Global Journal of Researches in Engineering
Mechanical and Mechanics Engineering
Volume 12 Issue 5 Version 1.0 Year 2012
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4596 Print ISSN:0975-5861

Numerical Modeling of Surface Roughness in Grinding under Minimum Quantity Lubricants (MQL) using Response Surface Method (RSM)

By Mamun A A & Dhar N R

University of Engineering and Technology, Bangladesh.

Abstract - Grinding is primarily a finishing operation where high temperature at the wheel-work interface adversely affects the physical properties of the ground surface in terms of induced surface and sub surface residual stress, surface roughness, micro cracks and dimensional deviation. Conventional application of cutting fluid often cannot control the high temperature generated especially during high speed grinding. Besides, environmental pollution, effect on human health and higher cost has been a great concern of researchers and industries. One of the possible solutions of such problems is the Minimum Quantity Lubricants (MQL) technique which has both economical and environmental advantages. The present investigation is to evaluate the influence of MQL on chip formation mode and surface roughness in grinding AISI 1045 steel with CBN wheel at different level of process parameters. The result indicated that, MQL enables the reduction in surface roughness and more favorable chip formation mode compared to dry grinding.

Keywords : Grinding, Temperature, MQL.

GJRE-A Classification : FOR Code : 091306, 091307

Numerical Modeling of Surface Roughness in Grinding under Minimum Quantity Lubricants (MQL) using Response Surface Method (RSM)

Mamun A A [α] & Dhar N R [σ]

Abstract - Grinding is primarily a finishing operation where high temperature at the wheel-work interface adversely affects the physical properties of the ground surface in terms of induced surface and sub surface residual stress, surface roughness, micro cracks and dimensional deviation. Conventional application of cutting fluid often cannot control the high temperature generated especially during high speed grinding. Besides, environmental pollution, effect on human health and higher cost has been a great concern of researchers and industries. One of the possible solutions of such problems is the Minimum Quantity Lubricants (MQL) technique which has both economical and environmental advantages. The present investigation is to evaluate the influence of MQL on chip formation mode and surface roughness in grinding AISI 1045 steel with CBN wheel at different level of process parameters. The result indicated that, MQL enables the reduction in surface roughness and more favorable chip formation mode compared to dry grinding. The whole experiment has been repeated with Alumina wheel under same experimental conditions to assess the performance of CBN wheel. A Response Surface model has been developed to predict the surface roughness while grinding AISI 1045 steel with CBN wheel under MQL technique. The model is then checked and validated by comparing with experimental results and found reasonably accurate.

Keyword : Grinding, Temperature, MQL.

I. INTRODUCTION

Grinding is a manufacturing process widely used in manufacture of parts and components requiring smooth surface and fine tolerance. Abrasive processes like grinding are the natural choice for machining very hard materials. In grinding operation a wheel containing the abrasive particles rotate at a specified velocity and a table below the wheel moves with reciprocal motion. As the abrasive particle come in contact with the workpiece surface they rub against the surface and removes a chunk of metal from it. This rigorous process on the metal surface produces ridges and valleys which can be quantified by the term surface roughness.

In high speed machining, conventional cutting fluid application fails to penetrate the chip-tool interface and thus cannot remove heat effectively [1], [2], [3]. Addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip-tool interface to provide lubrication and cooling [4]. However, high-pressure jet of soluble oil, when applied at the chip-tool interface, could reduce cutting temperature and improve tool life to some extent [5], [6]. Grinding becomes an environmentally unfriendly manufacturing process when a large of amount of cutting fluid is used. Now-a-days efforts are being made to minimize the use of cutting fluid for its detrimental effect on human health and environment and for covering a large percentage of total manufacturing cost (around 17%). Cutting fluids are difficult and expensive to recycle. They can cause skin diseases like dermatitis and have fatal effect on respiratory and dietary system of the machine operator [7], [8], [9]. Inappropriately handled and poorly disposed cutting fluid may have great environmental impact [10]. As the result of these consequences significant pressure is needed to adopt toward stricter standard and rigid regulations. In today's manufacturing industry cost effectiveness depends largely upon the high production rate which entails the need of high speed machining. The use of MQL is of great significance in conjunction between large cutting fluids application and dry machining. Minimum quantity lubrication (MQL) also known as Near Dry Machining (NDM) or semi dry machining is an alternative to traditional use of cutting fluids. As the name implies, MQL uses a very small quantity of lubricant delivered precisely to the cutting surface. Often the quantity used is so small that no lubricant is recovered from the piece.

Minimum quantity lubricants (MQL) systems employ mainly cutting fluids that are nonsoluble in water, especially mineral oils. These oils, inhaled in the form of aerosol, reduce the health hazard factor [11]. It is found that the MQL technique provides efficient lubrication, reducing the grinding power and the specific energy to a level of performance comparable or superior to that obtained from conventional soluble oil, while at the same time it significantly reduces grinding wheel wear [12]. Another characteristic of this technology is that when properly applied, both parts and chips remain dry and are easier to handle [13]. Better cutting performance can be obtained with Minimum Quantity lubrication (MQL) than dry and flood cooling [3]. In MQL a mixture of pressurized air and oil micro-droplets are

---

Author α σ : Department of Industrial and Production Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh.

applied directly into the interface between the tool and the chip [14].

