Investigation to study the applicability of solid lubricants in machining for clean and green manufacturing

Mayurkumar Ashwinbhai Makhesana and Kaushik M. Patel
Department of Mechanical Engineering, Institute of Technology, Nirma University, Ahmedabad, India

Abstract

Purpose – The quality of the surface being machined and tool life are greatly affected by heat generated during machining. Abundant use of cutting fluid leads to higher production rates and a threat for environment and worker's health. Hence, the need is to identify eco-friendly lubricants. The purpose of the current work is to investigate the effects of solid lubricants (boric acid and molybdenum disulphide) mixed with oil during turning of EN-31 using cemented carbide tools. The concentration of solid lubricants in oil is varied to analyze output parameters such as surface roughness, process temperature, power consumption and tool wear.

Design/methodology/approach – EN 31 steel material is machined at various cutting speeds and constant feed and depth of cut to determine the effects of dry, wet and solid lubricant assisted machining.

Findings – Experimental study revealed that the solid lubricants performed better while machining and therefore it may be considered as environment friendly and cost effective way of lubrication as compared to flood cooling.

Research limitations/implications – The work can be extended to identify the effects of solid lubricants on micro hardness and cutting force.

Practical implications – From the findings of the work, solid lubricants may be considered as suitable choice as compared to fluid cooling because it improves process performance without much affecting the environment and worker's health.

Originality/value – So far the use of solid lubricants in machining is limited. The results of the work will be useful to explore various efficient way to apply solid lubricants.

Keywords Environmental impact, Manufacturing technology, Lubrication, Lubricants, Solid lubricants, Machining

Paper type Research paper

1. Introduction

Increasing demand for machine tools around the globe indicates that the demand for components produced by using machine tools is undergoing rapid increases. Machining is considered as one of the important manufacturing process which uses a cutting tool to remove the extra amount of metal available on work piece surface and brings it to required dimensions. For decades, machining processes have relied on the use of cutting fluids to extract the heat generated during the process. The heat generated at the primary and secondary cutting zones has a negative effect on the cutting tools, promoting wear. Increasing wear degrades the cutting tool's performance, consequently affecting the quality of machined parts/components, which is essential in machining processes. Therefore, the use of cutting fluids is an important part of a machining process. This provides a measure of control with respect to the thermal behavior within the machining zone and enables "bulk" cooling of the machining process. Nevertheless, the application of fluids account for an extensive proportion of the total manufacturing cost. The costs attributed to the use of machining fluids do not only comprise the initial purchase and delivery logistics but also the storage, energy consumption, treatment, filtration, and the end-of-life disposal (Klocke and Eisenblatter, 1997). The majority of fluids are semi-synthetic soluble oils that also require the use of water. In this respect, industry is required to comply with regulations that control the use and disposal of lubrication materials that are potentially hazardous to or place unacceptable burdens on natural resources and the environment. However, the increased demand of machining increases the consumption of cutting fluids, as well as demand for energy. Cutting fluids and energy supplies are mainly met from natural resources. Although cutting fluid, made from chemical substances has been widely used, dependence on mineral-based cutting fluids is still prominent. Meanwhile, the availability of natural resource has declined persistently. Besides limited availability of natural resources, the impact caused by the use of cutting fluids and increasing consumption of energy would create negative effects on the environment. Apart from this, high amount of mist is generated with the use of cutting fluid. Large number of workers are working in industries and around the machines, but the effects of these cutting fluids and mist generated on the worker's health is generally ignored. With the use of solid lubricant, this

The current issue and full text archive of this journal is available on Emerald Insight at: **www.emeraldinsight.com/0036-8792.htm**

Industrial Lubrication and Tribology
68/5 (2016) 591–596

[ISSN 0036-8792]
[DOI 10.1108/ILT-03-2015-0037]

Received 25 March 2015
Revised 10 August 2015
Accepted 28 August 2015

problem can be avoided which leads to green manufacturing (Byrne and Scholta, 1993).

