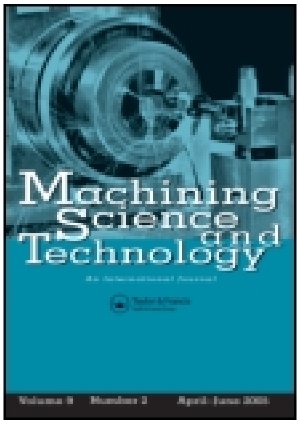

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Application of Solid Lubricants in Grinding: Investigations on Graphite Sandwiched Grinding Wheels

S. Shaji [a] & V. Radhakrishnan [a]

[a] Manufacturing Engineering Section, Department of Mechanical Engineering, Indian Institute of Technology--Madras, Chennai, India, 600 036

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Application of Solid Lubricants in Grinding: Investigations on Graphite Sandwiched Grinding Wheels

S. Shaji* **and V. Radhakrishnan**

Manufacturing Engineering Section, Department of Mechanical Engineering, Indian Institute of Technology-Madras, Chennai, India

ABSTRACT

The intense heat generated in grinding process, if not controlled, will lead to major quality defects. Conventional liquid coolants, employed in flood form, have many limitations from technical, environmental and economic angles. Minimization or possible elimination of cutting fluids by substituting their functions by some other means is emerging as a thrust area of research in grinding. The authors have reported the feasibility of application of solid lubricants in grinding. This paper deals with the detailed investigations on solid lubricant integrated grinding wheels, by providing peripheral graphite sandwiching. Improvement in process results has been observed with this concept.

Key Words: Grinding; Lubrication; Coolant; Graphite; Solid lubricant.

*Correspondence: S. Shaji, Manufacturing Engineering Section, Department of Mechanical Engineering, Indian Institute of Technology-Madras, Chennai, 600 036 India; Fax: (44) 257-8578; E-mail: shajisenadhipan@rediff.com.

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INTRODUCTION

Cutting fluid is an essential element in any machining system in order to ensure product quality and enhance process stability. The distinctiveness of grinding process such as random tool geometry, high friction between tool and workpiece, high specific energy requirement, intense heat generation, risk of transfer of major portion of this heat to the workpiece and the consequent development of thermal damage etc. make the role of cutting fluid in grinding more decisive (Brinksmeier et al., 1999a; Malkin and Anderson, 1974; Marshal and Shaw, 1952; Outwater and Shaw, 1952; Snoeys et al., 1978). Conventionally, liquid coolants in flood form are employed in grinding. But, many limitations have been observed in this approach. The 'air barrier' inhibits the accessibility of the fluid to the actual grinding zone (Brinksmeier et al., 1999a). Even if a little quantity reaches there, 'film boiling' is another limitation for heat control (Howes, 1987, 1990). Further, cutting fluids generally have a negative impact on the environment. Internationally, increasingly strict legislations are coming up with regards to its use and disposal (Byrne and Scholta, 1993; Howes et al., 1991). There is an economic advantage also in avoiding the cutting fluid, as the fluid management constitutes a significant share of the total manufacturing cost (Brinksmeier et al., 1999b; Klocke and Eisenblaetter, 1997). All these factors prompt investigations on the minimization or possible elimination of cutting fluids in grinding. But, any attempt to minimize the cutting fluid must provide alternative means for fulfilling the functions which are normally met by the fluid, so as to ensure the product and process qualities. The use of bio-degradable and cryo-coolants, the concept of minimum quantity lubrication (MQL) etc. are the alternative techniques, recently attempted, in this direction (Brinksmeier et al., 1999a; Inasaki et al., 1993).

Towards finding out alternative approaches for replacing fluid coolants, an attempt to reduce the heat at its generation stage in the process would be ideal, rather than removing the heat after its generation. The advancement in the modern tribology has identified many solid lubricants, which can sustain and provide lubricity over a wider range of temperatures (Bhushan, 2001; Stachowiak and Batchelor, 2001). If solid lubricant can be successfully applied to the grinding zone in a proper way, as a means to reduce the heat generated due to friction, it should yield better process results. A detailed investigation on the feasibility of this concept in surface grinding, with a variety of solid lubricants including graphite, has been reported (Shaji and Radhakrishnan, 2002). In this study, solid lubricant was applied in a suitable paste form to the working surface of the wheel with a special attachment. The effective role of solid lubricant in grinding was evident from the improvement of process results related to frictional factors. But, wheel clogging in the absence of proper flushing and non-uniformity of lubricant admission were found to be major hindrances in obtaining more desirable results. Solid lubricant applied in paste form was enhancing the clogging of the wheel. If lubricant could be applied in a more uniform way, just sufficient for effective lubrication, improved process results could be expected. As an attempt to apply solid lubricant in a more refined and defined way, some preliminary investigations on solid lubricant integrated grinding wheel in different forms, which provide built-in supply of solid lubricant to the grinding zone from the wheel itself, have also been reported there (Shaji and Radhakrishnan, 2002).

This paper deals with the detailed investigations on solid lubricant sandwiched grinding wheels with graphite as lubricant. Graphite was bonded in the wheel structure itself in the peripheral slots cut across its width. Three such wheels were developed with varying number of slots for lubricant sandwiching. Performance of these wheels were studied and analyzed in comparison to conventional wheel in dry and coolant grinding.

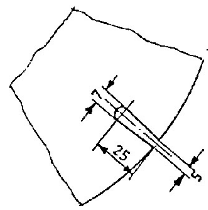
DEVELOPMENT OF GRAPHITE SANDWICHED WHEELS

The concept of the solid lubricant sandwiched wheels is an integration of two different approaches, that is, the interrupted grinding technique and the application of solid lubricants in grinding so that the advantages of both these approaches could be achieved. The basic principle of interrupted grinding technique is to combine the good surface finish aspect of a fine dressing procedure with low forces, specific energy and surface temperature associated with coarse dressing procedure (Shaw, 1996). Several methods have been developed, by modifying the wheel, to interrupt the grinding action (Radhakrishnan and Achyutha, 1986; Rezaei et al., 1992; Shaw, 1996). By employing the interrupted grinding technique, better coolant action, reduced forces and specific energy, reduced temperature and related damage and increased surface roughness are generally observed. Here, the integration was done by bonding solid lubricant into the slots cut for interrupted grinding.

