JAFFERY, S.H.I., YOUNAS, M., KHAN, M. and ALI, L. 2020. Energy consumption analysis in turning Ti-6Al-4V alloy. In *Proceedings of the 11th IEEE (Institute of Electrical and Electronics Engineers) International conference on mechanical and intelligent manufacturing technologies 2020 (ICMIMT 2020), 20-22 January 2020, Cape Town, South Africa.* Piscataway: IEEE [online], pages 18-21. Available from: https://doi.org/10.1109/ICMIMT49010.2020.9041194

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JAFFERY, S.H.I., YOUNAS, M., KHAN, M. and ALI, L.

2020

Energy Consumption Analysis in Turning Ti-6Al-4V alloy

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***Abstract*—One of the major concerns in manufacturing industries include the amount of energy consumed during machining processes. Therefore, the study of the specific energy during machining must be analyzed in relation to the process parameters (feed rate, speed and depth of cut). This work demonstrates the analysis of specific cutting energy (SCE) and cutting power during titanium alloys machining under dry conditions. Turning experiments with uncoated carbide inserts were performed applying Taguchi Design of Experiments technique and analyzed the effect of speed, feed and depth of cut during turning Ti-6Al-4V titanium alloys. ANOVA was done to find out the influence of the machining parameters on energy consumption. The outcome of this analysis indicates that feed rate is the highly dominant factor responsible for the SCE of a machine tool, whereas, cutting speed was found as the influential factor affecting the power during the machining process. The environmental and economic performance for a machining process may be significantly improved by reducing energy consumption using appropriate machining conditions.**

Keywords-cutting power, specific cutting energy (SCE), machining, Ti-6Al-4V

I. Introduction

The increase in energy costs is mainly associated with the increasing demands of energy consumed in the manufacturing industry [1]. As enormous energy is consumed by the machine tools in machining, thus, the performance of the processes and systems can significantly improve by minimizing the energy consumed in a process.

A number of studies have been reported for energy minimization during machining different nature of materials [2]-[7]. These studies mainly include optimization of the machining processes or energy modelling of the machine tool. Gutowski [8] reported a model for predicting the energy utilization in the manufacturing process. It was thus confirmed that the amount of energy used by a machine tool has a direct relation with the material removal rate. Li and Kara [4] reported that energy used by a machine tool involves the energy consumed at the tool-work interaction as well as by the various components used to run the machine. The model proposed provides an estimation of the electrical energy consumed under different machining conditions. Balogun et al. [2] introduced an upgraded model for electrical energy consumption based on the operating state of the machine. Machining operation is classified into well-known states; the basic state and the cutting state. The machine is set ready for operation in the basic state with all its components in ready mode, whereas, in cutting state the machine requires electrical energy to cut the material as well as overcome the friction.

Machining conditions also affect the energy need of a process thus the associated ecological and financial aspect of the manufacturing activity [6]. Based on the minimum energy requirement a novel method for the selection of cutting parameters in turning of 7075 Al alloy was presented [9]. Optimized cutting parameters (feed, speed, and depth of cut) were identified using the composite desirability values of the responses and analysis of variance performed to determine the contribution of the parameters. Few studies [10, 11] related to turning Al 6061 T6 alloys at high speed reported the optimal cutting conditions responsible for the optimization of multiple responses like surface roughness, material removal rate and specific cutting energy (SCE). The proposed method reduced the SCE by 5 % and an increase in MRR by 33%. The research also highlighted the use of process maps as a guide for machinist and process planners to benefit during the machining process. Key studies [12-14] about energy analysis in machining have identified the importance of the appropriate choice of feed, speed, and depth of cut to ensure energy-efficient processes.

The literature summarized above tells that cutting conditions in machining has a vital role in producing variation in the energy consumption of the machine tool. This research work also focuses on the analyses of cutting power along with SCE consumption concerning dry turning of titanium alloys. Taguchi L9 array was employed for turning experiments as presented in Table 1. These cutting conditions were carefully chosen based on the tool manufacturer's recommendation and literature [8]. ANOVA was done using MINITAB Software to identify the important cutting parameters that affect energy consumption in cutting titanium alloys.

