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Development and performance evaluation of self-lubricating drill tools

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Abstract

Drilling is one of the most commonly employed manufacturing processes for any material. However, the frequent tool changes resulting from tool wear limit the efficiency of the process. Unlike in other forms of machining, external lubrication is not very effective in drilling and, hence, the usual strategy is to supply coolants through a hole drilled in the tool, along the axis. However, cutting fluids pose several threats to the environment and workers' health and there are stringent regulations on their usage and disposal. To address this problem, self-lubricating drill tools were prepared using high-speed steel drill bits in the present work. Channels for the flow of solid lubricant were made in the tools. Further, side channels of various angles (0°, 8°, 15°, 22°, 30°) were cut on the flutes. Solid lubricants were filled in the central supply channels and also in the side micro-channels. The performance of the fabricated self-lubricated tools was assessed while machining AISI 1040 and mild steel. The variation in drilling torque, thrust force, surface roughness and tool wear under dry, wet machining environment, and self-lubricated conditions were studied experimentally. It was observed that by employing self-lubricated drill bits there was an improvement in surface finish of the holes drilled and considerable reduction in tool wear.

Keywords

Drilling, solid lubricants, self-lubrication, machining

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Introduction

Among the various problems encountered in a shop floor, tool wear occupies a place of prominence. Tool wear is accompanied by increased cutting forces and temperatures, resulting in poor surface finish of the products. Friction along the tool-work piece interface is often attributed to the cause of tool wear and associate effects. Hence, reducing friction is critical to control tool wear. This has led to the use of cutting fluids in machining, as both lubricants and coolants.[1] However, cutting fluids are generally vulnerable to microbial contamination and cause severe environmental concerns. There are severe restrictions on their usage and disposal across the globe. Emel Kuram et al.[2] studied the effect of using vegetable oil based cutting fluids in machining and have reported encouraging results. Though vegetable-based fluids are bio-degradable, they are often more prone to microbial contamination and can cause health problems like dermatitis to the worker.

Attempts for improving the properties of cutting fluids by tuning their composition can be found in literature. Rao and Srikant[3] studied the role of emulsifier content in cutting fluids in deciding the properties. It was reported that thermal conductivity, kinematic viscosity and pH increased with an increase in the content of emulsifier whereas flash and fire points decreased with an increase in the amount of emulsifier. In another study, decrease in cutting forces, temperatures, surface roughness, and tool wear with an increase in the emulsifier content were found by Srikant et al.[4] However, emulsifier that is derived from petroleum products are vulnerable to microbial contamination and degrade over time. In addition, they have a harmful effect on workers' health.

For the past few years, several researchers have been working on the application of solid lubricants as potential alternatives to cutting fluids in machining. Dilbagh and Rao[5] studied the influence of solid lubricants like graphite and MoS_2 in machining AISI 1045 steel. It was reported that friction was greatly reduced

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while using MoS_2 compared to graphite and cutting fluids. This also led to better surface finish of the product. Self-lubrication of sintered ceramic tools with CaF_2 addition was studied in dry machining.[6]

Graphite is valued in industrial applications for its self-lubricating and dry lubricating properties. There is a common belief that graphite's lubricating properties are solely due to the loose inter-lamellar coupling between sheets in the structure. However, it has been shown that in a vacuum environment (such as in technologies for use in space), graphite is a very poor lubricant. This observation led to the discovery that the lubrication is due to the presence of fluids between the layers, such as air and water, which are naturally adsorbed from the environment. This hypothesis has been refuted by studies showing that air and water are not absorbed. This molecular property is unlike other layered, dry lubricants such as MoS_2. Recent studies suggest that an effect called super lubricity can also account for graphite's lubricating properties.

Reddy and Rao[7] used graphite and MoS_2 as lubricants in hard turning. It was reported that flow rate of the lubricant, or the rate at which the lubricant is made available to the machining zone has an influence on the cutting forces. Hence, proper flow of the solid lubricant is important. However, beyond a particular limit, i.e. after 2 g/min, the flow rate did not have any impact on the results. It could be due to the fact that the extra quantity of lubricant is redundant and does not take part in the process. Solid lubricant produced lesser values of surface roughness compared to dry machining. While using graphite the improvement was about 8–10% and about 13–15% in case of MoS_2.

Reddy et al.[8] studied on the influence of solid lubricants in machining AISI 1040 steel using coated carbide inserts. Surface finish was reported to have improved compared to wet machining. Krishna and Rao[9] used boric acid as a lubricant for machining AISI 1040 steel using high-speed steel (HSS) and carbide cutting tools. Cutting temperatures, forces, tool wear and surface roughness were shown to be improved while using boric acid compared to wet machining. Formation of a thin film of the lubricant on the surface of the product was held responsible for the results. Further, boric has a very low coefficient of friction. Also, boric acid does not pose any health hazards like the cutting fluids. In addition to the application as an external lubricant, nano-coatings of boric acid are also reported in Kustas et al.[10] However, since these coatings do not possess high toughness, they wear easily.[11] Once the coating is lost, there is no lubrication and hence tool wear is rapid. Further, the process needs expensive equipment is not economical.[12,13]