MQL grinding is still a relatively new research area, and only a few researchers have studied MQL grinding. Dhar et al. [15] investigated the effect of MQL technique to grind 16MnCr5 alloy steel on the cutting performance compared to completely dry cutting and flood cooling with respect to grinding temperature, surface roughness, chip morphology. The results indicated that the use of minimum quantity lubrication (MQL) by cutting oil (VG-68) leads to lower surface roughness compared to dry and wet environments. Silva et al. [16] investigated the performance of MQL system to grind ABNT 4340 steel (HRC 60) with alumina wheel. It was found that, MQL system leads to finer surface finish and higher compressive residual stress compared to dry and conventional cooling. The performance of MQL technique is investigated by Tawakoli et al. [17] for both hard steel 100cr6 and soft steel 42CrMo4. For LB8000 MQL oil with wheel speed 25 m/s and depth of cut 25μm the surface quality improvement in MQL grinding is found to be more significant in comparison to dry and fluid grinding. Barczak [18] studied the machining performance of MQL for mild steel (BS 970 080M40, 32±2 HRC), bearing steel (BS534A99, 62±2 HRC) and tool steel (BS BM2, 52±2 HRC) with alumina wheel. The performance was evaluated in terms of tangential force, surface roughness, force ratio and grinding arc temperature. It has been found that, Low grinding force makes the MQL a low temperature process. But the suitability of MQL is found limited to relatively softer material.

Experimental investigation to assess the surface quality of a ground surface for a specific wheel-work combination is time consuming. Predictive model in this case can give useful insight about the expected value of surface roughness. A probabilistic approach to predict surface roughness in ceramic grinding is depicted in [19] considering the random grit protrusion height and assuming individual grain as spherical.

II. EXPERIMENTAL CONDITIONS AND PROCEDURE

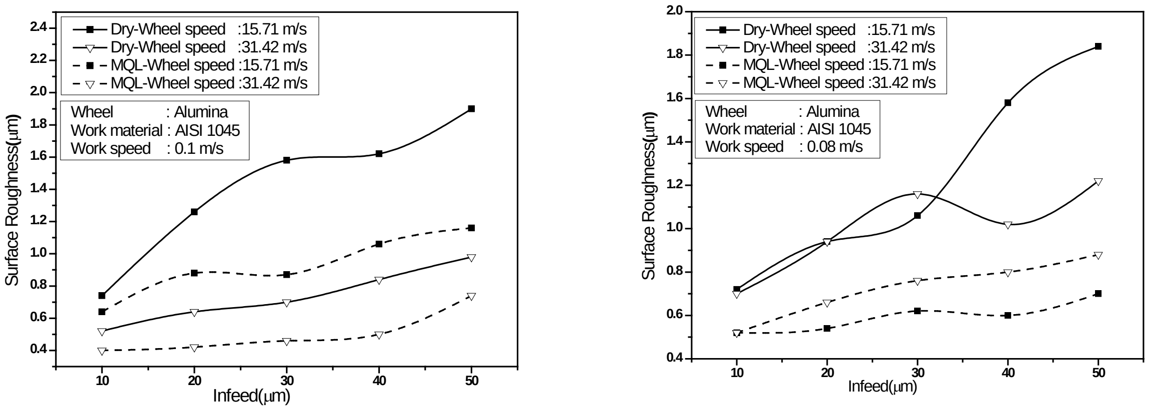
The purpose of the experimental investigation in this present research work is to measure the grinding surface roughness under Minimum Quantity Lubrication. The machining tests were carried out by grinding AISI 1045 steel with both alumina wheel and CBN wheel in a rigid surface grinder at different cutting condition under dry and Minimum Quantity Lubrication environment shown in Fig.2. The ranges of cutting conditions chosen in the present investigation are representative of the current industrial practice for the tool-work material combination that has been investigated. The conditions under which the machining tests have been carried out are briefly given in Table 1.

Fig. 2 : Photographic view of the experimental setup

Table 1 : Experimental conditions

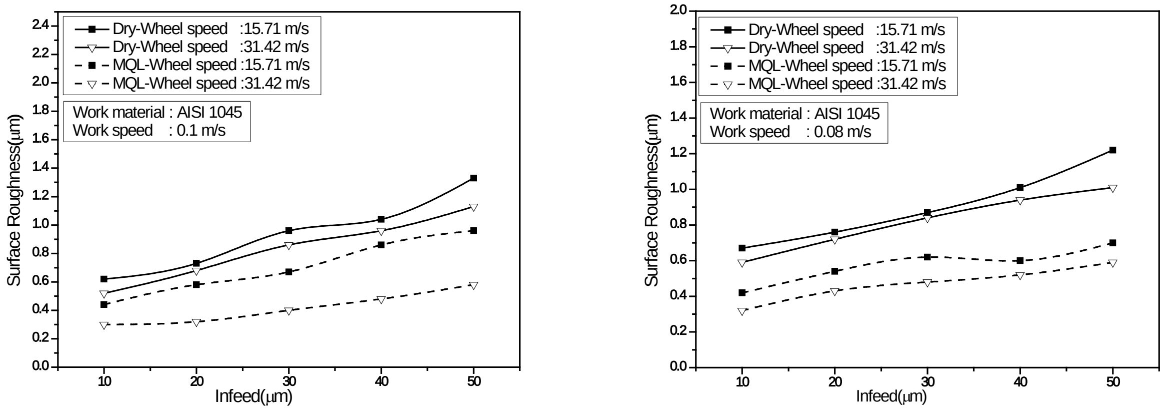
Machine tool	:	Surface Grinder, China(2.1/2.8 KW)
Work materials	:	AISI 1045 steel
Grinding Wheel	:	CBN Wheel(Grain Size-107 µm, Grain Concentration-4.4 cts/cm^3, CBN layer thickness-4 mm)
Grinding Mode	:	Down cut
Process parameters		
Spindle Speed	:	1500 rpm, 3000 rpm
Wheel speed, v_s	:	15.21 m/s, 31.42 m/s
Infeed, a_o	:	10, 15, 20, 25, 30, 40, 50 µm
Table Speed, v_w	:	0.08 m/sec, 0.1 m/sec
Minimum Quantity Lubrication (MQL)	:	30 bar, Coolant: 2.0 ml/min through external nozzle
Coolant type	:	VG-68 (ISO grade)
Environment	:	Dry and Minimum Quantity Lubrication (MQL)

