Int J Adv Manuf Technol (2008) 38:529–535
DOI 10.1007/s00170-007-1079-8

ORIGINAL ARTICLE

Performance improvement of hard turning with solid lubricants

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Received: 10 January 2007 / Accepted: 30 April 2007 / Published online: 7 July 2007

Abstract Product quality is one of the most important criteria for the assessment of hard turning process. However, in view of the high temperatures developed in hard turning process, the surface quality deteriorates due to the tool wear. Because of the strict environmental restrictions on the use of cutting fluids, new cutting techniques are required to be investigated to reduce the tool wear. In the present work, the use of solid lubricants during hard turning has been explored while machining bearing steel with mixed ceramic inserts at different cutting conditions and tool geometry. Results show considerable improvement in the surface finish with the use of solid lubricants. Due to the presence of solid lubricants, there is a decrease of surface roughness values from 8 to 15% as compared to dry hard turning.

Keywords Hard turning · Effective rake angle · Nose radius · Solid lubricants

1 Introduction

Hardened steels are widely used in automobile, bearing, tool and die industries. The traditional method of machining hardened materials includes rough turning, heat treatment, and then grinding process. However, hard turning eliminates some of the unnecessary steps involved in the machining of hard materials and hence results in the increase of productivity rate. The various advantages of hard tuning are higher productivity, reduced set up times, surface finish closer to grinding and ability to machine the complex parts. Nowadays, hard turning is being employed in industries as a substitute for grinding process. This has become possible due to the development of new cutting tool materials such as CBN and mixed ceramics [1].

Various researchers have studied the mechanism of chip formation, residual stresses, surface finish, and tool wear in the hard turning process. Lot of attention is being given to the quality of the surface finish produced in the hard turning process. There are a large number of parameters which affect the cutting forces and surface roughness. These include cutting tool variables, workpiece material variables, and cutting conditions and the type of lubrication. Tool variables include tool material, nose radius, rake angle, cutting edge geometry, tool vibration, tool overhang, tool point angle. Workpiece variables include material, hardness and other mechanical properties. Cutting conditions include speed, feed, and depth of cut. Type of lubrication includes dry hard turning, hard turning with flooded or with minimum quantity of lubricant and solid lubrication. Low surface roughness, minimal microstructural alterations and high dimensional accuracy can only be attained with new cutting tools. So, the proper selection of all these variables facilitates the objectives to be achieved in hard turning.

Due to the strict regulations and their enforcement regarding the use of the cutting fluids in industries, the researchers have started exploring the alterative methodologies. One of the solutions is to use the solid lubricants in order to reduce the tool wear and to improve the overall performance of the machining process. In the present study, the effect of tool geometry and the cutting conditions on the surface finish by using solid lubricants graphite and

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molybdenum disulphide in the hard turning of the bearing steel with the mixed ceramic tools was studied and the comparison has been made with dry hard turning.

2 Literature review

Hard turning process is associated with the high tool wear due to the high temperature developed. Cutting fluids are generally used in machining processes to reduce friction and wear, thus improving the tool life and surface finish. These are also used to reduce the forces and energy consumption, to cool/lubricate the cutting zone, wash away the chips, and to protect the machined surfaces from environmental corrosion. Tonshoff et al. [2] investigated the tribological aspects of hard turning with ceramic tools. According to this study, cooling effect reduces the thermal load of the cutting edge, and thus increases tool life as compared to dry cutting. In addition, surface finish of the workpieces can be improved either by chemical interaction between the workpiece surface and extreme- pressure additives of the coolant or by mineral oil application. But, rehardened layers were found both in dry and wet cutting. Ávila and Abrao [3] investigated the effect of cutting fluids on the machining of hardened AISI 4340 steel. In this work, the performance of three types of cutting fluids (two emulsions and one synthetic fluid) has been compared to dry machining using mixed alumina inserts. Results show that the application of a cutting fluid based on an emulsion without mineral oil results in longer tool life compared to dry cutting and the use of cutting fluid is responsible for reducing the scatter in the surface finish values at high cutting speeds. Diniz et al. [4] studied the influence of refrigeration/ lubrication condition on SAE 52100 hardened steel turning at several cutting speeds. Dry and minimum volume of oil (MVO) showed the similar values of flank wear, which is always smaller than the values for wet machining. Also wet machining did not show better values of surface roughness compared to MVO and dry machining. Varadarajan et al. [5] investigated the hard turning with minimal fluid application (HTMF), and its application with dry and wet turning. Results show that overall performance during minimum cutting fluid application is found to be superior to that during dry turning and conventional wet turning on the basis of cutting forces, tool life, surface finish, cutting ratio, cutting temperature and tool-chip contact length.