As an alternative, Jianxin et al.[14] made micro-holes on the rake and flank faces of turning tools and filled the holes using solid lubricants like MoS_2, thus fabricating a self- lubricated tool. Dry machining was carried out using these tools and conventional tools. It was reported that cutting forces and tool wear greatly reduced in case of fabricated tools compared to the conventional tools. It was advocated that a lubricating film was formed due the smearing of MoS_2 on the rake and flank faces of the tools. Lei et al.[15] used textured cutting tools for turning mild steel. Micro-holes and grooves were made on the rake face of cutting tools. Similar results as in above study were reported. It was also found that friction force decreased by over 20% compared to conventional tools. In another study, Lei et al.[16] studied the performance of lubricated cutting tool in machining mild steel. Finite element analysis was conducted to estimate the effect of micro-holes on strength and other mechanical aspects of the cutting tools. Cutting forces measured in turning were used for the analysis. It was reported that the mechanical properties are not significantly affected by the micro-holes and that the tools produced about 10-30% lesser forces compared to conventional tools.

In brief, it can be concluded from literature that solid lubricants offer several advantages compared to cutting fluids. Though in literature, filling the solid lubricants in micro-holes is reported in turning, work is not done in drilling. Further, drilling is more complex compared to turning and supplying lubricant externally is not very easy. To fill the gap, the present work aims at developing and testing a self-lubricating drill tool.

Experimentation

The proposed tools were developed in two stages, initially channels for the flow of lubricant were drilled in the chosen tool bits and then those were filled with the solid lubricant. After preparing the tools, they were tested in machining for their performance. Figure 1 shows the flow diagram of the process.

Drilling of vertical holes in the drill blocks

HSS drill bits were chosen for the present work due to their extensive use in the metal cutting industry. Each bit was drilled using EDM drilling machine (Make: Saprkonix, Model DSH 3) to produce 2 vertical passages and some inclined passages, connecting the flutes to the vertical passages as shown in Figure 2. The central axis was chosen, as literature points out, such that maximum temperatures in the drill occur near the axis.[17–19] This temperature will be helpful to melt the solid lubricant. The Sparkonix Disintegrator micro-drill machine DSH-3 is a high-speed EDM drill for high performance, high quality, low cost, small hole, deep drilling capacity. Figure 3 shows the experimental set-up used and Figure 4 shows the drilled tool bits. Initially, vertical passages were drilled on the drill tool blocks (without any flutes or tip).

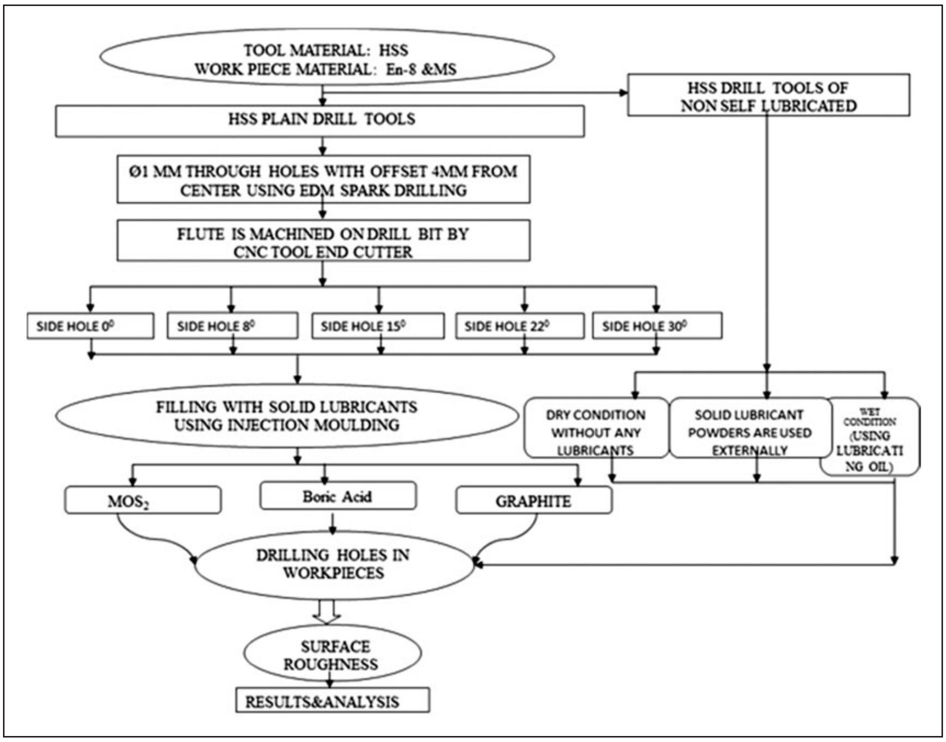

Figure 1. Experimental flow sheet.

