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Effects of minimum quantity lubrication on turning of En8 alloy steel using combination of solid and liquid lubricants

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Abstract - *Use of cutting fluids in machining processes can reduce the cutting temperature and provides lubrication to tool and work piece in order to have longer tool life and improved surface quality. A technique called Minimum Quantity Lubrication (MQL), which sprays small amount of cutting fluid (in the range of approximately 10 – 100mL/h) to the cutting zone area with the aid of compressed air, was developed to merge the advantages of both dry cutting and flood cooling. The concept of Minimum Quantity Lubrication (MQL) has been suggested since a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting particles on factory shop floors. This paper evaluates the performance of MQL using solid lubricants (Graphite / Boric Powder with vegetable oils and compressed air) as cutting fluid. The work piece used for evaluation is MS bar and En8 (Black). It was seen from the results that inclusion of solid lubricants such as boric powder and graphite powder is advantageous over the conventional MQL method.*

Key Words: **MQL, Graphite powder, Boric acid, Thrust force, Surface roughness.**

1. INTRODUCTION

A lubricant is a substance introduced to reduce friction between surfaces in mutual contact, which ultimately reduces the heat generated when the surfaces move. It may also have the function of transmitting forces, transporting foreign particles, or heating or cooling the surfaces. The property of reducing friction is known as lubricity. Typically, lubricants contain 90% base oil (most often petroleum fractions, called mineral oils) with less than 10% additives. Vegetable oils or synthetic liquids such as hydrogenated polyolefin, esters, silicones, fluorocarbons and many others are sometimes used as base oils. Additives deliver reduced friction and wear, increased viscosity, improved viscosity index, resistance to corrosion and oxidation, aging or contamination, etc. Non-liquid lubricants include grease, powders (dry graphite, PTFE, molybdenum disulfide, tungsten disulfide, etc.). Dry lubricants such as graphite, molybdenum disulfide and tungsten disulfide also offer lubrication at operating temperatures (up to 350°C) higher than liquid and oil-based lubricants. Limited interest has been shown in low friction properties of compacted oxide glaze layers formed at several hundred degrees Celsius in metallic sliding systems, however, practical use is still many years away due to their physically unstable nature. [1]

Lubricants are broadly divided into four basic classes.

1. Oils: A general term used to cover all liquid lubricants, whether they are mineral oils, natural oils, synthetics, emulsions, or even process fluids.
2. Greases: Technically these are oils, which contain a thickening agent to make them semi-solid. It is convenient, however, to include the anti-seize pastes and the semi-fluid greases under the same heading.
3. Dry lubricants: These include any lubricants, which are used in solid form, and may be bulky solids, paint-like coatings, or loose powders.
4. Gases: The gas usually used in gas bearings is air, but any gas can be used which will not attack the bearings, or itself decompose.

A good lubricant should have high boiling point and low freezing point (in order to stay liquid within a wide range of temperature) high viscosity index, thermal stability, hydraulic stability, demulsibility, corrosion prevention, high resistance to oxidation. [1, 2]

There are few notable limitations in conventional lubrication techniques such as wastage of lubrication fluid thereby higher lubrication cost and less control over the process. The disadvantages associated with flood cutting fluid supply or dry cutting can be significantly reduced by application of the Minimum Quantity Lubrication (MQL) method, which means supplying cutting fluid as a mist directly into cutting zone with a flow rate not higher than 100 ml/hour. This fluid supply method can also contribute to better working conditions for machine operators and fewer environmental threats. Consequently, from the point of view of the business and ecology, this method seems to be competitive. In our paper we are comparing the results by using various combination of lubricants. We are interested in checking surface roughness of material by mixtures given below:

1. Coconut Oil + Boric Powder + Compressed air
2. Coconut Oil +Graphite Powder + Compressed air
3. Coconut Oil + Compressed air

1.1 Properties of solid lubricants used

Solid lubricants used are graphite and boric acid. Their properties are as follows:

a. Graphite:

Graphite is best suited for lubrication in a regular atmosphere. Water vapor is a necessary component for graphite lubrication. The adsorption of water reduces the bonding energy between the hexagonal planes of the graphite to a lower level than the adhesion energy between a substrate and the graphite. Because water vapor is a requirement for lubrication, graphite is not effective in vacuum. In an oxidative atmosphere graphite is effective at high temperatures up to 450ºC continuously and can withstand much higher temperature peaks. The thermal conductivity of graphite is generally low ~1.3 W/mK at 40ºC.

