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Specific cutting energy and surface roughness analysis of dry, wet and cryogenic turning of Ti-6Al-4V

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Abstract

Manufacturing systems are designed to generate productivity which is economical and sustainable. Different manufacturing systems are interpreted in various terms which highlight their manufacturing output. Machining represents a major portion of all manufacturing processes. In the present research a turning manufacturing system is designed, experimented and analyzed to highlight the importance of employment of appropriate input parameters. Use of coolant is taken as an input variable in cutting aerospace alloys (Ti-6Al-4V) to analyze the system in terms of output responses including surface roughness and specific cutting energy. Results showed that surface integrity and specific cutting energy can be significantly improved by using an appropriate cooling system. Cutting speed (contribution ratio 57.33%) and feed rate (contribution ratio 92.37%) proved to be the significant input parameters for specific cutting energy and surface roughness respectively. Confirmatory tests optimized the selected responses maximizing process output.

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Keywords: Aerospace alloy; Ti-6Al-4V; Material removal; Taguchi design of experiment; Sustainability; Productivity;

1. Introduction

Sustainability, productivity and quality are the main research subjects of present manufacturing industries [1]. Manufacturing industries accounts for around 20% of global energy consumption [2]. It has a 90% environmental impact in addition to financial aspect [3].

Nomenclature	
f	Feed Rate (mm/rev)
V	Cutting Speed (m/min)
ME	Machining Environment
SCE	Specific Cutting Energy
Ra	Surface Roughness

Keeping in view the increasing energy requirement and depleting energy resources, the process parameters needs to be carefully selected to make the process efficient and sustainable. Beside optimizing the input parameters, use of an appropriate cooling system warrants due consideration as it constitutes around 20% of overall manufacturing cost [4]. High pressure coolant [5], minimum quantity lubrication [6] and cryogenic cooling [7] are few of the cooling systems currently used world over. Particularly, use of cryogenic cooling is on the rise owing to its exceptionally low temperature [8] and no disposal cost [9].

Machining is a widely used process as 10% of worldwide manufacturing sector energy consumption can be attributed to it [10]. Although machining of aerospace alloys has always been a daunting task because of their hard to cut nature [11], nevertheless they are used extensively in a number of industries [12], [13]. In comparison with aluminium alloys[14], [15], their high corrosion resistance [16] and low weight to strength ratio [17] makes them an ideal choice in a number of applications. Ti-6Al-4V, being the most sought after member of aerospace alloys, constitutes 60% of all titanium requirements [18]. A few undesired properties includes low thermal conductivity and propensity to work harden [19]. These properties are even more detrimental at elevated cutting zone temperature generated at

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high cutting speeds [20]. Past researchers have carried out various studies to have insight into sustainability and productivity of manufacturing systems. Endeavour is to make the process sustainable and productive at the same time. Bagherzadeh and Budak [21] investigated the surface roughness and cutting temperatures of Ti-6Al-4V and Inconel 718 under cryogenic minimum quantity lubrication (CMQL) and cooling conditions. It was concluded that tool life was improved by 30% under CMQL conditions. In another related study [22] dry, wet and cryogenic conditions were compared in terms of cutting forces and hole surface quality under constant cutting parameters during drilling of Inconel 718. Cryogenic conditions produced better results than dry and wet drilling. Mia et al [23] studied specific cutting energy, surface roughness and cutting forces during turning of Ti-6Al-4V under cryogenic conditions. Results showed that cryogenic conditions consumed lesser energy and produced better surface finish. In another work [24], specific cutting energy during turning of Ti-6Al-4V was mapped under cryogenic condition. It was concluded that under optimum machining parameters sustainability of the process was improved up to 16%. Machinability characteristics analysis of dry turning of Ti-6Al-4V alloy was carried out in a separate work [25]. Feed rate was found to the most influential variable affecting surface roughness with contribution ratio of 93.86%. Similarly, surface roughness along with other machining responses of additively manufactured Ti-6Al-4V, fabricated by direct metal laser sintering, was analysed during flood cooling [26]. Multi objective optimization was achieved at 0.1 mm depth of cut, 0.1 mm/rev feed rate and 70 m/min cutting speed.