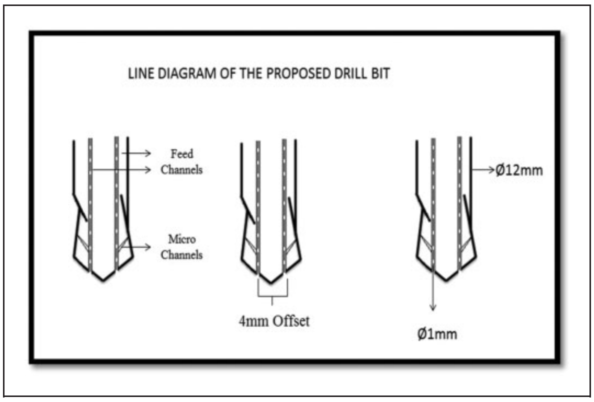

Figure 2. Line diagram of proposed drill bit.

ANCA MX7 CNC Tool End Cutter Grinder machine (Figure 5) was used to make two flute on the body of HSS tool bit. The nomenclature of the obtained drills is shown in Table 1.

Drilling of side holes with various angles

A Sparkonix Disintegrator micro-drill machine DSH-3 with brass or copper electrode was used to drill micro-holes in the HSS tool. With the help of EDM spark drilling machine, the side holes (from the surface to through holes) were drilled on the drill bits at the fluted end with various angles as shown in the proposed line diagram. The electrodes along with side holes of the tool are shown in Figure 6. Tools having different sets of side holes of different orientations such as 0°, 8°, 15°, 22° and 30° were prepared.

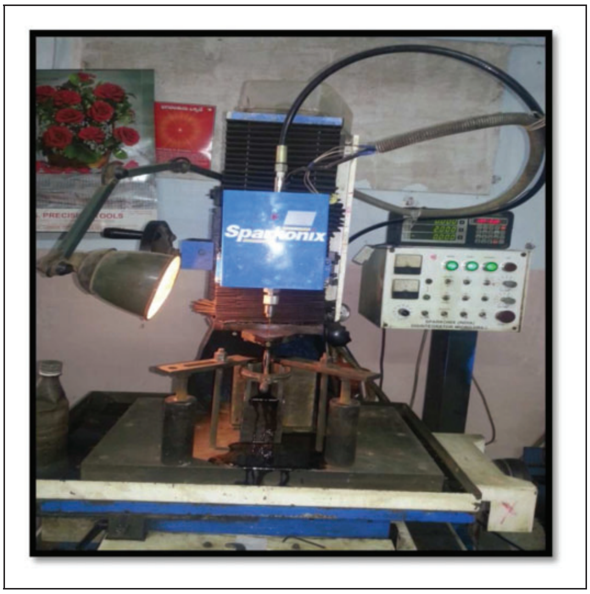

Figure 3. Experimental setup of EDM machine.

Filling of holes

Once the tools were prepared, they were filled with solid lubricant using injection molding process. In the present work, graphite, MoS_2 and boric acid were chosen as filling materials. After filling with the lubricant, the tops of the channels were sealed with wax (Figure 7).

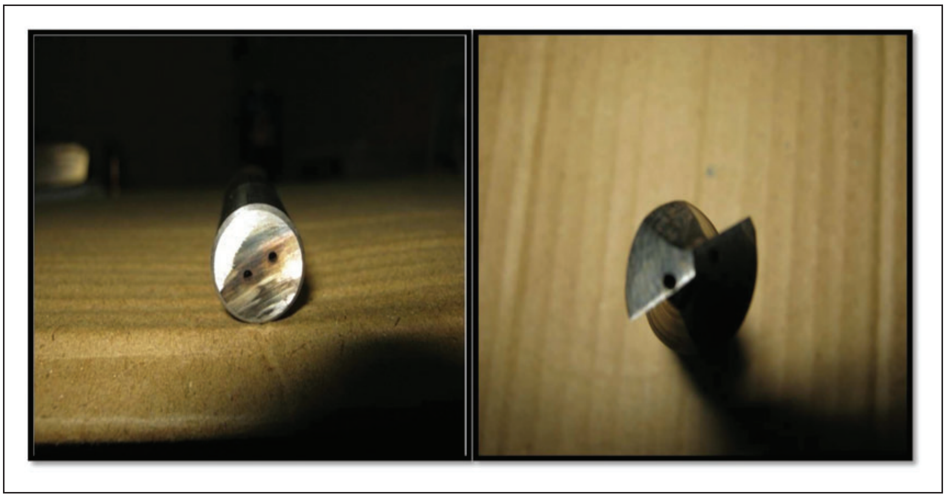

Figure 4. Micro-hole drilled tool bits.

Figure 5. ANCA MX7 CNC tool end cutter machine.

Performance testing of developed tools

The prepared drill tools were used for drilling mild steel and AISI 1040 on a radial drill machine and the forces were measured using a drill tool piezo-electric dynamometer (Make: Kistler, Type: 9272) which analyzes the forces (F_x, F_y, F_z) and moment. In the present work, since the trust force acts in the Z-direction only F_z and moment were directly taken as measured by the dynamometer. The output from the dynamometer was exported as a data file and different data series were compared. The specifications of the radial drill machine used for the tests are given in Table 2. The experimental set-up is shown in Figure 8. The following machining conditions were adopted: Speeds – 900 r/min, 1500 r/min, Feeds – 1 mm/min, 3 mm/min, Drill bits – HSS, Diameter – 12 mm, 20 mm. Different machining conditions and workpiece material were taken to verify if similar trends are observed in all cases. All the tests were done in triplicates and average values of the responses/measurements are reported in the paper. The standard deviations of the observations were found to be less than 5% in all the cases. As a sample, the standard deviation values of moments while machining AISI 1040 steel are shown in the paper at appropriate place.