Graphite is characterized by two main groups: Natural and Synthetic. Synthetic graphite is a high temperature sintered product and is characterized by its high purity of carbon (99.5-99.9%). The primary grade synthetic graphite can approach the good lubricity of quality natural graphite. Natural graphite is derived from mining. The quality of natural graphite varies as a result of the ore quality and post mining processing of the ore. The end product is graphite with a content of carbon (high grade graphite 96-98% carbon), sulfur, SiO2 and Ash. The higher the carbon content and the degree of graphitization (high crystalline) the better the lubricity and resistance to oxidation.

It exhibits the properties of a metal and a nonmetal, which makes it suitable for many industrial applications. The metallic properties include thermal and electrical conductivity. The nonmetallic properties include inertness, high thermal resistance and lubricity. Some of the major end uses of graphite are in high-temperature lubricants, brushes for electrical motors, friction materials, and battery and fuel cells.

b. Boric acid:

Boric acid (H3BO3) is one of the most popular solid lubricants and has excellent lubrication properties without calling for expensive disposal techniques. The most important characteristics of boric acid for use as a lubricant are that it is readily available and environmentally safe. The Environmental Protection Agency has established that boric acid is benign and the Clean Water Act does not classify it as a pollutant. Several studies have indicated that boric acid's unique layered inter-crystalline structure makes it a very promising solid lubricant material because of its relatively high load carrying capacity and low steady state friction coefficient (0.02).

At atmospheric pressure boric acid it stable up to 443.9 K which is its melting temperature. It is water soluble and its solubility increases with temperature (2.52gm/100ml at $0^{\circ}C$, 5.7 gm/100ml at 373 K). It is soluble in lower alcohols also while it is moderately and slightly soluble in pyridine and acetone respectively.

In metal forming applications, it is shown that boric acid provided very low friction between an aluminum work-piece and a steel forming tool. During these processes, the post-fabrication cleaning of boric acid was environmentally safe, non-toxic and water-soluble. Drilling experiments with sapphire tools indicated that the addition of boric acid to distilled water increased the rate of drilling of polycrystalline alumina by a factor of two. In addition, boric acid was found to help in reducing friction and corrosion when mixed with cutting and grinding fluids during machining processes. It is very important to note, however, that the success of boric acid in each of the above studies was dependent on the continuous replenishment of boric acid into the contact region. In the present work, Boric acid is used as solid lubricant during turning of EN8 steel using HSS and carbide cutting tools. Tool wear, cutting forces, cutting temperatures and surface roughness were measured during machining. Cutting tests carried out under dry and wet conditions were compared with those carried out with solid lubricant. Particular attention was paid to the application of solid lubricant in a continuous and uniform manner throughout machining.

The selection of above solid lubricants is done on the basis of their characteristics, cost and availability in market. The main advantages of these solid lubricants are their thermal stability and ability to work under high loads. [3, 4]