In this context, there is a clear need to explore the potential for using solid lubricants within machining to make it environmentally friendly without the use of cutting fluid which leads to clean and green manufacturing.

2. Literature review

To overcome the effects of dry machining and fluid cooling, minimum quantity lubrication (MQL) and use of solid lubricants may be a feasible alternative. MQL is the way to achieve nearly dry machining; it uses the cutting fluid in optimize and minimum quantities, which can be considered very less as compared to the amount of cutting fluid which is used in fluid cooling (Machado and Wallbank, 1997).

The study about the effects with the use of cutting fluid on workers' health and environment has been reported by Bennett (1983). The use of cutting fluid is reduced by using the concept of mist lubrication. However, it was reported about the adverse effect of mist lubrication on health. Researcher has suggested and worked on the concept of MQL in machining. The application of 42 l/min as fluid coolant has been reported and compared with the results obtained from MQL of 8.5 ml/hr, and the improvement was reported in surface finish and reduction in cutting force. Improved surface finish was reported with the use of MQL compared to dry and wet cooling (Rahman *et al.*, 2002). It states to the supply of small quantities of fluid via an aerosol to the machining area. The mixture of air and oil can be prepared in a tank or on the nozzle tip (Weiner *et al.*, 2004; Klocke *et al.*, 2000). The study and comparison of the costs of storage and disposal of fluids in fluid delivery and MQL application in BMW company has been done by Dörr and Sahm (2000). A comparative study was carried out by Hadad and Sadeghi (2013) and they reported the effectiveness of MQL by comparing the performances of dry, MQL and flood lubricating conditions during machining of AISI 4,140 steel. Li and Liang (2007) reported the reduction in tangential forces with the use of MQL. Experiments were performed on AISI 1,040 steel under dry and MQL lubricating conditions by Dhar *et al.* (2007). The Fz (cutting force) and Fx (feed force) reduced significantly (5-15 per cent) with increasing cutting velocity in MQL condition. A study has been reported with the application of MQL for the machining of difficult-to-cut materials, and the outcome was compared with wet and dry machining. The obtained results were found to be improved as compared to other lubricating conditions (Varadarjan *et al.*, 2002).

One of the widely used solid lubricant is Boric acid, and it does not require any costly disposal techniques and possesses very good lubricating properties. The properties which makes it the most famous solid lubricant are that it is cheaper and environmentally safe. Study has been reported with the properties of boric acid as a solid lubricant (Edemir, 1991). The work mainly revealed the use of boric acid in high-temperature environment.

The possibility of the application of solid lubricants for machining of AISI 1,040 steel material is assessed by Mukhopadhyay *et al.* (2007). The results obtained were reduced chip thickness ratio and value of surface roughness and improved machinability. Singh and Rao (2008a, 2008b) identified the molybdenum disulphide as a solid lubricant for bearing steels and about the reduced friction and better surface finish of materials. Abhang and Hameedullah (2010) applied solid lubricant mixed with oil and reported considerable improvement in machining performance. Reddy and Rao (2006) investigated the role of solid lubricant-assisted end milling machining with graphite and molybdenum disulphide lubricants on surface quality, cutting forces and specific energy while machining AISI 1,045. Shaji and Radhakrishnan (2003) tried to develop solid lubricant-moulded grinding wheels with different bonds to provide effective solid lubrication in process. Agarwal and Paruchuri (2007) used graphite and molybdenum disulphide as solid lubricants to reduce the heat generated and friction in grinding and observed the effect of graphite and MoS_2 on the tangential grinding force. Work has been reported by applying graphite and MoS_2 as lubricants in turning. The values of surface roughness and cutting force was compared in turning with graphite and MoS_2-assisted machining (Singh and Rao, 2008a, 2008b).

Solid lubrication involves the inclusion, bonding or development of film coatings to separate otherwise interacting surfaces. Solid lubricants are often found in systems when conventional lubricants are not acceptable. For example, in circumstances of extreme temperatures and pressures, inaccessible locations, atmospheric and environmental protection.

