Improvement in Surface Quality with Solid Lubrication in Hard Turning

Dilbag Singh, P. Venkateswara Rao

Abstract— **Hard turning is characterized by development of high temperatures at the cutting zone, which impairs the surface quality of the final product. Thus, an effective control of heat generated at the cutting zone is essential to ensure workpiece surface quality. Cutting fluids are generally used to avoid this. However, cutting fluids are being restricted due to their direct influence to human health and environment. New alternative approaches are in process to alleviate the problems associated with dry and wet hard turning. This study deals with an investigation of molybdenum disulphide as a solid lubricant as an alternative to the cutting fluids to reduce friction and thereby improve the surface finish of bearing steels. Experiments have been conducted using central composite rotatable design, to study the effect of molybdenum disulphide lubricant on surface roughness while hard turning bearing steel. Results indicate that there is a considerable improvement in the performance of hard turning of bearing steels using molybdenum disulphide as a solid lubricant when compared with dry hard turning in terms of surface roughness**

Index Terms- **Hard turning, surface roughness, solid lubricant, tool geometry,**

I. INTRODUCTION

Hard turning process can be defined as turning hardened materials into finished components. The greatest advantage of using finish hard turning is the reduced machining time and complexity required to manufacture metal parts. In hard turning, surface quality is one of the most important performance measures. Surface roughness is mainly a result of process parameters such as tool geometry and cutting conditions. In any metal cutting operation, lot of heat is generated due to plastic deformation of the work material, friction at the tool-chip interface and friction between tool and the workpiece. The heat produced in hard turning adversely affects the quality of the products produced. Thus, the effective control of heat generated at the cutting zone is essential to ensure good workpiece surface quality in machining [1, 2].

Cutting fluids have been the conventional choice to deal with this problem. Cutting fluids are introduced onto the machining zone to improve the tribological characteristics of the machining processes and also to dissipate the heat generated.

But, the application of conventional cutting fluids creates some techno-environmental problems like environmental pollution, biological problems to operators, water pollution, etc [3]. Further, the cutting fluids also incur a major portion of the total manufacturing cost [4]. All these factors prompt investigations on the use of biodegradable cutting fluids or the elimination of the use of cutting fluids. But any attempt to minimize or to avoid the coolant can be dealt with only by the substitution of the functions normally met by the coolants with some other means. Machining with solid lubricants [5, 6, 7, 8] and cryogenic cooling by liquid nitrogen [9, 10] and minimum quantity lubrication [11, 12] are some of the alternative approaches in this direction.

Application of solid lubricant in machining has proved to be feasible alternative to cutting fluids, if it can be applied properly. If the friction at the tool and workpiece interaction can be minimized by providing effective lubrication, the heat generated can be reduced to some extent. Advancement in modern tribology has identified many solid lubricants, which can sustain and provide lubricity over a wide range of temperatures [13, 14]. If a suitable lubricant can be successfully applied in the machining zone, it leads to process improvement. The feasibility of application of graphite as a solid lubricant in surface grinding was investigated by applying it in a suitable paste form to the working surface of the wheel, with a special attachment [5]. The effective role of graphite as solid lubricant was evident from the process results related to frictional factors. If the lubricant can be applied in a more refined and defined way, just sufficient for effective lubrication, improved process results may be expected.

The present study focuses on the application of molybdenum disulphide (MoS_2) solid lubricant, which is a high temperature lubricant, as a means to reduce the heat generated at the cutting zone and to study the process performance in hard turning. An experimental set-up was developed for supplying solid lubricant powder during hard turning. Comparative performance analyses of solid lubricant assisted hard turning with dry hard turning were made.

II. EXPERIMENTAL SET-UP

The experimental study was conducted using a NH-22 HMT lathe machine. A new experimental set-up was designed and developed for the supply of fine graphite at the desired flow rate as shown in Fig.1.