The design of the slot, cut in the wheel periphery, is shown in Figure 1. Slots were cut at equal spacing, extending radially inward. More width was given to the slot at the inner side so that the taper formed at the slots converged towards the wheel periphery. This would help in preventing the solid lubricant mass, which had to be bonded into the slots, coming out of the wheel during running due to centrifugal force and due to any possible weak adherence of the lubricant filler with the wheel structure. The inner edge of the slots was given a radius so as to avoid any possibility of stress concentration at the sharp corners of the slots, when in operation. The slots across the width of vitrified wheel, A60K5 (300–76.2–25 mm) were cut by abrasive water jet cutting. Three such wheels were cut with equally spaced 10, 15 and 20 slots. After several trials, suitable composition of lubricant filler were found out by which graphite could be resin bonded to the slots. The ingredients added for making the filler were phenolic liquid resin, powder resin, and fine AA grit along with 50% by weight fine graphite powder. After proper filling of the slots with lubricant filler, curing was done followed by atmospheric cooling. The wheels were then sized and subjected to balancing and speed testing. The wheels successfully withstood the standard tests. The wheel after the slots cut on it and the graphite sandwiched wheel ready for experimentation are shown in the Figure 1.

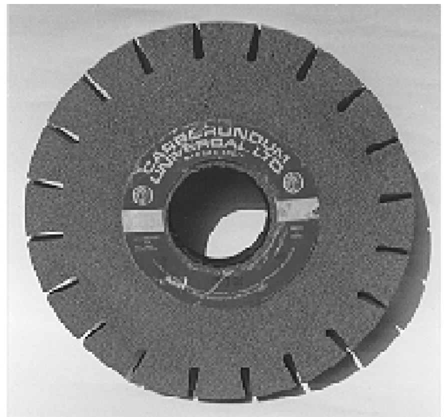
EXPERIMENTATION

The experimental study was done in a horizontal spindle surface grinding machine, in plunge grinding mode and engaging the full wheel width. As infeed and mode of dressing were found as the most critical factors influencing the process forces and

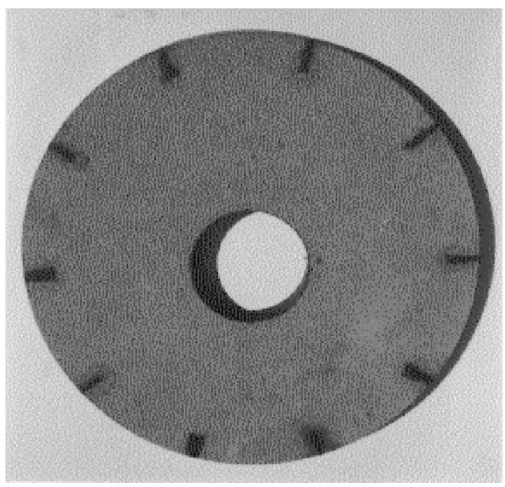


All dimensions in mm (not to scale)

(a)



(b)



(c)

Figure 1. (a) Design of the slot for lubricant sandwiching, (b) wheel after the slots cut on it—20 slots, (c) lubricant sandwiched wheel ready for experimentation—10 slots.

surface finish, these factors were taken as variables throughout the experimentation (Shaji and Radhakrishnan, under review). The experimental conditions are shown in Table 1. The experiments were conducted in three modes of dressing, varying the infeed for each dressing mode. Coolant assisted grinding was done with the coolant supply set-up of the machine itself, employing soluble oil in water in 1:20 ratio at the rate of 4 lit/min. Studies were done in terms of normal force (*Fn*), tangential force (*Ft*), grinding force ratio(*Ft*/*Fn*), specific energy, surface roughness (*Ra*), wheel wear, intermittent workpiece surface profiles and force pattern in continuous grinding test, subsurface microhardness distribution and residual stress in the ground pieces. For force measurements, a 3-component quartz dynamometer with charge amplifier and a

Table 1. Experimental conditions.

Machine	:	BLOHM Horizontal spindle surface grinding machine, 6.5 kW
Wheel	:	A60K5V, 300–76.2–25 mm
Workpiece material	:	Medium carbon steel (En-2), HRC 22 Bearing steel (En-31), HRC 60
Cutting speed	:	30 m/s
Feed	:	10 m/min
Infeed	:	10 to 40 μm in steps of 10 μm, in each dressing mode
Methods of grinding	:	1) Dry grinding with ordinary wheel 2) Coolant flood grinding with ordinary wheel 3) Dry grinding with graphite sandwiched wheels having the sandwiching slots of 10, 15 and 20
Dressing conditions	:	with single point diamond dresser, 1 carat, at wheel speed of 1800 rpm in dry condition in three modes
1. Fine	:	10 μm depth, cross feed ∼75 mm/min, 2 passes with one spark out pass
2. Medium	:	20 μm depth, cross feed ∼150 mm/min, 2 passes with no spark out pass
3. Coarse	:	30 μm depth, cross feed ∼ 300 mm/min, 2 passes with no spark out pass

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. Surface roughness (*Ra*) of the ground part and its profiles were taken using a Talysurf. Microhardness was measured by a Vickers hardness tester and residual stress by an X-ray stress analyzer.