II. Experimental Features

Turning tests were done on a CNC turning facility (ML-300) for cutting conditions shown in Table 1 under dry environments. Figure 1 illustrates the experimentation method and Table 2 gives the elements present in the composition of the alloy material used in this research. Three repeats of the experiments were performed with a fresh uncoated carbide H13 insert used for each machining run.

TABLE I. DESIGN OF EXPERIMENT USING L9 ORTHOGONAL ARRAY

Exp #	f (mm/rev)	V (m/min)	d (mm)
1	0.12	50	1
2	0.12	100	1.5
3	0.12	150	2
4	0.16	50	1.5
5	0.16	100	2
6	0.16	150	1
7	0.2	50	2
8	0.2	100	1
9	0.2	150	1.5

TABLE II. COMPOSITION BY WEIGHT PERCENTAGE OF TI-6AL-4V ALLOY

Ti	V	Al	Fe	Cu	Cr
89.3	4.3	5.8	0.16	0.0041	0.0025

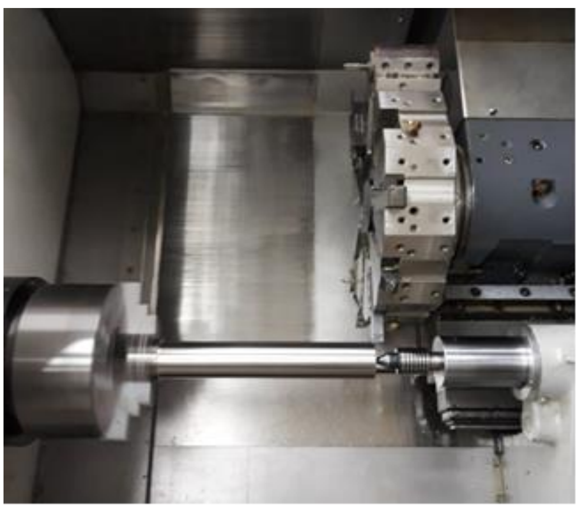

Figure 1. Experimental setup for turning of Ti-6Al-4V

The specific cutting power was quantified using a power meter (Yokogawa CW 240) attached to the central supply of the CNC system. First, the air cut energy (P air cut, machine in ready mode)) was recorded for the machine tool followed by the actual cut energy (P actual, machine involved in cutting). Fig 2 illustrates the measurement of the SCE during the machining process. The methodology is also used by previous researchers [4, 12] for the measurement of SCE.

Eq. (1). is used to estimate the (P_{cut}) which stands for the power used in eliminating the workpiece material only.

$$P_{cut} = P_{actual} - P_{air} \quad (1)$$

Equation (2). Was used to measure the SCE (J/mm^3) that gives the amount of energy expended for removing material (unit volume) in a machining cycle.

$$SCE = P\ cut / MRR\ (v\ f\ d) \quad (2)$$

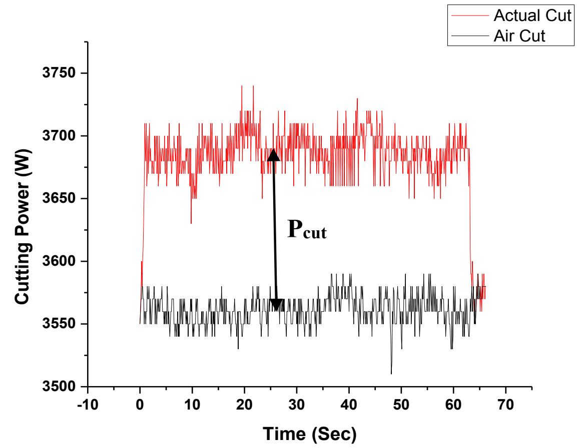

Figure 2. Measurement of the cutting power (P cut) of the machine.