However, dry machining is a new trend because of increased concern about environmental issues and strict regulations regarding the use of cutting fluids. Dry cutting is beneficial because of pollution free environment. Also the machining cost is reduced due to the elimination of the cutting fluids. Klocke and Eisenblätter [6] have reported on dry cutting. According to this study, cutting fluids help to achieve a specified result in terms of tool life, surface finish and dimensional accuracy, and facilitate chip breaking and transport. However, these also impose problems related to waste disposal and environmental problems. So, with dry cutting, all the problems related with wet machining can be eliminated. Sreejith and Ngoi [7] have reported the dry machining as the machining of the future. This paper concludes that the dry machining can eliminate cutting fluids and this is possible due to the advancement of the cutting tool materials. Diniz and Micaroni [8] have studied the cutting conditions for finish turning process in dry cutting. According to this study, dry machining requires less power and produces smoother surface than wet turning.

It is clear from the above-mentioned literature that dry turning improves the surface finish, but the tool life and wear problems are associated with it. And hard turning with cutting fluids (whether flooded or minimum quantity) is not environmental friendly and their use is being restricted. So, an alternative method of increasing the life of the cutting tool is essential in hard turning. This can be done by providing the negative chamfer angle on the cutting tool inserts and by reducing the friction between the cutting tool and the workpiece. Recently the effects of the solid lubricants on the machining processes have been investigated.

The current liquid lubricants appear to be ineffective for applications involving high temperatures [9]. Lubricants and additives of new types are urgently needed. Solid lubricants are the only option available for controlling wear and friction in all types of tribosystems involving severe tribological conditions (e.g., high temperature, corrosive media, vacuum environment, high load and speed). Strong adhesion is essential for long service of solid lubricant films. Ion-beam processes are capable of imparting strong adhesion between solid lubricant films and ceramic substrates. Ion-beam mixing of ceramics with conventional solid lubricants, such as MoS_2, is feasible and appears promising for demanding aerospace applications. A unique solid lubricant, boric acid, which forms naturally on the surfaces of ceramics containing boric oxide and boron, has been recently been discovered. It has been established that this lubricant can impart remarkably low friction coefficients to sliding ceramic interfaces in humid environments, where MoS_2 is known to be ineffective. Erdemir et al. [10] have reported the solid/liquid lubrication of ceramics at elevated temperatures. According to this study, the simultaneous use of liquid and solid-film lubricants at sliding interfaces of ceramic/ceramic and gray cast iron/ceramic pairs can significantly reduce friction and wear. The solid lubricant was the silver film and the liquid was polyolester-base synthetic oil.

Some researchers have reported the use of solid lubricants in the machining process. Shaji and Radhakrishnan [11] have investigated the effect of solid lubricant (graphite) on the surface grinding process. Results show the improvement of surface finish in case of harder materials with the application of solid lubricant. Shaji and Radhakrishnan [12] have also reported the application of solid lubricants in grinding as an alternative for the conventional coolants. The solid lubricants used in this investigation were graphite, calcium fluoride, barium fluoride and molybdenum trioxide. Improved process results related to friction have been reported in this study. Nakamura et al. [13] have studied the lubrication behavior of solid lubricants in the upsetting process. Four kinds of solid lubricants were tested in order to examine the frictional characteristics and the yield shear stress by the friction testing apparatus. The solid lubricants used were PTFE, UHMWPE, MoS_2 and graphite. It was confirmed in the FEM simulation and also by the experiment that solid lubricants could lubricate successfully with metal to metal contact.

Gopal and Rao [14] have investigated the use of the solid lubricant in the grinding of the SiC has been investigated. It has been established by these authors that the surface finish improves with the graphite assisted machining. Reddy and Rao [15] have reported the performance of the end milling process by the use of the solid lubricants graphite and MoS_2. Recently, Jianxin et al. [16] have reported the tribological behaviors of hot-pressed Al_2O_3/TiC ceramic composites with the additions of CaF_2 solid lubricants. These studies have confirmed that friction coefficient of Al_2O_3/TiC/CaF_2 ceramic composites decreased when sliding against cemented carbide and hardened steel with an increase in CaF_2 content. The reason was that the CaF_2 released and smeared on the wear surface and acted as a solid lubricant between the sliding couple. Also the wear rate of these composite decreased with the addition of CaF_2.

