Performance Assessment and Selection of Solid Lubricants for Environmentally Benign Lubrication in Machining

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Abstract: The traditional machining methods introduce high-volume and high-pressure machining fluid systems to provide cooling and lubrication between the tool and the work piece. However the application of fluids account for an extensive proportion of the total manufacturing cost and adversely affects the health of person and also creates environmental problems . In this respect, industry is required to comply with regulations that control the use and disposal of lubri-cation materials that are potentially hazardous, or place unacceptable burdens on natural resources and the environment. In this context, there is a clear need to explore the potential for using Solid Lubricants within machining in order to establish a stable and reliable machining process. The current research work aims to assess the performance of solid lubricants mixed with SAE-40 base oil during the machining. The results shows the bet-ter performance of lubricant mixture as compared to dry machining and flood cooling. It is difficult to select best combination of lubricant as the values of output parameters are varying. Hence the methodology is proposed to select the most suitable combination of lubricant by using multiple attribute decision making technique. The lubricant selection factors identified are process temperature, surface roughness, power consumption and tool wear.

Keywords: Machining, Solid lubricants, Multiple attribute decision making.

1. INTRODUCTION

Machining is considered as one of the important manufacturing process which uses a cutting tool to remove the extra amount of metal available on workpiece surface and brings it to required dimensions. Since the basic mechanism involved in machining is shear deformation of workpiece, lot of friction occurs in the contact area of tool and workpiece which results the heat generation. When machining of low strength alloys, this heat generation is less but when ferrous and other high strength alloys are machined, lot of heat is generated which increases with a subsequent increase in the cutting speed. The traditional machining methods introduce high-volume or high-pressure machining fluid systems to provide cooling and lubrication between the tool and the work piece. This provides a measure of control with respect to the thermal behaviour within the machining zone and enable a general ‘bulk’ cooling of the machining process. Nevertheless the application of fluids account for an extensive proportion of the total manufacturing cost. The costs attributed to the use of machining fluids do not only comprise of the initial purchase and delivery logistics but also the storage, energy consumption, treatment, filtration, and the end of life disposal. The majority of fluids are semi-synthetic soluble oils that also require the use of water. In this respect, industry is required to comply with regulations that control the use and disposal of lubrication materials that are potentially hazardous to, or place unacceptable burdens on natural resources and the environment.

The concept of minimum quantity lubrication (MQL) has been proposed since before many years as an alternative to overcome the issues related to environmental effect and employee health with the flying cutting fluid particles on factory shop floors. Minimum quantity lubrication (MQL) is the way to achieve nearly dry machining (NDM), it uses the cutting fluid in optimize and minimum quantities, which is considered very less as compared to the amount of cutting fluid which is used in fluid cooling (Machado and Wallbank, 1997, Rahman et al., 2002).

In this context, there is a clear need to explore the potential for using Solid Lubricants within machining, in order to establish a stable and reliable machining process. The solid lubricants can be applied in power form to the machining area or it can be mixed with oil (Reddy and Rao, 2006) or it can be mixed with compressed air and applied to cutting zone (Vamsi Krishna et al., 2010).

In the present work, solid lubricants with different concentration are mixed with SAE-40 base oil for machining of EN-31 steel material and the parameters measured are compared with the value available in case of dry machining and machining with fluid lubricants. In order to find the best combination of lubricants, multiple attribute decision making technique is applied.

2. LITERATURE REVIEW

Many work is reported in the area of application of lubricants by using the concept of minimum quantity lubrication and solid lubricants. Minimum quantity lubrication states to the supply of small quantities of fluid via an aerosol to the machining area. The mixture of air and oil can be prepared in a tank or on the nozzle tip (Klocke et al., 2000). The amount of fluid quantity required can be found based on the width of wheel. It is suggested as 1 L/min of fluid per 1 mm of wheel width (Barczak et al. 2010.

The minimum quantity lubrication (MQL) is to reap the benefits of cutting fluids without getting affected with the harmful effects of the cutting fluids. It involves the usage of minimal quantity of cutting fluid with a typical flow rate of 50-500 ml/h which is directly applied to the cutting zone thereby avoiding the need of fluid disposal as it happens in flood cooling. Since MQL involves significantly lesser amount of cutting fluid, this phenomenon is popularly referred to as ‘near dry machining’ or ‘micro lubrication’ or ‘spatter lubrication’ (Klocke et al., 2000).

Varodarajan et al. (2002) claimed to have used 2ml/hr oil in a flow high pressure air at 20 Mpa, while hard turning AISI4340 steel. The effort may be considered as near to dry machining.Dhar et al. (2002) carried out analysis on cryogenic machining of plain carbon steels C-40 by changing cutting velocities and feed rate and found the improvement in machinability and also reported the environment safety as compared to other lubrication methods.

