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Performance and life cycle analysis of soybean oil based minimum quantity lubrication in machining of Ti6Al4V

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Abstract

Titanium alloys are used in various applications due to their properties. However, these alloys are difficult to machine. Several techniques have been proposed in literature to deal with the problem. This paper presents a study on the performance and life cycle analysis of the dry machining, flood lubrication and minimum quantity lubrication (MQL) of titanium alloy, Ti6Al4V. Machining was carried out at different speeds 30 m/min, 55 m/min and 80 m/min. Soybean based fluid was used in both flood lubrication and MQL. Cutting forces, tool wear and surface roughness were measured in all three cases. MQL was found to have better performance with longer tool life by almost two times, cutting forces by about 18% and surface roughness by about 10% compared to dry machining. Flood lubrication results were intermediate between the two. However, flood lubrication had the highest carbon footprint followed by dry machining and MQL.

***Keywords*:** Ti6Al4V, machining, MQL, carbon footprint

1. Introduction

Titanium alloys are popularly utilized to make parts for various applications in aerospace, energy and medical/dental sectors due to their superior properties such as high strength, bio-compatibility and corrosion resistance compared to other metals or alloys [1]. Among the alloys, Ti6Al4V is the most commonly used. These alloys have high yield strength, fatigue strength, heat resistance, specific strength, corrosion resistance, etc. [2, 3]. Due to high strength of these alloys, cutting temperatures are usually high in their machining [4, 5]. Further, these alloys continue to have high strength even at elevated temperatures, hence, cutting forces do not decrease with higher cutting speed. Also, as the titanium alloys have low thermal conductivity, heat due to machining is not dissipated and it remains in the tool/chip interface causing increased tool wear and early tool failure. Most of the heat (about 80%) is retained in the tool [6,7]. This problem is more severe at high cutting speeds. Also, because of higher spring back present in the materials causes chatter and poor surface finish. This is extremely important due to the nature of the applications of the alloys. It was reported in literature that the preferred cutting speed for machining the titanium alloys is about 60 m/min with tungsten carbide/PVD coated tools [8-10], which are usually the best tools for machining titanium alloys [11]. In addition, titanium alloys have high reactivity with cutting tool materials. This results in exacerbated tool wear and premature failure of the tool [12]. Though cutting tools with composite coatings are also used, single layer coatings/single phase coatings were found to be better than composite coated tools in terms of extended tool life. Also, titanium easily strain hardens and results in the formation of built-up-edge (BUE) while machining at low speeds that are preferred for the material. Thus, machining of titanium alloys involves several problems. In the recent years, several works are reported in literature on the machining of titanium alloys. Various techniques such as flood lubrication, MQL and cryogenic cooling were tried by various researchers [13].

Dry machining results in high cutting temperatures and small tool life. Since cutting temperatures greatly depend on cutting speed, the allowable range of speeds in dry machining is usually limited. This reduces the productivity of the industry. Hence, investigations on techniques to effectively cool and lubricate the machining zone gained prominence. The usual technique to reduce cutting temperatures is applying the cutting fluids. Cutting fluids help in carrying away the heat and reduce the friction in the machining zone through lubrication. The fluids are generally applied with the nozzle in one or more of the three directions: backside of the chip, underneath the chip, on the rake face of the tool or on the tool flank surface. To increase the carrying away of heat and lubrication, cutting fluids are applied in large quantities, called flood lubrication. This also helps to compensate the losses due to evaporation. For better convection of heat, cutting fluids are supplied under high pressure delivery systems in the machining of titanium alloys. Further, high pressure jet can help to break the chip and result in smaller tool/chip contact length leading to reduced friction. However, due to the complex nature of the ingredients, EPA mandates proper treatment before disposal. Some researchers have suggested cryogenic cooling in machining of titanium. Nitrogen in its liquid form is applied in machining at -196^{o}C [13]. This helps in reducing the temperatures and forms a layer at the tool/chip interface and reduces the friction. Due to its ability to reduce the temperature by over 59%, cryogenic cooling has become popular in machining of titanium alloys. However, the cutting forces are very high, and the quality of product is poor. Extreme cooling causes various hardening of the workpiece and dimensional/form inaccuracies. As another solution, vegetable oils replaced the paraffin oil in the cutting fluids. However, even these oils require treatment and disposal. However, if used in MQL, there is no need for disposal. MQL reduces cutting forces, temperatures, tool wear and improves the quality of the product. Though MQL improves the machining performance, it needs fluids of very high quality to obtain significant cooling and lubrication.

