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Energy Consumption and Surface Finish Analysis of Machining Ti6Al4V

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***Abstract*—**Greenhouse gases (GHG) emissions impose major threat to global warming potential (GWP). Unfortunately manufacturing sector is one of the major sources that contribute towards the rapid increase in greenhouse gases (GHG) emissions. In manufacturing sector electric power consumption is the major driver that influences CO2 emission. Titanium alloys are widely utilized in aerospace, automotive and petrochemical sectors because of their high strength to weight ratio and corrosion resistance. Titanium alloys are termed as difficult to cut materials because of their poor machinability rating. The present study analyzes energy consumption during cutting with reference to material removal rate (MRR). Surface roughness was also measured in order to optimize energy consumption.

***Keywords*—**Energy Consumption, CO2 Emission, Ti6Al4V.

I. Introduction

A significant amount of greenhouse gases (GHG) is released in atmosphere due to the metal cutting sector. To protect the environment strict legislations are being developed and implemented by the global community. Manufacturing sector is also under immense pressure to avoid all environmental hazardous practices. Energy consumption during manufacturing operations is one of the key parameters that play an important role towards environmental burden. By optimizing energy requirements for a given machining operation greenhouse gases can be reduced.

Many researchers have focused their work to optimize energy consumption with respect to the cutting conditions. Interaction between minimum cost and minimum energy consumption for machining operations revealed that minimum energy criterion resulted in less cost, energy consumption, and carbon foot print [1]. Reference [2] explored utilization of polynomial networks to develop models for multistage turning. The study investigated possibilities of maximizing production and minimizing production cost. An analytical model was developed to determine the environmental burden of core machining phase [3]. The research utilized energy utilization, cutting mechanics and lubricant flow rate for developing machining model. This study revealed that energy consumed by a machining process is a function of product geometry, workpiece material and cutting environment.

In general electrical energy is consumed in a machine tool to perform machining task. Reference [4] revealed detailed analysis of energy consumption used to perform different tasks during machining. The experimentation was conducted using injection molding, manual/ automatic milling and automated lathe machines. Reference [5] describes a methodology of calculating environmental burden of a machining operation. The study also provided formulation to calculate equivalent CO2 emissions using electrical energy consumption. Reference [6] proposed an online energy monitoring method for machine tool. It was revealed that energy efficiency can be increased by reducing idle time through efficient managerial skills or by optimizing cutting parameters through technical means.

A framework consists of six steps process to characterize energy consumption was recommended to illustrate power and energy consumption [7]. The research work revealed that a high portion of the energy consumption was utilized in machine controller and idle movements. It was revealed that spindle utilized 35% of total energy. Reference [8] recommends design and process based approaches to minimize energy utilization. The research analysed different model based on kinetic energy recovery system (KERS), process parameter selection strategy and web-based energy estimation tool. It was observed that KERS can save energy up to 25%. An empirical expression was formulated to explain the interaction between energy utilization and cutting conditions [9]. Experimental validation of model was performed using different milling and turning machine tools.

Reference [10] represents a model for prediction of energy foot print of machined components. The work was conducted using turning experiments. The study also discussed boundaries and interaction of machining economics and environmental impact of reduction in energy consumption. Different machining strategies were investigated to analyse energy consumption of a machine tool [11]. Different components of a machine tool were treated as variables. All numerical results were verified experimentally. The study was useful to evaluate different part programs with respect to their energy consumption. Reference [12] shows machining performance of six different cutting fluids. The study was conducted using four vegetable based and two semi-synthetic/ mineral based cutting fluids. Experimentation was designed using Taguchi (L18) mixed level parameter design. The study revealed that sunflower and canola based cutting fluids

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performed better than other available cutting fluids.

This paper presents an experimental study to examine behavior of energy consumption and surface finish under different material removal rates. Energy consumption data was also interpreted in the form of equivalent CO2 emissions with reference to the energy mix of United Arab Emirates. Graphical representations of energy consumption and surface finish were generated for better understanding and visualization. These plots can be a useful tool for environmental sustainability assessment.

II. Experimental Setup

Machining experiments were conducted on a CNC turning center under dry cutting environment. Mitutoyo Roughness Tester SJ 201P was utilized for the measurement of surface finish. Each surface roughness reading was repeated four times in order to minimize experimental error and then average values were reported in the study. Power logger was employed to monitor power and energy consumption. Power sight manager was used as data acquisition software. Fig. 1 shows the schematic representation of experimental setup.

