11th International Conference on Through-life Engineering Services – TESConf2022
8-9 November 2022, Cranfield UK

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

Muhammad Ali Khan[1,2*], Syed Husain Imran Jaffery[2], Aamer Ahmed Baqai[1], Mushtaq Khan[2]

[1]*Department of Mechanical Engineering (CEME), National University of Sciences and Technology (NUST), Islamabad, 44000, Pakistan.*
[2]*School of Mechanical and Manufacturing Engineering (SMME), National University of Sciences and Technology (NUST), Islamabad, 44000, Pakistan*

* Corresponding author. Tel.: +923335248284; fax: +925154444350; *E-mail address:* mak.ceme@ceme.nust.edu.pk

Abstract

Energy consumption of a manufacturing system represents its sustainability and efficiency. Sustainable manufacturing processes increase the productivity by improving the input to output ratio. Machining of hard to cut alloys demands higher energy input to overcome their high strength. The energy requirement also elevates with increasing speed which becomes the limiting factor. In the present study the specific cutting energy analysis of aerospace alloy Ti-6Al-4V was carried out at different cutting speeds. Different machining environments including wet and cryogenic media were employed in addition to dry cutting for comprehensive analysis. It was found that cryogenic conditions reduced 8% and 11% SCE in comparison with dry and wet conditions respectively. Analysis of variance highlighted contribution ratio of cutting speed and cutting condition as 51.87% and 46.98%, respectively.

Keywords: Ti-6Al-4V; Cryogenic machining; Specific cutting energy; Analysis of variance

1. Introduction

Higher energy consumption is associated with a number of issues. It can add to cost of the process and subsequently product [1]. It makes the process less environmental friendly because of the undesired CO_2 emissions [2].

Nomenclature	
CC	Cutting Condition
LPM	Litre Per Minute
SCE	Specific Cutting Energy
ANOVA	Analysis of Variance

Keeping in view the fact that manufacturing industries consumes about 20% of global energy usage [3] the need to make the process sustainable is imperative. Turning of aerospace alloys have always posed challenges because of their high strength. In addition to their obvious attrition on tooling [4], they consume greater amount of energy as compared to lighter alloys like aluminum. Therefore, careful selection of suitable cutting parameters ensures higher efficiency and productivity. Different methods are used to analyze the energy requirements of manufacturing systems. Bhushan et al[5] highlighted the importance of selection of suitable machining parameters for the process to be energy efficient. Cutting speed, feed rate, and depth of cut were selected as the input machining parameters. Another study [6] analyzed the response of machining conditions on energy consumption and associated environmental aspects. Energy consumption during turning was modeled which satisfied minimum energy requirements. Comprehensive work [7][8][9] was done to study the effect of cutting speed, feed rate and depth of cut during turning of Al 6061. SCE requirements were reduced by 5% under optimum cutting conditions. The use of cooling/lubrication system has always merit great concern because it accounts for about 15% of total manufacturing cost [10]. Lately the use of cryogenic media has increased overall productivity owing to the fact that no extra disposal measures are required in addition to the ease of availability [11]. Mia et al [12] studied the effect of cryogenic media and cutting parameters on energy consumption in comparison with dry cutting. It was found that cryogenic condition had the highest contribution ratio on the outcome of the process. In the present study the use of dry, wet and cryogenic condition is analyzed in combination with machining parameters in terms of their effect on the sustainability of the system.

2. Experimental design

CNC milling center (ML-300) was used for turning experiments. Additional cryogenic kit was installed on the machine using cryogenic nozzles as shown in Fig 1. Cryogenic cylinder having capacity of 160 liters was connected to nozzles via decanting pipe and cryogenic valve. A steady flow rate of 3 LPM was maintained for LN2. For wet runs, the internal cutting fluid was used having a flow rate of 5 LPM. Aerospace alloy Ti-6Al-4V (composition in Table 1) was selected as the work piece material because of its preferred physical and mechanical properties [13]. Table 2 highlights the design of experiment formulated for comprehensive analysis. Three levels of cutting speeds were selected for experimentation whereas feed rate and depth of cut were kept constant because of their insignificant effect on SCE as highlighted in the literature [14].