Apart from the performance aspect of the cutting fluids, the environmental impact is important. Not many works are available in literature on the life cycle analysis. In one interesting work [14], total carbon footprint was calculated as:

$$CE = CE_{elec} + CE_{tool} + CE_{coolant} + CE_{m} + CE_{chip} \quad (1)$$

Where, CE_{elec}, CE_{tool} , $CE_{coolant}$, CE_{m} and CE_{chip} are the carbon emissions due to production of electricity necessary for machining, producing cutting tools, production of cutting fluid, production of raw materials and chip removal. In the calculation of CE coolant, only the carbon emissions of production and disposal are considered, without regard to the individual ingredients of the fluid. Hence, a vegetable-based oil or a petroleum-based oil would essentially give the same results.

In summary, though MQL is popularly used, its application in machining of titanium alloys is not popular, mostly due to the inadequate cooling. Hence, the application of cutting fluids in MQL is a potential solution. Though few works dealing with MQL in titanium are found in literature, most of them deal with petroleum-based oils. Of the few works dealing with vegetable-based fluids, LCA analysis is not done. Many works dealing with sustainability, consider only the reduced forces in machining, and hence reduced power consumption, due to the use of cutting fluids. However, the energy consumption during the life cycle is often neglected. The present work attempts to test the performance of soybean based cutting fluids in the machining of Ti6Al4V and studies the sustainability aspects through life cycle analysis.

2. Experimentation

In the present work, Ti6Al4V was machined on HAAS SL-20 turning center (20 HP) using TiN/TiAlN coated carbide tools till the end of the tool life for different cutting conditions. Cutting speeds of 30 m/min, 55 m/min and 80 m/min, feed rate of 0.3mm/rev and depth of cut of 0.5 mm were selected.

Fig.1 Experimental setup

Soybean based cutting fluid was supplied at the rate of 40 mL/hr using MQL system. The nozzle is so placed that the fluid is supplied behind the chip. Dry machining and flood cooling were also carried under the same cutting conditions for comparison. In flood lubrication, cutting fluid was diluted with 95% water and supplied at the rate of 100 L/hr. In all cases, the limiting value of flank wear was taken to be 0.6 mm. Tool wear was measured using a toolmaker's microscope (Make: Mitutoyo) at different intervals of machining. Cutting forces and surface roughness were measured using lathe tool dynamometer (Make: Kistler) and surface roughness tester (Make: Mahr). The experimental setup is shown in Fig. 1.

3. Results & Discussions

Tool wear was significantly influenced by cutting speeds, higher speeds resulted in higher tool wear. However, for each speed the trends for the three lubricating conditions were similar. Hence, tool wear data at cutting speed of 80 m/min only is presented in this paper for brevity (Fig. 2). It may be seen that tool wear is low for MQL compared to the other two conditions. Dry machining produces highest heat due to the absence of any coolant/lubricant and hence has highest tool wear. Flood lubrication effectively curtails heat and reduces the chance of plastic deformation of the tool, however, the cutting fluid may not reach the actual machining zone (tool-chip interface, secondary shear zone) and hence may not reduce friction, especially at high cutting speeds. In MQL the fluid is supplied underneath the chip in this study. When applied underneath the chip, the cutting fluid can reach the tool-chip junction via capillarity through the micro cracks on the surface of the chip. Usually, lubrication is required in the secondary shear zone, where the chip is in contact with the rake face of the tool. The lubricant forms a thin lubricating film at the tool/chip interface and reduces the adhesion of the chip with the tool. This results in decrease of friction and thus tool wear. It may be seen that tool life (max. tool wear = 0.6 mm) was almost twice for MQL compared to Dry machining and about 25% more compared to flood lubrication. The tool wear data was used to formulate tool life equation for TiN/TiAlN coated tools in machining of titanium (Eqs. 2-4).

