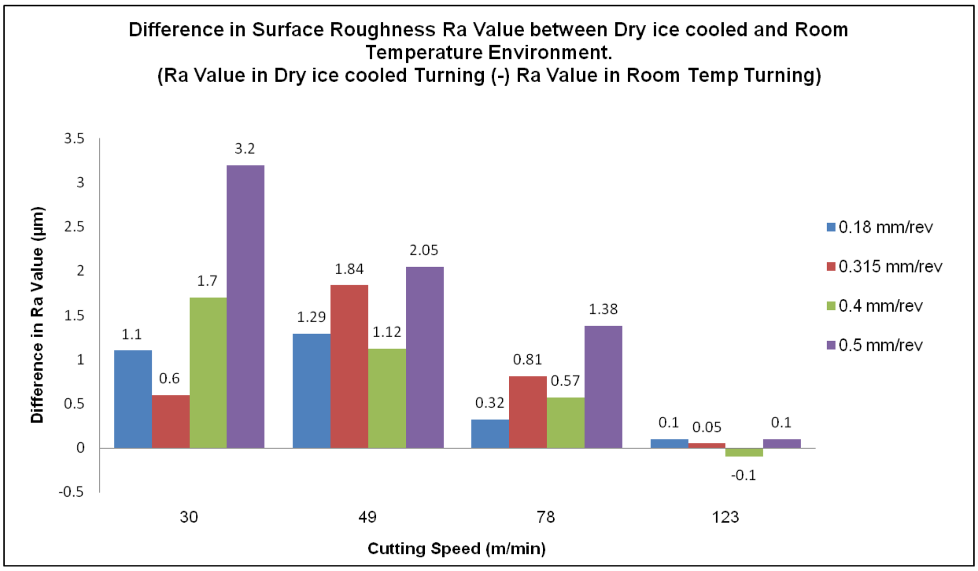


Fig.6 Difference in Surface roughness Ra value (µm) between two turning environments. (Surface roughness Ra in dry ice cooled tuning minus Surface roughness Ra in room temperature turning).

Fig.7a

Fig.7b

Fig.7 Chip formation at 123 metres/minute and feed rate of 0.315 mm/revolution.a)Room temperature turning and b) -45˚C temperature using Dry Ice.

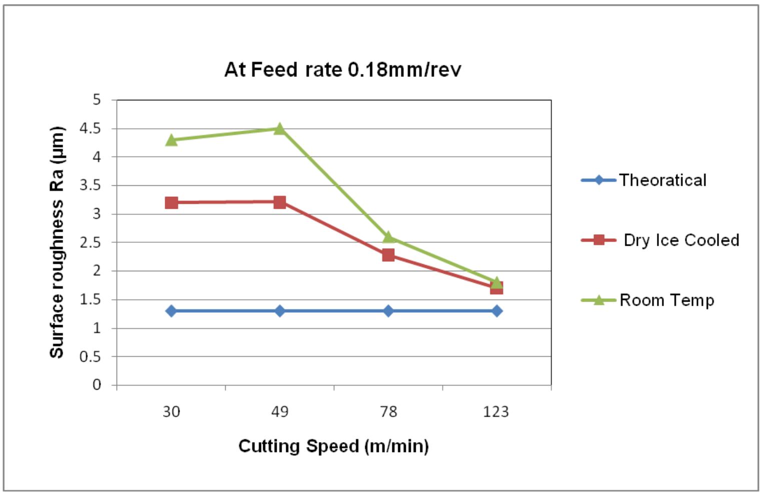


Fig.8 Surface roughness Ra (µm) vs. Cutting speed at a feed rate of 0.18mm/rev.

B. Surface roughness Prediction model.

I.A.choudury et al[13] used response surface graphs to find out optimum cutting parameters for given surface roughness value.

I.Puertas Arbizu, C.J. Luis Pérez [14] used both first order and second order polynomial regression method to design a surface roughness prediction model. Tugrul ozel et al[15]predicted flank wear of cutting tool and surface roughness using regression model and feed forward neural network and compared their merits. Tugrul ozel et al [16] used similar methodology while turning D2grade tool steel rod having hardness 61 HRC.