Figure 9 shows the work pieces with holes drilled using different tools. Surface roughness of the machined samples was measured using a surface roughness tester (Make: Mitutoyo, Type: Surftest SJ-201P) (Figure 10). The length of flank wear on the cutting edge was measured using microscope (Make: Olympus, Type: GX51).

Results and discussions

Drilling torque, thrust force, surface roughness and tool wear were measured under dry and wet machining environments. The results are presented and discussed in the present section. For the results pertaining to moments and forces, at the initial stage, only results for graphite (for one diameter of tool and one set of cutting conditions) are shown to find out the best side angle. Then at that optimal level, results from all lubricating conditions are compared. This is done for the sake of brevity of the paper, as in all cases the results followed identical trends, with variations in numerical values.

Table 1. Nomenclature of the drill bit.

Rake angle	10°
Helix angle	30°
Flute drill	2 flute
Relief angle	118°
Shank length	42 mm
Body	33 mm

Moments

Figure 11 compares the moments when AISI 1040 was drilled by self-lubricated graphite tool (12 mm) with different side angles at 900 r/min cutting speed and feed rate of 1 mm/min. The values of standard deviation are shown in Table 3. It can be seen that the values of standard deviation are below 5%. It was observed that the moments of the graphite self-lubricated tool with side channel 30° are lesser when compared to other side channels. This is attributed to

Figure 6. Drilled tool bits of side holes.

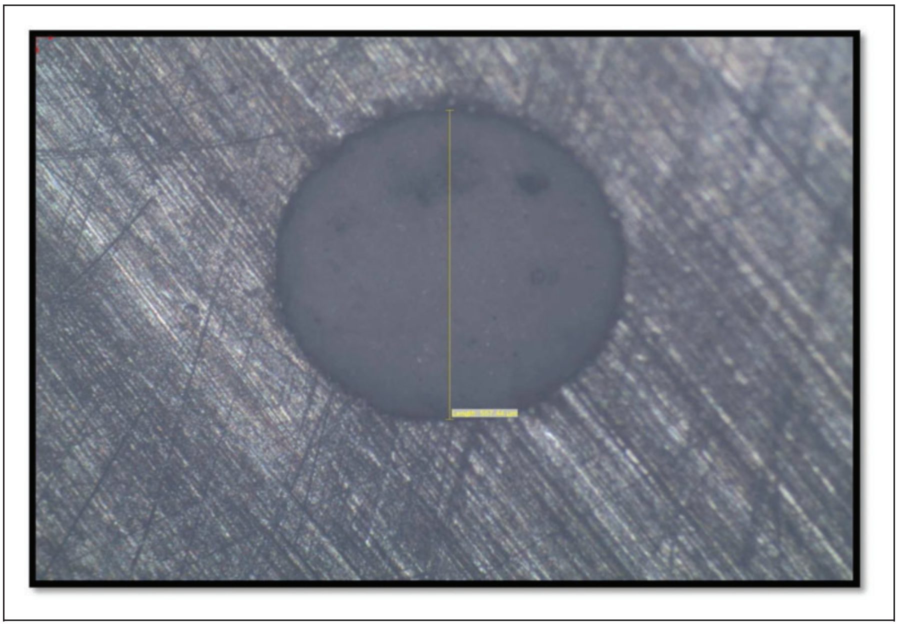

Figure 7. Filled micro-holes.

the reason that while the machining process continues, high temperatures developed in the cutting region are sufficient to melt the solid lubricant. The melted lubricant smears on the surface of flutes due to capillary effect. The continuous supply of the lubricant is by gravity action and this will be more when the side channel is 30° when compared with other side channels. It may be pointed out at this time that further increasing the side angle may cause the solid lubricant to be consumed more rapidly and thus have a detrimental effect on the performance. It may also be noticed that initially the trends are not consistent and tend to stabilize over time. The possible cause may be in the initial break-in wear of the tools at the first instance of contact between the tool and the workpiece. Since the lubricant is solid, it is not instantaneously available in the first instance as the regular cutting fluid, but starts acting within very short time. So, the action of the lubricant cannot be judged during the first 3–5 s but once lubricant melts and smears on the surface, the performance of the tools improves. It may also be noted that literature provides evidence that better lubrication can sometimes lead to hardening of the workpiece due to cooling characteristics.[20] This may be one of the reasons that though improvement is observed for 30° channel tool, improvement is not more than 10–15% as compared to the closest contestant case. However, compared with 0° tool, the improvement is over 30% on an average. Similar reasoning may be applicable for all the other measurements of forces/moments. In the present work, cutting temperatures were not measured due to lack of facilities. Measurement of temperature can endorse the above reasoning. Though moments/forces may be higher than expected due to hardening, the advantage can be clearly seen in terms of other factors in tool wear and surface roughness. Nevertheless, tool with 30° channel has better performance in terms of moments.