The solid lubricant powder apparatus was attached to the tool post. The fine solid lubricant powder of 2 μm average particle size was placed in the container. On the top of the container, a DC motor having variable speed was attached for the rotation of the rotary feeder. A spiral shaft was attached to the motor shaft. A desired quantity of the solid lubricant can be supplied onto the cutting zone with the rotation of the

motor shaft. The apparatus was so designed that it could supply the solid lubricant at the required rate from 0.5 gm/min to 15 gm/min just by changing the RPM of the DC motor. After ensuring the adaptability of the set-up for proper lubrication, the experiments were conducted to evaluate the performance of this procedure.
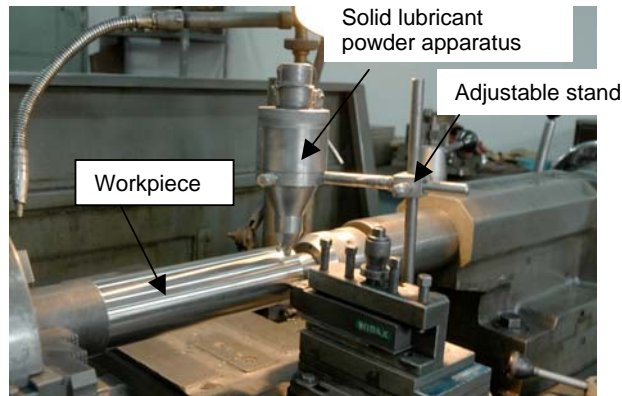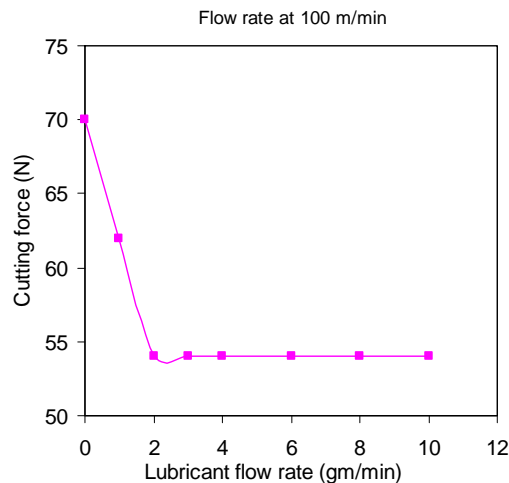

Fig. 1 Photograph of experimental setup

Fig. 2 Variation of cutting force with lubricant flow rate

Table I Process parameters and their levels

Parameter	Value of variables at five levels				
	-2	-1	0	+1	+2
Cutting speed (v), m/min	50	75	100	125	150
Feed (f), mm/rev	0.04	0.08	0.12	0.16	0.20
Effective rake angle (α)	16°	21°	26°	31°	36°
Nose radius (r) mm	0.4	0.8	1.2	1.6	2.0

Table II. Central composite design matrix

Run no.	Speed	Feed	Rake angle	Nose radius
1	-1	-1	-1	-1
2	-1	-1	-1	1
3	-1	-1	1	-1
4	-1	-1	1	1
5	-1	1	-1	-1
6	-1	1	-1	1
7	-1	1	1	-1
8	-1	1	1	1
9	1	-1	-1	-1
10	1	-1	-1	1
11	1	-1	1	-1
12	1	-1	1	1
13	1	1	-1	-1
14	1	1	-1	1
15	1	1	1	-1
16	1	1	1	1
17	-2	0	0	0
18	2	0	0	0
19	0	-2	0	0
20	0	2	0	0
21	0	0	-2	0
22	0	0	2	0
23	0	0	0	-2
24	0	0	0	2
25	0	0	0	0
26	0	0	0	0
27	0	0	0	0
28	0	0	0	0
29	0	0	0	0
30	0	0	0	0
31	0	0	0	0

While conducting experimentation with molybdenum disulphide assisted hard turning, the amount of molybdenum disulphide powder supplied per unit time to the machining zone is important because an accurate determination of flow rate helps to achieve the desired machining performance. In order to arrive at an optimum flow rate, experiments were conducted to observe the effect of increasing flow rate on the cutting force. Fig. 2 shows the variation of cutting force with flow rate at a cutting speed of 100 min/min, feed of 0.12 mm/rev, 26° effective rake angle and 1.2 mm nose radius in molybdenum disulphide assisted machining. It has been observed from molybdenum disulphide assisted hard turning that the cutting force decreases as the flow rate increases from 1 gm/min to 2 gm/min. After that there is no substantial reduction of the cutting force even if the flow rate has been increased from 2 gm/min to 10 gm/min. The similar trend has been observed for the other cutting conditions. It can be concluded that flow rate of 2 gm/min is sufficient to provide the required lubrication. Hence, in the present investigation, flow rate of molybdenum disulphide powder has been kept at 2 gm/min during the machining of hardened bearing steel.