The above-mentioned studies indicate that the surface finish can be improved by reducing the tool wear. Dry machining and machining with the use of cutting fluids (flooded or minimum quantity) have not responded properly for the requirement of improved tool life and surface finish. The use of the solid lubricants in machining may be the viable alternative of cutting fluids as has been reported in some of the above mentioned studies. So an attempt has been made in this work to investigate the effect of tool geometry and the cutting conditions on the surface finish by using solid lubricants graphite and molybdenum disulphide in the hard turning of the bearing steel with the mixed ceramic tools and the comparison has been made between dry hard turning and the solid lubricants assisted hard turning.

3 Experimentation

The performance of hard turning is measured in terms of cutting forces, surface finish, and tool wear. There are a large number of variables affecting the performance. The main important parameters are the cutting conditions, tool geometry and the type of lubricant. That is why, the four parameters namely cutting speed, feed, effective rake angle and the nose radius of the cutting tool were selected for the experimentation in this study. Five levels of each factor were selected in order to see the effect of each parameter. Design of experiment plays a very important role in performing the experiments with the available resources. According to the design of experiments, a central composite design was selected for experimentation to reduce the number of experiments. The cutting forces and surface finish were selected as the response variables. The cutting speed, feed, effective rake angle, and the nose radius are the independent variables in this study. The various process variables and their levels are shown in the Table 1 as under:

According to central composite design, a total of 31 experiments were carried out with and without the solid lubricants as per the design matrix shown in the Table 2. All the experiments were carried out at a constant depth of cut of 0.2 mm. A high precision NH-22 HMT lathe was used for experimentation. It has high degree of accuracy and rigidity, which are required for the hard turning process.

In this investigation, the workpiece material was the AISI 52100 steel of diameter 70 mm. The workpiece material was heat treated (through-hardened) to get 58±02 HRC. This material is being used for the manufacturing of the ball and roller bearings and automotive components. The chemical composition of the material is shown in the Table 3. Mixed ceramic inserts of different geometry were used. ISO designation of ceramic inserts is SNGN with different nose radii and chamfer angles. ISO fesignation of the tool holder is CSBNR 2525M12. The approach angle of this tool holder was 75°. The surface roughness was measured with a Talysurf-6 at 0.8 mm cut-off value. An average of three measurements was used as a response value. The tool wear was checked with a Mitutoyo optical

Table 1 Process variables and their levels

Factors	Level–1	Level–2	Level–3	Level–4	Level–5
v(m/min)	50	75	100	125	150
f (mm/rev)	0.04	0.08	0.12	0.16	0.20
α (°)	16	21	26	31	36
r (mm)	0.4	0.8	1.2	1.6	2.0

Table 2 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

microscope (1 μm resolution) at 30× magnification to measure the wear after experimentation. For each experimental set, new cutting inserts have been used.

The solid lubricants selected for this study were graphite and molybdenum disulphide. The fine powder of 2 μm average particle size has been used. An experimental set up for supplying the solid lubricant onto the cutting zone has been designed and developed for this study. The apparatus has been so designed that it can supply the solid lubricant from 0.5 gm/min to 15 gm/min. A provision has been provided on the apparatus for its proper positioning to supply the exact quantity of solid lubricants onto the cutting zone. Investigation was carried out to determine the optimum flow rate of solid lubricant powder using the designed apparatus. At this stage it is also required to see the effect of increasing the flow rate on the cutting force for the machining of hardened bearing steels. Figure 1 shows the variation of cutting force with flow rate at a cutting speed of 100 m/min, feed of 0.12 mm/rev, 26° effective rake angle and 1.2 mm nose radius in graphite and molybdenum disulphide assisted machining, respectively. It has been observed from graphite assisted machining that the cutting force decrease 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. The same is the case for molybdenum disulphide assisted machining also. 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 graphite and molybdenum disulphide powders has been kept at 2 gm/min during the machining of hardened bearing steel (Fig. 1).

