Investigating the Energy Efficiency and Surface Integrity when Machining Titanium Alloys

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Abstract

Sustainable manufacturing strategies will need to address the resource efficiency and surface quality challenges in cutting processes. This paper aims to provide a systematic methodology for modelling the input and outputs of a turning process to find the best balance between production rate and input cost, while improving or adhering to the quality standards. Ti6Al4V were cut under flood cooling using carbide cutting tools and a Taguchi design of experiments was used with ANOVA. Surface integrity and energy use were measured and analysed for selected cutting parameters. The experimental results highlighted the importance of selecting optimum cutting parameters and machining strategy. More energy was consumed at lower cutting parameters, whilst higher feed rates resulted in less energy consumption, but lower surface finish quality. These results will also assist to define the boundary conditions for various input parameters.

Keywords

Ti6Al4V, energy efficiency, surface integrity

1 INTRODUCTION

Industry is a major contributor to a nation's economic development and growth. In fulfilling this mandate manufacturing industries consume significant energy, often inefficiently, and as such are a major contributor of CO_2 emissions. There seem to be an inherent conflict between industrial energy efficiency and economic growth in rapidly industrialising economies. As such energy efficiency of production systems, especially machining operations, is becoming increasingly relevant and is a key element of consideration in most machining manufacturing operations [1]. Titanium alloys are gaining significant usage in aircraft structural and engine components, requiring excellent surface finish as the surface integrity of the components is critical due to the safety, reliability and sustainability concerns [8]. Ti6Al4V being a high strength material poses surface quality and energy consumption difficulties during machining.

Surface integrity is one of the most relevant parameters used for evaluating the quality of finish machined components especially when dealing with features made with the intention of attaining the highest level of reliability such as those used in the aircraft industry [2, 3].

Good surface quality is desirable for the proper functioning of most machined parts as well as meeting one of the most specific customer requirements. Surface Integrity (SI), therefore, refers to a broad range of surface quality characteristics encompassing the topography, mechanical, chemical and metallurgical state of a machined surface as well as its functional performance [4, 5, 6 and [7]. Most titanium aircraft structural components are finish-machined [8]. Surface roughness is the most used quality index for assessing the desirability of the machined parts in machining engineering [9]. Machining for the purpose of achieving the desirable surface integrity standard is energy intensive especially when dealing with high strength alloys such as Ti6Al4V. The main causes of surface alterations during material removal processes through machining are high thermal gradients, mechanical working in and beyond the limit of plastic deformation and chemical reactions and subsequent absorptions into the machined nascent surfaces [10, 11, 12 and 13].

The growing demand, and continued rise in the value of energy, serve to emphasise the importance of enhancing the energy and material-related efficiency of the Ti6Al4V alloy machining. Efficient energy management forms an integral part towards sustainable production systems [14] [15]. Optimising machining processes will also significantly help to address the sustainable manufacturing requirements set by various governing bodies. Efficient energy management also helps to enhance component surface quality acceptability, cut the operational costs of manufactured products and to reduce the ecological impact [16].

Energy efficiency during a machining operation gives prominence to the relationship between the amounts of energy resources deployed for a task as compared to the output achieved from the activity, [17]. It is important at this stage to establish the cutting parameters which will lead to the production of fit for purpose components with appropriate surface quality at the optimum level of energy consumption. Yet not many publications are available about this aspect. Optimising and predicting the energy usage in advance of the machining process would be important in enhancing cost effective machining. Reducing energy consumption through using optimum machining conditions contributes to sustainable manufacturing and this involves minimising material energy resources, [18].

Thus, the experimental study sought to establish the critical machining parameters (cutting speed and feed rate) required to minimising energy use and surface roughness during the turning of Ti6Al4V.

The model was used to establish optimum operating parameters. The energy consumed during a machining operation was segmented into different functional activities as an improvement on the previous research findings [19, 20, 21 and 22]. The machining energy refers to the energy required to remove the work-piece material under different process conditions. Broadly the required power for a given machine tool is composed of the constant and the variable components [19, 23]. The constant power component relate to the power assigned to the machine tool accessories such as the computer, pumps, fans and lighting. This power is not influenced by the machining parameter settings as the variable power is. Variable power depends on the process parameters [23].

The main purpose of this research study, therefore, is to experimentally investigate the interaction of the machining parameters (cutting speed and feed rate) for the purpose of systematically achieving optimal quality performance with regard to surface integrity of the work piece and energy consumption during the machining process. This is anticipated to greatly enhance machining processes unlike the current scenario whereby generally the desirable cutting parameters are determined based on the machine operator's experience or by using handbooks that does not address sustainability. Furthermore ANOVA is done to see which process parameters are statistically significant. Thus, the ultimate goal is to optimise the machining process with regards to energy efficiency for the machining of the Ti6Al4V.