After grinding the steel specimen with alumina and CBN wheel the surface was checked rigorously. The surface features include general textures, plastic deformation of asperities, oxidations and cracks. All of them are usually the result of high grinding temperature. A typical parameter that has been used to quantify the quality of a surface is the surface roughness, which is represented by arithmetic mean value, R_a. Here experimental investigation is performed on AISI 1045 steel under dry and MQL condition with different cutting condition. The roughness of the ground specimen is measured in transverse direction by a Taylor Hobson Talysurf Surtonic 3+ roughness checker, UK. The sample length is taken as 0.8 cm. Fig. 3 shows the experimental surface roughness of the ground surface for Alumina wheel with different process parameters for both dry and MQL cooling environment. High roughness value is observed for dry cutting at higher infeed value. Fig.4 shows the roughness values for machining AISI 1045 steel with CBN wheel. From figure it has been found that Surface roughness value is substantially lower for MQL than dry in all conditions. It is also observed that in most of the cases for both dry and MQL condition CBN produced better surface finish than alumina wheel.



(a) (b)

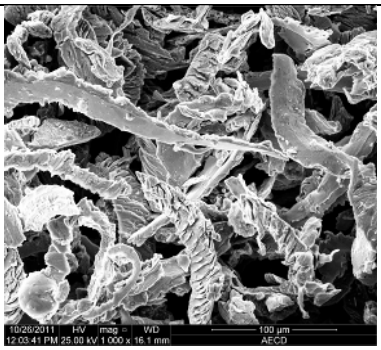
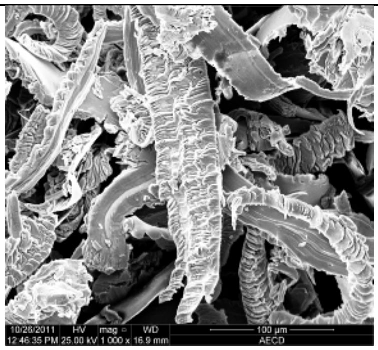
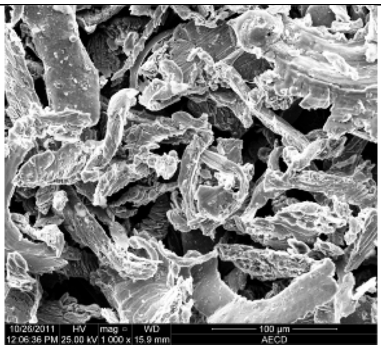
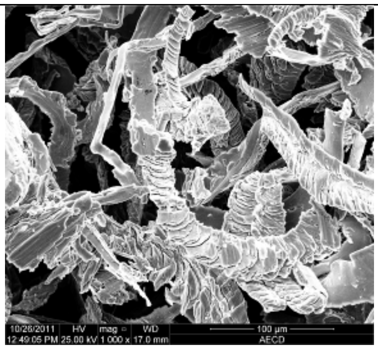
Fig. 3 : Variation of Surface roughness under dry and MQL condition for AISI 1045 steel with Alumina wheel



(a) (b)

Fig. 4 : Variation of Surface roughness under dry and MQL condition for AISI 1045 steel with CBN wheel

The grinding chips are collected during the experiment by placing a glass coated with lubricating oil. The glass slide is placed near the spark stream after steady state is obtained with no vibration and change in the magnitude of grinding force with the number of passes. The chips are then placed on a clean glass slide and thoroughly washed with acetone, dried and separated from grinding wheel debris. The dried chips are then attached to carbon tape, mounted on a small disk and observed under Scanning Electron Microscope (SEM) to study the morphological characteristics. Fig 5 shows the SEM view of the chips that are obtained for three different infeed with dry and MQL machining environment when grinding AISI 1045 steel with CBN wheel.