Current research is undertaken to analyse sustainability and productivity indices of manufacturing system using vital machining variables under different machining environments. Three machining environments including dry, wet and cryogenic condition were employed. Sustainability index of energy consumption is selected whereas productivity is gauged by surface integrity. Machining of aerospace alloys is challenging because of their difficult-to-cut nature. Installation of an appropriate cooling system is necessary to facilitate the post-machining characterization of measured responses and disposal of waste. Novelty of the undertaken work lies in understanding the effects of coolant in combination with machining variables. Chosen inputs are of value to manufacturing setups being representative of manufacturing output.

2. Design of experiment

Turing of Ti-6Al-4V was carried out under dry, wet and cryogenic machining environments (ME) using different feed rate (f) and cutting speed (V) values. Cryogenic setup was installed on CNC turning center (ML 300) as shown in Fig. 1. It includes cryogenic pipe, cryogenic valve and cryogenic nozzles. Two nozzles configuration (rake and flank face) was adopted because of its efficiency [27]. CNC machine internal cooling system was used for wet runs at flow rate 6 L/min. Table 1 displays the different input parameters with their selected levels. F, V and ME (dry, wet, cryogenic) have been observed to have reasonable effects on machining responses[28]. The selected levels and range of these input parameters were based on literature [29], [30], concerned ISO standards [31] and tool manufacturer guidelines [32]. Depth of cut was kept constant because of its insignificant nature as determined in published literature[7]. As per the recommendations of ISO 3685[31], depth of cut was kept as 1 mm for the selected insert (corner radius of 0.4 mm).

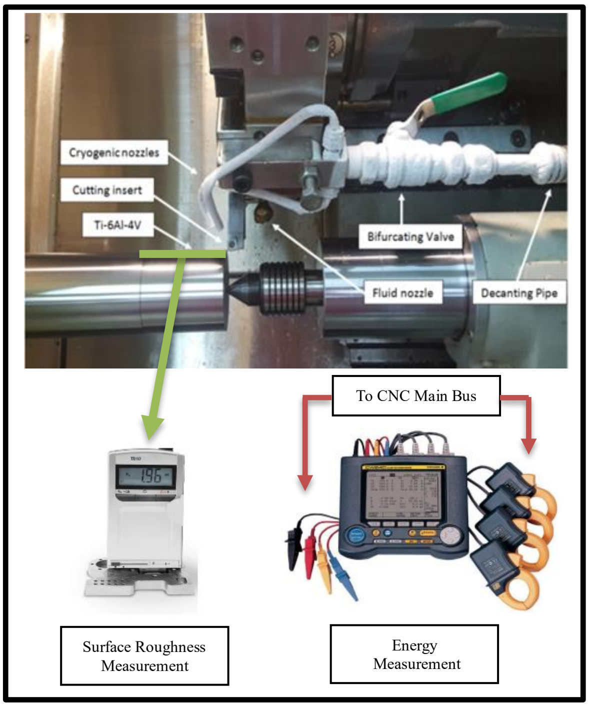

Fig. 1 CNC turning centre with cryogenic setup

Table 1. Taguchi L9 Array

Condition	Input		
	f (mm/rev)	V (m/min)	ME
1	0.10	75	Dry
2	0.10	125	Wet
3	0.10	175	Cryogenic
4	0.15	75	Cryogenic
5	0.15	125	Dry
6	0.15	175	Wet
7	0.20	75	Wet
8	0.20	125	Cryogenic
9	0.20	175	Dry

3. Response measurement

Eq. 1 [33] is used to determine SCE which is the amount of energy required to remove a unit volume of a material.

$$\mathrm{SCE}\ (\mathrm{J/mm^3}) = \frac{\mathrm{P_{cut}(W)}}{\mathrm{MRR(mm^3/s)}} \qquad (1)$$

Two-cycle approach [34] is used to calculate P_{air} and P_{actual} which are then used to calculate P_{cut} using Eq. 2 [24].

$$\mathrm{P_{cut}(W)} = \mathrm{P_{actual}(W)} - \mathrm{P_{air}(W)} \qquad (2)$$

Whereas MRR is the material removal rate determined using Eq. 3 [35].

$$\mathrm{MRR} = \mathrm{f} \times \mathrm{V} \times \mathrm{d} \qquad (3)$$

Ra was measured using piezoelectric roughness tester times TR 110. Each response was measured twice by repeating the same condition.