Table 1. Chemical Composition (wt. %) of Ti-6Al-4V

Element	Percentage
V	4.2
Al	5.7
Fe	0.15
Cu	0.003
Cr	0.0023
Ti	balance

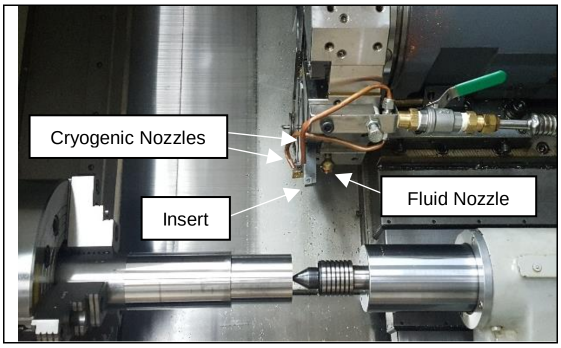

Fig. 1. Experimental setup

Table 2 Design of experiment

Condition	Inputs			
	f (mm/rev)	V (m/sec)	d (mm)	$CC*$
1	0.20	60	1	1,2,3
2	0.20	90	1	1,2,3
3	0.20	120	1	1,2,3

*1 = Dry, 2 = Wet, 3 = Cryogenic

3. Measurement of response

Yokogawa CW 240 clamp on power meter was used to calculate power during air cut (P_{air}) and actual cut (P_{actual}) which were then used to determine P_{cut} using Eq. (1) [15]. P_{cut} determined using Eq. (1) is given in Table 3. Material removal rate (MRR) is calculated using Eq. (2).

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

$$MRR = f \times v \times d \quad (2)$$

Specific cutting energy is calculated by Eq. (3) as shown below:

$$SCE = \frac{\mathrm{P_{cut}}}{\mathrm{MRR}} \quad (3)$$

4. Analysis of results

Energy consumption comparison of different cutting conditions i.e., dry, wet and cryogenic conditions is graphically displayed in Fig. 2. It is highlighted that for all machining conditions SCE for wet machining has a higher value than corresponding dry and cryogenic conditions. The reason is that the thermal softening effect, evident at higher temperatures, is reduced by the cooling effect and hence results in higher SCE than dry machining. Similarly the increase in cutting forces during wet machining [16] is another factor for higher energy consumption. In case of cryogenic machining the energy consumptions tends to be lower due to the fact that strain hardening, which causes the strength of Ti-6Al-4V to increase at high cutting speeds [14], [17], depends upon temperature. As the low temperature of cryogenic media reduces stain hardening [18] the SCE reduces during cryogenic machining. It is pertinent to mention that this gain was not present under wet cutting due to its mediocre cooling capacity, in comparison with cryogenic cooling. Liquid Nitrogen (LN2), used in the present research, is known to reach temperatures as low as -196°C [19], [20]. The same was experimentally verified using thermocouple (K-type) which showed a temperature range of -170°C to -196°C during cryogenic machining.

Table 3 P_{cut} Results

Condition	P_{cut} (J / sec)		
	Dry	Wet	Cryogenic
1	0.22	0.24	0.21
2	0.36	0.37	0.33
3	0.50	0.52	0.48

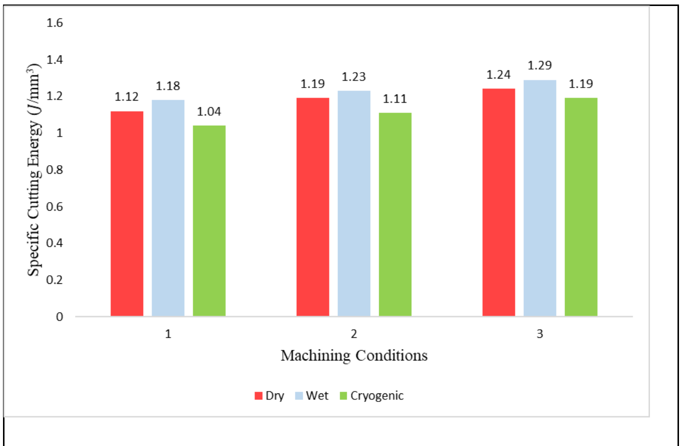

Fig. 2. Comparison of SCE under different machining environments

Fig. 3 displays the main effects plot. The cutting speed has a direct relationship with SCE. Energy consumption increases linearly with cutting speed. This situation is because of the strain hardening of titanium alloys as already pointed out. Cooling condition also has an influential impact on energy consumption. Analysis of variance (ANOVA) of obtained result was conducted to identify significant input parameters. ANOVA results (given in Table 4) showed that cutting speed is the most effective member with contribution ratio of 51.87% whereas cutting condition had an impact of 46.98%.