Figure 12 compares moments when mild steel was drilled by self-lubricated graphite tool under different side angles. From this figure it can be observed that even though the trend in the moments of the graphite self-lubricated tool with side channel 22° was lesser than that of 30° side channel, the variation in moment values was considerably lesser in 30° side channel when compared with 22° side channel. Hence 30° side channel was considered to be better as far as moments are concerned. Clear cut difference between 22° and 30° tools can be found here unlike in AISI 1040 as AISI 1040 has better hardening characteristics compared to mild steel. Hence, the effect of

Table 2. Specifications of the radial drilling machine.

Make	Machine tool traders
Speeds	8 (882–2424 r/min)
Maximum drilling capacity	32 mm
Column size	762 mm
Arm size	1082 mm
Feeds	Course (26 mm/min) and fine (18 mm/min)
Motor capacity	0.5 hp and 0.5hp

Figure 8. Experimental setup of dynamometer mounting on radial drilling machine.

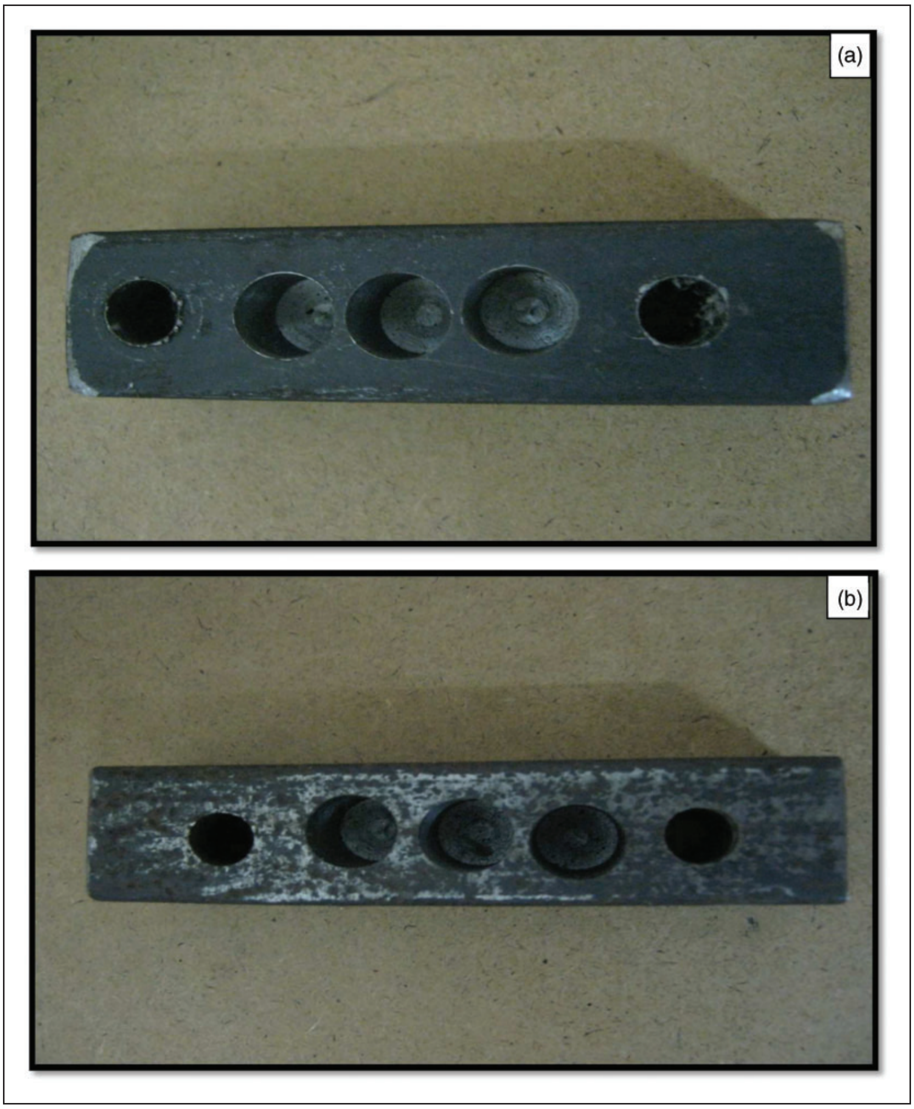

Figure 9. Drilled holes on: (a) AISI 1040; (b) mild steel with the self-lubricated drill tools.

Figure 10. Surface roughness machine.

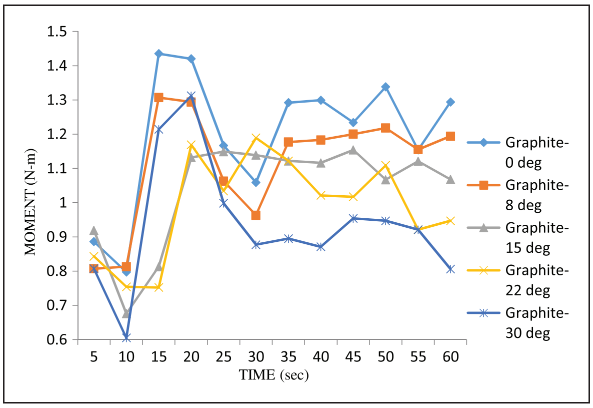

Figure 11. Comparison of moments when AISI 1040 is drilled by self-lubricated graphite tool with different side angles.