Surface roughness Ra value decreaseswith respect to cutting speed and increases with feedrate. Feed rate is dominant factor in deciding the surface roughness value[14]. The Fig 2 to 5 also proves that surface roughness has almost a linear positive relationship with respect to feed rate. This paper aims at a) to find out the significance of dry ice cooled turning over room temperature dry turning in terms of surface roughness. b) To design a prediction model for dry ice cooled turning and to compare with room temperature dry turning. Minitab17 software is used for creating a fit regression model. Fit regression model is created using stepwise procedure. The confidence level is taken at 95% and on both lower and upper bound. For stepwise procedure the alpha (α) value to enter and exit is 0.15. The list of factors and response is shown in the "Table 3". Speed and feed are taken as continuous predictors where as environment in which turning was done (Dry ice cooled turning and Room temperature dry turning) is taken as constant predictor. The ANOVA table [Table 4] and co-efficient table [Table 5]is listed below. The P value shown in the Table 4 for all the three factors are less than confidence interval (α) of 0.05, the factors found to be significant. The main effect factors plot[Fig 9] show that feed, speed and turning environment has an effect on surface roughness. The R^2 and Adjusted R^2 found to be 92.68 and 91.89% shows that the factors are well defined in the regression model. The Predicted R^2 value found to be 90.4% shows that the statistical prediction model will have a good ability for future prediction of surface roughness value Ra for any value of continuous factors speed and feed.

TABLE.4ANOVATable for fit regression model.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	248.169	82.723	118.14	0.000
Speed (mm/rev)	1	16.446	16.446	23.49	0.000
Feed (mm/rev)	1	225.521	225.521	322.06	0.000
Turning Environment	1	5.958	5.958	8.51	0.007
Error	28	19.607	0.700		
Lack-of-Fit	27	17.252	0.639	0.27	0.934
Pure Error	1	2.354	2.354		
Total	31	267.775			

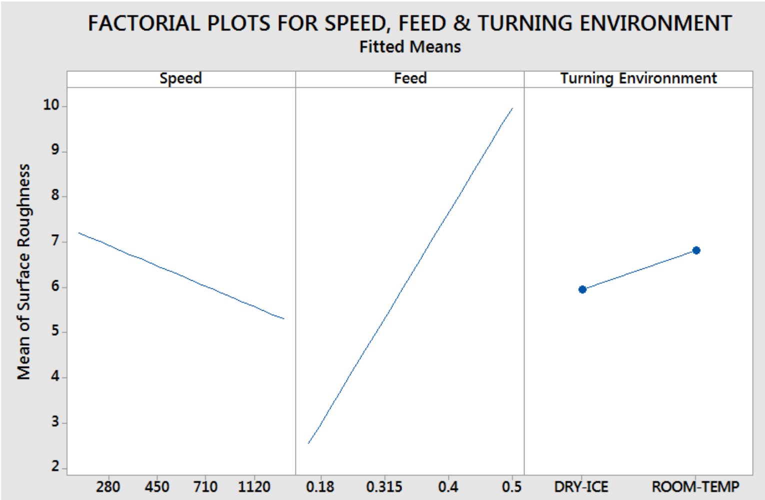


Fig.9 Main effect factors plot.

P value for lack of fit is more than confidence interval of 0.05 which also shows that model is well defined. The values of variation inflation factor (VIF) in Table 5 suggest that the factors cutting speed, feed and environment are not correlated with each other in defining of the model. Fig 10 shows a normal probability plot for fit regression model which is linear and variance is very less. Residual versus fitted value is plotted in Fig 11also shows that variance in residual is distributed both sides of mean value evenly and shows linearity. Fig 12 shows a residualversus observation order, in which observation order number 20 shows a large residual value. Other than order number 20 all other values fall within a smaller range.

Table.5 Prediction model'sCoefficient table.

Term	Coefficient	SE Coefficient	T-Value	P-Value	Variation Inflation Factor
Constant	-0.600	0.570	-1.05	0.301	
Speed (rpm)	-0.002264	0.000467	-4.85	0.000	1.00
Feed (mm/rev)	23.17	1.29	17.95	0.000	1.00
Turning Environment					
2	0.863	0.296	2.92	0.007	1.00

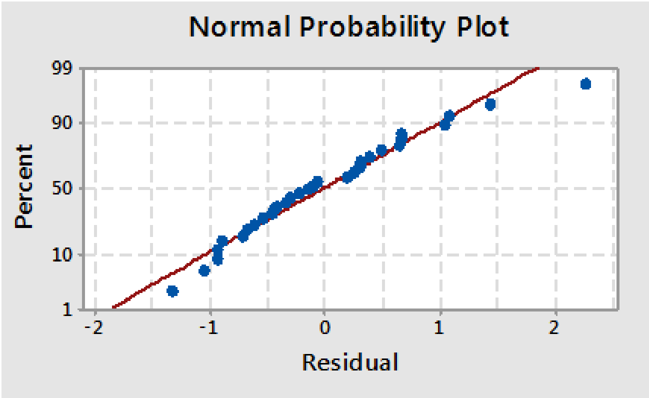


Fig.10 Normal probability plot for fit regression model.