Table 3 Chemical composition of bearing steel

C%	Mn%	Si%	Cr%	S% (max)	P% (max)
0.98–1.1	0.25–0.45	0.15–0.35	1.3–1.6	0.025	0.025

4 Results and discussion

During hard turning, much 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. So, there is a need to control the cutting zone temperature within the tolerable limits for the overall improvement of hard turning process. Hence, in the present work, graphite and molybdenum disulphide were used as solid lubricants 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.

Surface roughness generally plays an important role as it influences the fatigue strength, wear rate, coefficient of friction, and corrosion resistance of the machined components. Surface quality is affected by many interrelated parameters during the hard turning process. The reduction in the tool wear during hard turning will also affect the surface quality to a greater extent. And again the tool wear is dependent upon the cutting conditions and tool geometry, and properties of the workpiece and tool material. Hence in order to see the effect of the solid lubricants, graphite and molybdenum disulphides, on the surface quality, experiments were conducted to see their effect at different cutting conditions.

The variation of surface roughness with respect to cutting speed for dry hard turning and solid lubricants assisted hard turning is shown in the Figs. 2 and 3. It can be observed from these figures that surface roughness was found to be decreasing with the increase of the cutting speed upto 125 m/min and after that it again started

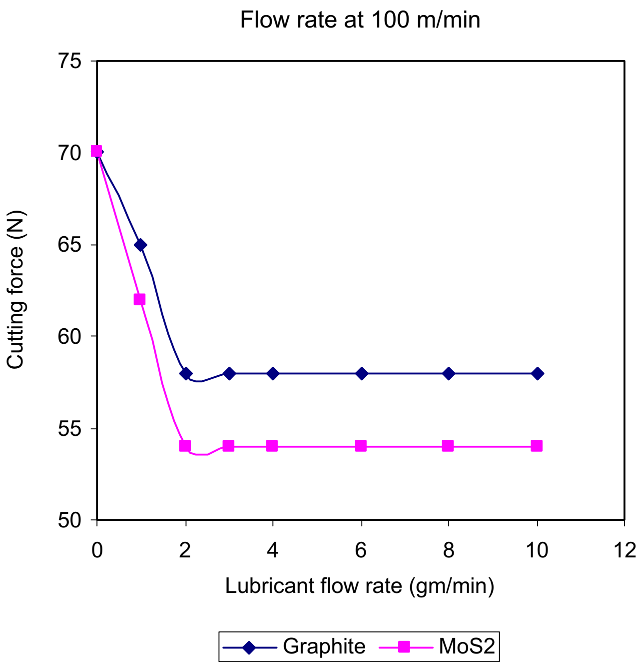

Fig. 1 Variation of cutting force with solid lubricants flow rate

increasing at high cutting speeds. This could be due to the reduction in the cutting forces at high speeds. The high value of surface roughness above 125 m/min could be due to the wear of the cutting tools associated at higher speeds. Solid lubricant assisted hard turning produced low values of surface roughness compared to the dry hard turning. Among the two variants of the solid lubricant assisted machining, molybdenum disulphide assisted hard turning shows better results as compared to graphite assisted hard turning.