Table 3. Standard deviation of measurements (AISI 1040, dry).

Time (s)	Moments (N-m)				Std. dev (%)
	Trial 1	Trial 2	Trial 3	Average	
5	0.56	0.63	0.6	0.6	3.51
10	1.15	1.24	1.2	1.2	4.51
15	2.19	2.12	2.16	2.16	3.51
20	2.17	2.15	2.15	2.17	1.15
25	2.7	2.63	2.63	2.64	4.04
30	2.7	2.72	2.69	2.7	1.53
35	2.71	2.71	2.67	2.7	2.31
40	2.89	2.85	2.86	2.87	2.08
45	2.9	2.86	2.85	2.88	2.65
50	4.06	4	3.97	3.9	4.58
55	4.05	4.01	4.1	3.93	4.51
60	4.1	4.05	4.08	4	2.52

hardening due to the lubricants is not very predominant.

Once the optimal angle for the side channel is chosen, its performance is compared with other lubricating conditions. Graphs showing the moments when AISI 1040 and mild steel were drilled by HSS tool under different lubrication conditions are shown in Figures 13 and 14. It was clearly observed from these graphs that HSS tool filled with MoS_2 as lubricant has shown better performance by resulting in lower values of moments when compared with other lubricated conditions including HSS tool filled with graphite as lubricant. Dry cutting causes high moments and forces. External application of the lubricant is not very useful since it is very difficult for the lubricant to reach the actual machining zone due to the prevalent centrifugal forces because of the tool rotation. Tools filled with lubricants do not have this problem as the lubricant is directly deposited in the machining zone. This is the probable reason for better performance of the tools.

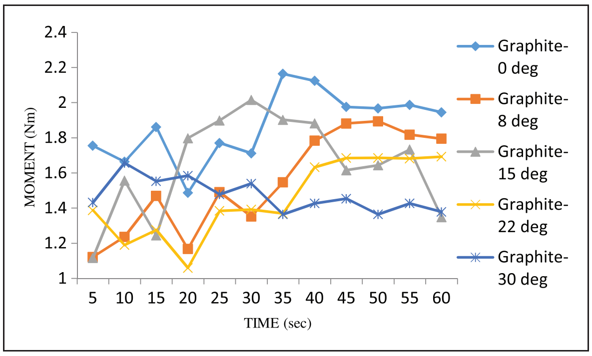

Figure 12. Comparison of moments when mild steel is drilled by self-lubricated graphite tool with different side angles.

Among the chosen solid lubricants, MoS_2 showed the best performance. This is attributed to the fact that in MoS_2 each Mo (IV) center is trigonal prismatic, being bound to six sulphide ligands, each of which is pyramidal. The trigonal prisms are interconnected to give a layered structure, where in molybdenum atoms are sandwiched between layers of sulphur atoms. Due to the weak van der Waals interactions between the sheets of sulphide atoms, MoS_2 will have a low coefficient of friction. Also, the melting point of graphite is very high (about 4500°C) as compared to MoS_2 (about 1000°C) or boric acid (about 350°C). So, the capillarity effect may not be possible in case of graphite. Hence, lubrication is solely due to the loose inter-lamellar coupling between sheets in the structure. This molecular property is unlike other layered, dry lubricants such as molybdenum disulfide. In case of boric acid, the lubricant melts at a much earlier stage due to its low melting point and may be entirely consumed fast. This is not desirable for a self-lubricated tool.

To summerize, it can be seen that the performance of HSS tool filled with MoS_2 as lubricant is better with lower values of moments when compared with other lubricated conditions including HSS tool filled with graphite or boric acid as lubricant.

Cutting forces

Graph showing comparison of forces when AISI 1040 was drilled by self-lubricated graphite tools with different side angles is shown in Figure 15. It can be observed that the forces of the graphite self-lubricated tool with side channel 30° was lesser when compared to other side channels, due to reasoning similar to the case of moments. Similar trends were obtained for mild steel. Different lubrication conditions are compared for AISI 1040 and mild steel in Figures 16 and 17. It was clearly observed that HSS tool filled with MoS_2 as lubricant has shown better performance by resulting in lower values of forces when compared with other lubricated conditions including HSS tool filled with graphite as lubricant.

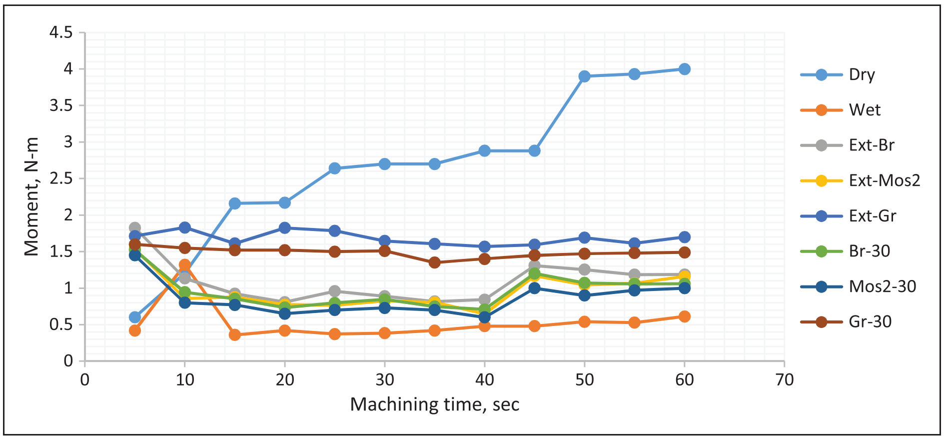

Figure 13. Comparison of moments when AISI 1040 is drilled by HSS tool under different lubrication conditions.

