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A STUDY ON CALCIUM FLUORIDE AS A SOLID LUBRICANT IN GRINDING

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Cutting fluids are a source of environmental hazard, and internationally increasingly strict legislations are coming up with regard to its use and disposal. It also incurs a significant share of total manufacturing cost. Minimization and possibly elimination of cutting fluids, by substituting their functions by some other means, is of current research interest. Cutting fluids play a decisive role in grinding because of the intense heat generation and the consequent thermal damage associated with the process. Conventionally, liquid coolants in flood form are employed in grinding. Solid lubricants can be used in grinding, as a means to reduce the heat generated due to friction at the grinding zone, towards the attempt for eliminating cutting fluid. This paper deals with an investigation on using calcium fluoride as a lubricating medium in surface grinding. A detailed performance analysis has been done in terms of forces, specific energy, temperature, surface finish and wheel wear. A comparative study with dry and coolant grinding has shown some interesting trends.

***Key words*: grinding, lubrication, coolant, calcium fluoride**

INTRODUCTION

Cutting fluids generally have a negative impact on the environment and they cannot be recommended in the light of ecological manufacture. Besides the environmental threat, due to its poor waste disposal, they cause severe health hazard even within the factory [1]. Dermatological diseases are common in workers using cutting fluids. There is increased susceptibility to respiratory problems and regular exposure to oil mist may cause cancer. Poor maintenance of the cutting fluid may lead to microbial attack [2,3]. Hence, increasingly strict legislations are coming up with regard to the use and disposal of cutting fluid [1,4]. Moreover, proper management of the cutting fluid incurs a significant share of the total manufacturing cost. So its use cannot be justified on economic grounds [5]. These factors prompt investigations on the minimization or possible elimination of cutting fluid, by substituting its functions by other means [6].

Grinding is employed as a common finishing process in manufacturing. It employs large quantity of cutting fluid, usually in flood form, to ensure product quality. In fact, the cooling and lubrication by cutting fluid plays a decisive role in grinding tribology, as intense heat is generated due to high friction involved in the process and there is high risk of thermal damage associated with the workpiece [7,8]. The effectiveness of conventional flood supply is questionable as the 'air barrier' inhibits the accessibility of

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the cutting fluid to the grinding zone [9]. The film boiling of the fluid due to the high temperature prevailing in the grinding zone is another limitation to the stock removal [10]. However, it provides excellent wheel cleaning and bulk cooling [11,12]. Development of alternative approaches for replacing the cutting fluid in grinding should take into consideration all of these aspects. Use of biodegradable coolants, the concept of minimum quantity lubrication (MQL) and use of refrigerated jet of gas are some of the attempts made in this direction [5,6,12,13].

Towards finding out alternative approaches for replacing fluid coolants, an attempt to reduce the heat at its generation stage itself would be ideal, rather than removing the heat after its generation. Authors have investigated the possibility of applying graphite as a lubricating medium to reduce the heat generated due to friction at the grinding zone and some interesting results have been obtained [14]. This paper deals with the investigation on using calcium fluoride (CaF_2), another high temperature solid lubricant [15,16], as a lubricating medium in surface grinding. The performance analysis has been made in terms of force components, specific energy, surface finish, temperature, tool wear etc. Performance comparison of the proposed method with dry and coolant grinding has also been made.

EXPERIMENTAL STUDY

The experimental study was done in a horizontal spindle surface grinding machine (6.5kW). The set-up for CaF_2 assisted grinding for the investigations is shown schematically in Figure 1. A photograph of the set-up is shown in Figure 2. Fine CaF_2 powder was mixed with water-soluble oil and a little quantity of grease (4:4:1 by weight) into a paste form. This was loaded into cylinder A, shown in Figure 1. The paste was pushed out through a rectangular nozzle D (1x25 mm size) by a pneumatically operated piston B. The soft rubber wheel C, driven by the grinding wheel, smeared the paste to the periphery of the grinding wheel. The flow rate was calibrated for different pressures given to the piston and a rate of delivery of 4 mm^3/s was employed for the experiment.