For the performance study, the experiments were designed using design of experimentation. The design of

experimentation has a major effect on the number of experiments needed. The most important factors considered for the experimentation and analysis were cutting speed, feed, effective rake angle and nose radius. In order to compare the performance of molybdenum disulphide assisted machining with that of dry hard turning, experiments were conducted considering five levels for each factor as shown in Table I. Central composite rotatable design was employed to reduce the number of experiments to 31 instead of 625 (as per full factorial design). Based on this, 31 experiments were carried out each for dry and molybdenum disulphide assisted hard turning as shown in the design matrix Table II.

The experimental results were used to develop the surface roughness models by Response Surface Methodology (RSM). Response Surface Methodology is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which response of interest is influenced by several variables and the objective is to optimize the response. The mathematical models commonly used are represented by:

$$Y = \Phi (v, f, \alpha, r) + \varepsilon \qquad (1)$$

Where Y is the hard turning response, Φ is the response function, and v, f, α, r are the cutting speed, feed, effective rake angle and the nose radius and ' ε' is the error which is normally distributed with zero mean according to observed response. In most of the RSM problems, the form of relationship between the response and the independent variables is not known. Thus, the first step in RSM is to find a suitable approximation for the true functional relationship between the response and the set of independent variables. Usually, a low order polynomial in some region of independent variables is employed. Hence, the first -order linear model between response and other independent variables is modeled as follows:

First order model can be written as:

$$Y_1 = \beta_0 + \sum_{i=1}^{k} \beta_i x_i \qquad (2)$$

Where $x_1, x_2, \ldots x_k$ are the input variables which influence the response Y_1. The set of regression coefficients β's are unknown parameters and estimated by least squares, and ε is a random error which is normally distributed with zero mean according to observed response. The first-order model is to be appropriate in approximating the true response surface over a relatively small region of the independent variable space in a location where there is a little curvature. Often the curvature in the true response surface is strong enough that the first order model (even with the interaction terms included) is inadequate. The second order model is widely used in response surface methodology for several reasons because (a) the second order is very flexible. It can take on a wide variety of functional forms, so it will work well as an approximation to the true response surface, (b) it is easy to estimate the parameters in the second order model. The method of least squares is used for this purpose and (c) There is considerable practical experience indicating that second-order models work well in solving real response surface problems [15, 16].

Second order-model can be written as:

$$Y_2 = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} X_i X_j + \varepsilon$$

$$(3)$$

Where $x_1, x_2, \ldots x_k$ are the input variables which influence the response Y_2. The set of regression coefficients β's are unknown parameters and estimated by least squares, and ε is a random error which is normally distributed with zero mean according to observed response.

A computer program was developed in the MATLAB environment, to calculate the value of these coefficients for different responses. The adequacy of the models was tested using the analysis-of-variance technique (ANOVA) [15, 16].

III. RESULTS AND DISCUSSION

During hard turning, lot of heat is generated at the primary deformation zone, secondary deformation zone and maximum temperature is developed at the tool/chip interface which may result in the early cutting tool failure leading to poor quality of the surface produced. Hard turning, employing molybdenum disulphide as a solid lubricant, is a possible environmental friendly alternative for effective control of cutting zone temperature. Hence, in the present work, molybdenum disulphide has been used as solid lubricant to provide the proper lubrication and reduce the friction between the tool and workpiece and thereby reducing heat generation at the tool and workpiece interface.

It has been found in this study that first order models of surface roughness were not adequate. Hence the second order models were developed from the experimental results. The second order surface roughness models developed using response surface methodology for the dry hard turning and molybdenum disulphide assisted hard turning are as follows.

$$Y_{2,Dry} = 0.65 - 0.1017x_1 + 0.1117x_2 - 0.0075x_3 - 0.1375x_4$$
$$+ 0.0515x_1^2 + 0.0440x_2^2 + 0.0565x_3^2 + 0.0540x_4^2$$
$$+ 0.0413x_1x_2 - 0.0725x_1x_3 - 0.0075x_1x_4 - 0.0675x_2x_3$$
$$- 0.1025x_2x_4 + 0.0713x_3x_4$$

$$(4)$$

$$Y_{2,MoS_2} = 0.5557 - 0.09x_1 + 0.0975x_2 - 0.0058x_3 - 0.12x_4$$
$$+ 0.0511x_1^2 + 0.0423x_2^2 + 0.0486x_3^2 + 0.0486x_4^2$$
$$+ 0.0338x_1x_2 - 0.065x_1x_3 - 0.0088x_1x_4 - 0.06x_2x_3$$
$$- 0.0938x_2x_4 + 0.0625x_3x_4$$