2 EXPERIMENTAL SETUP AND DESIGN

Turning experiments were performed on an Efamatic CNC lathe (model: RT-20 S, Max. spindle speed 6000 RPM). The sample material was Ti6Al4V (Grade 5) titanium alloy supplied in annealed condition at 36 HRC as a solid round bar (Ø=75.4 mm x 180 mm long). Figure 1 illustrates the various levels at which energy management can be performed in a manufacturing system.

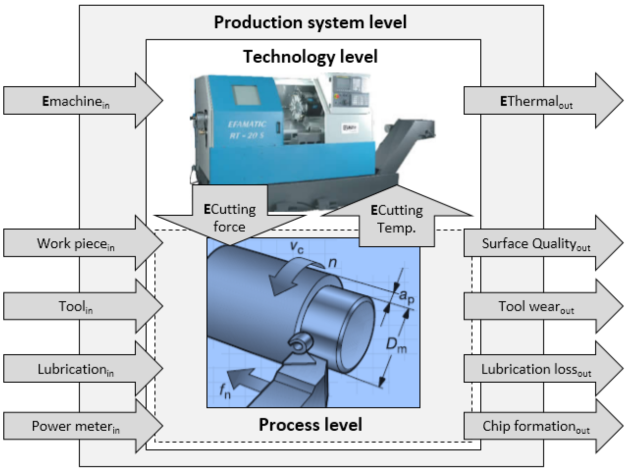


Figure 1 - The input and expected output at different levels of a machining operation that effects energy management [1, 14]

It also illustrates the input and output levels. The focus of this research study was the energy transformation stage at the machining process level. Electrical energy is supplied to the CNC lathe and is converted into mechanical energy (kinetic) which is used to separate the material during cutting at the different cutting speeds and feeds. Some of the energy is used to power the machine functional unit modules (as constant power) as well as to supplying lubrication and cooling at the cutting tool work piece interface. At process level during cutting the kinetic energy is transformed into various energy outputs. The experimental set-up is shown in Figure 2.

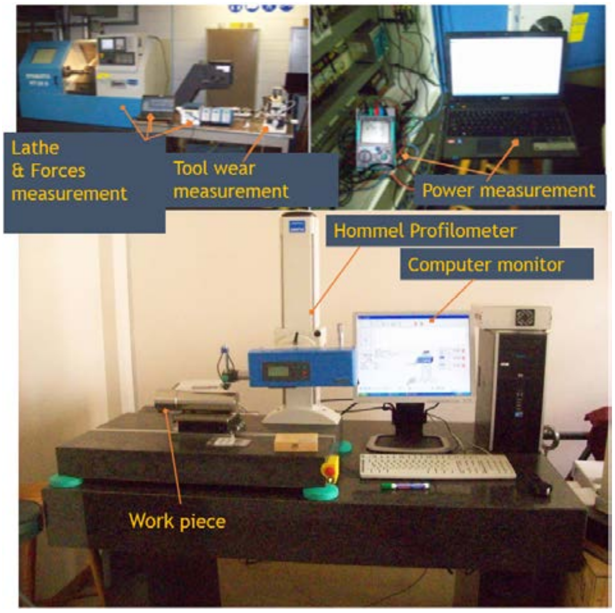


Figure 2 - Experimental setup of the machining experiment, the energy measurement system and the surface roughness measurement facility

A solid carbide tool (CNXMX 12 04 A2-SM, rhombic insert 80°) in a Sandvik tool holder (DCLNL 2525 M12) was used for turning Ti6Al4V with conventional flood cooling. The cutting conditions were varied during the experimental process with cutting speed, v_c= 150- 250 m/min in steps of 50 m/min and f_n= 0.1-0.3 mm/rev in steps of 0.1 mm/rev. The depth of cut was kept constant at 0.5 mm. To conform with the ISO Standard 3685-1977 (E) for single point turning tools a wear criterion of V_B=300 µm [24] was used for all the machining experiments. Surface roughness (Ra) was measured using a Jenoptik Hommel Etamic T1000 profilometer connected to a computer with Hommel tester Turbo-Datawave software. Power measurements were taken using a KYORITSU ELECTRICAL MODEL 6300 3 phase digital power meter with the KEW POWER PLUS2 power signal recordings captured and read off an Acer Aspire 5551 Laptop running on Windows 7.

Taguchi L9 Orthogonal Array were used to plan the experiment matrix. This provides a set of well-balanced minimum experiments number which serves as an objective function for optimisation, i.e. the entire parameter space can be studied with a small number of experiments only. The levels of independent test parameters and the coding identification, as used on the experiments, are shown in Table 1.