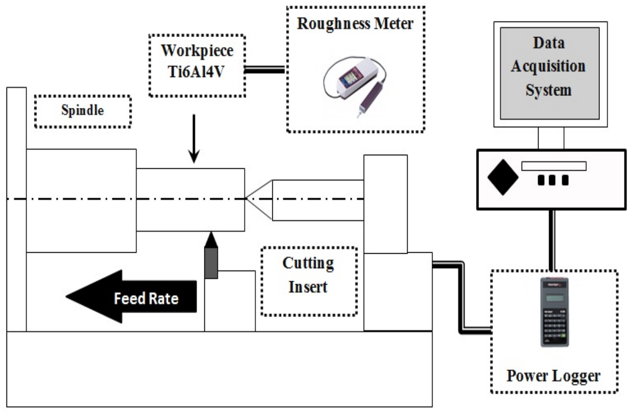

Fig. 1 Schematic representation of experimental setup

For any metal cutting operation cutting tool material, workpiece material, cutting conditions (depth of cut, cutting speed and feed rate) and cutting environment plays an important role. Previous studies [12]-[14] showed that for any machine tool energy consumption is manly dependent on material removal rate of process. The present study used Titanium alloy Ti 6Al 4V as a workpiece material. Titanium alloys are nominated as difficult to cut materials due to their low thermal conductivity and high heat capacity. Cutting environment plays significant role towards the machinability of titanium alloys. To analyse and understand the core mechanisms dry and flood cutting environments were used for this study. The composition of Ti6Al4V is provided in Table I. Experimentation was performed using uncoated carbide cutting inserts. The specifications for inserts are reported in Table I.

TABLE I
Cutting Conditions

Machining Parameters	
Workpiece material	Ti6Al4V C: < 0.08%, Al: 5.5 – 6.75%, Fe:<0.4%, V:3.5-4.5%, H: 0.05%, N:0.01%, O<0.2%
Insert type	Uncoated carbide TCMT 16 T3 04-KM H13A
Depth of cut	0.8 mm
Cutting Speed	30 – 60 – 90 (m/min)
Feed	0.1 – 0.2– 0.3 – 0.4 – 0.5 (mm/ rev)
Machining length	125 mm
Machining Environment	Dry - Flood

The study was conducted using three different levels of cutting speeds and five levels of feed. Dry and flood cutting environment was utilized during the study. However depth of cut and machining length were kept constant.

III. Results and Discussion

Power consumed during each machining test was recorded and analyzed using power sight manager software. After filtering the power signal energy consumption (KWh) was calculated. Fig. 2 shows a sample calculation for power and energy consumed during turning of Ti6Al4V. A sample plot for energy consumption is shown in Fig. 2 Energy consumed during the process was approximately 0.036 kWh.

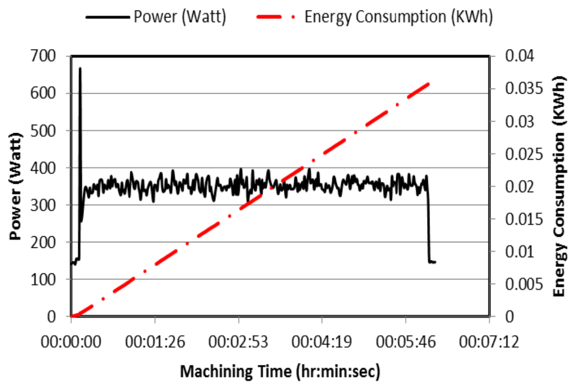

Fig. 2 Power and energy consumption, Material removal rate = 240 mm3/ sec, Cutting speed = 60 m/min, Feed = 0.3 mm / rev, Depth of cut = 0.8 mm, Dry environment

A. Dry Environment

To set the reference base line, experimentation was first performed under dry cutting environment. Fig. 3 shows plots for energy consumption and surface finish for different material removal rates calculated at constant speed of 30 m/ min and different feed levels. Fig. 3 represents that energy consumption decreased with increase in material removal rate.

Trends line was fitted using second order polynomial equations.