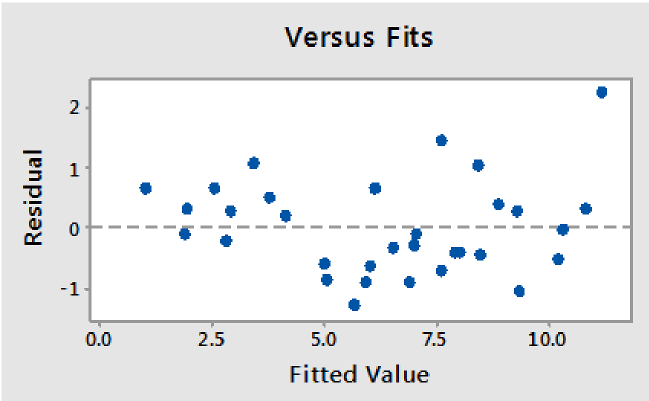


Fig.11 Residual versus fitted value for fit regression model

The linear regression model for dry ice cooled turning is given in equation (2) and for room temperature turning is given in equation (3).

Surface roughness Ra (μm)= (-0.600)–(0.002264) cutting speed (rpm) + 23.17 feed (rev/min)(2)

Surface roughness Ra (μm)= (0.263)–(0.002264) cutting speed (rpm) + 23.17 feed (rev/min)(3)

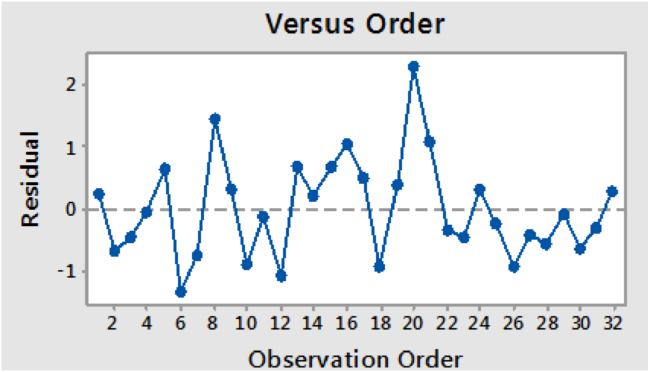
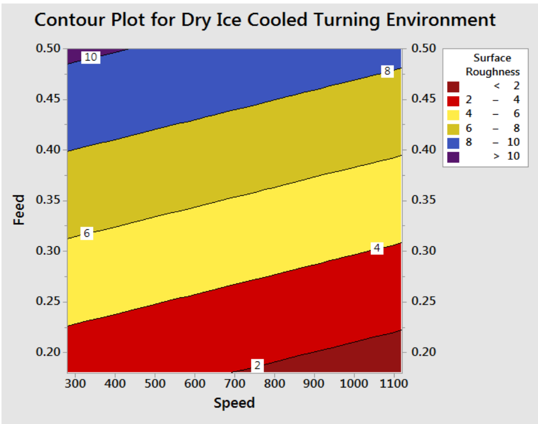


Fig.12 Residual Versus observation order for fit regression model.



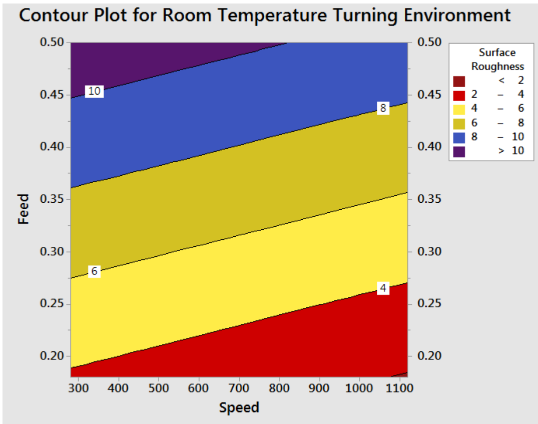


Fig.13a **Fig.13b**

Fig.13 contour plots for speed Vs feed at a) Dry ice cooled turning environment & b) Room temperature turning environment.

Fig.13 a &13b shows that to maintain a desirable surface roughness Ra value in dry ice cooled turning environment higher feed rate can be selected for given speed. The surface plot is converted in to table form [Table 6] for selectable feed rates at given speeds at achieve a desirable surface roughness Ra value. This clearly shows that at dry ice cooled turning environment the material removal rate (MRR) will be higher as both feed rate and cutting speed has positive linear relationship with material removal rate (MRR) [17].Toachieve a surface roughness of 4 µm, at a speed of 280 rpm an 80% increase in feed rate is possible where as at a speed of 1120 rpm a 15% increase is only possible. The % increase in feed rate is 8% to 16%,when desirable surface roughness Ra value to be achieved is more than 6µm. Hence it is proved that productivity will increase at least by 8% and up to 16% when desirable surface roughness Ra value to be achieved is between 6 to 8µm at dry ice cooled environment.

TABLE.6 Selectable feed rates for given speed to achieve specific surface roughness Ra (µm).