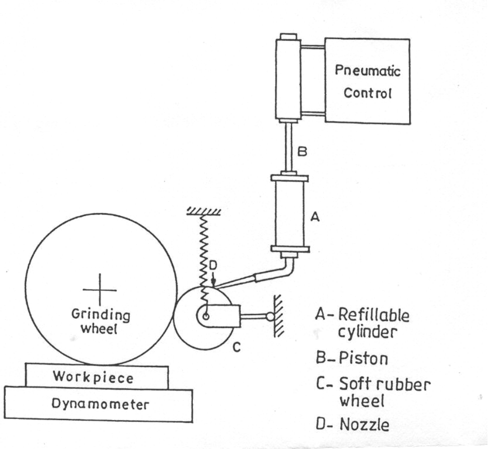

Figure 1. Schematic diagram of the experimental setup

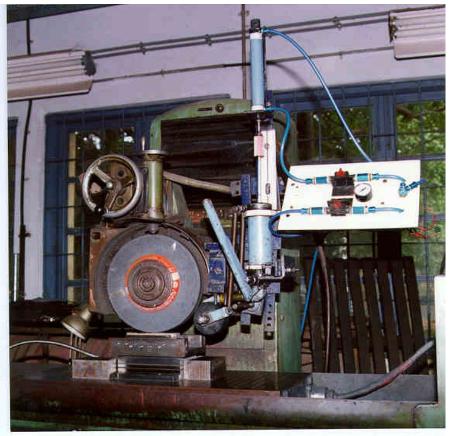

Figure 2. Experimental setup in photograph

Coolant assisted grinding was done with the coolant supply set-up in the machine itself employing soluble oil in water in 1: 20 ratio at the rate of 4 l/min. En-2 steel and En-31 steel hardened to bulk HR_C of 22 and 60 respectively were used as workpieces. Horizontal surface grinding was done with the wheel A60K5V10 (250-25-76.2 mm size) engaging its full width.

Initially, the most influential factors were identified by conducting a 3-level 4-factor (speed, feed, infeed and mode of dressing) experiment following the Taguchi's L_9 orthogonal array with 4 repetitions in dry, coolant and CaF_2 assisted grinding, taking force components and surface finish as quality characteristics. ANOVA based on S/N data showed that infeed and mode of dressing respectively were the most influential parameters on forces and surface finish in all the three modes of grinding. These two factors were taken as variable parameters for further study.

For the performance comparison study, the experimental conditions shown in Table 1 were employed. In each mode of dressing, normal force (F_n), tangential force (F_t) and temperature were sensed on line during grinding at different infeeds. The surface roughness was measured off line. Continuous wear test was done and wheel wear and force components were noted at regular intervals.

For force measurements, a 3-component quartz dynamometer (Kistler-type 9257B) with charge amplifier (Kistler-type 5019B) and a 2-channel oscilloscope connected directly to a PC were employed. The forces reported are those when the process was in stable state with almost steady pulses. Temperature was sensed by an infrared thermometer (Raytek-Raynger MX4) focusing at the wheel-work interface. Surface roughness of the ground part was measured by using a Talysurf. Specific energy was calculated using the formula $(F_tV_s)/(V_wa\ b)$, where F_t = tangential force, V_s = peripheral speed of the grinding wheel, V_w = feed, a = infeed, b = width of cut [22,23].

Cutting speed : 30m/s
Feed : 10m/min
Infeed : 10 to 40μm in steps of 10 μm
Environment : Dry, Soluble oil (1:20 oil in water) and CaF_2
Dressing conditions : with single point diamond dresser , 1carat, at wheel speed of 1800 rpm in dry condition in the modes of
1.Fine : 10μm depth , cross feed ~75 mm/min, 2 passes with one spark out pass
2.Medium : 20μm depth , cross feed ~150 mm/min, 2 passes with no spark out pass
3.Coarse : 30μm depth , cross feed ~300 mm/min, 2 passes with no spark out pass

Table1. Experimental conditions:

RESULTS AND DISCUSSION

Figure 3 shows the variation of grinding forces in the normal and tangential directions with the infeed under different dressing conditions and grinding environment. Grinding forces are based on different elements, which largely depend on the wheel characteristics, work material characteristics, process parameters, nature of wheel-workpiece interaction and the chosen environment. In all the cases under study, force components increased with infeed as expected [17]. This agrees with the various physical and empirical models reported [18,19]. The force components are directly proportional to the mean undeformed chip thickness, which in turn is directly proportional to the infeed. As the infeed increases, the productive components of the forces associated with shearing, micro fracturing and secondary plowing increases. The non-productive components of forces such as friction, wheel loading, primary plowing etc. depend on the wheel-work characteristics and are almost independent of the infeed

[13,22,23]. The force components in dry and coolant grinding were more or less the same. It indicates the ineffectiveness of the coolant to serve its purpose. In some cases of dry grinding, the forces were lower than that of coolant grinding. This may be attributed to the thermal softening of the material.