1.2 Minimum quantity lubrication

Sample paragraph, The entire document should be in In MQL process, oil is mixed with high-pressure air and the resulting aerosol is supplied near to the cutting edge. This aerosol impinges at high speed on the cutting zone through the nozzle. Air in the aerosol provides the cooling function and chip removal, whereas oil provides lubrication and cooling by droplet evaporation. The flow of lubricant in MQL process varies from 10 to 100 ml/h and air pressure varies from 4 to 6.5 Kgf/sqcm. Different ranges for flow rate were also reported such as 50 to 500 mL/hr. However, in industrial applications consumption of oil is approximately in the range of 10-100 ml/hr. When the flow rate of cutting fluid in MQL is less than or equal to 1 ml/h it is termed as Micro-Liter Lubrication (μLL). As the quantity of cutting fluid in MQL is very less (in ml/hr instead of ltr/min) in comparison to flood cooling, the process is also known as Near Dry Machining. If oil is used as fluid medium in NDM, better lubrication is obtained with slight cooling effect whereas, when emulsion, water or air (cold or liquid) were used, better cooling is achieved with slight/no lubrication so, the processes were termed as Minimum Quantity Lubrication and Minimum Quantity Cooling respectively. In MQL, cooling occurs due to convective and evaporative mode of heat transfer and thus is more effective than conventional wet cooling in which cooling occurs due to convective heat transfer only. In addition, cutting fluid droplets by virtue of their high velocity penetrates the blanket of vapor formed and provides more effective heat transfer than wet cooling. But aerosols do not act as lubricants or boundary lubricants as they do not have access to the tool-chip and tool-work-piece interfaces due to too low penetration ability. In addition, the cooling action due to droplet evaporation is also small due to very small flow rate of oil. MQL action on forming chip is also negligibly small as compared to high pressure water soluble metal working fluids due to low mass of aerosol. Astakhov a researcher in this field, suggested that the application of MQL enhances the rebinder effect and thus reduces the work due to plastic deformation. As little quantity of cutting fluid is utilized in MQL process, the cutting fluid should possess significantly higher lubrication qualities than mineral oil. The main advantage of MQL technique is less tool wear and less surface roughness than traditional lubrication.

2. Experimentation and results

2.1 Experimentation

Experiments were carried out by plain turning a 55mm diameter and 600mm long rod of En8 steel under different cutting velocities and feeds by using various composition of lubricants in MQL setup. These experiments were conducted in order to explore the role of solid lubricants on the machinability characteristics of work material in terms of surface roughness and cutting forces. The experimental conditions are listed in the table given below.

Various components used in the experiment and their specifications are as follows:

1. Cylinder – By taking length to diameter ratio 2, and cylinder capacity of 2 liters we calculated the dimensions as, L= 220mm and D= 110mm. The cylinder was manufactured by cast iron material.
2. Air Compressor – Pressure of 5 bar was kept constant throughout the experiment. Air compressor of max pressure 10 bar was used.
3. Nozzle – Bronze nozzle of tip diameter 1mm was used.
4. Flow control valve and Non-return valve of 1/3 inches was used.
5. Pressure gauge of 10 bar maximum capacity was used.
6. PVC pipes of outer diameter 8mm was used.

Table -1: Experimental conditions

Machine tool	CNC lathe
Material	En8 alloy steel (C 0.36-0.44%, Si 0.10-0.40%, Mn 0.60-1.00%, S-0.05% max, P-0.05% max)
Hardness	50-55HRC
Tool insert	PCB tool insert
Cutting velocity	198, 216, and 259 m/min
Feed rate	0.077, 0.12, 0.188 mm/rev
Depth of cut	0.1, 0.2,0.3 mm
Cutting fluid	Coconut oil: viscosity 80cP at 293 K
Cutting fluid supply	At constant 5 bar pressure

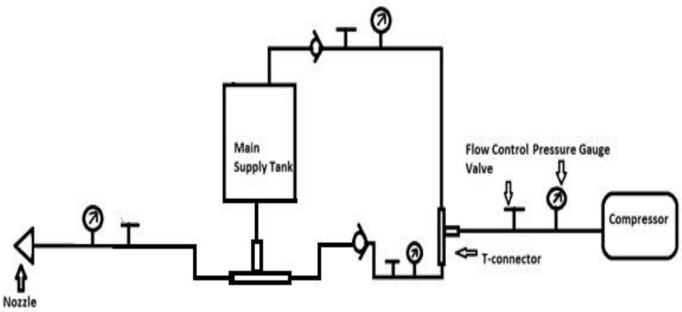

Fig -1: Schematic of experimental setup

Experiments were carried out in 3 stages. In first stage boric powder was used in combination with oil and compressed air. Secondly graphite powder was used with oil and compressed air. Finally only oil and compressed air mix was used for lubrication purpose. The surface roughness and forces were measured using Taylor Hobson surface roughness tester and dynamometer respectively.