	Dry	**MQL**
10 µm		
20 µm		

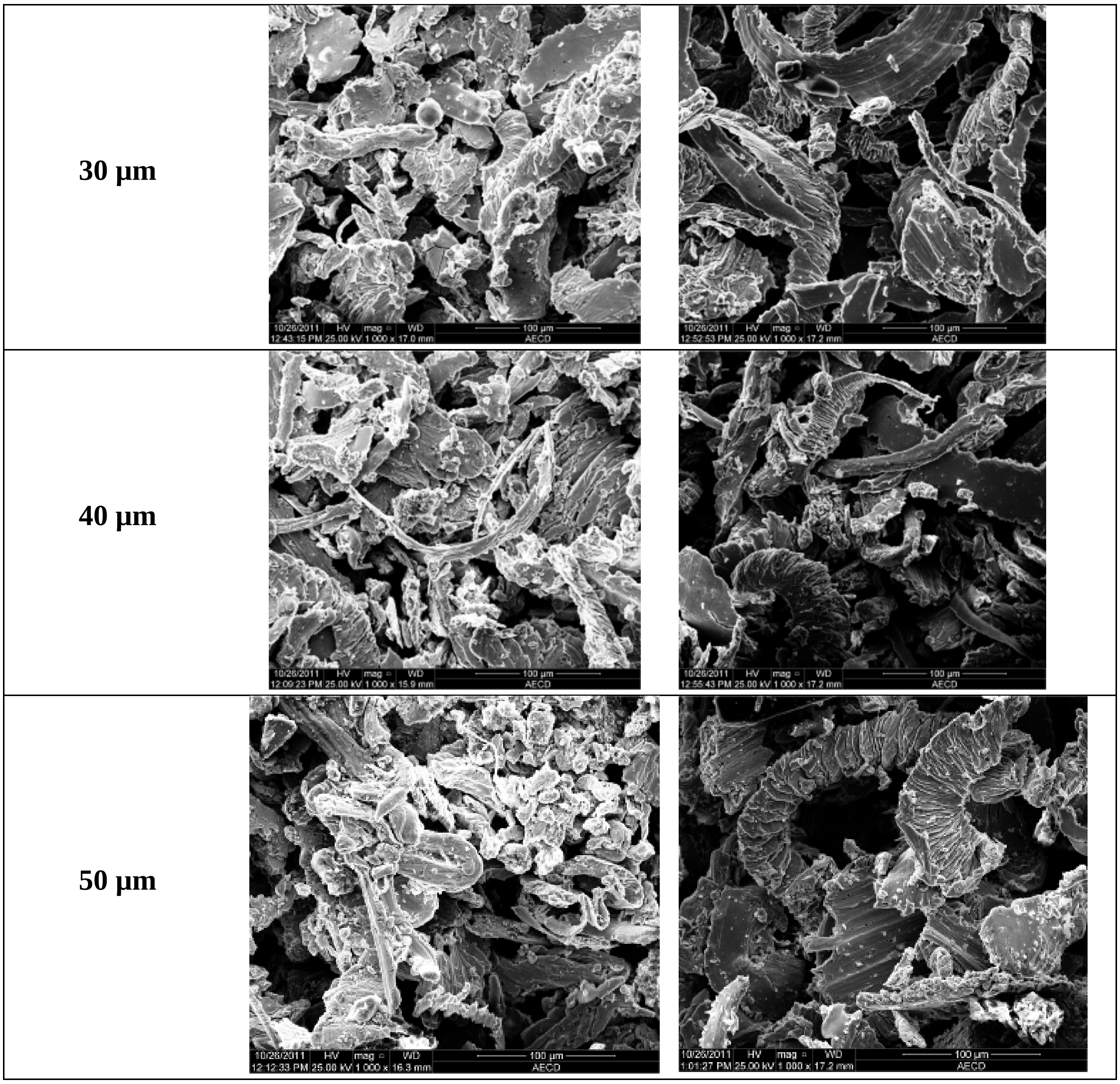


Fig. 5 : SEM photograph of grinding chips at 31.42 m/s wheel speed and 0.1 m/s workspeed while grinding AISI 1045 steel with CBN wheel under dry and MQL condition

III. SURFACE ROUGHNESS MODELLING AND VALIDATION

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building by careful design of experiments. The objective is to optimize a response (output variable) which is influenced by several independent variables (input variables).

Here a statistical model is developed to make an appropriate approximating relationship between response η and individual variables $\xi_o, \xi_1, \xi_2, \xi_3 \ldots \xi_n$ .In general the relationship is,

$$\eta = f\left(\xi_o, \xi_1, \xi_2, \xi_3 \ldots \xi_n.\right) + \varepsilon \qquad (1)$$

Here *f* is the true response function which is unknown and perhaps very complicated and ε is a term that represents other sources of variability not accounted for in *f*. usually ε includes effects such as measurement error on the response, background noise, the effect of other variables, and so on. Usually ε is treated as a statistical error, often assuming it to have a normal distribution with mean zero and variance.

In much RSM work it is convenient to transform the natural variables to coded variables $x_o, x_1, x_2, x_3 \ldots x_n$, which are usually defined to be dimensionless with mean zero and the same standard deviation. In terms of the coded variables, the response function, which is the expected value of η can be written as,

$$E(\eta) = y = f\left(\xi_o, \xi_1, \xi_2, \xi_3 \ldots \xi_n.\right) + E(\varepsilon) = f\left(x_o, \mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3 \ldots \mathrm{x}_n.\right) \qquad (2)$$

For the case of two independent variables, the second-order model in terms of the coded variables is,

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^{\ 2} + \beta_{22} x_2^{\ 2} + \beta_{12} x_1 x_2 \tag{3}$$

In general the second order response surface model takes the following form,

$$y = \beta_o + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^{\ 2} + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j \tag{4}$$