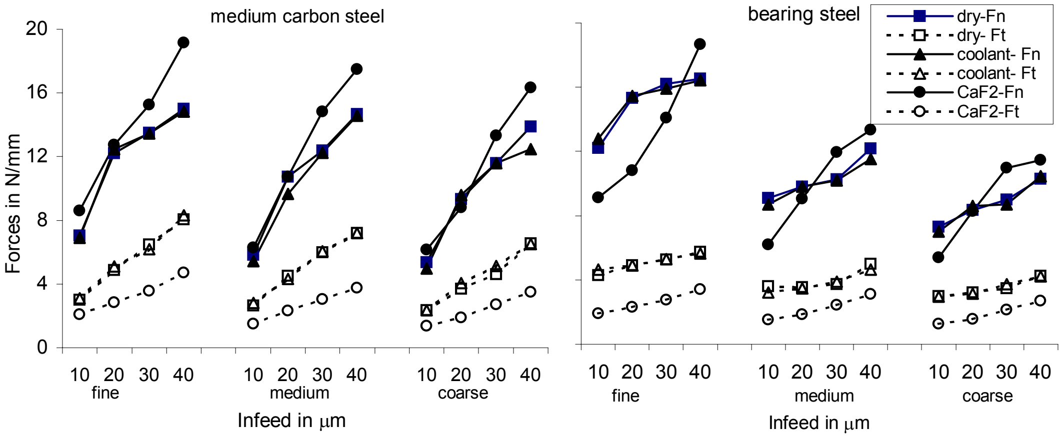

Figure 3. Variation of force components with respect to infeed under various grinding conditions.

In all cases of grinding, tangential force component is generally lower for brittle material (bearing steel), compared to ductile material (medium carbon steel). The nature of the material removal is different in both the cases. In the case of ductile material, during chip formation it is first subjected to elastic deformation, then the material starts to yield and then plastic deformation takes place. But in the case of brittle material, the chip formation is characterized by the generation of micro cracks, its propagation and finally the fragmentation of chip occur. The tangential force component in the case of brittle material is relatively smaller, because the generation of cracks and fracture requires less energy than plastic deformation [18].

In the case of CaF_2-assisted grinding, the tangential force components were substantially lower compared to dry and coolant grinding. This indicates that the lubricating property of the CaF_2 was effective in reducing the frictional forces at the wheel-workpiece interface. The normal force components in lubricant assisted grinding should also decrease correspondingly. But in some cases, these components were found to be more than those in the case of dry and coolant grinding. The normal force depends upon the amount of wheel loading also. Here, the lubricant supplied in paste form often got mixed with the chip formed and got loaded on to the wheel periphery. In some cases, the excess supply of lubricant worsened the situation leading to higher values of normal force.

The ratio of tangential force to normal force (F_t/F_n) was termed as grinding coefficient [17] or grinding force ratio [18,19]. This ratio, though it does not give the actual coefficient of friction [μ], it is a similar term like μ and gives an indication of the frictional effects in the grinding zone [17]. Figure 4 shows the variation of grinding force ratio under different grinding situations. This ratio is substantially lower in the case of CaF_2 assisted grinding. This substantiates the effective lubrication by CaF_2 in the proposed method. This ratio has been reported as differing considerably depending upon the material of the workpiece and it would describe the workpiece behavior in the process [18,19]. The present investigation shows that with the same material itself the grinding environment which provides effective lubrication can change this ratio markedly. This may be attributed to the behavior of the material in the presence of lubricant.