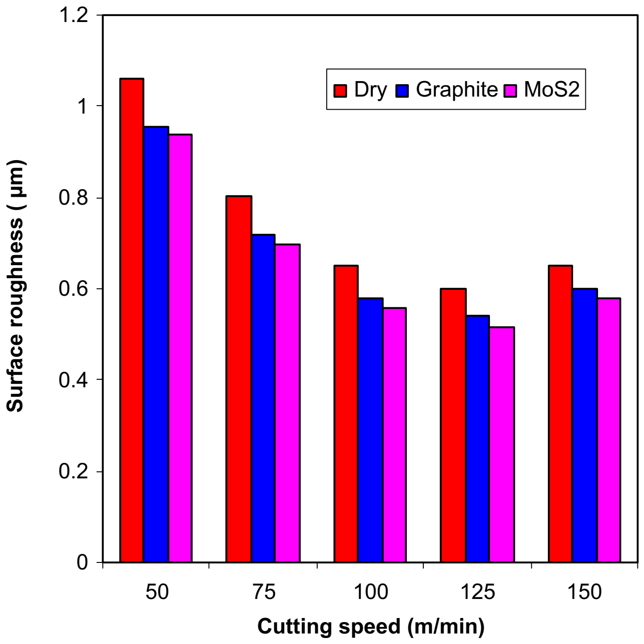

Fig. 2 Bar graph showing surface quality improvement

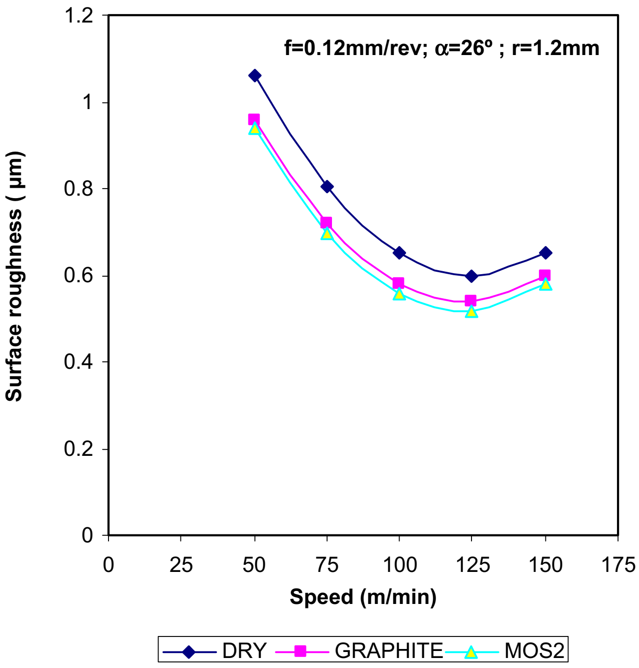

Fig. 3 Surface roughness variation with speed

The variation of surface roughness with respect to the feed is shown in the Fig. 4. Surface roughness is approximately constant upto 0.08 mm/rev and after this, it starts increasing with the increase of the feed. This is due the fact that more material has to removed per revolution, for which more energy is required, which ultimately increases the cutting forces and temperatures leading to high wear of the cutting tool, which might have resulted in the increase of surface roughness. However, surface roughness produced by the solid lubricants is again lower than that of dry hard turning process.

The trend of variation of the surface roughness with respect to the effective rake angle can also be observed from the Fig. 5. It first decreases and then again increases. This could be due to the fact that the increase in effective negative rake angle reduces the tool wear 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. Again surface roughness decreases with the application of the solid lubricants as can be seen from the figure.

The variation of the surface roughness with respect to the nose radius can be seen from the Fig. 6. Surface roughness decreases with the increase of the nose radius. However, a slight increase in surface roughness can be observed beyond a nose radius of 1.8 mm, which is due to the combined effect of the other process parameters in addition to the nose radius. Hence the judicious selection of nose radii in combination with suitable effective rake angle and cutting conditions should be used to produce the better