The major advantages to solid lubrication being more effective than fluid lubricants at high loads and speeds, high resistance to deterioration and highly stable in extreme temperatures, pressure, radiation and reactive environments.

While the major disadvantage is poor self-healing properties of film structure in comparison to fluids. The above study reveals that the use of solid lubricants while machining can be a feasible option to reduce the environmental effects and develop a clear machining process (Rahmati *et al.*, 2013).

3. Experimental conditions and procedure

The machining tests were performed using Kirloskar Turnmaster lathe machine. The experiments performed on EN-31 alloy steel (Ø50*100 mm) in dry, wet and solid lubricants mixed with oil environment. To eliminate the effect of tool coatings on the results, an uncoated carbide tool is used for the study. The process parameters considered are cutting speed (*v*) 7, 18, 44, 112 m/min and constant value of feed rate (*f*) 0.224 mm/rev, depth of cut (*d*) 0.4 mm and tool nose radius (*r*) 0.8 mm to obtain the values of cutting temperature, surface roughness, power consumption and tool wear during machining. These parameters are chosen based on the present day industrial requirements and kept constant throughout the experiments. The properties of work piece material and experimental details are presented in Tables I and II respectively.

Table I Chemical composition of EN-31 workpiece

Composition	C	Si	Mn	Cr	Co	S	P
Weight (%)	0.95-1.2	0.10-0.35	0.30-0.75	1-1.6	0.025	0.040	0.04

Table II Experimental conditions

Machine tool	10 HP lathe machine
Work specimen material	En-31 alloy steel
Process parameters	Cutting speed $V = 7, 18, 44, 112$ m/min
	Feed $f = 0.224$ mm/rev
	Depth of cut $d = 0.4$ mm
	Tool nose radius $R = 0.8$ mm
Lubricants	Dry (no lubricant)
	Wet (soluble oil mixed with water in the ration of 1:20)
	Minimum quantity lubrication
	10% MoS_2 + SAE-40 base oil
	10% boric acid + SAE-40 base oil

Experiments were carried out at the selected cutting speed, feed rate and depth of cut under dry, wet and solid lubricant-assisted cutting conditions. The experimental results revealed lower value temperature, improved surface finish, reduced power consumption and tool wear in case of solid lubricant assisted machining as compared to dry and wet lubrication.

3.1 Lubricant composition

It has been reported that the value of kinematic viscosity increases with increase in proportion of solid lubricant in oil, and, thus, it results in improved lubricating property of lubricant mixture. It was also reported that with the increase in temperature, kinematic viscosity decreases. The thermal conductivity of lubricant mixture was found to be decreased with the increase in proportion of solid lubricant in oil. Thus, for proportion of 10 per cent solid lubricant in oil resulted with the better thermal conductivity. The minor change was reported in thermal conductivity with increase in temperature (Reddy *et al.*, 2010).

Solid lubricants performed well because of its lattice layer structure that allows it to create an effective lubricant film in machining. Crystallized boric acid forms weak van der Waals' bonds between individual layers and strong hydrogen (covalent) bonds within the layer. Such a bonding structure makes the structural properties of some solid lubricant highly anisotropic. When applied to cutting zone, the layers easily slide over another. Hence, when properly aligned with substrate, solid lubricants exhibit minimal friction and provide effective separation between surfaces (Vamsi Krishna and Rao, 2008).

SAE 40 base oil was used for the fluid cooling in machining. Based on the reported studies, two solid lubricants – boric acid and molybdenum disulphide – were mixed with cutting fluid and applied to the machining zone. The solid lubricants were mixed by proportion of 10 per cent in SAE 40 base oil to get better thermal conductivity and kinematic viscosity.