			Coding of Factor Levels		
			Low	Centre	High
			-1	0	1
Cutting speed	v_c (X_1)	m/min	150	200	250
Feed rate	f_n (X_2)	mm/rev	0.1	0.2	0.3

Table 1 - Levels of independent test parameters and the coding identification

Significant process parameters are determined by using the statistical approach of Analysis of Variance (ANOVA) at the confidence level of 95%. This implies that an input parameter is considered to have significant influence on the response factor if its P value on the ANOVA is equal or less than 0.05. The experimental results are then transformed into the signal-to-noise (S/N) ratio in order to measure the quality characteristics deviating from the desired values. The objective function values are converted to S/N ratio in order to determine the performance characteristics of the levels of control factors against these factors. The three categories of the quality characteristics in the S/N ratio analysis are:

Smaller is better characteristic which is computed from the equation (1);

$$SN_S = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right] \tag{1}$$

nominal is best characteristic which is computed from equation (2);

$$SN_T = 10\ log\left[\frac{\bar{y}^2}{s^2}\right] \tag{2}$$

And larger is better which is computed from equation (3);

$$SN_B = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right] \tag{3}$$

Regardless of the category of the quality characteristic the optimum operating conditions are obtained by selecting the parameters that gives the maximum values of S/N ratio. This is done by using the main effects plots of the S/N ratios [25, 26, 27]. Joint consideration of the S/N and the ANOVA provides the prediction platform for the optimum combination of operating parameters.

3 RESULTS AND DISCUSSION

ANOVA results show that feed rate has a significant influence on surface finish. The P-value for cutting speed is insignificant at 0.074 which is above 0.05 the cut-off point of significance at 95% confidence interval. Thus variation of the feed rate will have significant effect on the quality of the surface finish on the work piece.

The experimental matrix and the results summary of the surface roughness and energy consumption are detailed on Table 2.

Experimental Plan		Response Parameters	
		Surface Roughness R_a [Microns]	Machining Energy [kJ]
150	0.1	0.200	332.595
150	0.2	0.633	175.001
150	0.3	1.167	122.113
200	0.1	0.267	235.356
200	0.2	0.867	132.912
200	0.3	1.467	96.020
250	0.1	0.233	190.650
250	0.2	0.767	106.025
250	0.3	1.600	59.193

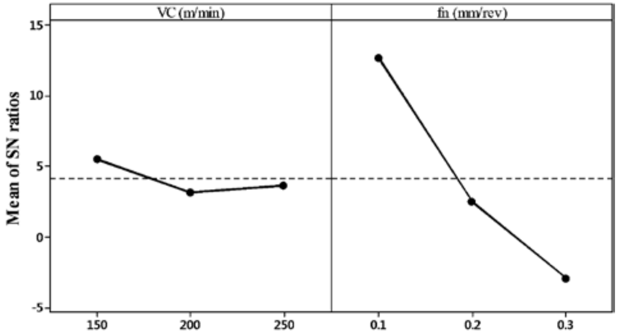
Table 2 - Experimental Matrix and Results Summary

The Regression model depicting the mathematical relationship between cutting speed, feed rate and surface roughness is shown in equation (4).

Surface $R_a = -0.778 + 0.002000\, v_c + 5.889\, f_n$ (4)

The coefficient of determination (r^2 value) of 96.53% depicts a good fit of the regression model to the underlining data.

Optimisation of the machining parameters for surface roughness is achieved by performing a Taguchi analysis of surface roughness considering the main effects plots of the signal-to-noise ratios. Figure 3 as well show that feed rate has prominent influence on the response parameter. Feed rate has the highest positive value on the main effects plots and it is ranked number one in terms of its influence on the surface roughness as shown on the response Tables extracted. The ranking shows that feed rate has the more pronounced effect on the surface roughness.



Signal-to-noise: Smaller is better

Figure 3 - Main Effects Plot for S/N Ratio on Data Means of Surface Roughness (Ra)

In terms of the statistical procedure of Signal-to-Noise assessment, the S/N response with the highest positive value presents the most optimum operating point. Noise factors cannot be controlled during processing, but during the planning [28]. Higher values of S/N ratio pin point control factor settings that minimise the effects of the noise factors. Thus accordingly the best optimal surface roughness of 0.2 microns is achievable when the machine parameters setting are at cutting speed of 150 m/min and feed rate set at 0.1 mm/rev. Figure 4 shows that as feed rate increases the surface roughness also increases, but the net cutting energy decreases. This arises due to the fact that as feed rate increases, the material removal rate also increases. Thus time is saved. The same trend is observed with the process total energy (Figure 5) where in as the feed rate increases the process energy required decreases due to the fact that less cutting time will be reduced

Analysis of variance of the material removal rate shows that both cutting speed and feed rate have significant influence on the MRR. It is apparent from the ANOVA that MRR is significantly influenced by both cutting speed and feed rate as their p – values are below the 0.05 value. The response shows that feed rate is ranked number one for influencing the material removal rate.