RESULTS AND DISCUSSION

Analyses of performances of graphite sandwiched wheels are done in comparison with those of conventional wheel in dry and coolant conditions. The effects on increasing the number of sandwiched slots are also discussed. Figures 2 and 3 show the comparison of grinding forces in the normal and tangential directions obtained under different grinding environments. Grinding forces are important parameters by which performance of any grinding process can be evaluated. The normal force is responsible for the penetration of abrasive grains into the workpiece for material removal. This force also causes the wheel wear, as it is the thrust force exerted on the wheel. Wheel clogging by grinding swarf also causes increase of the normal force to some extent. This force can affect surface roughness and geometrical and dimensional accuracy of the finished component. Tangential force component determines the power requirement in the process. The intensity of heat generation depends upon this force and is primarily important as far as the grinding temperatures and surface integrity aspects of the

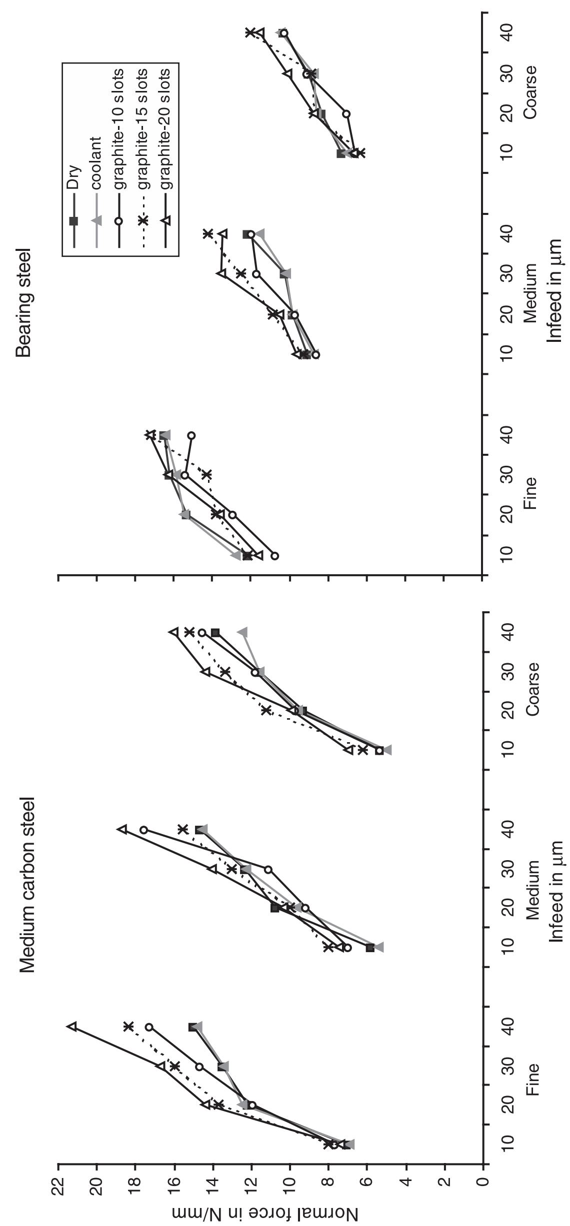


Figure 2. Comparison of normal force obtained under various grinding conditions.

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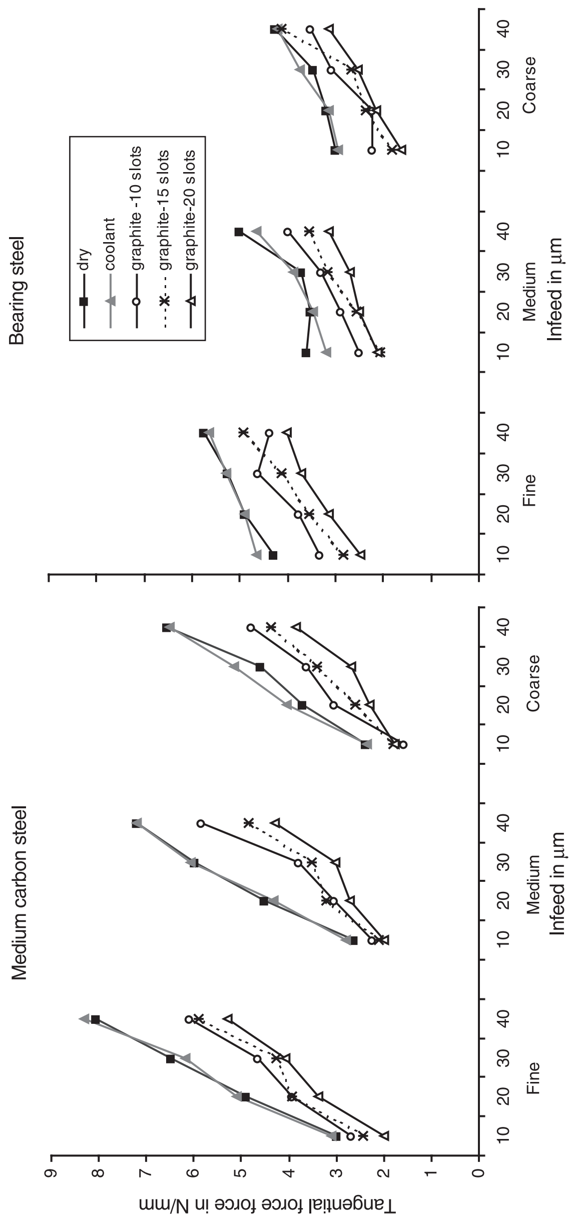

Figure 3. Comparison of tangential force obtained under various grinding conditions.

products are concerned. The development of grinding forces depends upon the wheel characteristics, work material characteristics, process parameters, nature of wheel-workpiece interaction and the chosen environment (Paul and Chattopadhayay, 1996). In all the cases under study, force components increased with infeed as expected. This agrees with the various physical and empirical models reported, which mention that force components are directly proportional to the mean undeformed chip thickness, which in turn is directly proportional to the infeed (Brinksmeier et al., 1993; Tonshoff et al., 1992). As the infeed increases the productive components of the forces, which result in material removal, such as shearing, micro fracturing, secondary plowing etc. increase. The non-productive components of forces such as wheel loading, primary plowing and friction between the grain flats, bonding material, redeposited debris etc. and the workpiece are almost independent of the infeed (Paul and Chattopadhayay, 1996).