3.2 Experimental results

The experimental results are shown in Table III. Experiments were performed by taking the values of cutting speed, feed and depth of cut as mentioned in Table II. There are various methods to measure the cutting temperature such as tool work thermocouple, embedded thermocouples, radiation pyrometers, temperature sensitive paints and indirect calorimetric technique. From these methods, the tool work thermocouple method is used to measure the cutting temperature. The hot and cold junction produces a voltage, and this voltage is in the proportion to the difference in temperature between reference and measuring junction. Surface roughness is measured by Mitutoyo surface roughness tester which has 0.01 μm resolution and the Ra measurement is taken perpendicular to the machining direction. The power consumption is obtained by placing wattmeter between the power supply and the machine tool. The tool wear is measured on a sensitive single pan balance. Tool wear is obtained by measuring the weight of tool before and after machining for dry, wet and solid lubricant environment for all considered cutting speed.

3.3 Temperature

In machining, the tool wear is sensitive to the cutting temperature. Thus, the higher value of temperature results in higher tool wear which further results in reduced tool life and poor surface quality. It is clear from the comparison that with

Table III Experimental results

Lubricants → / Output parameters ↓	Cutting speed (m/min)	Dry	Wet	10% MoS_2 + SAE-40 base oil	10% boric acid + SAE-40 base oil
T (°C)	8	90	70	50	52
	18	170	154	82	66
	44	460	258	150	130
	112	610	360	170	146
Ra (μm)	8	6.640	4.230	4.702	4.770
	18	4.770	3.350	3.607	3.969
	44	4.740	3.295	2.033	2.296
	112	4.436	2.810	2.019	2.179
P (W)	8	110	70	95	90
	18	180	140	150	144
	44	240	184	180	200
	112	460	420	400	380
Tool wear (mg/min)	8,18,44,112	0.338	0.335	0.274	0.249

the increase in cutting speed, the cutting temperature is increased because of increase in cutting energy input.

It is clear from the comparison that with the increase in cutting speed, the cutting temperature is increased because of increase in cutting energy input. Experimental results show minimum value of temperature in case of solid lubricant-assisted machining, particularly with the use of 10 per cent boric acid mixed with SAE-40 base oil. The results of temperature measured is shown in Figure 1 by considering different cutting speed and constant value of feed, depth of cut and tool nose radius. The use of solid lubricant and SAE 40 lubricating oil results low coefficient of friction because solid lubricants soften at elevated temperatures. And another reason can be the excellent cooling properties in form of thermal conductivity and kinematic viscosity of boric acid at higher speeds. It conforms the reported work that for proportion of 10 per cent solid lubricant in oil leads to increase in kinematic viscosity and thus it results improved lubricating property and thermal conductivity of lubricant mixture (Reddy *et al.*, 2010).

3.4 Surface roughness

The effectiveness of any machining process can be seen from the obtained surface quality of work piece. Surface finish obtained in machining is affected by many parameters and machining conditions. It is concluded that the surface finish can be improved by reducing the cutting forces and heat generated during machining (Nam and Nannaji, 1987). It was also reported that the application of graphite as a solid lubricant had reduced the surface roughness as compared to dry machining and machining with fluid cooling (Brinksmeier *et al.*, 1999). From the experimental results, it can be concluded that the minimum surface roughness is found in machining while using 10 per cent MoS_2 mixed with SAE-40 base oil. This is because of good lubricating properties of solid lubricant at a higher temperature which leads to lower friction and heat and thus reducing tool wears and improves surface roughness. The value of surface roughness reduces as the speed increases. The performance of dry, wet and solid lubricants is compared and shown in Figure 2. The use of solid lubricants has reduced the friction between tool and work piece and thus reduced surface roughness is obtained as compared to fluid lubricant.

It has been reported that the surface roughness has reduced by an average of 23 per cent with MoS_2 solid lubricant as compared to wet cutting and 43 per cent as compared to dry cutting during machining of medium carbon steel (Reddy and Rao, 2006). In fact, the surface roughness is more dependent on the lubricant and cooling actions of the fluids.