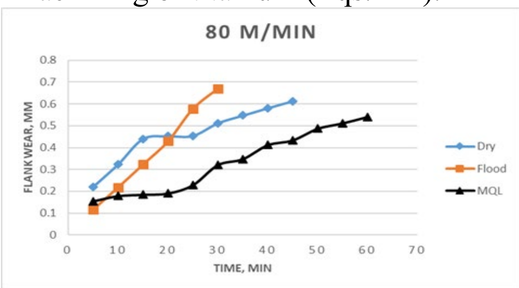

Fig. 2 Tool wear at 80 m/min

$VT^{0.69}=533$ (flood lubrication) (2)

$VT^{0.588}=495.26$ (MQL) (3)

$VT^{0.65}=398$ (Dry machining) (4)

where, V = cutting speed, m/min and T = tool life, min. The cutting data for cutting speeds of 30 m/min and 55 m/min were used to build the model, while the values at 80 m/min were used to test the model. The errors in prediction were found to be 9.2%, 2.5% and 3.5% for dry machining, flood lubrication and MQL respectively. The equations are helpful in predicting tool life under different cutting speeds. This will give the measure of tools spent and help to carry out the LCA of fluids.

Cutting forces and surface roughness were also recorded for the entire tool life. Surface roughness and cutting forces were observed to be less with MQL than other conditions. Figs 3 & 4 present surface roughness and cutting forces at the end of tool life while machining at a cutting speed of 80 m/min.. Dry machining had the highest surface roughness followed by flood lubrication. Due to lesser tool wear, MQL resulted in least surface roughness about the considered conditions, about 6% less than flood lubrication and about 10% less than dry machining. Cutting forces were found to be almost similar for different cutting speeds, despite the high tool wear at higher speeds. This may be due to the high amount of heat that is contained in the workpiece, which softens the workpiece, reducing the cutting forces. Since, titanium alloys have low thermal conductivity; most of the heat is not carried away by the chip, but is retained in the tool and workpiece. This causes the workpiece to get heated up very quickly. However, within the different conditions of lubrication, difference can be observed.

Cutting forces are consistently low for MQL compared to dry machining and flood lubrication. Dry machining is devoid of any lubrication and hence obviously has higher forces. In flood lubrication, the cutting fluid helps mainly by cooling the machining zone, however, the fluid may not reach the tool-chip interface. In case of MQL, the fluid reaches the secondary shear zone, thereby considerably reducing the cutting forces. Further, the lower tool wear helps in reducing the cutting forces in case of MQL. It may be observed that MQL has about 18% lesser forces compared to dry machining and about 9% compared to flood lubrication.

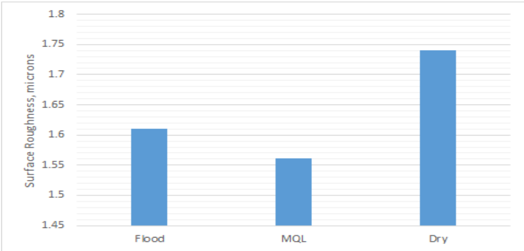

Fig. 3 Surface roughness for different lubricating conditions at 80 m/min

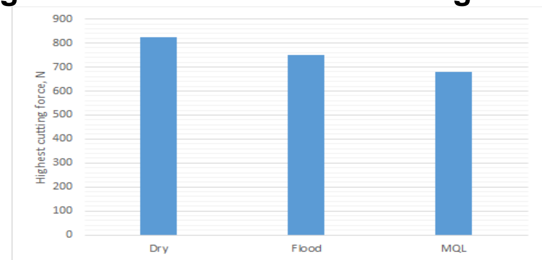

Fig. 4 Highest cutting force recorded for different lubricating conditions at 80 m/min

LCA of titanium alloy machining was carried out based on literature [14]. The carbon footprint calculations are presented in table 1. It may be seen that flood lubrication leaves higher carbon footprint compared to the other two conditions. This is due to the fact that flood lubrication results in better performance than dry machining, the impact of the production of the cutting fluid is high. In case of MQL, the carbon footprint is small due to the small quantity of fluid used and longer tool life/smaller cutting forces. Further, MQL does not need disposal, thus reducing the carbon footprint.

4. Conclusions

The following conclusions may be drawn based on the present work:

1. At the considered cutting conditions, MQL gave the best performance compared to dry and flood lubrication.
2. Better lubrication in MQL helped to reduce cutting forces, tool wear and surface roughness.
3. Flood lubrication was better than dry machining in terms of performance. However, LCA revealed that flood lubrication is not sustainable compared to the other two cases.
4. MQL is found to the most sustainable under the considered conditions.

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Table 1. Carbon footprint calculations

Cutting speed, m/min	Carbon Footprint (kg CO_2)		
	Dry	Flood	MQL
30	10.267	10.256	10.230
55	10.419	10.427	10.372
80	10.559	10.644	10.546

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