Conventional flood cooling does not cause appreciable changes in the magnitude of forces, when compared to dry grinding. This is because the low pressure supply of grinding fluid hardly reaches the grinding zone due to the 'air barrier' effect (Brinksmeier et al., 1999a). Even if a little quantity reaches the grinding zone, it might loose its cooling effectiveness due to film boiling (Howes, 1987, 1990). The high temperature might also lead to loss of lubricating property of the fluid (Cholakov et al., 1992).

Compared to the conventional dry and coolant grinding, the normal forces in the case of graphite sandwiched wheels were found to be more or less the same or even slightly higher at lower infeeds. But, at increased infeeds these forces were apparently higher in most cases, compared to the normal grinding. In the case of sandwiched wheels, the absence of effective swarf removal and consequent wheel loading can be considered as worse than those in the case of dry grinding with conventional wheel. The mixing of fine lubricant particles with the chips and grinding debris enhances the wheel clogging tendency. This increased clogging effect might generally lead to higher normal forces in such cases. In the experimentation, for each dressing mode, the initial 10 μm depth of cut was given when the wheel was in freshly dressed condition. The subsequent cutting in steps of 10 μm allowed the swarf of the previous grinding getting accumulated on the wheel. This wheel loading effect would be higher in the lubricant environment and this could be responsible for the higher normal force at increased infeeds with sandwiched wheels, compared to conventional wheel. In the case of medium carbon steel, the wheel clogging tendency is further higher due to the softer nature of the material and it might cause normal force to have higher degree of difference with the conventional grinding, when compared to bearing steel. 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 wheel loading (Khudobin, 1969; Tonshoff et al., 1992). In the case of brittle material, the chip formation is dominated by the fracture mode and it has fewer tendency to stick on to the abrasive grains.

In the case of lubricant sandwiched wheels, the tangential forces were substantially lower compared to conventional grinding. This indicates that the lubricating property of the graphite getting entrapped into the wheel-workpiece interface was effective in reducing the frictional effects. Tangential force variation depends upon the frictional characteristics of the wheel-workpiece interaction. The coarseness of cutting due to the interrupted grinding by the sandwiched slots might also contribute to the reduction of force components. On increasing the number of slots, an increase of normal force and a decrease of tangential force were the general tendency which could be observed. In such cases, more lubricant supply from the increased sandwiched slots tends to increase the wheel clogging and thereby the normal force, while the increased interruptions tend to decrease the force. Due to these opposing effects a substantial increase of normal force was not observed in some cases, on increasing the number of sandwiched slots. But, the effective lubrication by the increased quantity of lubricant supply along with more interruption of cutting due to the increased number of sandwiched slots contribute towards a clear reduction of tangential forces in almost all cases.

The ratio of tangential force to normal force (F_t/F_n) is termed as grinding coefficient (Marshal and Shaw, 1952) or grinding force ratio (Brinksmeier et al., 1993; Tonshoff et al., 1992). This ratio, though may not give the actual coefficient of friction (μ), is a similar term like μ and gives an indication of the frictional effects in the grinding zone (Marshal and Shaw, 1952). Figure 4 shows the variation of grinding force ratio under different grinding situations. This ratio is substantially lower in all the cases of lubricant sandwiched wheels. This substantiates the effective lubrication by solid lubricant in the proposed method. On increasing the number of sandwiched slots, a clear decrease in tendency on this ratio could be observed. This is because of higher reduction of tangential force on increasing the number of sandwiched slots, compared to the corresponding reduction of the normal force.

Figure 5 shows the comparison of specific energy, which is the energy required for unit volume of material removal, under various situations of grinding. The size effect, that is, the drastic increase of specific energy at comparatively lower infeeds could be observed in all the cases. The grinding energy requirement in material removal can be classified as due to sliding, plowing and chip formation components. The size effect in grinding is due to the variation of relative amount of these components in contributing towards the unit material removal. At relatively lower infeeds, domination of sliding and plowing components with relatively less chip formation calls for higher specific energy (Malkin, 1989). The chip formation process in fine grinding can also be treated as a special high strain extrusion process that involves rapidly increasing strain rate with a decrease of the undeformed chip thickness at lower infeeds, necessitating high specific energy (Shaw, 1996). The specific energy requirement is lower in the case of sandwiched wheels, compared to the normal grinding. On increasing the number of slots, a clear decreasing tendency on specific energy requirement could also be observed.

In the case of solid lubricant sandwiched wheel, two factors i.e., the solid lubricant inclusion in grinding and the interrupted grinding effect due to the weakly bonded lubricant inter-spaces, affect the grinding performance. In a separate study, the individual effects of these factors and their combined effects during grinding have been reported (Shaji and Radhakrishnan, 2002). Accordingly, normal grinding, with and without lubricant application and interrupted grinding by a slotted wheel, with and without lubricant application were studied. The effectiveness of solid lubricant in interrupted grinding was evident from the reduction of force components and their related parameters and workpiece surface roughness obtained in such cases, compared to the interrupted grinding without lubricant application. So, the improved process results observed here are due to the combined effects of solid lubricant application and interrupted grinding.