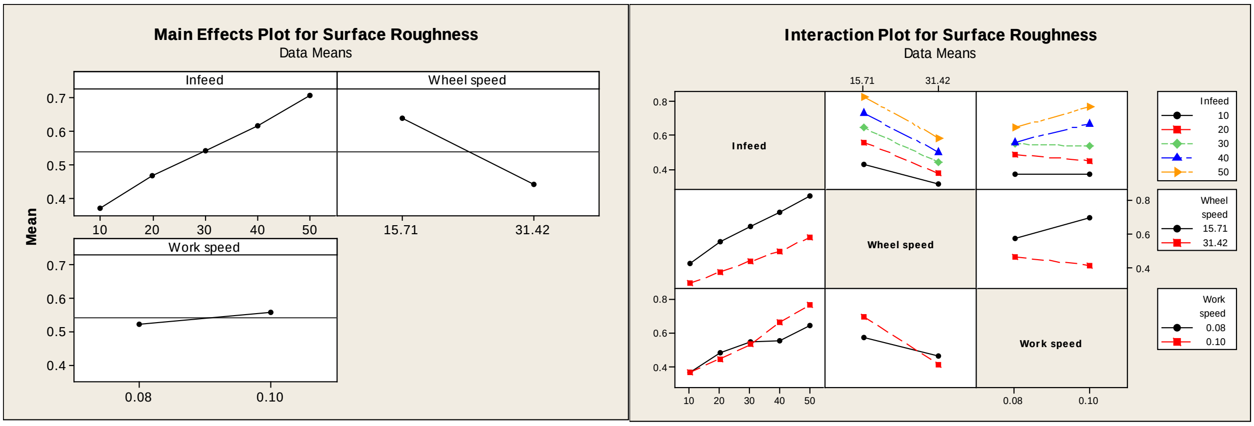
Where, f is the response function and a_o, v_s, v_w are the infeed, wheel speed and workspeed and 'ε' is the error which is normally distributed with mean zero. The second order response function for surface roughness R_a as a function of the infeed, wheel speed and workspeed can be written as in Eq. (5).

$$\begin{aligned} R_a = {} & \beta_o + \beta_1 \text{ a}_o + \beta_2 \text{ v}_s + \beta_3 \text{ v}_w + \beta_{11} \text{ a}_o^{\ 2} + \beta_{22} \text{ v}_s^{\ 2} + \beta_{33} \text{ v}_w^{\ 2} \\ & + \beta_{12} \text{ a}_o \text{v}_s + \beta_{13} \text{a}_o \text{v}_w + \beta_{23} \text{ v}_s \text{v}_w \end{aligned} \tag{5}$$

Where R_a is the response, β_0, β_1, β_2, β_3, β_{11}, β_{22}, β_{33}, β_{12}, β_{13} and β_{23} are the constants.

Here a custom Response Surface Design is created using Minitab 16.1.1 statistical software package and experimental results are used to predict the relationship between three input variables (infeed, wheel speed, work speed) and the response (surface roughness). To assess the influence of the factors to response and interaction between them, the main effect plot and interaction plot is created. The points in the plot are the mean of the response variable at the various levels of each factor, with a reference line drawn at the grand mean of the response data.

Fig. 5(a) show the variation of individual responses with the three parameters i.e. infeed, wheel speed and work speed separately. The plot indicates that, for increasing infeed there is a continuous increase in surface roughness. Roughness decreases with increase of wheel speed but increase a little with increasing work speed. Fig.5(b) shows the interaction plot, that means the variation of main cutting force due to interaction between infeed and wheel speed ($a_o \times v_s$), wheel speed and workspeed ($v_s \times \text{v}_w$), infeed and workspeed ($a_o \times \text{v}_w$) etc. Interaction effect is highly significant for infeed and wheel speed combination and moderately significant for other two combinations in different degree. For this reason a second order regression model is developed and validated with experimental result to understand the level of effect of order of the equation.



(a) (b)

Fig.5 : (a)Main effect and (b)interaction plot for Surface Roughness

The second order model was postulated in obtaining the relationship between the main cutting force and the machining independent variables. The developed second order mathematical model is given in Eq. (6).

$$R_a = -0.3845 - 0.00459\ a_o + 0.04408\ v_s + 9.275\ v_w \\ -0.00001\ a_o^{\ 2} - 0.00019\ a_o v_s + 0.1975\ a_o v_w - 0.56652\ v_w v_s \qquad (6)$$

where,

R_a = Surface Roughness
a_o = Infeed
v_s = Wheel speed
v_w = Work piece

The total analysis was done using uncoded units. The term R^2 is the percentage of response variable variation that is explained by its relationship with one or more predictor variables. The greater the value of R^2 the better the model fits the given data. Here the co-efficient of determination R-Sq = 96.46 % indicate that the equation is able to predict the roughness values with 96.46 % accuracy.

The detailed statistical analysis of the variables that are used in the equation has been given in Table 2.

Table 2 : Regression table for the second order mathematical model

Term	Co-efficient	SE Co-efficient	T	P
Constant	-0.38450	0.31951	-1.203	0.252
a_o	-0.00459	0.00691	-0.664	0.519
v_s	0.04408	0.01071	4.115	0.001
v_w	9.27500	3.44537	2.692	0.020
$a_o^{\ 2}$	- 0.00001	0.00005	-0.165	0.872
$a_o \times v_s$	- 0.00019	0.00008	-2.305	0.040
$a_o \times v_w$	0.19750	0.06398	3.087	0.009
$v_w \times v_s$	- 0.56652	0.11519	-4.918	0.000

Here, the P-values are used to determine which of the effects in the model are statistically significant. The α value is assumed as 0.05. From Table 3, it can be clearly stated that, linear and the interaction effects of the cutting process variables are statistically significant since their P-values are less than 0.05.

Analysis of variance (ANOVA) is similar to regression in that it is used to investigate and model the relationship between a response variable and one or more predictor variables.