$$(5)$$

Where ' Y_2' is the estimated response of second order surface roughness and x_1, x_2, x_3, x_4 are the coded variables of speed, feed, effective rake angle and the tool nose radius respectively. The significance of these models has been established with analysis of variance ANOVA (Table III and Table IV). The multiple regression coefficients of the second order models of dry and molybdenum disulphide assisted hard turning are estimated as 0.9216 and 0.9255 respectively. The calculated values of the F-ratio for the second order regression models are greater than the standard values of the F-ratio as shown in the ANOVA Tables, the models are adequate at 99% confidence level to represent relationship between the machining responses and the considered machining parameters of the hard turning process. The

calculated lack of fits for the second order surface roughness models are less than the tabulated value for the lack of fit at 99% confidence level, which implies that the quadratic models are adequate.

Table III ANOVA for the second order roughness model (dry machining)

Source	Sum of squares	d.o.f	Mean squares	F_{cal}	$F_{0.01}$
Model	1.6692	14	0.1192	13.43	3.503
Residual error	0.1421	16	0.0088	-	-
Lack of fit	0.1305	10	0.0130	6.75	7.87
Pure error	0.0116	6	0.0019		
Total	1.8113	30			

Table IV ANOVA for the second order surface roughness model (molybdenum disulphide assisted machining)

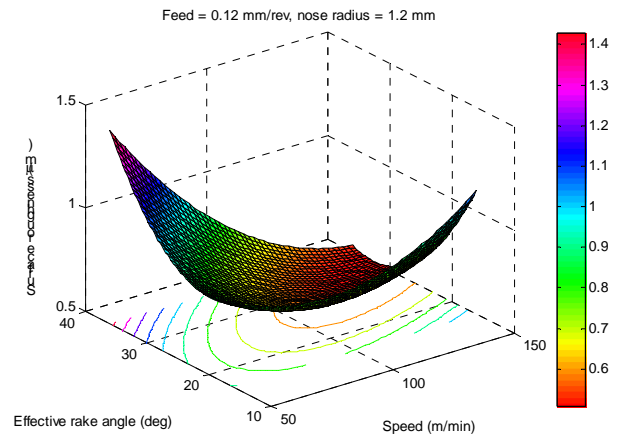| Source	Sum of squares	d.o.f	Mean squares	F_{cal}	$F_{0.01}$
Model	1.3148	14	0.0939	14.20	3.503
Residual error	0.1058	16	0.0066	-	-
Lack of fit	0.0964	10	0.0096	6.18	7.87
Pure error	0.0093	6	0.0015		
Total	1.4206	30			

Fig. 2(b)

Fig. 2 Interaction effect of cutting speed and effective rake angle on surface roughness in (a) dry hard turning (b) molybdenum disulphide assisted hard turning
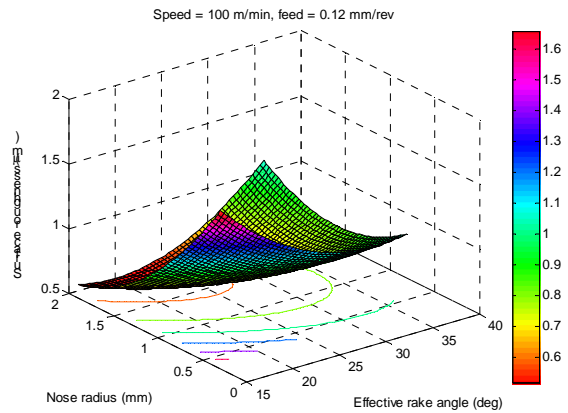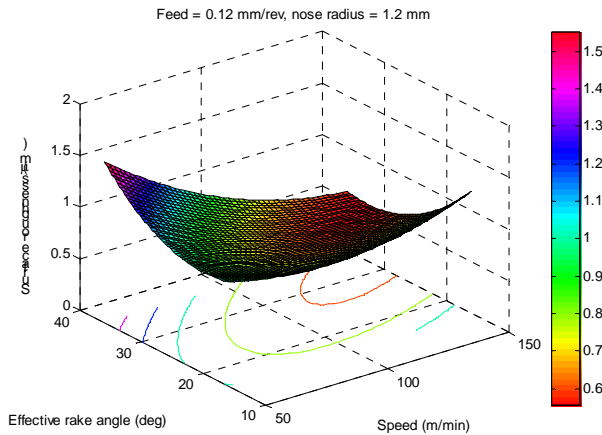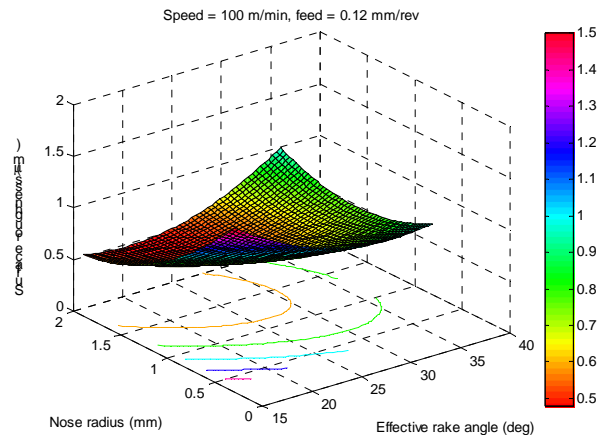