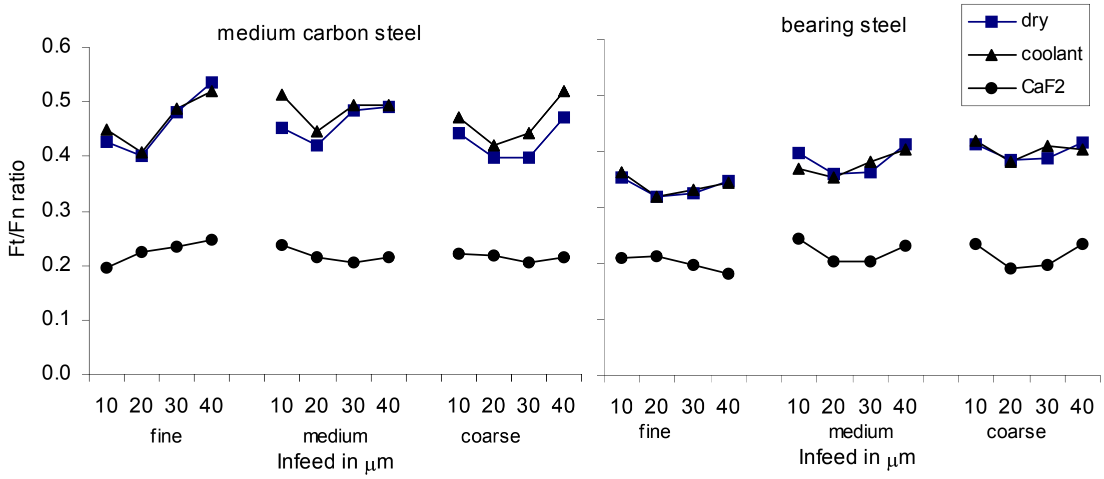

Figure 4. F_t/F_n ratio obtained under various grinding conditions

Figure 5 shows the variation of specific energy requirements under various situations of grinding. Specific energy increases with a decrease of the infeed in all conditions of grinding under study. This established behavior, termed as size effect, is due to the domination of sliding and plowing components at lower infeeds [22]. Moreover, the chip formation process is a special high strain extrusion process that involves rapidly increasing strain rate with a decrease of the undeformed chip thickness at lower infeeds [23].

The dressing condition of the wheel has profound influence on the parameters under study. Dressing controls the distribution of active grits, their initial sharpness or bluntness and the chip accommodation space. Finer dressing with lower dressing lead and depth produces high density cutting edges with wider flats on the grains, which penetrate less easily into the work material causing high normal forces. In such cases, sliding and plowing components will be higher, resulting in high friction and increased amount of plastic deformation, leading to higher tangential force. With coarser dressing, grits are damaged severely and the plateau area per grit would be smaller, leading to lower force components [20,21]. Accordingly, the related parameters such as specific energy, temperature etc. were found to decrease with coarser dressing modes in all the environments under study.

Figure 6 shows the temperature variations under different grinding conditions. The temperature sensed by the infrared radiation thermometer used here can be taken only as a representative figure for comparison purposes, as this method will not give the correct cutting zone temperature. However, the temperatures obtained are found to be substantially lower in the case of CaF_2-assisted grinding. This is due to the reduction in frictional heat generated at the grinding zone.

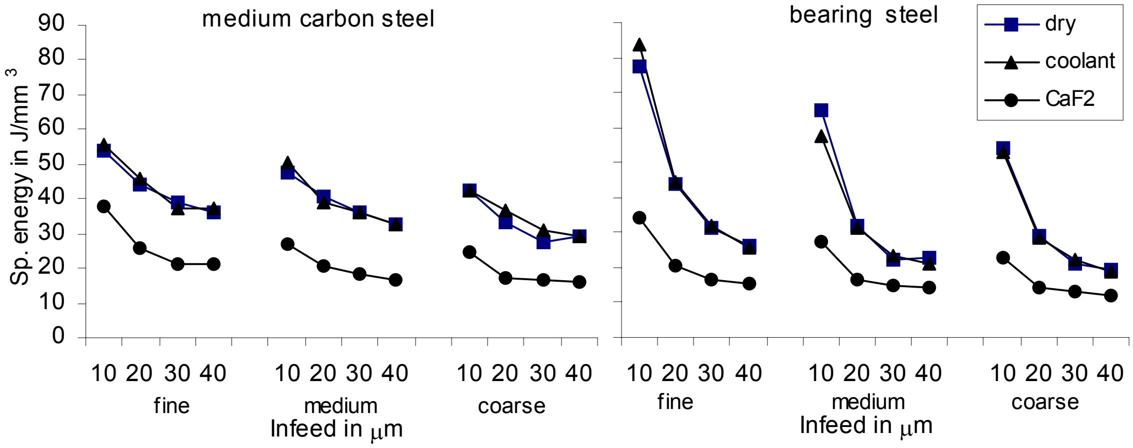

Figure 5. Variation of specific energy with infeed under various grinding conditions