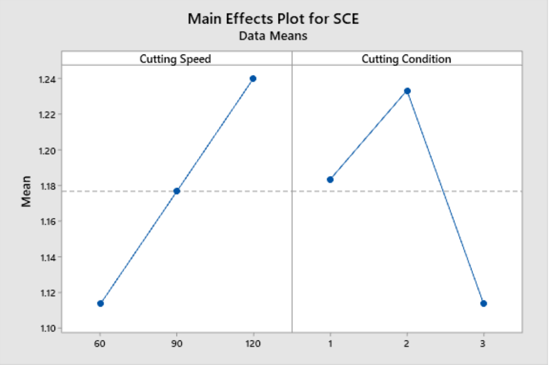

Fig. 3. Main effects plot for SCE at different cutting speeds (60, 90, 120 m/sec) under different cutting conditions (dry (1), wet (2) and cryogenic (3))

Table 4 ANOVA for SCE

Source	DF	Seq SS	Adj MS	F	P-Value	CR (%)
V	3	0.024067	0.012033	90.25	0.000	51.87
CC	2	0.021800	0.010900	81.75	0.001	46.98
Error	6	0.000533	0.000133			1.15
Total	11	0.046400				100
S = 0.0115470 R-Sq = 98.85% R-Sq(adj) = 97.70%						

5. Conclusion

Current research analyzed the sustainability of turning aerospace alloy Ti-6Al-4V under dry, wet and cryogenic conditions. Following conclusions were drawn:

- Wet cutting yielded the highest SCE followed by dry and then cryogenic machining. The high values were because of the lower thermal softening phenomena and increase in cutting forces under wet conditions.
- Cryogenic conditions reduced the strain hardening and consumed lowest energy. An improvement of around 11% resulted at lower values of speed. At higher values the benefit was reduced to 7% because of the difficulty in penetration of cryogenic media in cutting zone.
- Dry machining consumed lower energy than wet machining because of the thermal softening effect. Its SCE consumption was 6% less than wet cutting at lower speeds.
- Specific cutting energy is found to increase with increasing cutting speed. It is due to the strain hardening of titanium alloys at elevated cutting speeds.
- Cutting speed is the most influential member with contribution ratio of 51.87% whereas cutting condition had a contribution ratio of 46.98%.

References

[1] T. Peng and X. Xu, "Energy-efficient machining systems: A critical review," *Int. J. Adv. Manuf. Technol.*, vol. 72, no. 9–12, pp. 1389–1406, 2014, doi: 10.1007/S00170-014-5756-0.

[2] S. Kara and W. Li, "Unit process energy consumption models for material removal processes," *CIRP Ann. - Manuf. Technol.*, vol. 60, no. 1, pp. 37–40, 2011, doi: 10.1016/j.cirp.2011.03.018.

[3] G. Zhao, C. Hou, J. Qiao, and X. Cheng, "Energy consumption characteristics evaluation method in turning," *Adv. Mech. Eng.*, vol. 8, no. 11, pp. 1–8, Nov. 2016, doi: 10.1177/1687814016680737.

[4] M. Younas *et al.*, "Multi-objective optimization for sustainable turning Ti6Al4V alloy using grey relational analysis (GRA) based on analytic hierarchy process (AHP)," *Int. J. Adv. Manuf. Technol.*, vol. 105, no. 1–4, pp. 1175–1188, 2019, doi: 10.1007/s00170-019-04299-5.

[5] R. K. Bhushan, "Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites," *J. Clean. Prod.*, vol. 39, pp. 242–254, 2013, doi: 10.1016/j.jclepro.2012.08.008.

[6] M. F. Rajemi, P. T. Mativenga, and A. Aramcharoen, "Sustainable machining: Selection of optimum turning conditions based on minimum energy considerations," *J. Clean. Prod.*, vol. 18, no. 10–11, pp. 1059–1065, 2010, doi: 10.1016/j.jclepro.2010.01.025.