Hadad and Sadeghi (2013) conducted the experiments during machining of AISI 4140 steel to analyse the performance of dry, wet and MQL techniques. It was reported that the least value of cutting force was found in case of minimum quantity lubrication and in wet condition.Khan et al. (2009) used water and vegetable oil as cooling medium during machining through a jet. The MQL application causes better surface finish, reduced tool wear and temperature as compared with dry machining.

Solid lubricant assisted machining is one attempt to avoid the use of cutting fluids (Rao and Vamsi Krishna 2008). Venu Gopal and Rao (2004) used the graphite as a solid lubricant in grinding process which resulted the decrease in heat generation. And it was noted that the entire improvement in the process because of graphite.During the machining of hardened AIS I52100 steel with ceramic inserts, it was found that solid lubricants are more effective at higher cutting speeds (Dilbagh Singh and Rao, 2007).Another study focused on the use of solid lubricant (boric acid and MoS2) in forming and drilling (Liang et al. 1995). In metal forming applications it is shown that the boric acid provided very low friction between an aluminum work piece and steel forming tool.Shen et al. (2008) applied water based Al2O3 and diamond nanofluids in the grinding of cast iron under MQL conditions and compared the results with dry and wet lubricating conditions. It was reported that the MQL increases the surface finish, reduces the force developed and also prevents the burning of workpiece form the heat generated.Mao et al. (2014) investigated the role of the nanofluid in grinding operation by conducting friction and wear experiments which can establish various tribological properties of the nanofluid. They observed that nanoparticle based fluid showed a superior anti wear characteristics which led to a reduction in tangential cutting forces and improved the surface texture.

3. EXPERIMENTAL PROCEDURE

The machining tests were carried out on heavy duty lathe machine TURNMASTER 35.The work piece has a dimension of 100mm in length and 50mm in diameter. The chemical composition of work piece is shown in table 1.

EN-31 alloy steel material was used and the machining parameters considered were cutting speed (v) m/min, feed rate (f) mm/rev, depth of cut (d) and tool nose radius (r) mm. The values of chip tool interface temperature, power consumption, surface roughness and tool wear during steel turning in dry and wet condition and solid lubricants mixed with SAE-40 base oil were obtained.

The experimental details are given in table 2. The cutting tests were carried out on EN-31 steel using tungsten carbide insert under dry and wet and solid lubricant assisted lubrication. Surface roughness is measured by surface roughness tester and tool wear is measured on a sensitive single pan balance. The machining force is measured by lathe tool dynamometer. Two solid lubricants namely boric acid and molybdenum disulphide (MoS_2) were mixed with SAE-40 base oil in different concentrations.

TABLE 1: Chemical composition of (EN-31) w/p

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

TABLE 2: Experimental details

Machine tool	10 HP lathe machine
Work specimen material	En-31 steel alloy
Process parameters	Cutting speed V=112 m/min Feed f=0.4 mm/rev Depth of cut d=0.4 mm Tool nose radius R=0.8 mm
Lubricants	(i) Dry (no lubricant)
	(ii) Wet (soluble oil mixed with water in the ration of 1:20)
	(iii) Minimum quantity lubrication (a) 10% MoS_2 + SAE-40 base oil (b) 10% boric acid + SAE-40 base oil (c) 15% MoS_2 + SAE-40 base oil (d) 15% boric acid + SAE-40 base oil

4. RESULTS AND DISCUSSION

Experiments were performed by taking the mentioned values of speed, feed and depth of cut and value of process temperature, surface roughness, tool wear and power consumption are obtained.

TABLE 3: Experimental results

Lubrication condition	T (°C)	P (W)	Ra (μm)	Toolwear (mg/min)
Dry (no lubricant)	550	520	6.652	0.338
Wet	448	440	4.750	0.335
10% MoS_2 + SAE-40 base oil	248	560	5.483	0.274
10% boric acid + SAE-40 base oil	260	520	5.174	0.249
15% MoS_2 + SAE-40 base oil	210	540	5.221	0.276
15% boric acid + SAE-40 base oil	230	530	5.120	0.247

4.1 Process Temperature

Experimental results shows the highest value of temperature observed in case of dry machining because of the absence of lubricating action. However the average value of temperature generated is not that much affected in case of wet condition and solid lubricants mixed with base oil. It can be concluded that reduction in process temperature is observed while using MoS_2 added with base oil because of it good lubricating action.

4.2 Surface Roughness

Surface roughness produced during the machining reveals the quality of machining process. However it depends on various factors like lubricating medium, material and cutting tool geometry. The result shows that no significant change in Ra value in case of wet and solid lubricant added machining but the highest value of Ra is observed in case of dry machining because of the increase in cutting force and temperature which leads to greater tool wear. The minimum value of surface roughness is achieved in case of machining with boric acid and MoS_2 added with base oil, as it has improved lubricating properties. The roughness value reduced almost by 20% as compared to wet lubrication and 40% as compared to dry machining.