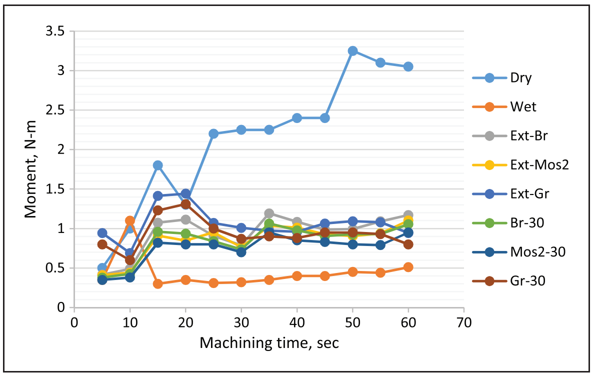

Figure 14. Comparison of moments when mild steel is drilled by HSS tool under different lubrication conditions.

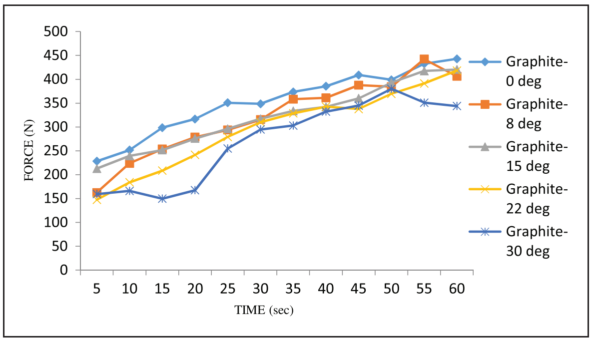

Figure 15. Comparison of forces when AISI 1040 is drilled by self-lubricated graphite tool with different side angles.

Surface roughness

Surface roughness, is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough and if they are small the surface is smooth. The values of the surface roughness of holes drilled on AISI 1040 and mild steel work pieces by HSS tool under different lubricated conditions and with different side channels are given in Table 4. From these values it was clearly evident that the surface finish of holes drilled with HSS tool

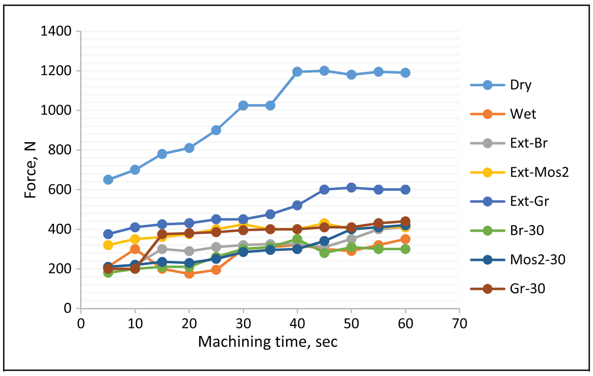

Figure 16. Comparison of forces when AISI 1040 is drilled by HSS tool under different lubrication conditions.

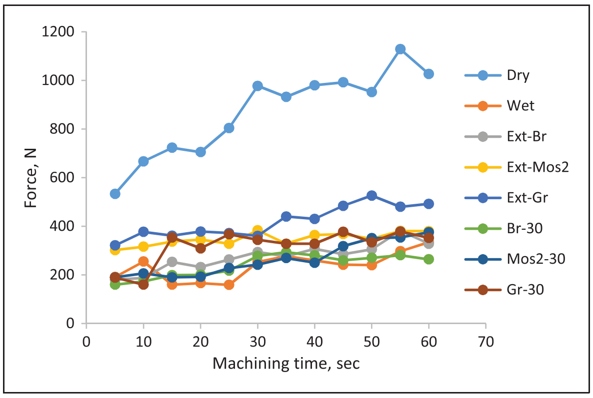

Figure 17. Comparison of forces when mild steel is drilled by HSS tool under different lubrication conditions.

filled with solid lubricants was improved when compared with the holes drilled under dry and external powder lubrication conditions. It was also observed that the HSS tool filled with MoS_2 results in better surface finish of the holes drilled when compared with the holes drilled by HSS tool filled with graphite lubricant. Though hardening of the workpiece could have resulted in lesser variations in moments/forces, the effect of lubrication is clearly seen in surface roughness measurement. Due to the structural properties, MoS_2 has shown better performance in terms of

Table 4. Surface roughness values (Ra, microns).