[7] S. Warsi, S. Husain, I. Jaffery, A. Riaz, and M. Khan, "Development of energy consumption map for orthogonal machining of Al 6061-T6 alloy," *journals.sagepub.com*, vol. 232, no. 14, pp. 2510–2522, Dec. 2017, doi:

10.1177/0954405417703424.

[8] S. S. Warsi, S. H. I. Jaffery, R. Ahmad, M. Khan, M. H. Agha, and L. Ali, “Development and analysis of energy consumption map for high-speed machining of Al 6061-T6 alloy,” *Int. J. Adv. Manuf. Technol.*, vol. 96, no. 1–4, pp. 91–102, Apr. 2018, doi: 10.1007/S00170-018-1588-7.

[9] S. S. Warsi, M. H. Agha, R. Ahmad, S. H. I. Jaffery, and M. Khan, “Sustainable turning using multi-objective optimization: a study of Al 6061 T6 at high cutting speeds,” *Int. J. Adv. Manuf. Technol.*, vol. 100, no. 1–4, pp. 843–855, Jan. 2019, doi: 10.1007/S00170-018-2759-2.

[10] A. Shokrani, V. Dhokia, and S. T. Newman, “Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids,” *Int. J. Mach. Tools Manuf.*, vol. 57, pp. 83–101, 2012, doi: 10.1016/j.ijmachtools.2012.02.002.

[11] I. S. Jawahir *et al.*, “Cryogenic manufacturing processes,” *CIRP Ann. - Manuf. Technol.*, vol. 65, no. 2, pp. 713–736, 2016, doi: 10.1016/J.CIRP.2016.06.007.

[12] M. Mia, “Multi-response optimization of end milling parameters under through-tool cryogenic cooling condition,” *Meas. J. Int. Meas. Confed.*, vol. 111, no. April, pp. 134–145, 2017, doi: 10.1016/j.measurement.2017.07.033.

[13] J. I. Hughes, A. R. C. Sharman, and K. Ridgway, “The effect of cutting tool material and edge geometry on tool life and workpiece surface integrity,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 220, no. 2, pp. 93–107, 2006, doi: 10.1243/095440506X78192.

[14] M. A. Khan *et al.*, “Statistical analysis of energy consumption, tool wear and surface roughness in machining of Titanium alloy (Ti-6Al-4V) under dry, wet and cryogenic conditions,” *Mech. Sci.*, vol. 10, no. 2, pp. 561–573, 2019, doi: 10.5194/ms-10-561-2019.

[15] M. A. Khan, S. H. I. Jaffery, A. A. Baqai, and M. Khan, “Comparative analysis of tool wear progression of dry and cryogenic turning of titanium alloy Ti-6Al-4V under low, moderate and high tool wear conditions,” *Int. J. Adv. Manuf. Technol.*, vol. 121, no. 1–2, pp. 1269–1287, Jul. 2022, doi: 10.1007/S00170-022-09196-Y.

[16] S. Pervaiz, I. Deiab, and B. Darras, “Power consumption and tool wear assessment when machining titanium alloys,” *Int. J. Precis. Eng. Manuf.*, vol. 14, no. 6, pp. 925–936, Jun. 2013, doi: 10.1007/S12541-013-0122-Y.

[17] M. A. Khan *et al.*, “Multi-objective optimization of turning titanium-based alloy Ti-6Al-4V under dry, wet, and cryogenic conditions using gray relational analysis (GRA),” *Int. J. Adv. Manuf. Technol.*, vol. 106, no. 9–10, pp. 3897–3911, 2020, doi: 10.1007/s00170-019-04913-6.

[18] D. R. Chichili, K. T. Ramesh, and K. J. Hemker, “The high-strain-rate response of alpha-titanium: Experiments, deformation mechanisms and modeling,” *Acta Mater.*, vol. 46, no. 3, pp. 1025–1043, 1998, doi: 10.1016/S1359-6454(97)00287-5.

[19] M. J. Bermingham, J. Kirsch, S. Sun, S. Palanisamy, and M. S. Dargusch, “New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V,” *Int. J. Mach. Tools Manuf.*, vol. 51, no. 6, pp. 500–511, 2011, doi: 10.1016/j.ijmachtools.2011.02.009.

[20] Z. Y. Wang and K. P. Rajurkar, “Cryogenic machining of hard-to-cut materials,” pp. 168–175, 2000.