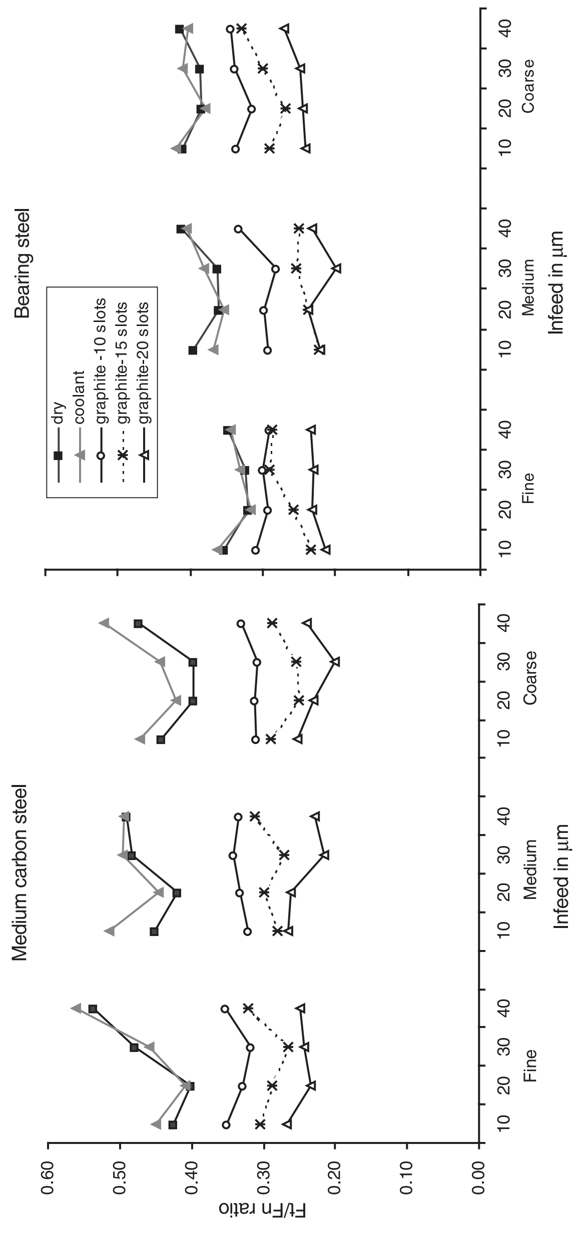

Figure 4. Comparison of grinding force ratio under various grinding conditions.

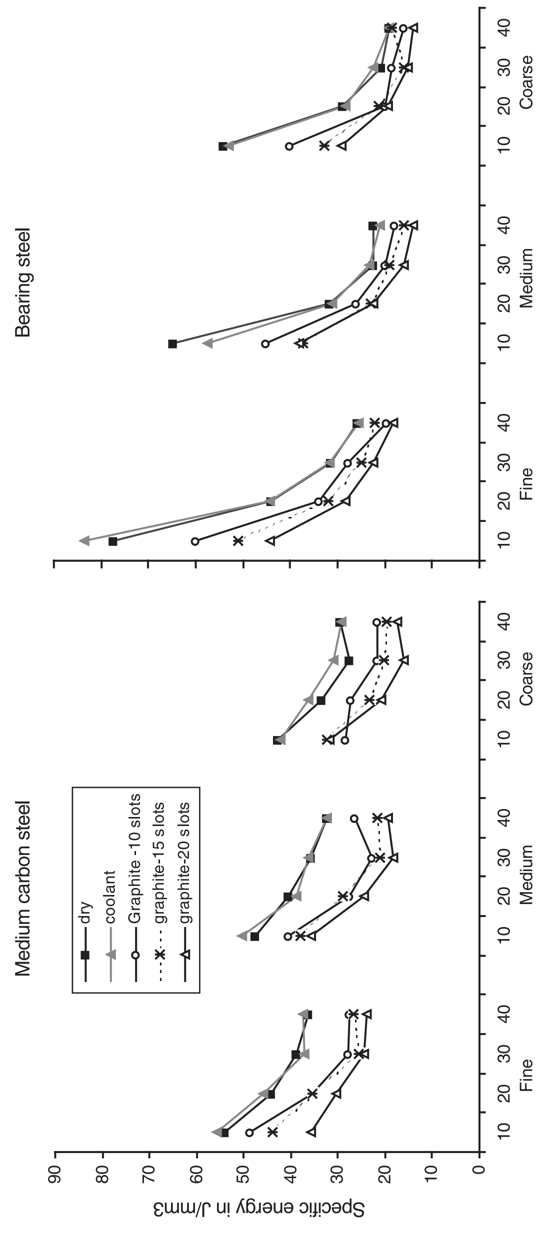

Figure 5. Comparison of specific energy obtained under various grinding conditions.

Figure 6 shows the comparison of workpiece surface roughness. Great reduction in surface roughness was obtained in the case of lubricant sandwiched wheels with both types of workpiece. This is noticeable with ductile material, wherein the increased chance of wheel clogging would adversely affect the surface finish, by the way of third body abrasion by debris (Hutchings, 1992; Khudobin, 1969). The coarseness of cutting due to interrupted action of sandwiched slots might also impair the surface finish (Shaji and Radhakrishnan, 2002; Shaw, 1996). The effective lubrication by graphite getting entrapped into the grinding zone was even able to suppress these adverse effects on finish. With sandwiched wheels, in brittle materials, better finish could be obtained compared to that in ductile material. In this case, the difference in chip formation, which is characterised by the domination of fracture mode and reduced plastic flow of material around the abrasive grains, promotes better finish in the presence of lubricant.

The dressing condition of the wheel has great 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. But, the workpiece surface roughness would be lower due to the wider grain flats. With coarser dressing, grits are damaged severely and the plateau area/grit would be smaller, leading to lower force components and higher surface roughness (Bateja et al., 1972; Verkerk and Pekelhering, 1979).