Table 3 : Analysis of Variance for the second order mathematical model

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	0.535447	0.535447	0.076492	46.72	0.000
Linear	3	0.471492	0.471492	0.157164	95.99	0.000
Square	1	0.000045	0.000045	0.000045	0.03	0.872
Interaction	3	0.063910	0.063910	0.021303	13.31	0.000
Residual error	12	0.019648	0.019648	0.001637		
Total	19	0.555095				

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. The residual plots are used to check the goodness of the model fit. The points in this plot should generally form a straight line if the residuals are normally distributed. Here in the **normal probability plot** the data points are fairly close to the fitted line. Small deviation at two ends may be due to the small number of observations. **Residuals versus fits** plot shows the comparison of fitted value against the residuals. This plot should show a random pattern of residuals on both sides of zero. Here the points are random and evenly distributed on both side of zero line moreover, no pattern is detected. . In Fig.6 (c) the **histogram plot** shows nearly a normal distribution with slight evidence of skewness at the right end. This may be due to small number of observations. **Residuals versus order** plot shows all residuals in the order that the data was collected and can be used to find non-random error, especially of time-related effects. No such effect was detected in the current experiment.

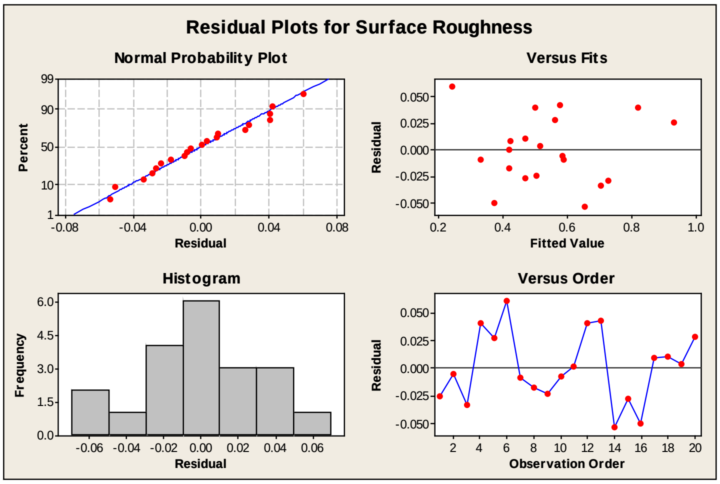


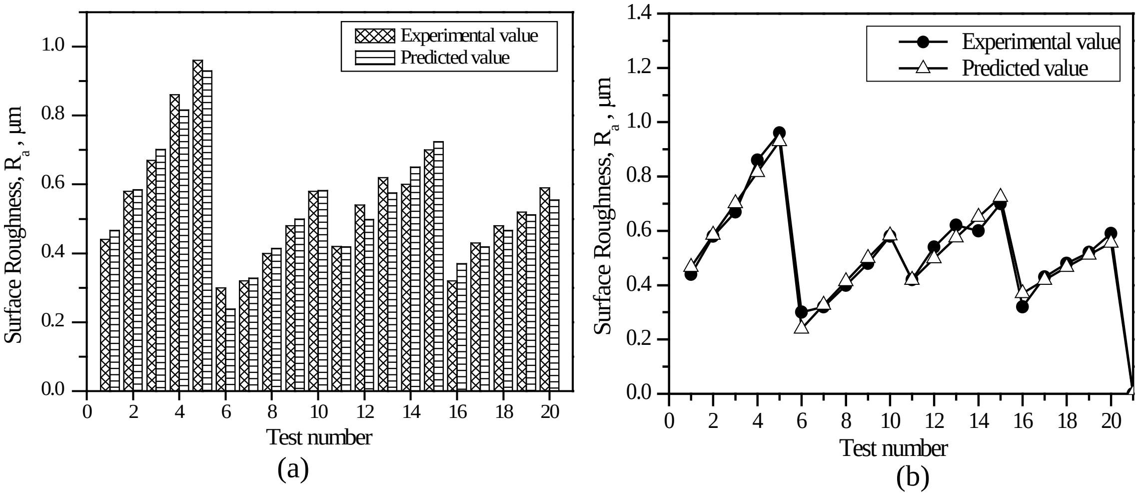
Fig. 6 : Second order mathematical model (a) Normal probability plot for residuals (b) Residual VS fitted value plot (c) Histogram of residuals (d) Residual vs. Order plot

In order to validate the developed model, the experimental surface roughness at different infeed, wheel speed and workspeed has been compared with the predicted value. The pressure and flow rate of the MQL are maintained at 80 bar and 2.0 l/min respectively. In Table 4 the combination of infeed, wheel speed and workspeed for different test have been shown.

Table 4 : Test conditions for Surface roughness validation

Test No.	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Infeed, $a_o(\mu m)$	10	20	30	40	50	10	20	30	40	50
Wheelspeed, v_s (m/s)	15.71	15.71	15.71	15.71	15.71	31.42	31.42	31.42	31.42	31.42
Work speed, v_w (m/s)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Test No.	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20
Infeed, $a_o(\mu m)$	10	20	30	40	50	10	20	30	40	50
Wheelspeed, v_s (m/s)	15.71	15.71	15.71	15.71	15.71	31.42	31.42	31.42	31.42	31.42
Work speed, v_w (m/s)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

The comparison of experimental and predicted value of surface roughness for 20 test samples are illustrated in Fig 7.



(a)

(b)

Fig.7 : Comparison of the experimental surface roughness and the predicted surface roughness from the second order mathematical model for different tests for turning AISI 1045 steel with CBN wheel under MQL condition.