Figure 1 The variation in temperature with different speeds (7, 18, 44, 112 m/min), at constant feed (0.224 mm/rev) and depth of cut (0.4 mm) under different lubricating condition

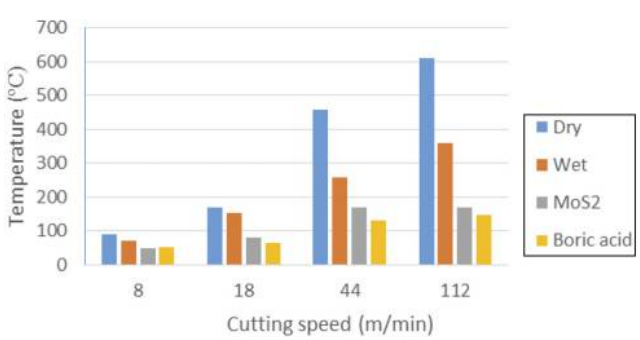
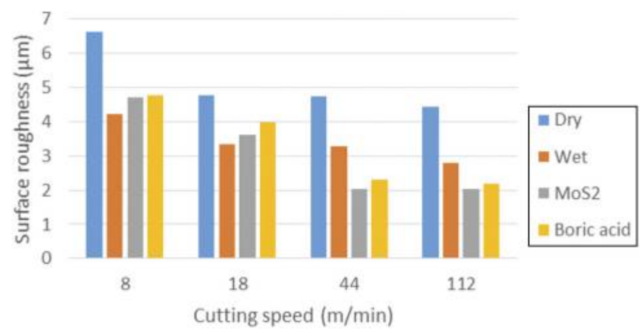


Figure 2 The variation in surface roughness with different speeds (7, 18, 44, 112 m/min), at constant feed (0.224 mm/rev) and depth of cut (0.4 mm) under different lubricating condition



3.5 Power consumption

The Figure 3 shows the comparison of power consumed during machining in case of dry, wet and solid lubricants mixed with oil. The rate of power consumed increases with increase in speed. From the comparison, it can be noted that there is no significant variation in power consumed during machining with all the lubricating condition considered. The reason behind this can be the improved lubrication properties of solid lubricants at higher cutting speeds.

3.6 Tool wear

Tool wear is one of the most important parameter required to consider in machining because it not only affects the performance of process but also decides the effective tool life during machining. The amount of tool wear is considered at various speeds and constant feed rate and depth of cut for each. The significant reduction is observed in case of solid lubricant-assisted machining as lubricating condition compared to dry and wet lubrication. This is because of reduced friction and heat generation which results less tool wear and increases tool life. The comparison on the effect of tool wear is shown in Figure 4. The reduction in tool wear can

Figure 3 The variation in power consumption with different speeds (7, 18, 44, 112 m/min), at constant feed (0.224 mm/rev) and depth of cut (0.4 mm) under different lubricating condition

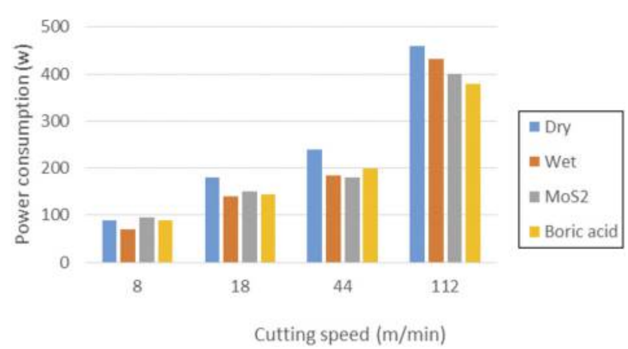
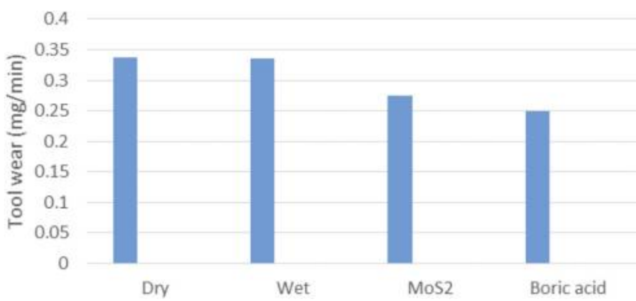