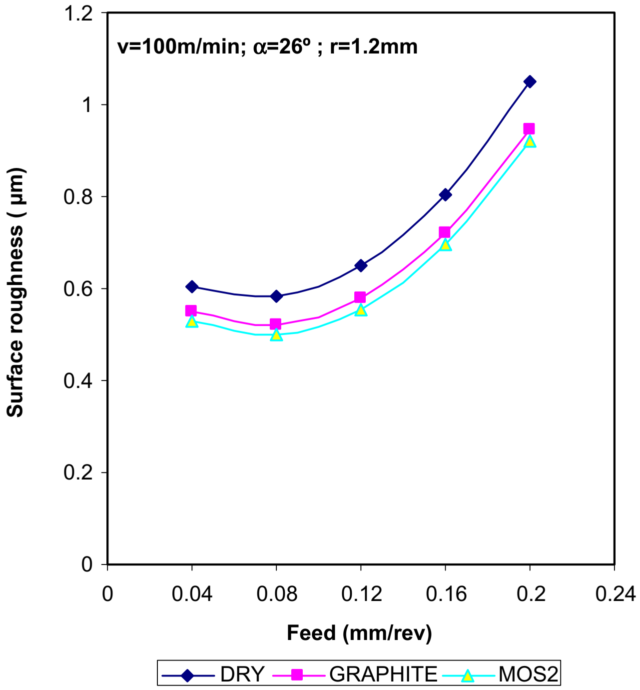

Fig. 4 Surface roughness variation with feed

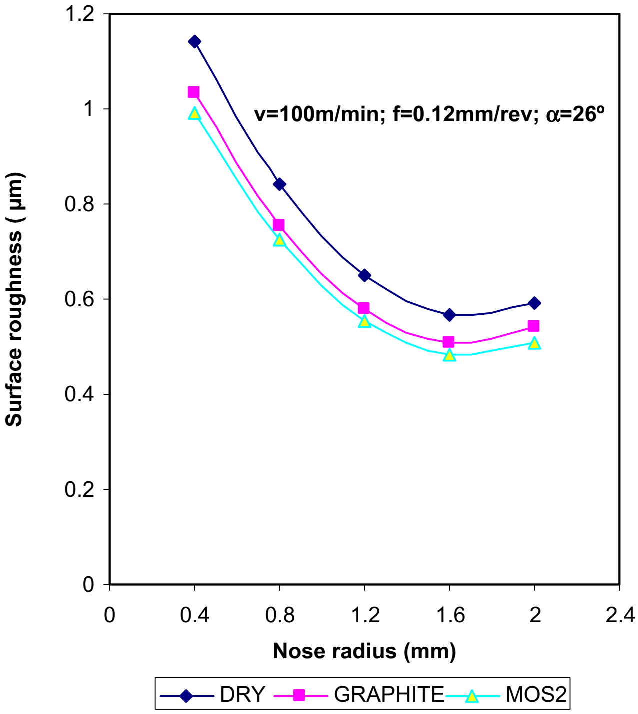

Fig. 6 Surface roughness variation with nose radius

surface quality. The effect of the solid lubricants can also be observed from this figure, which clearly indicates the solid lubricants are very much effective in producing the good quality hard turned parts.

From the above-mentioned results, it can be inferred that surface quality is better controlled by the solid lubricants in addition to the cutting conditions and the tool geometry parameters of the hard turning process. The net percentage decrease in the surface roughness value is also dependent upon the type of solid lubricant. So, there is a decrease of surface roughness values 8 to 10% due to graphite and 13 to 15% due to molybdenum disulphide. The decrease in the surface roughness due to solid lubricants can be attributed due the inherent lubricating properties of the solid lubricants even at extreme temperatures. This is due to the layered lattice structure of these lubricants. The lubricating action of the solid lubricants reduces the frictional forces between the chip and the tool interface and tool and the workpiece, hence reducing the temperatures developed and ultimately preventing the tool wear and prolonging the tool life, which result in surface quality improvement. The lower values of surface roughness produced by the molybdenum disulphide can be attributed to its strong adhesion as compared to the graphite.

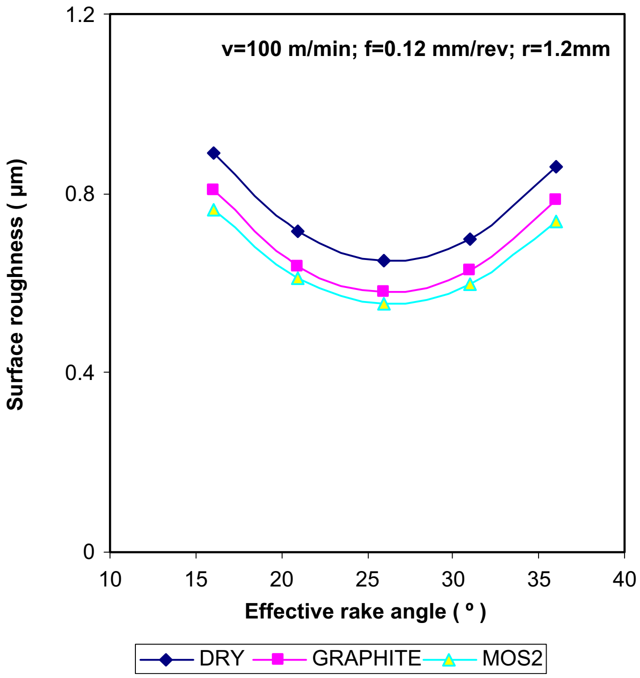

Fig. 5 Surface roughness variation with rake angle

5 Conclusions

The use of solid lubricants has been successful in reducing surface roughness during hard turning of bearing steel with mixed ceramic tools. Experimental results showed the superiority of the molybdenum disulphide hard turning over the graphite assisted hard turning. So, this methodology of using the solid lubricants appears to offer considerable benefits in terms of surface finish and environmental pollution point of view over the dry hard turning and hard turning with cutting fluids. This work also emphasizes that the proper selection of the solid lubricants along with cutting conditions and tool geometry is essential for achieving the overall improvement in hard turning process. The solid lubricant assisted hard turning may become a viable alternative to the dry and wet hard turning process.

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