Figure 7 shows the volume of wheel worn (per unit width) obtained with the bearing steel workpiece in the continuous grinding test under different environments. The reciprocal of the slope of the curve at any point gives the grinding ratio (G-ratio). In the case of lubricant sandwiched wheels, the wear was generally higher compared to that in case of conventional dry and coolant grinding. An increasing tendency of wear was obtained with the wheels having increased number of sandwiched slots. It can be explained in terms of the normal force, which is the thrust force on the wheel, responsible for grain fracture and bond fracture. When the thrust on the wheel reaches a critical value, fractures of the grains and bonds occur. The higher normal force obtained with increased number of sandwiched slots is responsible for higher wheel wear in such cases, especially on prolonged use of the wheels. On prolonged use, in the absence of proper flushing action, wheel loading will be dominant, causing higher thrust on the wheel.

The comparison of workpiece surface profiles obtained in the continuous grinding tests for every 50 passes is shown in Figure 8, for various systems of grinding. The wheel clogging situation and the friability of the grains can be observed from the profile patterns also. In the case of coolant flood grinding, the wheel cleaning is excellent and it can maintain the sharpness of the grains for a longer duration. In the cases of dry grinding and with lubricant sandwiched wheels, grain dullness can be clearly observed as the grinding progresses. The surface roughness values are remarkably lower in the case of sandwiched wheels during the initial stages of the test compared to dry and coolant grinding. The effect of wheel loading hampered the roughness on subsequent passes. Even on later stages, the roughness values obtained with sandwiched wheels are considerably lower than dry grinding and are comparable to those in the case of coolant flood grinding, where wheel cleaning is excellent. This is

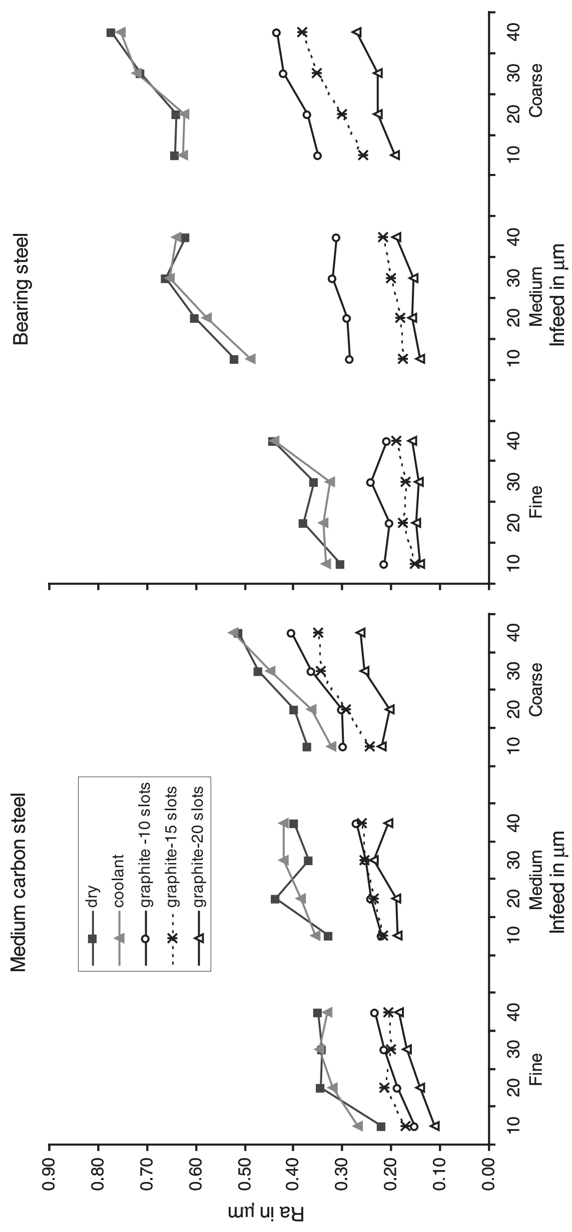

Figure 6. Comparison of surface roughness obtained under various grinding conditions.

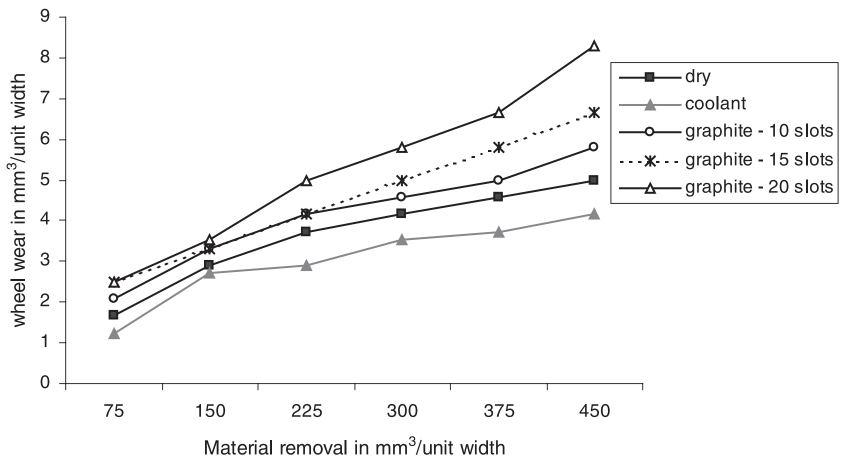

Figure 7. Comparison of wheel wear obtained with different wheels.

commendable based on the fact that the interrupted grinding would generally increase the surface roughness. If effective means for wheel cleaning and swarf removal from the grinding vicinity could also be ensured, more desirable results could be expected in the case of sandwiched wheels.

Figure 9 shows the forces obtained in the case of lubricant sandwiched wheels in the continuous grinding test, taken at every 25 passes for 10 μm infeed. The wheel loading and the friability effect of the grains are evident from the force pattern. The force values are seen to rise and drop in a periodic fashion. The tangential force values are not having much variation as compared to the normal force. The normal forces also show a gradually increasing tendency on prolonged grinding. The specific energy requirement also varies against the grinding time, depending upon the variation of the tangential force component.