Figure 4 The variation in tool wear with feed rate (0.224 mm/rev), cutting speed (8, 18.44, 112 m/min) and depth of cut (0.4 mm) under different lubricating condition



be credited to the development of coating film of lubricant on the tool surface that reduces friction (Vamsi Krishna *et al.*, 2010) and leads to the cooling action that reduces temperature and tool wear.

Using solid lubricant-assisted machining the effective temperature is controlled, so that the plastic deformation is reduced. The reasons for reduction of tool wear are low coefficient of friction, sliding action and low shear resistance within the contact interface.

4. Conclusion

The analysis of experimental results of the work led to following conclusions for the solid lubricant assisted turning of EN-31 material. The solid lubricant assisted machining may be a suitable and environmental friendly alternative as compared to fluid cooling. In most of the condition, solid lubricant-assisted machining performs better and improves surface finish, reduces temperature, tool wear and power consumption, may be because of excellent lubrication properties. Use of solid lubricant improved the machinability with the reduction in frictional forces between the tool and workpiece. This work also highlights that solid lubricant assisted machining is necessary for making it an important alternative to eliminate the use of cutting fluids in metal cutting and thus making the machining cleaner and pollution free.

References

Abhang, L.B. and Hameedullah, M. (2010), "Experimental investigation of minimum quantity lubricants in alloy steel turning", *International Journal of Engineering Science and Technology*, Vol. 2 No. 7, pp. 3045-3053.

Agarwal, S. and Paruchuri, V.R. (2007), "Performance improvement of sic grinding using solid lubricants", *Machining Science and Technology*, Vol. 11 No. 1, pp. 61-79.

Bennett, E.O. (1983), "Water based cutting fluids, and human health", *Tribology International*, Vol. 16 No. 3, pp. 213-216.

Brinksmeier, E., Heinzel, C. and Wittmann, M. (1999), "Friction, cooling and lubrication in grinding", *CIRP Annals – Manufacturing Technology*, Vol. 48 No. 2, pp. 581-594.

Byrne, G. and Scholta, E. (1993), "Environmentally clean machining processes-a strategic approach", *CIRP Annals – Manufacturing Technology*, Vol. 42 No. 1, pp. 471-474.

Dhar, N.R., Ahmed, M.T. and Islam, S. (2007), "An experimental investigation on effect of minimum quantity lubrication in machining AISI 1040 steel", *International Journal of Machine Tools & Manufacture*, Vol. 47, pp. 748-753.

Dörr, J. and Sahm, A. (2000), "The minimum quantity lubricant evaluated by the users", *Machines and Metals Magazine*, Vol. 418, pp. 20-39.

Edemir, A. (1991), "Tribological properties of boric acid and boric acid forming surfaces: part I", *Crystal Chemistry and Mechanism of Self Lubrication of Boric Acid, Lubrication Engineering*, Vol. 47, pp. 168-178.

Hadad, M. and Sadeghi, B. (2013), "Minimum quantity lubrication-MQL turning of AISI 4140 steel alloy", *Journal of Cleaner Production*, Vol. 54, pp. 332-343.

Klocke, F., Beck, T., Eisenblatter, G. and Lung, D. (2000), "Minimal quantity of lubrication (MQL) – motivation, fundamentals, vistas", *12th International Colloquium*, pp. 929-942.

Klocke, F. and Eisenblatter, G. (1997), "Dry cutting", *Annals of CIRP*, Vol. 46 No. 2, pp. 519-526.

Li, K.M. and Liang, S.Y. (2007), "Performance profiling of minimum quantity lubrication in machining", *International Journal of Advanced Manufacturing Technology*, Vol. 35, pp. 226-233.