2.2 Result

After carrying out experiments in above conditions following observations are noted:

Table -2: Results for mixture of boric acid, oil and compressed air

Speed(RPM)	Feed(mm/r ev)	Depth (mm)	Surface roughness (µm)				Force (kg)		
			1	2	3	Avg	Ft	Fr	Fa
1145	0.077	0.1	1.31	1.26	1.33	1.30	-2	+2	+4
1145	0.12	0.2	0.91	0.99	1.12	1.02	+4	-4	+235
1145	0.188	0.3	1.06	1.11	1.08	1.08	+10	-4	+350
1250	0.077	0.1	0.89	0.91	0.87	0.89	-1	-2	+4
1250	0.12	0.2	0.64	0.64	0.76	0.71	+4	-3	+4
1250	0.188	0.3	1.08	1.01	1.08	1.05	+8	+3	-1
1500	0.077	0.1	0.49	0.48	0.51	0.49	+5	-1	+5
1500	0.12	0.2	0.88	0.71	0.78	0.79	+4	+2	+3
1500	0.188	0.3	1.12	1.08	1.05	1.08	+8	-3	+3

Table -3: Results for mixture of graphite powder, oil and compressed air

Speed(RPM)	Feed(mm/r ev)	Depth (mm)	Surface roughness (µm)				Force (kg)		
			1	2	3	Avg	Ft	Fr	Fa
1145	0.077	0.1	1.08	0.91	0.98	0.99	+3	-2	+6
1145	0.12	0.2	1.18	1.04	1.15	1.12	+5	-3	+8
1145	0.188	0.3	1.39	1.27	1.24	1.3	+9	+3	+5
1250	0.077	0.1	0.83	0.72	0.57	0.70	+2	-2	+3
1250	0.12	0.2	0.85	0.86	0.94	0.88	+5	-2	+5
1250	0.188	0.3	1.31	1.30	1.28	1.29	+8	-2	+4
1500	0.077	0.1	0.65	0.56	0.52	0.57	+4	-2	+4
1500	0.12	0.2	0.85	0.91	0.87	0.87	+4	-2	+4
1500	0.188	0.3	1.26	1.25	1.26	1.25	+8	+3	+4

Table -3: Results for mixture of oil and compressed air

Speed(RPM)	Feed(mm/r ev)	Depth (mm)	Surface roughness (µm)				Force (kg)		
			1	2	3	Avg	Ft	Fr	Fa
1145	0.077	0.1	1.48	1.41	1.35	1.41	+2	-2	+4
1145	0.12	0.2	1.15	1	1	1.05	-3	-2	+5
1145	0.188	0.3	1.33	1.35	1.41	1.36	-7	+3	+5
1250	0.077	0.1	0.79	0.83	0.69	0.77	+2	-2	+3
1250	0.12	0.2	1.04	1.02	1.99	1.01	+8	-3	+5
1250	0.188	0.3	1.37	1.50	1.45	1.44	+8	-3	-4
1500	0.077	0.1	0.53	0.57	0.55	0.55	+9	+12	+12
1500	0.12	0.2	1.42	1.35	1.39	1.38	-9	-3	+4
1500	0.188	0.3	1.42	1.35	1.39	1.38	-9	-3	+4

These results are plotted in the form of following bar charts:

1. Keeping feed and depth of cut 0.077mm/rev and 0.1mm respectively a bar chart is drawn for variable speed. The same can be drawn for the other two combinations of feed and depth of cut.