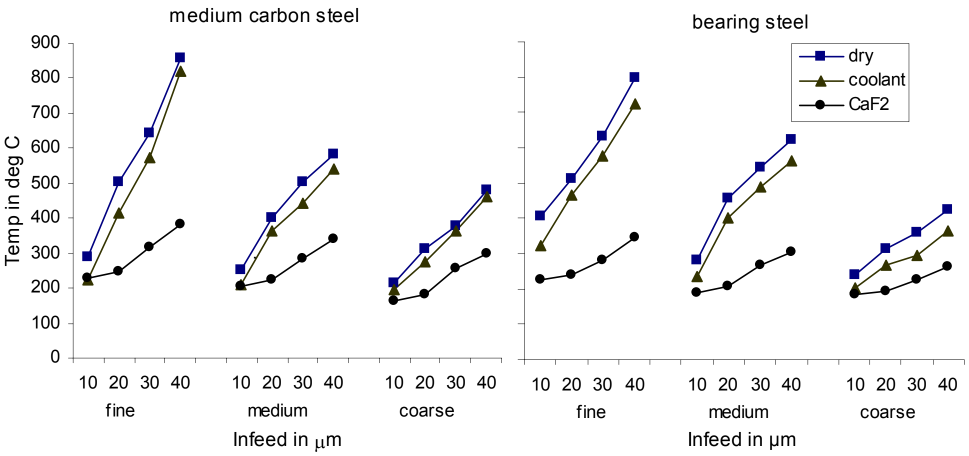

Figure 6. Temperature obtained under various grinding conditions

Figure 7 shows the surface roughness obtained under different grinding conditions. In the case of medium carbon steel under CaF_2 environment, roughness was found to be higher than those in the case of dry and coolant conditions. But, in the case of bearing steel, surface finish was found to be generally improved in the lubricant environment. Here, the material behavior in the process plays a major role. In the case of ductile material, which is characterized by yielding and plastic deformation during chip formation, chip may stick around the abrasive grains causing third body abrasion on the workpiece. The lubricant applied in paste form here worsened the situation by preventing the free escape of the swarf from the grinding zone. So a higher value of roughness was obtained in the case of medium carbon steel. In the case of brittle material, the chip formation is dominated by fracture mode and it has less tendency to stick on to the abrasive grains, leading to better finish. In this case also, if effective wheel cleaning could be provided, a more desirable result with regard to finish can be expected. It is noticeable that, with brittle material, the improvement in surface finish was relatively more in the coarser dressing modes compared to that in other dressing modes, as coarser modes have more swarf accommodation space.