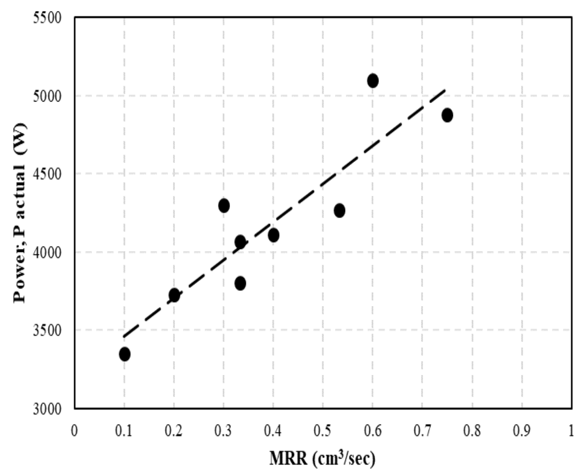

Figure 3. Cutting power Vs. MRR.

TABLE III. ANALYSES OF VARIANCE USED FOR POWER

Source	DF	SS	Mean SS	F	% CR
f	2	91022	45511	1.14	23.46%
V	2	1722689	861344	21.53	45.11%
d	2	517956	258978	6.47	19.16%
Error	2	80022	40011		13.23%
Total	8				100%

III. RESULTS AND DISCUSSIONS

A. Assessment of Power Used in Cutting

The machine cutting power increases as the MRR increases, shown in Figure 3. Thus, increasing feed rate, cutting speed or depth of cut, the energy demands for a process increases. Table 3 lists the ANOVA findings that conclude that cutting speed contributes the most towards an increase in cutting power. The main effect plot in Figure 4 also confirms rise in cutting power as the machine requires high power when the cutting speed and feed rate are set at high level. Different regions of the power consumed are highlighted in the contour map in Figure 5. It illustrates that with an increase in the cutting velocity the power band varies from low to high.

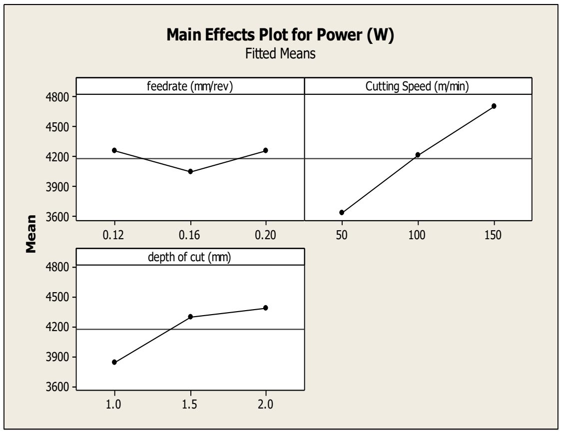

Figure 4. Main effect plot for power measured during machining

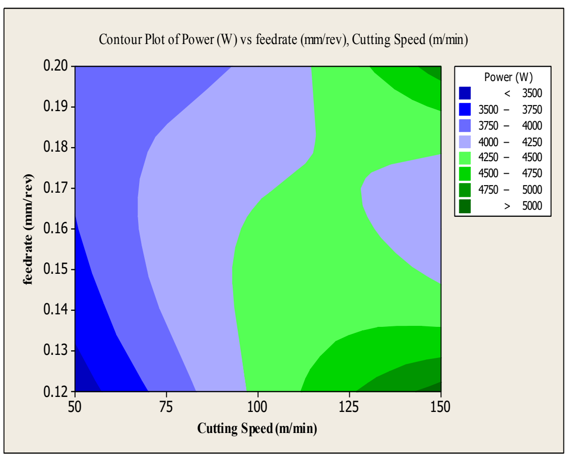

Figure 5. Contour map showing regions of power consumed

Analysis of specific cutting energy

The SCE consumed in a machining process is the energy spent on the cutting of a unit volume of raw material. ANOVA results for SCE show that feed rate and cutting velocity are the enormously affecting parameters with contribution ratios of 42% and 36 % respectively, as shown in Table 4. Thus, machining must be carried out at cutting conditions that result in minimum SCE values.