	12 mm drill			20 mm drill		
Ordinary drill bit		AISI 1040	MS		AISI 1040	MS
Dry	3.99	3.36	Dry	4.47	3.77	
Wet	2.8	1.43	Wet	3.14	1.61	
Ex.Gr	3.75	3.45	Ex.Gr	4.2	3.87	
Ex.MoS2	3.21	2.95	Ex.MoS2	3.6	3.31	
Ex. BA	3.6	3.1	Ex. BA	4.04	3.48	
HSS drill tools filled with graphite with different side angles (in degrees)	0	3.46	3.38	0	3.88	3.79
	8	3.35	3.21	8	3.76	3.6
	15	3.2	2.97	15	3.59	3.33
	22	3.1	2.87	22	3.48	3.22
	30	3.01	2.81	30	3.38	3.15
					0	0
HSS drill tools filled with MoS_2 with different side angles (in degrees)	0	2.84	2.76	0	3.19	3.1
	8	2.61	2.46	8	2.93	2.76
	15	2.54	2.39	15	2.85	2.68
	22	2.4	2.4	22	2.69	2.69
	30	2.25	2.19	30	2.52	2.46
HSS drill tools filled with boric acid with different side angles (in degrees)	0	2.93	2.74	0	3.29	3.07
	8	2.8	2.57	8	3.14	2.88
	15	2.72	2.48	15	3.05	2.78
	22	2.68	2.4	22	3.01	2.69
	30	2.63	2.31	30	2.95	2.59

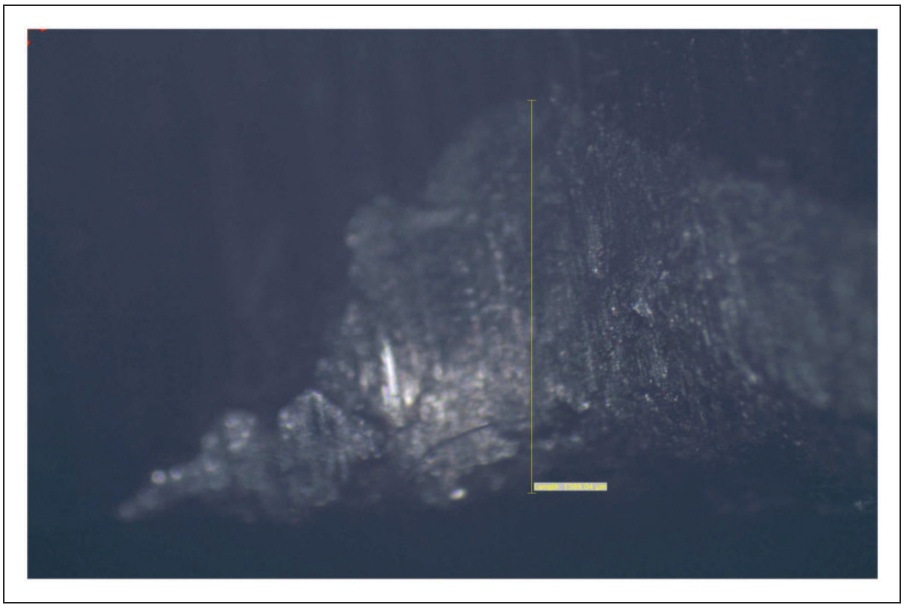

Figure 18. Microscopic image of tool worn in dry machining process.

surface roughness. As in other measurements, tools with 30° channels have shown better performance.

Tool wear

The microscopic images of worn edges of drill tools were taken using a microscope (sample picture shown in Figure 18). It was observed that wear on the cutting edges of self-lubricated drill tools after using the drill bits for 5–6 cycles was less when compared with the wear on tool edges of dry machined drill bit. The tool wear after drilling the holes were measured in terms of lengths of the worn portion on tool cutting edge and the values are given in Table 5. From these values also it was confirmed that the by using self-lubricated tools the tool wear becomes less.

Table 5. Tool wear (mm).

		12 mm drill		20 mm drill	
		Wear (μm)		Wear (μm)	
S.No.	Lubrication	AISI 1040	MS	AISI 1040	MS
1	Dry machining	1545	1399	1885	1707
2	Wet machining	168	144	205	176
3	Graphite 30°	347	320	424	391
4	Boric acid 30°	215	161	263	197
5	MoS_2 30°	154	120	188	147

Conclusions

In the present work, HSS tools were drilled with holes with various angles (0°, 8°, 15°, 22°, 30°). The holes were filled with solid lubricants like boric acid, MoS_2, and graphite. The self-lubricated drill bits were successfully employed for drilling holes in MS and AISI 1040. From the project, the following conclusions were drawn:

- Similar trend observed in studied cutting conditions i.e. with rise in cutting speed/feed, though numerical values were higher.
- Similar trend observed in drill tools of different diameters.
- Though wet condition gave lesser forces. Moments, it is characterized by various problems
- Drill tools with 30° side holes gave better lubrication for all solid lubricants
- MoS_2 provided better lubrication among the considered lubricants due to its structure
- Developed self-lubricating tools can be used successfully in the shop floor.

As a future scope of the work, other values of side angles, different solid lubricants and other tool materials may be studied. Chip morphology may also be included in the observable parameters.

Patent

A patent has been filed by the authors on the work under the Patents Act of India (File no. 6023/CHE/2013, date of filing – 23 December 2013, Title – Drill Tool Assembly).

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Conflict of interest

None declared.

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