Sl No	Desirable surface roughness Ra (µm) to be achieved.	Speed (rpm)	Selectable Feed rate		% Increase in Selectable Feed rate for Dry Ice cooled Temperature
			Dry Ice cooled Temperature	Room Temperature	
1	4	280	0.225	0.125	80
		1120	0.310	0.270	15
2	6	280	0.320	0.275	16
		1120	0.390	0.360	8
3	8	280	0.400	0.360	11
		1120	0.475	0.440	8

The Fig 14 shows the difference between predicted surface roughness values from fit regression model and actual surface roughness values from experiment.The % error found to be within +/- 21% for 90% of the experiments.

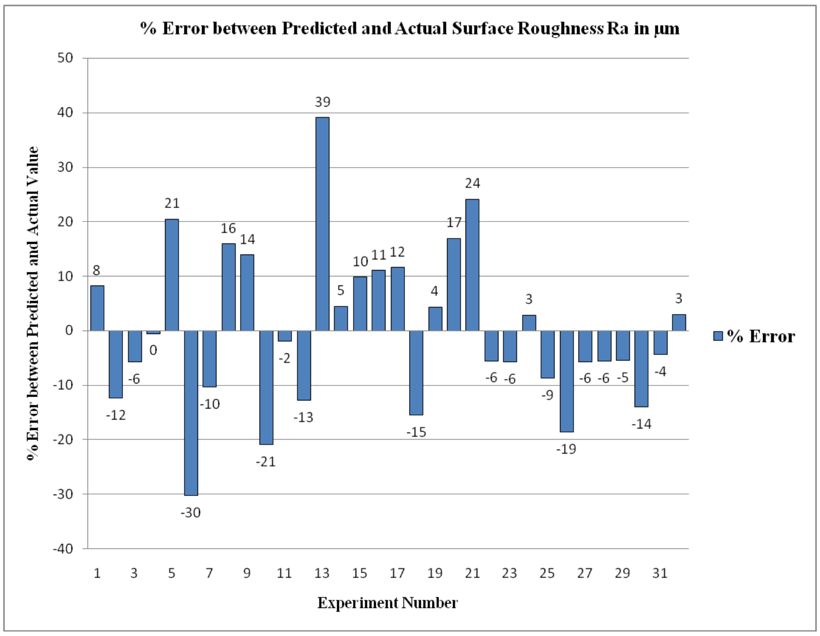


Fig.14 - % Error between Predicted and actual surface Roughness Ra in µm.

CONCLUSION

One set of EN8 steel rod had been cooled in dry ice chamber for 16 hours and turned at four different cutting speeds and feeds. Another set of rods were turned in room temperature in dry condition at similar cutting speeds and feeds. The surface roughness Ra values of dry ice cooled turning are compared with room temperature dry turning. The surface roughness prediction model is created based on speed, feed and turning environment namely dry ice cooled turning at -45˚C and room temperature dry turning.

Contour plots were made to find out possible feed rate and speed at which turning can be done in both turning environments to achieve a desirable surface roughness Ra value. The findings are listed below.

1. The surface roughness Ra value in dry ice cooled turning found to be lesser than room temperature dry turning up to cutting speed of 78m/min.
2. Surface roughness in dry ice cooled turning found to be very closer or lesser than theoretical surface roughness value Ra up to 78m/min.
3. At higher cutting speeds, there is no difference in surface roughness Ra values between dry ice cooled turning and room temperature dry turning for any feed rate.
4. At a desirable surface roughness Ra of 4µm, Feed rate (mm/rev) can be increased by 80% at 30m/min cutting speed and by 15% at123m/min cutting speedin dry ice cooled turning environment that room temperature dry turning environment.
5. For any desirable surface roughness Ra value, % increase in feed rate(mm/rev) between dry ice cooled turning and room temperature turning is higher at lower cutting speed (30m/min) and lower at higher cutting speed (123m/min).
6. Contour plot suggests that to achieve any desirable surface roughness value at least 8% in feed rate (mm/rev) can be increased in dry ice cooled turning than room temperature dry turning. Hence productivity can also be increased by at least 8%.
7. Dry ice cooled turning is useful for finish turning as it yields lower surface roughness value as experiment is conducted in single pass turning and with constant depth of cut.
8. A prediction model is designed for dry ice cooled and room temperature turning environments and % error found to be between +/- 21 % for 90% percent of experiments.

Acknowledgment

This project was fully funded by Amrita Vishwa VidyaPeetham University. Our special thanks to Dr.Sasangan, Dean Engineering, Amrita school of Engineering, Coimbatore Campus and to Dr.S.Thirumalini, Chair person, Mechanical Engineering Department, Amrita School of Engineering, Coimbatore campus. We acknowledge Mr.Sivaraman, CEO, Tool Tech Engineering, Chennai for giving cutting inserts at discounted value.

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