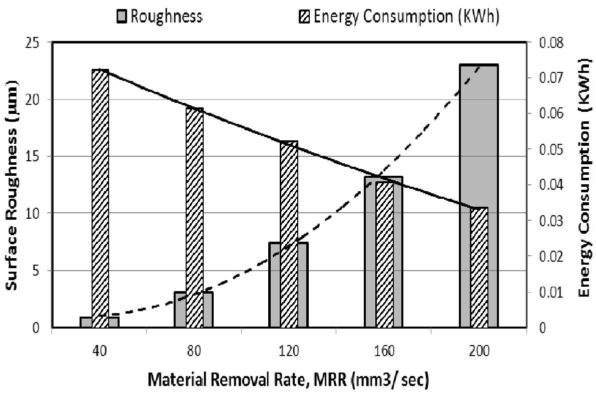

Fig. 3 Energy consumption and surface finish at different material removal rates, Vc= 30 m/ min, f = 0.1 – 0.5 mm/ rev

However as found in literature [15]–[16], surface roughness increased with increase in material removal rate. Increase is surface roughness was observed due to increase in the feed rate. The intersection point shows the best optimized value of surface roughness with respect to the energy consumption.

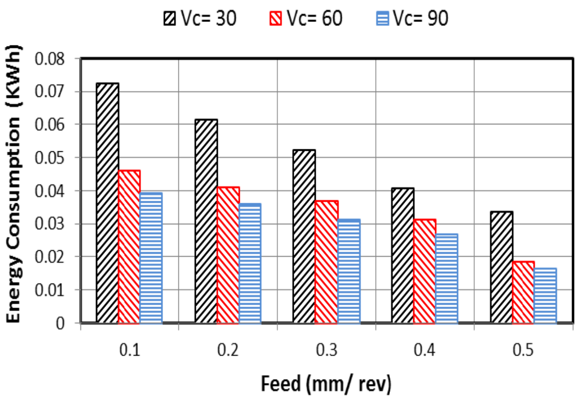

Fig. 4 Energy consumption

Fig. 4 shows behavior of energy consumption at all feed levels using different cutting speeds. It is observed that energy consumption is more sensitive to feed rate then cutting speed. However increase in both feed rate and cutting speed results in lower energy consumption. Fig. 5 represents plots for energy consumption and surface finish for different material removal rates calculated at constant speed of 60 m/ min and different feed levels.

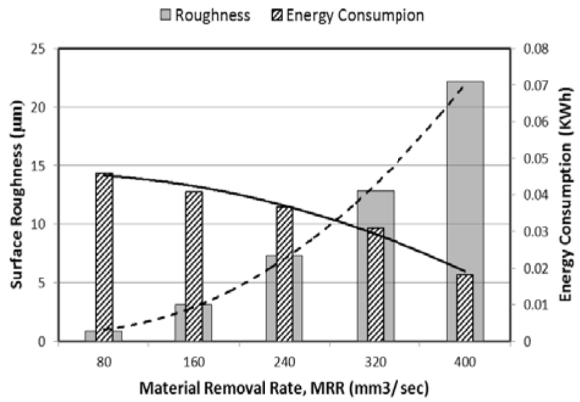

Fig. 5 Energy consumption and surface finish at different material removal rates, Vc= 60 m/ min, f = 0.1 – 0.5 mm/ rev

Similar trends for energy consumption and surface roughness were observed. With increase in cutting speed energy consumption decreased whereas minor difference in surface roughness was observed when compared to the cutting speed of 30 m/min. Point of intersection between both curves was lowered with increase in cutting speed. It points out that increase in cutting speed lowers both energy consumption and surface roughness but literature criticize high cutting speeds with high amount of heat generated.

Fig. 6 represents plots for energy consumption and surface finish for different material removal rates calculated at constant speed of 90 m/ min and different feed levels. At higher cutting speed best surface finish was obtained at expense of less energy consumed was known from the literature. The major limitation of using high cutting speed is high amount of heat generation that directly affects cutting tool life. As titanium alloys show poor heat dissipation due to their low thermal conductivity, presence of high amount of heat in cutting zone results in severe and rapid tool wear.