Fig. 3(a)

Fig. 2(a)

Fig. 3(b)

Fig. 3 Interaction effect of effective rake angle and nose radius on surface roughness in (a) dry hard turning (b) m molybdenum disulphide assisted hard turning

The mathematical models, given by Equations (4-5), can be used to predict the surface roughness by substituting the values, in coded form, of the respective factors. The responses calculated from these models, for each set of coded variables, can be represented in graphical form and the effect of the different process variables, on the surface roughness, can be interpreted with the help of the graphs.

The variation of surface roughness with respect to cutting speed and effective rake angle can be seen from the Fig. 2. It can be observed from this figure that combination of the cutting speed and effective rake angle is important for achieving the desired values of the surface roughness. Therefore, higher cutting speeds and medium values of effective rake angle are the favorable conditions for the lower values of the surface roughness. The variation of surface roughness with tool geometry parameters i.e. effective rake angle and nose radius can be seen from the Fig. 3. Surface roughness first decreases and then again increases with the increase of effective rake angle. This could be due to the fact that the increase in effective negative rake angle increases the edge strength of the inserts and hence surface finish improves. Further increase in the effective rake angle increases the cutting forces making the machining process difficult and hence the deterioration in surface quality has been observed in the experimental values. It can be concluded that judicious selection of the cutting conditions and the tool geometry is essential in order to produce the quality products in the hard turning. It can be seen that higher values of nose radii combined with the suitable effective rake angles yield good quality surfaces.

Further, it could be seen from the Figs. 2 and 3 that surface roughness values obtained in molybdenum disulphide assisted hard turning were lower as compared to dry hard turning. The substantial reduction in surface roughness by molybdenum disulphide assisted hard turning could be attributed mainly due to the retention of insert sharpness due to lower wear and plastic deformation at reduced temperature. Thus it indicated that the lubricating property of molybdenum disulphide was effective in reducing the rubbing action at the tool-workpiece contact zone. This resulted in lesser wear of the cutting insert, helping it to retain sharpness, which improves surface roughness. Therefore, it can be concluded that molybdenum disulphide assisted hard turning giving better finish in comparison to dry hard turning

IV. CONCLUSIONS

The experimental investigation established that the performance of hard turning could be improved by the presence of molybdenum disulphide at the machining zone. Thus, the use of molybdenum disulphide assisted hard turning leads to improved machinablity with significant improvement in surface quality. Hence, the employment of molybdenum disulphide as a solid lubricant in hard turning process makes the process more attractive and environmental friendly.

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V. NOMENCLATURE

v	Cutting speed (m/min)
f	Feed (mm/rev)
α	Effective rake angle (°)
r	Nose radius (mm)
x_1	Coded value for cutting speed
x_2	Coded value for feed
x_3	Coded value for effective rake angle
x_4	Coded value for nose radius
Y	Machining response
Y_1	Estimated response based on first order model
Y_2	Estimated response based on second order model
ε	Experimental error constant in mathematical model
d.o.f	Degree of freedom
F_c	Tangential cutting force, N
$Y_{2,Dry}$	Surface roughness in dry hard turning (μm),
$Y_{2,MoS2}$	Surface roughness in molybdenum disulphide assisted hard turning (μm),