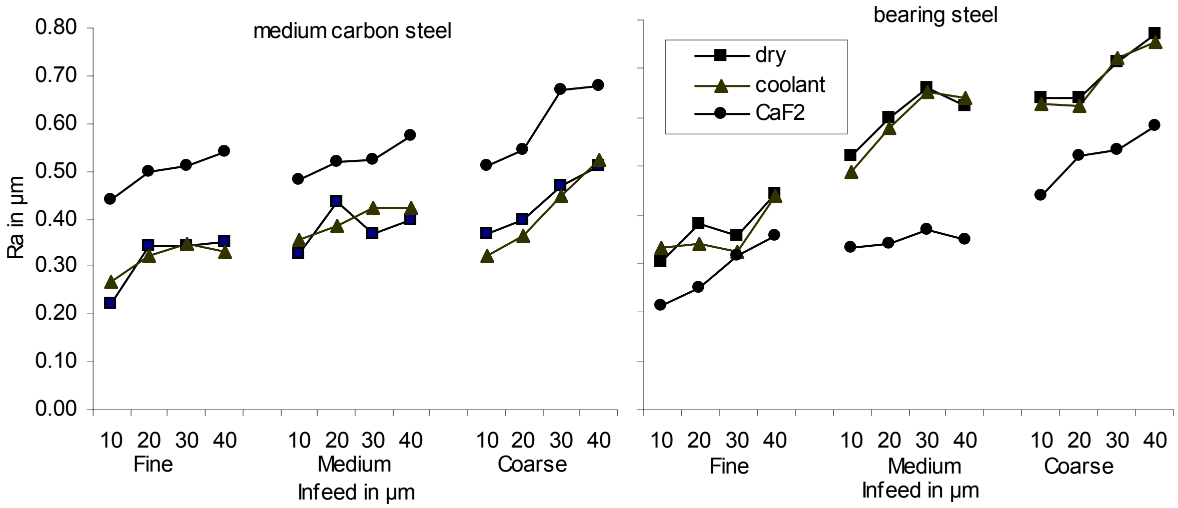

Figure 7. Surface roughness obtained under various grinding conditions

Figure 8 shows the volume of wheel worn (per unit width) and forces obtained with the bearing steel workpiece in the continuous grinding test under different environments. During the Initial stages of grinding in the case of CaF_2 environment, the wheel wear rate was less compared to the dry and coolant conditions and there after it was found increasing. This was due to the effective lubrication by CaF_2 during the initial stages of grinding and there after the wheel surface became smooth, with the pores filled up with the swarf. The intermittent force values taken, for CaF_2 assisted grinding, for every 10μ infeed as shown in Figure 8 indicates the self sharpening effect of the abrasive grains in the process. The normal force after rising was dropping down intermittently. The tangential force did not have much variation as compared to the normal force. As a catastrophic wear is not seen in the lubricant environment and the self sharpening effect of grains is also there, if proper wheel cleaning could be provided, effective cutting could be ensured in prolonged grinding also.

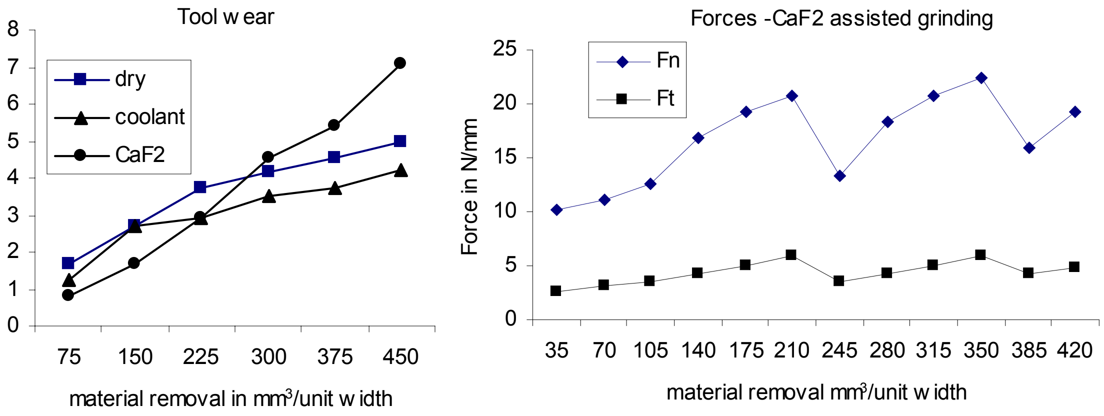

Figure 8. Tool wear (per unit width) and forces obtained in the continuous grinding test (bearing steel)

CONCLUSION

Towards an attempt to avoid environmentally harmful cutting fluid, investigation on application of CaF_2 as lubricating medium has been conducted with surface grinding. A comparative performance analysis of the proposed method with dry and coolant grinding has been done. The effective role of lubricant has been evident from the improvement of output parameters related to the wheel-workpiece friction. The wheel loading, due to the absence of effective removal of swarf, was found to be a major hindrance in obtaining more desirable results. If proper application of the solid lubricant to the grinding zone could be ensured, with the means for substituting the flushing function of the coolant, it would be an effective alternative for the conventional flood coolants.