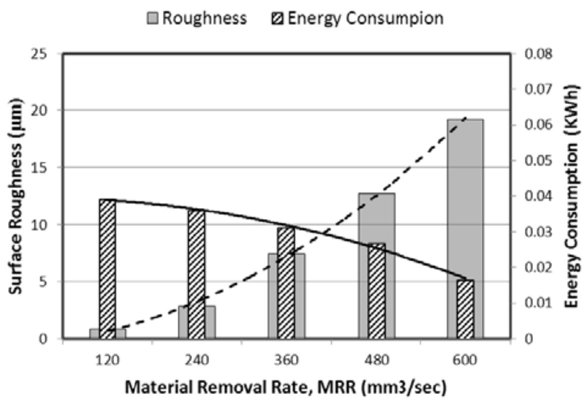

Fig. 6 Energy consumption and surface finish at different material removal rates, Vc= 90 m/ min, f = 0.1 – 0.5 mm/ rev

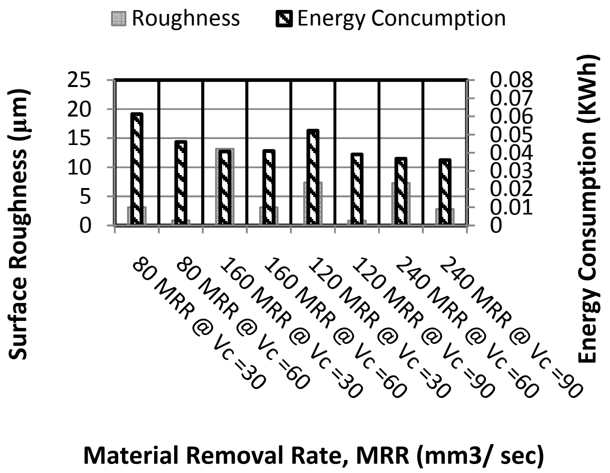

Fig. 7 Energy consumption and surface finish at similar material removal rates using different cutting speeds of 30, 60 and 90 m/ min

Fig. 7 shows that material removal rate of 80 mm3/ sec was maintained using two different cutting speeds of 30 and 60 m/ min. In the first case cutting speed of 30 m/ min was used with feed of 0.2 mm/ rev to attain 80 mm3/ sec. However for second reading cutting speed of 60 m/min was used with feed of 0.1 mm/ rev to reach 80 mm3/ sec. It was observed that for material removal rate of 80 mm3/ sec less energy consumption and better surface roughness was obtained for cutting speed of 60 m/ min. Similar behavior was observed for material removal rates of 160, 120 and 240 m/ min. This means that to minimize energy consumption and achieve good surface finish higher removal rates should be utilized by increasing the cutting speed. But cutting speed is directly linked with cutting temperature in the cutting zone that can affect tool life and associated wear mechanism significantly [17].

B. Flood Environment

In addition to dry cutting conditions the study was repeated for similar cutting conditions under emulsion based flood cooling environment.

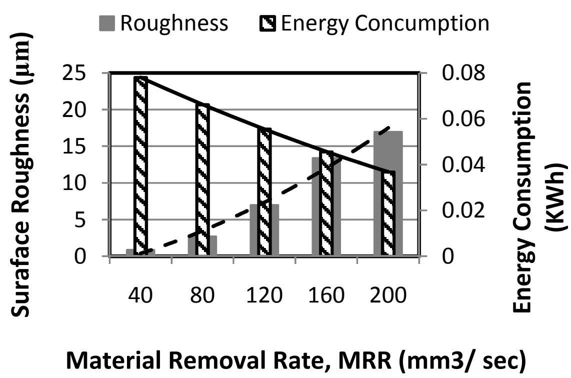

Fig. 8 Energy consumption and surface finish at different material removal rates, Vc= 30 m/ min, f = 0.1 – 0.5 mm/ rev

Fig. 8 shows plots for energy consumption and surface finish for different material removal rates calculated at constant speed of 30 m/ min and different feed levels. Fig. 8 shows that energy consumption decreased with increase in material removal rate. Optimal point at the intersection of both curves was slightly shifted towards higher material removal rate when compared with dry cutting.

Fig. 9 represents plots for energy consumption and surface finish for different material removal rates calculated at constant speed of 60 m/ min and different feed levels. Both curves and their intersection followed the similar trend as in Fig. 8.

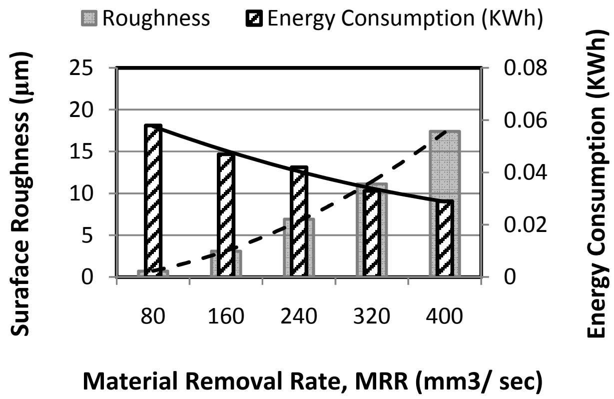

Fig. 9 Energy consumption and surface finish at different material removal rates, Vc= 60 m/ min, f = 0.1 – 0.5 mm/ rev

Fig. 10 represents plots for energy consumption and surface finish for different material removal rates calculated at constant speed of 90 m/ min and different feed levels. Similarly like the previous Fig. 9 optimal point was shifted further downward in Fig. 10.