Machado, A.R. and Wallbank, J. (1997), "The effect of extremely low lubricant volumes in machining", *Wear*, Vol. 210 Nos 1/2, pp. 76-82.

Mukhopadhyay, D., Banerjee, S. and Reddy, N.S. (2007), "Investigation to study the application of solid lubricant in turning AISI 1040 steel", *Transactions of the ASME Journal of Manufacturing Science and Engineering*, Vol. 129, pp. 520-526.

Nam, P.S. and Nannaji (1987), "Surface engineering", *CIRP Annals – Manufacturing Technology*, Vol. 36 No. 1, pp. 403-408.

Rahman, M., Kumar, A.S. and Salam, M.U. (2002), "Experimental evaluation on the effect of minimal quantities of lubricant in milling", *The International Journal of Machine Tools and Manufacture*, Vol. 42 No. 5, pp. 539-547.

Rahmati, B., Sarhan, A.A.D. and Sayuti, M. (2013), "Morphology of surface generated by end milling AL6061-T6 using molybdenum disulphide (MoS_2) nano lubrication in end milling machining", *Journal of Cleaner Production*, pp. 1-7.

Reddy, N.S.K., Nouari, M. and Yang, M. (2010), "Development of electrostatic solid lubrication system for improvement in machining process performance", *International Journal of Machine Tools & Manufacture*, Vol. 50, pp. 789-797.

Reddy, N.S.K. and Rao, P.V. (2006), "Experimental investigation to study the effect of solid lubricants on cutting forces and surface quality in end milling", *International Journal of Machine Tools & Manufacture*, Vol. 46 No. 2, pp. 189-198.

Shaji, S. and Radhakrishnan, V. (2003), "An investigation on solid lubricant moulded grinding wheels", *International Journal of Machine Tools & Manufacture*, Vol. 43 No. 9, pp. 965-972.

Singh, D. and Rao, P.V. (2008a), "Improvement in surface quality with solid lubrication in hard turning", *Proceedings of the World Congress on Engineering 2008, WCE, 2-4 July, London.*

Singh, D. and Rao, P.V. (2008b), "Performance improvement of hard turning with solid lubricants", *International Journal of Advance Manufacturing Technology*, Vol. 38 No. 5, pp. 529-535.

Vamsi Krishna, P. and Rao, D.N. (2008), "Performance evaluation of solid lubricants in terms of machining parameters in turning", *International Journal of Machine Tools & Manufacture*, Vol. 48, pp. 1131-1137.

Vamsi Krishna, P., Srikant, R.R. and Rao, D.N. (2010), "Experimental investigation to study the performance of solid lubricants in turning of AISI1040 steel", *IMechE Part J: Journal of Engineering Tribology*, Vol. 224, pp. 1273-1281.

Varadarjan, M.A.S., Philip, P.K. and Ramamoorthy, B. (2002), "Investigations on hard turning with minimal cutting fluid application (HTMF) and its comparison with dry and wet turning", *International Journal of Machine Tools & Manufacture*, Vol. 42 No. 2, pp. 193-200.

Weiner, K., Inasaki, I., Sutherland, J.W. and Wakabayashi, T. (2004), "Dry machining and minimum quantity lubrication", *CIRP Annals – Manufacturing Technology*, Vol. 53 No. 2, pp. 511-537.

About the authors

Mayurkumar Ashwinbhai Makhesana is working as an Assistant Professor in Mechanical engineering department of Institute of Technology at Nirma University, Ahmedabad, India. The interested area for the research is application of solid lubricants in machining and advanced machining techniques. Mayurkumar Ashwinbhai Makhesana is the corresponding author and can be contacted at: mayur.makhesana@nirmauni.ac.in

Dr Kaushik M. Patel is working as Professor in Mechanical engineering department of Institute of Technology at Nirma University, Ahmedabad, India. The interested area for the research is advanced manufacturing techniques and non-conventional machining processes. He has authored several research papers in reputed international journals.