IV. Results and Discussion

In this research AISI 1045 steel is ground with alumina and CBN wheel under dry and MQL cooling environment. The surface generated by grinding consists mostly of overlapping scratches produced by the interaction of abrasive grit with the workpiece. Figure 3 and 4 shows the surface roughness of the ground component for two different wheel speed, two different work speed and five different values of infeed consecutively for two different types of wheel. In all cases MQL produces lower values of roughness than dry environment. The lubrication is more effective at lower wheel rotational speed. The lower roughness value is due to more effective lubrication and cooling of the abrasive grains at the workpiece–tool interface. Efficient lubrication allows the chips to slide more easily over the tool surface and results in a better surface finish. Study of the ground surfaces also indicates that in MQL grinding the metal removal takes place mostly by shearing and fracturing, unlike prevalence of plastic deformation, grain pull-out and ploughing in conventional fluid and dry grinding.

Higher rpm of wheel produces lower surface roughness. In higher rpm more abrasive grit come into contact with the work surface thus overlapping cutting remove the surface flaws and smoother surface is obtained. From Fig. 3 it is evident that for higher rpm and higher work speed, MQL environment can produce better surface finish. There are some irregularities in the dry roughness value for 0.08m/s work speed and 30μm infeed. This may be the result of wheel loading and chip clogging. Roughness value increases with increasing infeed as for higher depth of cut, grains penetrate deep in the workpiece and remove bigger chunk of material in each contact. As a result higher peak and valley distance is created which in turn affects the surface roughness. Fig. 4 shows the roughness value with CBN wheel. Here surface roughness for both dry and MQL steadily increased with increasing infeed value.CBN grains are harder than conventional abrasive wheel so they retain their sharpness and can cut through the workpiece smoothly producing lower surface roughness.

The surface burn is observed during grinding under dry condition. The surface becomes burnt blue when machining at 50μm infeed in dry environment. Minimum Quantity Lubrication results burn free surface due to retained grit sharpness and less rubbing and ploughing though at very high infeed the surface become blackish indicating slight sign of surface burn.

The morphology of grinding chips produced by different infeed and cooling environment can be explained with the mechanism of chip formation and material removal. The chips produced during grinding AISI 1045 steel at lower infeed (10 μm and 20μm) have been shown in Fig. 5 under different cooling environment. Both 10μm and 20μm infeed produced different types of chips such as lamellar, flaky and irregular shaped particles with overlapping scratches produced by the interaction of abrasive particles with the workpiece. The flaky shape is produced mainly by rubbing action between abrasive grit and workpiece. At higher infeed (30 μm) some spherical chips are found indicating excessive heating. In all cases MQL produced longer lamellar chips with nearly equal width. The surface of the chips is also less rough in MQL than dry grinding environment. The reason is, in MQL effective lubrication allows the chip to slide more easily over the work surface providing better surface finish. In dry grinding the chip formation particularly involves shearing, ploughing and rubbing. However, the chip formation in MQL is mainly shearing due to low grinding zone temperature. Due to change in infeed no substantial variation in type and length of the chips could be found. In most of the cases wider chips are obtained at higher infeed which indicates higher penetration of abrasive particles into the workpiece.

In real life, application of grinding operation is not limited to these experimental values. Varity of grinding conditions may be used in different industries. So it is necessary to know the roughness value for other experimental conditions and this is where empirical modeling has come into action. The developed model in Eqn. 6 can predict the roughness value with 93.49% accuracy. The statistical conformity of the model is verified by Analysis of Variance (ANOVA) analysis in table 3 and by Residual plots in Figure 6. The model passed the conformity tests with slight variation which may be due to the small number of observations. In Fig.7 predicted values from RSM models have been plotted and compared with the experimental values. From these figures it can be concluded that the RSM can predict the trend of the experimental data and predict the surface roughness with a reasonable amount of error.

V. Conclusions

Based on the research work which is mainly analytical aided with experimental investigation, the following issues can be concluded,

I. Surface roughness of the ground surface is evaluated for AISI 1045 steel under dry and MQL condition with CBN and Alumina wheel. The MQL provided lower value of surface roughness with reduced burn of the surface than dry grinding. The roughness is found to be proportional to infeed and wheel rotational speed. The work speed is also found to have a strong correlation with the roughness value.

II. In all cases CBN wheel produces lower value of surface roughness than Alumina wheel. The increase of roughness value with the increase of infeed is more stable for CBN wheel than Alumina wheel. High thermal conductivity of CBN wheel enhances heat conduction away from the grinding zone to the wheel.

III. In MQL grinding chips are long, lamellar chips compared to the dry grinding where small and more irregular shaped chips are found. Chip formation mode shifted from ploughing, rubbing and shearing to sharp shearing due to retention of sharpness of abrasive grit and lesser ductility of steel under low temperature.

IV. A second order response surface model is developed to predict the surface roughness of AISI 1045 steel with CBN wheel under MQL condition. The model can predict the roughness with 96.46 % accuracy.

vI. Acknowledgement

This work has been funded by Directorate of Advisory Extension and Research Services (DEARS), Committee for Advanced Studies & Research (CASR), BUET, Dhaka, Bangladesh. The authors are also grateful to the Department of Industrial and Production Engineering, BUET for providing the facilities to carry out the experiment.