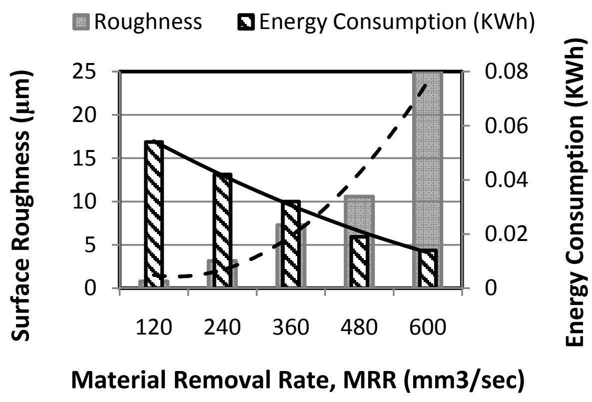

Fig. 10 Energy consumption and surface finish at different material removal rates, Vc= 90 m/ min, f = 0.1 – 0.5 mm/ rev

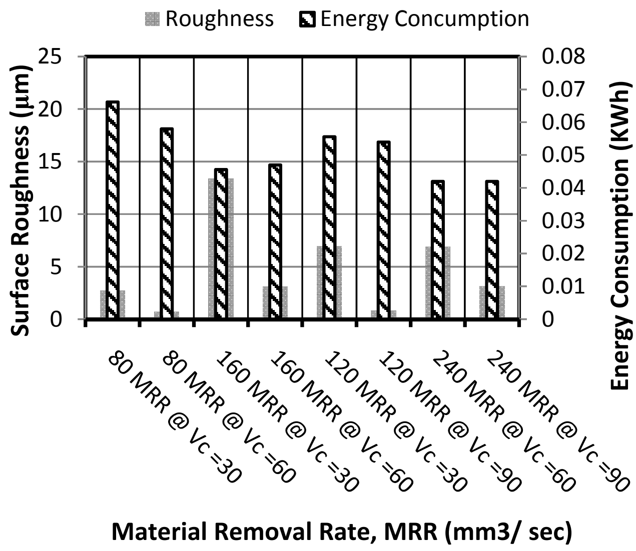

Fig. 11 Energy consumption and surface finish at similar material removal rates using different cutting speeds of 30, 60 and 90 m/ min

Fig. 11 shows the similar behavior as explained previously in Fig. 7 for dry cutting environment. Higher material removal rates maintained by using higher cutting speeds resulted in better surface finish and less energy consumptions.

IV. Conclusion

The conclusions drawn from the dry and wet machining of titanium alloy Ti – 6Al- 4V by using uncoated carbide inserts are as follows:

- It was observed in the study that increase in material removal rate reduces energy consumption significantly. It is due to the fact that machining time plays dominant role towards consumption of energy.
- Increase in material removal rate results in higher cutting load at the contact area in cutting tool and workpiece. However this increase in cutting load does not significantly increases energy consumed during cutting. It was observed that energy consumption for cutting process is highly sensitive to feed rate as compared to the cutting speed.
- It was also observed that surface roughness and energy consumption decreased by increasing cutting speed and material removal rate. Reduction in energy consumption with increase in feed rate is logical because high feed rate results in faster machining and less processing time. It is found in agreement with literature [18] – [20] that cutting speed of a machining process is directly linked with cutting force. Higher cutting speed generates low cutting forces which results in less energy consumption. However limitation of using higher cutting speed is that it generates high amount of heat during cutting process. High cutting temperature results in poor tool life and accelerated tool wear mechanisms.
- Graphical plots of energy consumption and surface roughness intersect each other at certain location pointing out at the optimized value. These curves can be utilized to predict the amount of energy required for achieving desired surface roughness at specific material removal rate.
- It was observed that optimized value at intersection point of two curves shifted below by an increase in material removal rate.

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