During prolonged grinding, without any dressing in between, the initial dressing condition of the wheel changes gradually. The pores exposed by initial dressing get filled up with the grinding swarf and the sharp abrasive cutting edges gradually become dull. The adhesive nature of the solid lubricant at high temperature, combined with the supply of lubricant in fine powder form, enhance the wheel clogging tendency, in the absence of proper flushing action (Bhushan, 2001; Stachowiak and Batchelor, 2001). So, the wheel surface became smooth and the effective cutting with sharp abrasive protrusions was not occurring on later stages. This led to the increase of the force components and specific energy against grinding time. Abrasion by the loaded debris also caused deterioration of the workpiece surface finish. The grain fracture and bond fracture, which occur when the thrust on the wheel reaches certain limits depending upon the grain toughness and the wheel hardness, expose new cutting edges and pores. But, this situation is not as significant as the freshly dressed condition of the wheel. These newly exposed pores will immediately get filled with the grinding swarf and the new cutting edges again become dull as the grinding progresses. This continues in a cyclic fashion. The tangential force variation in identical grinding situations mainly depends on the variation of the friction between the abrasive grains and the workpiece.

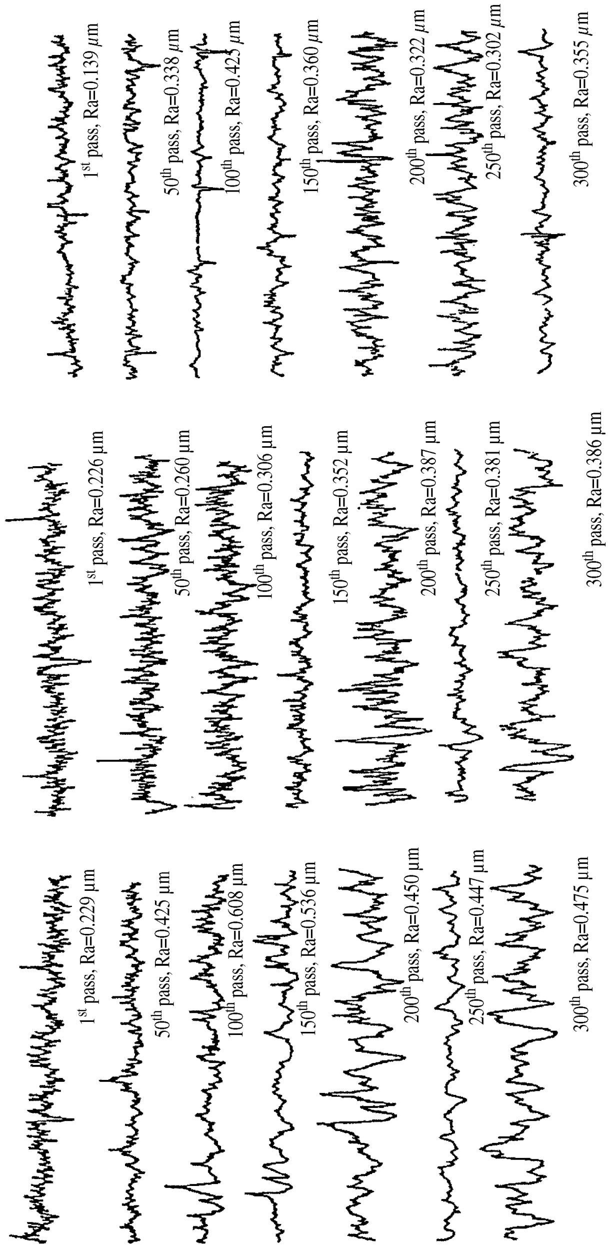

Figure 8. Intermittent workpiece surface profiles obtained in continuous grinding test. (a) Dry grinding with ordinary wheel, (b) coolant flood grinding with ordinary wheel, (c) grinding with graphite sandwiched wheel—20 slots.

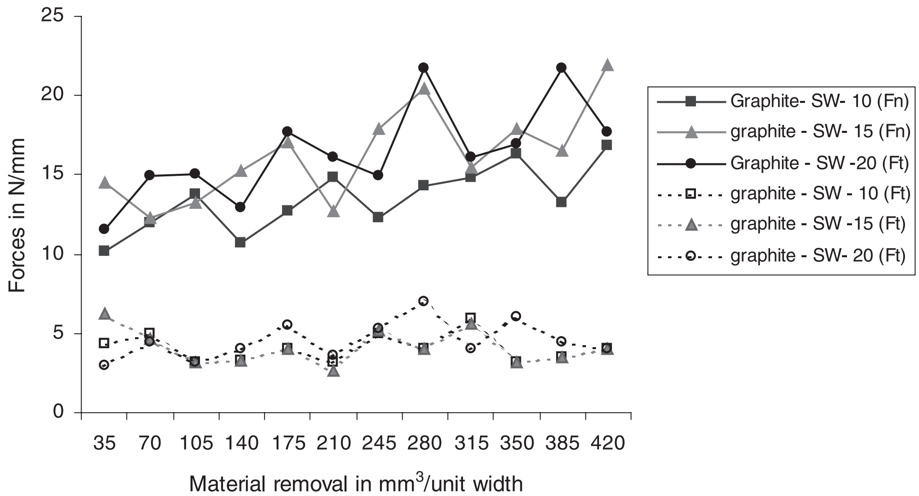

Figure 9. Intermittent force patterns obtained in continuous grinding test.

The cyclic friability of the grains limits the increase of the frictional force. Hence, not much variation in tangential force and thereby in the specific energy, were observed against grinding time as shown in Figure 9. But, the cumulative wheel clogging effect, in addition to the grain dullness, led to an increasing tendency and rapid variation of the normal force against grinding time.