References Références Referencias

1. Shaw, M. C., Piggtt, J. D. and Richardson, L. P., 1951, “Effect of Cutting Fluid upon Chip–Tool Interface Temperature”, Trans. ASME, Vol. 71, pp. 45–56.
2. Paul, S., Dhar, N. R. and Chattopadhyay, A. B. (2000), “Beneficial Effects of Cryogenic Cooling over Dry and Wet Machining on Tool Wear and Surface Finish in Turning AISI 1060 Steel”, Proc. of ICAMT-2000, Malaysia, pp.209-214.
3. Dhar ,N.R, Kamruzzaman, M., Ahmed, M., 2006, “Effect of minimum quantity lubrication (MQL) on tool wear and surface roughness in turning AISI-4340 steel”, Journal of Materials Processing Technology, vol-172, pp. 299–304
4. Cassin, C. and Boothroyd, G, 1965, “Lubrication Action of Cutting Fluids”, Journal of Mechanical Engineering and Science, Vol. 7 (1), pp.
5. Mazurkiewicz, M., Kubala, Z. and Chow, J., 1989, “Metal Machining with High Pressure Water-jet Cooling Assistance-A New Possibility”, Journal of Engineering for Industry, Vol.111, pp. 7–12.
6. Alexander, A., Varadarajan, A. S. and Philip, P. K., 1998, “Hard Turning with Minimum Cutting Fluid: A Viable Green Alternative on the Shop Floor”, Proceedings of the 18th AIMTDR, pp. 152–155.
7. Kalhofer, E., 1997, “Dry machining—principles and applications”,Proceedings of the 2nd Seminario International de Alta Tecnologia UNIMEP, Santa Barbara D’Oeste, SP, Brazil, Julho.
8. Anon, A., 2003, “Warnings for grinding coolants”, Metalworking Production, vol.147(5), pp. 44.
9. Derflinger,V., Brandle,H., Zimmermann,H., 1999, “New hard/lubricant coating for dry machining”, Surface Coating Technology, vol. 113, pp. 286–292.
10. Brinksmeier,E., Eckebrecht, J., 1994, “Possibilities for the disposal of grinding swarf” , CIRP Annals—Manufacturing Technology, vol. 43(2), pp.593–597.
11. Heisel, U., Lutz, D., Wassmer, R., Walter, U., 1998, “The Minimum Quantity Lubricant Technique and its Application in the Cutting Process”, Machines and Metals Magazine, Brazil, No.386, February, pp.22-38.
12. Hafenbraedl, D., Malkin, S., 2001 “Technology Environmentally Correct for Intern Cylindrical Grinding”, Machines and Metals Magazine, July, Vol.426, pp.40-55.
13. Itoigawa, F., Childs, T.H.C., Nakamura, T., and Belluco, W., 2006, “Effects and mechanisms in minimal quantity lubrication machining of an aluminum alloy," WEAR, Vol-260(3). Pp.339-344.
14. Rahman, M.M., Khan, M.M.A., Dhar, N.R., 2009, “An Experimental Investigation into the Effect of Minimum Quality Lubricant on Cutting Temperature for machinability of AISI 9310 Steel Alloy”, European Journal of Scientific Research,vol.29(4) , pp. 502-508
15. Dhar, N.R., Hossain, M., Kamruzzaman, M., 2005, “MQL applications in grinding of 16mncr5 steel: A comparison with wet and dry grinding”, Proceedings of the International Conference on Mechanical Engineering 2005, Dhaka, Bangladesh. ICME 05-AM-33.
16. Silva, L.R., Bianchi, E.C., Catai, R.E., Fusse, R.Y., Franc -a, T.V. and Aguiar, P.R.,2007 “Analysis of surface integrity for minimum quantity lubricant-MQL in grinding.”, International Journal of Machine Tools and Manufacture. Vol. 47, pp. 412–418.
17. Tawakoli, T., Hadad, M.J., Sadeghi, M.H., Danesh, A., Stockert, S. and Rasifard, A., 2009, “An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubrication—MQL grinding”, International Journal of Machine Tools & Manufacture, Vol. 49, pp. 924–932.
18. Barczak, L.M, Batako,A.D.L, Morgan, M.N, 2010, “A study of plane surface grinding under minimum quantity lubrication (MQL) conditions”, International Journal of Machine Tools and Manufacture, Vol. 50(11), pp. 977-985.
19. Agarwal Sanjay, P. Venkateswara Rao, 2005, “A probabilistic approach to predict surface roughness in ceramic grinding” International Journal of Machine Tools & Manufacture, Vol. 45, pp. 609–616.
20. Guo, C. and Malkin, S., 1995, “Analysis of transient temperatures in grinding,” Journal of Engineering for Industry, Vol. 117, pp. 571-577.

21. Mamalis, A.G., Kundra´k, J., Manolakos, D.E., Gyani, K., and Markopoulos, A., 2003, "Thermal Modelling of Surface Grinding Using Implicit Finite Element Techniques", International Journal of Advance Manufacturing Technologies, vol. 21, pp.929–934.
22. Li, Jing and Li, J.C.M., 2005, "Temperature distribution in workpiece during scratching and grinding", International Journal of Materials Science and Engineering vol. 409, pp. 108–119.
23. Anderson, D., Warkentin, A., and Bauer, R., 2008, "Comparison of numerically and analytically predicted contact temperatures in shallow and deep dry grinding with infrared measurements", International Journal of Machine Tools & Manufacture, Vol. 48, pp. 320–328.
24. Anderson, D., Warkentin, A., and Bauer, R., 2008, "Experimental validation of numerical thermal models for dry grinding", journal of materials processing technology, Vol. 204, pp.269–278.
25. Rowe, W.B., 2001, "Thermal analysis of high efficiency deep grinding", International Journal of Machine Tools & Manufacture, Vol. 41(1), pp.1–19.Batako, A.D, Rowe,W.B, Morgan, M.N, 2005, "Temperature measurement in high efficiency deep grinding" International Journal of Machine Tools and Manufacture, Vol. 45(11), pp. 1231-1245.

This page is intentionally left blank