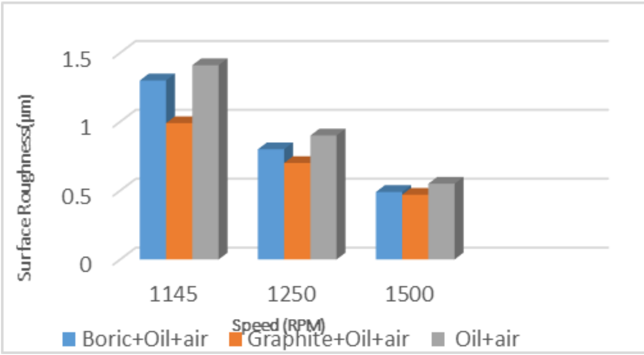

Chart -1: Surface Roughness Vs Speed

2. The next bar chart is drawn by varying the combination feed and depth of cut with constant speed of 1145RPM.

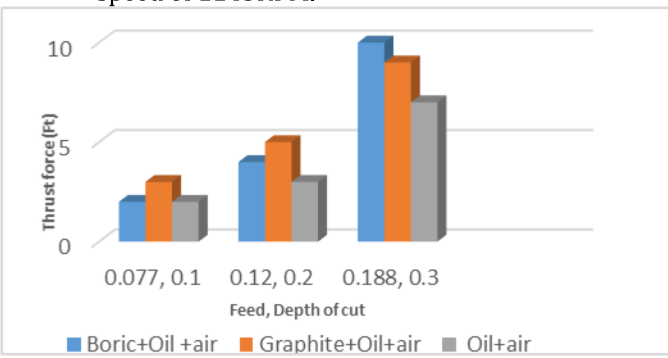

Chart -2: Thrust Force Vs Feed and Depth of cut

3. The similar graph is drawn by varying the combination of feed and depth of cut with constant speed of 1500RPM

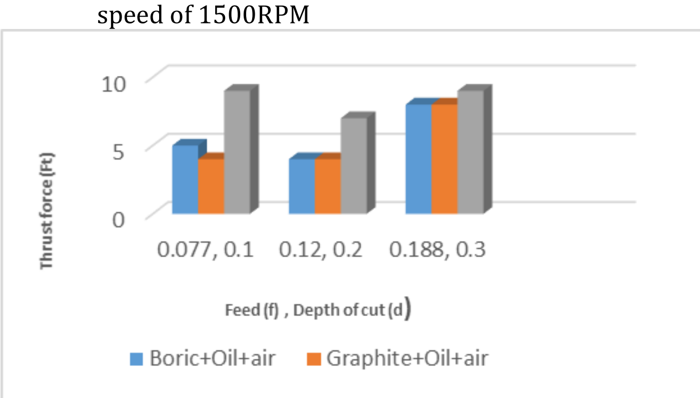

Chart -3: Thrust Force Vs Feed and Depth of cut

The following key observations are made from the bar charts:

1. For constant feed and depth of cut surface finish of machined workpiece is better at higher speed. Given any combination of working parameters, surface finish, using graphite powder mixed with oil and compressed air, is better than the other two lubricants' compositions. It is followed by boric acid mixed with oil and compressed air. Thus introduction of solid lubricant in conventional MQL improves surface finish.
2. With constant speed, thrust force on tool increases with increase in feed and depth of cut. At lower speed, thrust force on tool is minimum for oil and compressed air mixture but as speed increases, thrust force also increases and the same pattern is seen in remaining two mixtures of lubricants.
3. For constant speed thrust force is highest in case of oil and compressed air mixture over entire range of feed and depth of cut. At low feed and less depth of cut graphite powder with oil and compressed air has least thrust force while at higher feed rate and depth of cut, with both solid lubricants' combination, work piece faces similar thrust force.

3. CONCLUSIONS

The use of solid lubricants with combination of conventional MQL has provided very effective results. As the results interpret, at low as well as higher speed range, inclusion of solid lubricant with oil and compressed air has provided better surface finish. This certainly is a better method of lubrication which can be carried out in wide range of application with different speeds. At higher speeds when the thrust force is high with oil and compressed air MQL, this method provides superior results with lower thrust force. Lower thrust corresponds to less wear of tool is observed thereby life of tool also increases. Thus this method of lubrication has a very bright future considering the advantages of it over conventional MQL method.

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