REFERENCES

1. Howes T. D., H. K. Toenshoff and W. Heur. "Environmental Aspects of Grinding Fluids." Ann. of CIRP, Vol. 40, No.2 (1991), pp. 623-630.
2. Hill E. C. "Microbial Aspects of Health Hazards from Water-Based Metal Working Fluid." Tribology International, Vol.16, No.3 (1983), pp. 136-140.
3. Bartz W. J. "Ecological and Environmental Aspects of Cutting Fluids." Lubrication Engg., Vol. 57, No.3 (2001), pp.13-16.
4. Byrne G. and E.Scholta. "Environmentally Clean Machining Process – A Strategic Approach." Ann. of the CIRP, Vol.42, No.1 (1993), pp. 471-474.

5. Brinksmeier E., A. Walter, R .Janssen and P.Diersen. "Aspects of Cooling Lubrication Reduction in Machining Advanced Materials." Proc. Instn. Mech. Engrs.,Vol.213, No.B-8(1999), pp. 769-778.
6. Inasaki I., H. K. Toenshoff and T. D. Howes. "Abrasive Machining in the Future." Ann. of CIRP Vol.42, No.2 (1993), pp. 723-732.
7. Snoys R., K.U. Leuven, M.Maris and J.Peters. "Thermally Induced Damages in Grinding." Ann. of CIRP,Vol. 27, No.2 (1978), pp. 571- 581.
8. Brinksmeier E., C. Heinzel and M.Wittman. "Friction, Cooling and Lubrication in Grinding." Ann. of CIRP, Vol.48, No.2 (1999), pp. 581-597.
9. Ebbrel S., N.H.Wooley, Y.D.Tridimas, D.R.Allanson and W.B.Rowe, The Effects of Cutting Fluid Application Methods on the Grinding Process, Int. J. Machine Tools Manufact., Vol.40, No.1 (2000), pp. 209-223.
10. Howes T.D. "Assessment of Cooling and Lubricating Properties of Grinding Fluids." Ann. of CIRP Vol.39, No.1 (1990), pp. 313-316.
11. Khudobin L. V. "Cutting Fluids and Its Effect on Grinding Wheel Clogging." Machines and Tooling, Vol. XL, No.9 (1969), pp. 42-43.
12. Hafenbradl D. and S. "Malkin, Environmentally-Conscious Minimum Quantity Lubrication (MQL) for Internal Cylindrical Grinding." Transactions of NAMRI/SME, Vol. XXVIII, (2000), pp.149-154.
13. Paul S. and A. B. Chatopadhyay. "The Effect of Cryogenic Cooling on Grinding Forces." Int. J. Mach. Tools Manufact., Vol. 36, No.1(1996), pp. 63-72.
14. Shaji S.and V. Radhakrishnan. "An Investigation on Surface Grinding with Graphite as Lubricant." Int. J of Machine Tools and Manufacture (accepted and to appear in 2002).
15. Othmer K. "Encyclopedia of Chemical Technology, Vol. 10, John Wiley & Sons Inc, New York (1993).
16. .Lansdown A.R. "High Temperature Lubrication." Mechanical Engineering Publications Ltd, London, (1994).
17. Marshal E.R.and M.C.Shaw. "Forces in Dry Surface Grinding." Trans. ASME, Vol.74, (1952), pp. 51-59.
18. Tonshoff H.K., J. Peters. I, Inasaki and T. Paul. "Modeling and Simulation of Grinding Process." Ann. of CIRP, Vol. 41, No.2 (1992), pp.677- 688.
19. Brinksmeier E., H. K. Tonshoff, Inasaki and J.Peddinghans. "Basic Parameters in Grinding, Technical Reports, Ann. of CIRP, Vol. 42, No.2 (1993), pp. 795-799.
20. Pateja C. P., E. J . Pattinson and A. W. J Chisholm. "The Influence of Dressing on the Performance of Grinding Wheels." Ann. of CIRP, Vol. 21, No.1(1972), pp. 81-82.
21. Verkerk J. and A. J. Pekelhering. "The Influence of Dressing Operation on Productivity in Precision in Grinding, Ann of CIRP, Vol. 28, No.2 (1979), pp. 487-495.
22. Malkin S. "Grinding Technology, Theory and Applications of Machining with Abrasives." Ellis Harwood Ltd., Chichester, (1989).
23. Shaw M.C. " Principles of Abrasive Processing." Oxford University Press Inc. New York, (1996).