4. Results

Specific cutting energy (SCE) and surface roughness (Ra) were measured as tabulated in Table 2. Average of the two values was taken for further examination in plotting the main effects and analysis of variance (ANOVA).

Table 2. SCE and Ra results

Condition	SCE (J/mm^3)		Ra (μm)	
	Run 1	Run 2	Run 1	Run 2
1	1.173	1.181	1.51	1.54
2	1.306	1.323	1.18	1.20
3	1.249	1.260	0.97	1.01
4	1.063	1.077	1.70	1.75
5	1.213	1.231	1.77	1.81
6	1.366	1.372	1.53	1.58
7	1.101	1.119	2.85	2.89
8	1.118	1.228	2.45	2.51
9	1.213	1.231	2.58	2.63

4.1 SCE analysis

SCE analysis was carried out as shown by the main effects plotted in Fig. 2. The strong relation between the input parameters and SCE is evident by the sharp gradient of plot lines. SCE seems to have an inverse relationship with feed rate. Lower SCE at higher feed rate can be attributed to greater cutting load and greater material removal rate. Moreover higher shear angles at elevated feed rates [36] also decreases SCE. Also, it has been established in literature [37] that energy consumption elevates with tool wear. So all scenarios where tool wear increases like at higher feed vales, due to higher heat accumulation [38], results in higher energy consumption. Similar to feed rate, higher cutting speeds accelerates tool wear owing to elevated cutting zone temperature, resulting in greater energy consumption. Energy consumption also increases due to work hardening of material at elevated temperature [39] particularly at higher cutting speeds. This trend is in contrast of machining aluminium in which the energy consumption reduces at higher cutting speeds due to the thermal softening effect [40]. Energy consumption varied under different machining environments. Energy consumption under cryogenic media was found to reduce significantly especially in comparison with dry machining due to recessed work hardening at extremely low cutting zone temperature. Cutting fluid which does not have high cooling potential was found to be not as effective. On the contrary the increase in cutting forces [41] resulted in high energy consumption under wet conditions. Examination of ANOVA results given in Table 3 highlights the fact that cutting speed was the most significant member of the input domain with contribution ratio of 57.33%. Machining environment and feed rate had contribution ratios of 19.94% and 13.47% respectively.

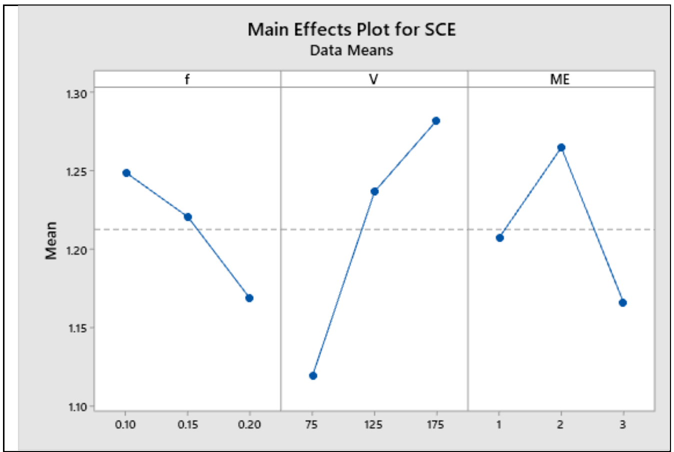

Fig. 2 Main effects plot for SCE

Table 3. Analyses of Variance for SCE

Source	DF	Seq SS	Adj MS	F	% CR
f	2	0.019920	0.019920	8.00	13.47%
V	2	0.084752	0.084752	34.05	57.33%
ME	2	0.029472	0.029472	11.84	19.94%
Error	2	0.013692	0.013692		
Total	8	0.006803			
S = 0.0286957 R-Sq = 97.88% R-Sq(adj) = 91.51%					