Figure 10 shows microhardness distribution obtained beneath ground surface with bearing steel samples, ground under coarse dressing mode, giving 40 μm infeed in dry, coolant condition and with graphite sandwiched wheel having 10 slots. Increase of

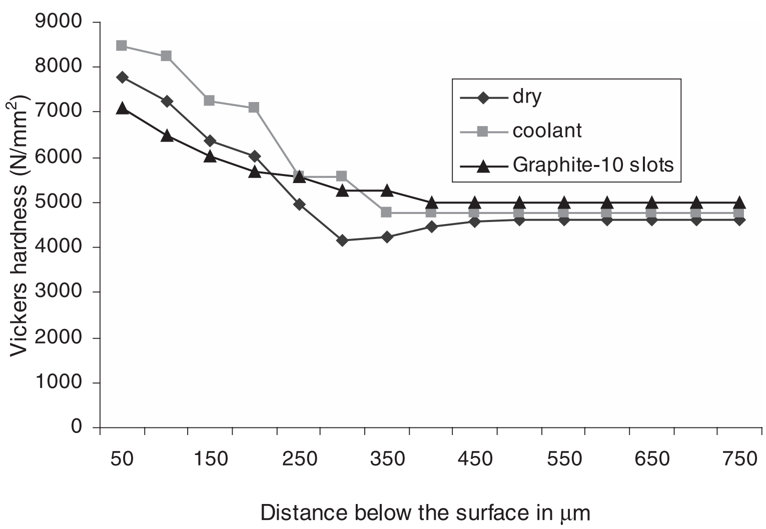

Figure 10. Subsurface microhardness distribution obtained in various systems of grinding.

hardness towards the surface from the bulk hardness was the general tendency obtained in all the cases. This type of pattern has been reported in literature, with hardened steel under certain grinding conditions (Abrao and Aspinwall, 1996; Snoeys et al., 1978; Takazawa, 1966). Here the abusive grinding situation might lead to the reaustenization and its subsequent quenching might result in rehardened layer due to the formation of untempered martensite (UTM) (Shaw and Vyas, 1994). But, the hardness distributions generally do not show an overtempered martensite (OTM) layer beneath the UTM layer. In the case of dry grinding, tendency of decreasing hardness below the bulk hardness shows the chance of OTM layer presence, but it is of insignificant magnitude. In the case of coolant flood grinding, the rapid quenching by the fluid might be responsible for comparatively higher values of microhardness. In the case of dry grinding, the cooling rate from the reaustenized state is lower, compared to coolant flood grinding, and hence resulted in lower hardness. With graphite sandwiched wheel, the low heat input and still lower rate of cooling, due to the lubricant coating, might contribute to comparatively less variation in microhardness.

Figure 11 shows the residual stress obtained in the case of bearing steel under coarse dressing mode and at various infeed conditions in different grinding systems. At 10 μm infeed, residual compressive stress was obtained in all the cases of grinding. Here, the gentle grinding conditions led to stresses of mechanical origin due to the Hertzian compression and shear force by the action of abrasive grains (Chen et al., 2000). The temperature involved might also be in the cold working range (Shaw, 1996). But, at higher infeeds, dominance of thermal deformations due to high heat input and the associated thermal gradients caused tensile residual stress to develop. In the case of abusive grinding situations, the formation of UTM layer might contribute an additional tensile component of stress (Shaw, 1996). But, in the case of graphite sandwiched wheels, comparatively less heat input reduced the magnitude of the tensile residual stress at higher infeeds. The results of microhardness and residual stress also show the effectiveness of solid lubricant in reducing the heat generation during

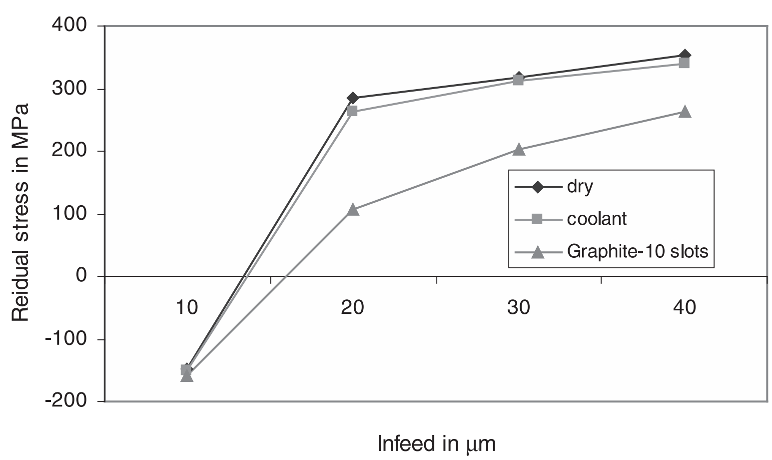

Figure 11. Comparison of residual stress parallel to the grinding direction obtained in various systems of grinding.

grinding and thereby minimizing the harmful alterations of metallurgical characteristics of the workpiece.

CONCLUSION

The concept of solid lubricant sandwiched wheels integrates the approaches of solid lubricant application in grinding and interrupted grinding technique, by providing built-in supply of solid lubricants from the slots cut for interrupted grinding. Various such wheels with graphite as lubricant were develpoed and their performances were studied. The effectiveness of graphite as lubricant was evident from the improvement of process results related to wheel–workpiece friction. The reduction in surface roughness was substantial with the new wheels. Though the wheel wear was slightly higher with graphite sandwiched wheels, the trends with regard to the grain friability and wear rate were similar to conventional wheels. The harmful alterations of metallurgical characteristics of the workpiece were also found reduced with the new wheels. With this concept, the advantages of both solid lubricant application in grinding and interrupted grinding could be achieved, while minimizing the disadvantages associated with them.

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