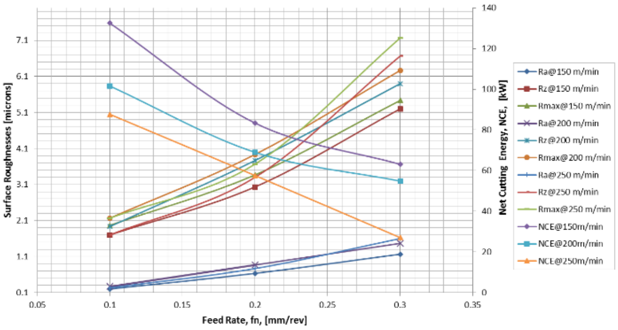


Figure 4 - Feed vs 3 Surface Roughness Types (R_a, R_z, R_{max}) vs Energy

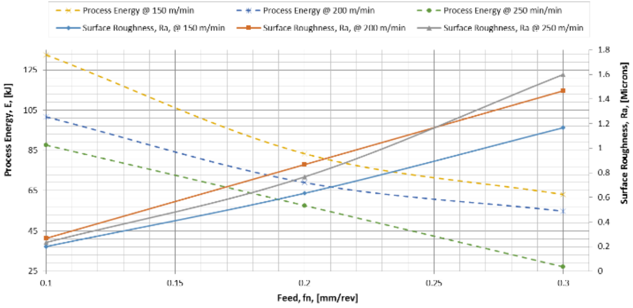
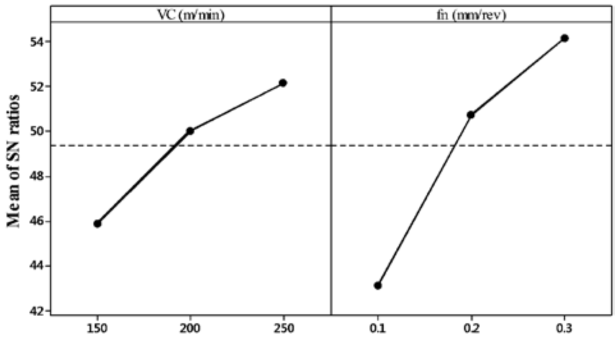


Figure 5 - Feed Rate vs Surface Roughness vs Process Energy

The Regression Equation relating the input factors to the response function (MRR) is given in equation 5:

MRR (mm^3/sec) = $-439.5 + 2.077\, v_c + 1848\, f_n$ (5)

The Optimising process parameters are obtained by considering the main effects plot (Figure 6) and the S/N ratio for energy shown on Table 3. The optimum condition for operating energy is 59.193 kJ achievable when operating at the cutting speed of 250 m/min and feed rate of 0.3 mm/rev.



Signal-to-noise: Larger is better

Figure 6 - Main Effects Plot for S/N Ratio on Data Means: Material Removal Rate (MRR)

Cutting Speed (m/min)	Feed Rate (mm/rev)	Total Energy (kJ)	SNRA2
150	0.1	332.595	-50.438
150	0.2	175.001	-44.861
150	0.3	122.113	-41.735
200	0.1	235.356	-47.435
200	0.2	132.912	-42.471
200	0.3	96.02	-39.647
250	0.1	190.65	-45.605
250	0.2	106.025	-40.508
250	0.3	59.193	-35.445

Table 3 - S/N ratio total energy

The MRR vs Machine total energy vs Efficiency graphical plot shown in Figure 8 shows that process energy use efficiency increases as the material removal rate increases and at the same stage when the machine energy use rate would also be decreasing respectively. This could be attributable to the reduced processing time when the feeding and cutting speeds are set high, ceteris paribus, the rate of material removal tends to be high. Thus the machining process efficiency keeps improving also.

4 CONCLUSION

The research set out to assess the energy efficiency and surface integrity of turning operations of Ti6Al4V titanium alloy. The machining experiments showed that feed rate has a higher significant effect on machined surface finish, but energy efficiency is influenced by both as they affect the rate of material removal. Optimum surface finish of 0.2 microns is achievable when the machine parameters setting are at cutting speed of 150 m/min and feed rate set at 0.1 mm/rev. Energy optimisation is attainable when operating at 250 m/min cutting speed and feed rate of 0.3 mm/rev given that MRR will be maximised. Regression models were deduced for the surface roughness and energy consumption. Thus, there is need to strike a balance between maximising MRR and reducing energy consumption as this provides the most optimum energy use rate during the machining.

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