4.2 Ra Analysis

Ra showed a comparatively strong relationship with feed rate as shown in Fig. 3. Increasing feed increased Ra due to the enhanced vibrations at the tool work piece interface [42]. Besides Ra also increases owing to high peaks and crest at elevated feed values [43]. On the other hand chatter, which is developed due the built up edge (BUE) at low cutting speeds [44], reduces with increasing cutting speed in turn reduces Ra. Use of cooling condition has improved Ra due to their added lubrication effect [45]. Dry condition with no lubrication effect and with excessive wear results in elevated Ra. ANOVA results showed that feed has the highest contribution ratio (92.37%) among the three input variables. Cutting speed was second in terms of its influence on output with contribution ratio of 4.82%. Machining environment had a contribution ratio of 2.60%.

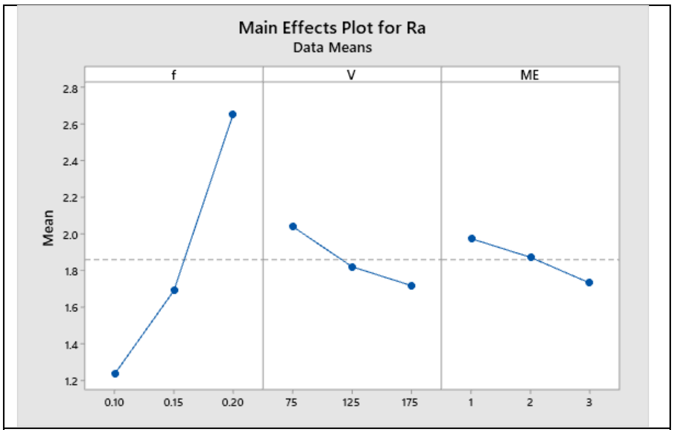

Fig. 3 Main effects plot for Ra

Table 4. Analyses of Variance for Ra

Source	DF	Seq SS	Adj MS	F	% CR
f	2	6.27754	3.13877	2379.31	92.37%
V	2	0.32724	0.16362	124.03	4.82%
ME	2	0.17668	0.08834	66.96	2.60%
Error	2	0.01451	0.00132		
Total	8	0.00591			
S = 0.0378594 R-Sq = 99.92% R-Sq(adj) = 99.67%					

5. Validation runs

Machining conditions for best and worst output response as identified from the main effects plot (Ref to Fig. 2 and Fig. 3) are tabulated in Table 5. Mono-objective experimental runs which also serves as confirmatory tests were conducted at these conditions with results given in Table 6.

Table 5. Machining conditions for best and worst response

Response	Condition	f	V	ME

		(mm/rev)	(m/min)	
SCE	Best	0.20	75	3
	Worst	0.10	175	2
Ra	Best	0.10	175	3
	Worst	0.20	75	1

Table 6. Confirmatory test results

Response	Condition	Result
SCE	Best	0.96 J/mm^3
	Worst	1.48 J/mm^3
Ra	Best	0.95 µm
	Worst	3. 03 µm

6. Conclusions

Results of this study presented the following conclusions:

- SCE of Ti-6Al-4V increases with increasing cutting speed because of the work hardening. On the contrary SCE is inversely proportional with the feed rate.
- Cryogenic conditions significantly reduce the energy consumption as work hardening decrease with temperature. Use of cutting fluid increases energy consumption because of the increase in cutting forces.
- Cutting speed was the most dominant factor for SCE with contribution ratio of 57.33% whereas contribution ratio of machining environment and feed rate was 19.94% and 13.47% respectively.
- Surface roughness increased with increasing feed and reducing cutting speed. Coolant, where applied, also acts as a lubrication agent improving Ra.
- Feed rate had a contribution ratio of 92.37% for Ra. Cutting speeds and machining environment of 4.82% and 2.60% respectively.

7. Future Scope

Current works guides the future research endeavors towards machinability analysis of other difficult to machine alloys. In addition, upcoming cooling techniques may be employed for gauging their effectiveness. In terms of machining responses, vital indices including chip morphology and subsurface damage can be characterized.

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