TABLE VI. ANALYSES OF VARIANCE USED FOR SCE

Source	DF	SS	Mean SS	F	% CR
f	2	0.059428	0.029714	18.05	42%
V	2	0.006902	0.003451	2.1	36%
d	2	0.0216	0.0108	6.56	12.5%
Error	2	0.003292	0.001646		8.5 %
Total	8				100%

Figure 6. Shows a decreasing trend for SCE with an increase in the feed rate and depth of cut, however, cutting speed first show a rapid increase in SCE at the start, up to the speed of 100 m/min and then increases gradually by increasing the cutting velocity [15]. The rise of SCE can be credited to rapid tool wear when machining at the higher cutting speed [16, 17], as these alloys are well known for their poor machinability as soon as the cutting speed approaches the higher speed conditions [18, 19] (above 100 m/min).

Furthermore, a study was also undertaken to see the effect of intermittent cutting operation compared to continuous cutting on the tool flank wear and SCE. The result indicated that the flank wear grows almost in a similar fashion whether cutting is performed continuously or in steps for the same cutting length. Thus, the effect on the SCE remained almost identical for continuous as well as intermittent cutting. The comparison is given in Table 5 where a turning experiment produced the same result for both wear rate and SCE. This experiment was performed such that first a straight cut of 100 mm was made, and the SCE and wear rate of the cycle was evaluated followed by performing the same cutting operation in four steps of equal cutting lengths (25mm) and the measurements for wear rate and SCE carried out.

TABLE V. INTERMITTENT VS. CONTINUOUS CUTTING

Speed (m/min)	Feed (mm/rev)	Length of cut (mm)	Wear rate	SCE (j/mm^3)
100	0.16	100	-5.91	1.13
100	0.16	25	-5.90	1.12
100	0.16	50	-5.92	1.13
100	0.16	75	-5.91	1.11
100	0.16	100	-5.92	1.12

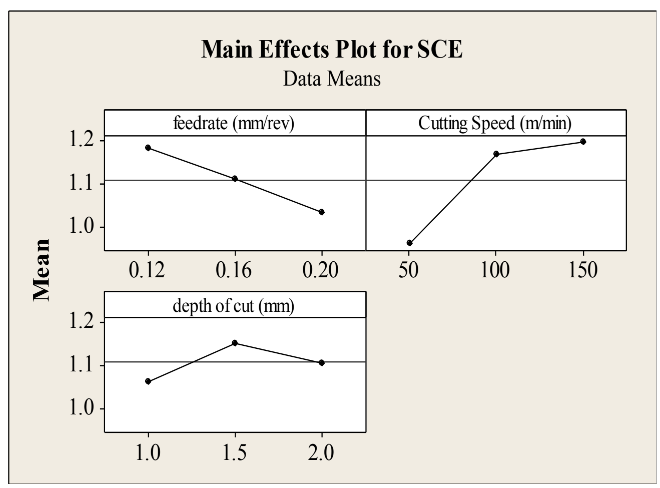

Figure 6. Main effects plot for specific cutting energy (SCE)

IV. CONCLUSION

This study presents the experimental analyses of turning of Ti-6Al-4V using uncoated H13 inserts employing Taguchi Design of Experiment technique. Following are some of the points made based on the observation of the SCE and power consumption during machining that will also contribute towards the goals of achieving sustainable production.

- The cutting condition used for machining greatly affects the energy demands of the process and thus results in variation in the SCE.
- From ANOVA analysis, cutting speed was the most major factor responsible for machine power.
- The highest significant element that contributes towards high SCE during machining process was the feed rate.
- Maps for energy consumption can also be used to indicate regions where machine requires high power for operation
- Careful selection of the machining condition can result in the sustainable machining of challenging materials like titanium alloys.
- To achieve higher productivity with less SCE consumed, feed rate and depth must be kept high within the limits of the tool manufacturer recommendation.

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