4.3 Power Consumption

From the results available from the experiments with different lubricating conditions, it can be concluded that the lowest value of power consumption is reported in case of machining with solid lubricants added with base oil. This is because of reduced value of cutting forces during the process and less effort required to perform the cutting action with increased lubricating action. Highest value of power consumption is reported in case of dry machining.

4.4 Tool Wear

Tool wear cannot be avoided in machining because of rubbing action and friction between tool and work piece surface. Tool wear is measured in all cutting conditions under different lubrication medium. It was found that significant reduction in tool wear in case of the application of solid lubricants mixed with base oil. Where in case of dry and wet lubrication, maximum tool wear was observed.

5. MADM METHOD FOR SELECTION OF BEST SUITABLE LUBRICANT

Based on the results available from the experiments, it shows that the conflict between the measured values available for different lubricating condition and it seems difficult to find out the best suitable lubricant. So a suitable multiple attribute decision making technique can be applied to decide the most suitable lubricant for the considered set of parameters.

Various approaches had been proposed in the past to help address the issue of material selection (Ashby et al., 2004; Edwards, 2005) However, these systems and methods are complex and knowledge intensive. Jee and Kang (2000) proposed TOPSIS method for material selection. Shanian and Savadogo (2006) presented material selection models using a multiple attribute decision making (MADM) method known as ELECTRE. Rao (2006) presented a material selection model using graph theory and matrix approach. However some of the above methods is complex and required much computational time. So to make the decision making process easy, here a technique called the multi-objective optimization on the basis of ratio analysis is proposed to select the best suitable lubricant. The method is introduced by Brauers (2004).

5.1 Steps of the method

The input of the method is a matrix which contains the alternatives considered with respect to its value measured with attributes considered. It is required to normalize the data available in decision matrix by considering various ratio systems, such as total ratio, Schärlig ratio, Weitendorf ratio, Jüttler ratio, Stopp ratio, Körth ratio etc. and concluded that for this denominator, the best choice is the square root of the sum of squares of each alternative per attribute Brauers (2004).This ratio can be expressed as below.

$$X_{ij} = \frac{x_{ij}}{\sqrt{[\sum_{i=1}^{m} x^2{}_{ij}]}} \quad (j=1, 2,\ldots..n) \qquad \text{(i)}$$

Where x_{ij} is a dimensionless number which belongs to the interval [0, 1] representing the normalized performance of i^{th} alternative on j^{th} attribute.

For multi-objective optimization, these normalized performances are added in case of maximization (for beneficial attributes) and subtracted in case of minimization (for non-beneficial attributes). Then the optimization problem becomes:

$$Y_i = \sum_{j=1}^{g} X_{ij} - \sum_{j=g+1}^{n} X_{ij} \qquad \text{(ii)}$$

Where g is the number of attributes to be maximized, (n-g) is the number of attributes to be minimized, and y_i is the normalized assessment value of i^{th} alternative with respect to all the attributes.

In case of weights considered for alternatives, it is multiplied with the x_{ij} values. When these attribute weights are taken into consideration, Eq. 2 becomes as follows:

$$Y_i = \sum_{j=1}^{g} W_j X_{ij} - \sum_{j=g+1}^{n} W_j X_{ij} \quad (j=1, 2,\ldots.n) \qquad \text{(iii)}$$

Where W_j is the weight of j^{th} attribute. This weight can be obtained by analytic hierarchy process (AHP) or entropy method or can be decided by decision maker. The value of Yi may be positive or negative. At last the alternative with highest Yi value will be best option for given application.

From the measured output parameters, the lower values is desirable for temperature, surface roughness, power consumption and tool wear. As the value temperature plays a vital role for deciding the surface finish and heat generation. The weightage considered are as below.

T_w= 0.300, Ra= 0.225, P_w=0.225, TW_w=0.20

By applying the steps of the method, the results obtained are as below.

Lubrication condition	Yi value	Rank
Dry (no lubricant)	-0.4930	6
Wet	-0.4099	5
10% MoS_2 + SAE-40 base oil	-0.3561	4
10% boric acid + SAE-40 base oil	-0.3409	3
15% MoS_2 + SAE-40 base oil	-0.3354	2
15% boric acid + SAE-40 base oil	-0.3307	1

Based on the Yi value obtained, the lubricating condition with 15% boric acid + SAE-40 base oil proved to be a best alternative followed by 15% MoS_2 added with oil among all considered conditions. Dry machining is suggested as last alternative.

6. CONCLUSION

It can be concluded from the experimental results that, the solid lubricant assisted machining is a feasible option in order to reduce the environmental effects of fluid cooling.

The results also reveals that with application of solid lubricants, reduced value of temperature, surface roughness, power consumption and tool wear is reported as compared to dry and wet lubrication. Further the work may be extended to assess the effects of solid lubricant assisted machining on cutting forces and micro hardness of work piece material.

A methodology based MADM is suggested for decision making, in such situations where the decision making is affected by conflicting criteria, such method can be useful to solve the decision making problem.

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