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Tool wear and cost evaluation of face milling grade 5 titanium alloy for sustainable machining

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A B S T R A C T

Cutting tool life, its wear rate and machining cost play significant role in a machining process. Effect of these parameters using face milling of titanium alloy is analysed to assess the economic factor of sustainability. Machining sustainability of Ti-6Al-4V hardened to 55 HRC is assessed through a novel technique of iso-response method, in which the response value, i.e. surface finish is taken as criteria for evaluation and comparison among dry, conventional and cryogenic machining. Experiments are designed in DOE for central composite design and performed face milling of Ti-6Al-4V with PVD coated carbide inserts using three conditions of cooling and measured the response values. Feed, speed, and depth of cut were used as input variables. Comparing the average results of tool life and machining cost for iso-response technique, it was found that 47.55 % less electricity cost and 47.59 % less machine operating cost and 10.76 times increased cutting tool life achieved for cryogenically cooled experiments as compared with dry machining. Coolant cost was found 13.33 times cheaper for cryogenic as compared with conventional machining. The results indicate that cryogenic cooling is more sustainable for tool life, having better surface finish of machined part with least energy and machining cost.

A R T I C L E I N F O

Keywords:
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1. Introduction

In machining of difficult-to-machine materials like Ti-6Al-4V, excessive tool wear and heat are produced making the surface quality poor [1]. Alternative solutions of dissipating the heat generated at chip-tool interface and cutting tool materials is in exploration since last few years. Main reasons for rapid tool wear are building of high cutting temperatures. Cost of a machined part mainly involves the cost of cutting tools, electrical energy, labour and coolant cost. High machining cost of titanium alloy Ti-6Al-4V has made it important to ensure longer tool life by selecting the favourable cutting conditions [2]. Bulk use of conventional coolant in machining industries is causing increase in environmental damage [3]. Trends are shifting from conventional to sustainable manufacturing due to increase in occupational diseases of workers and need for reduction in overall manufacturing cost [4]. For implementation of cryogenic machining at industrial level, investigations are required about the tool wear and tool life using cryogenic cooling [5]. Nowadays, machining industries are forced to adopt the manufacturing processes which are environment friendly. The objectives of this research work are to identify the effect of cryogenic cooling over tool wear and tool life for face milling of hardened Ti-6Al-4V, machining cost evaluation for dry, conventional and cryogenic cooling and identification of alternate cooling technique for sustainable machining. The results show that using cryogenic cooling, cutting tool life is enhanced and machining cost is reduced as compared with dry or conventional machining. A novel technique of iso-response method is introduced which is helpful in evaluation of machining sustainability.

2. Literature review

Sustainability achievement of difficult-to-machine materials is major concern now-a-days. Industrial trends are shifting from conventional to sustainable manufacturing principles. Such revolutions are outcome of diseases found in workers at shop floor, requirement of cost reduction for manufacturing and government policies for environmental protection [4]. Cutting fluids are dangerous to health and environment as found in presently performed investigations [6]. In a report it is stated that about 80 % of the skin diseases are due to the use of cutting fluids [7]. European union estimated for metal working fluid and found that 320,000 tons of it annually used and 66 % of which is disposed-off after usage [8]. Coolants used in cryogenic cooling are safe for workers and environment as compared with conventional coolants. The air consists of 79 % of nitrogen gas which is extracted and compressed to liquid nitrogen, which has no hazards for work's life; therefore can be used as cooling medium in cryogenic machining. Using N_2 gas as cooling medium has many advantages such as tool life enhancement, improvement of surface integrity, productivity improvement, reduction of build-up-edge, increasing chip breakability and reduction in burr formation [9, 10]. Alternates of cutting fluid like N_2, O_2 and CO_2 have been used and compared to wet and dry machining and found that fine surface finish obtained with increased flow rates and pressure of gases [11]. End milling of Ti-6Al-4V using liquid nitrogen, conventional cooling (flooded) and dry machining performed to check surface roughness, microscopic surface integrity, subsurface micro-hardness and found that using cryogenic cooling 39 % and 31 % lower surface roughness achieved when compared to dry and flood cooling methods [5]. Turning of stainless steel was assessed for sustainability using minimum quantity solid lubricant in comparison with dry, wet and minimum quantity lubrication technique and found reduction in tool wear with improved surface finish [12]. Sustainability is needed to be incorporated in all steps of the manufacturing.

Machining is one of the mostly used processes in developing a product. By involving the sustainability principles into machining process, the economic and health sectors can be improved in order to get saving in cost and enhanced environmental performance. Machining process contributes to worldwide economy therefore oil based coolants are generally not recommended as cooling and lubrication fluid (CLF) as they tend to make the machining process unsustainable. These coolants are formulated from mineral oil which is extracted from highly non-sustainable crude oil. Vegetable oils are not used as cooling and lubrication fluid due to their reduced performance and higher cost [13].

Cost of machining is a major element of a mechanical industry. Cutting tools having long tool life are preferred over those with short tool life in order to reduce overall machining cost and increasing productivity. A cost estimation model has been proposed in [14] for optimization of machining cost which includes material cost, tool cost, overhead and labour cost; in this proposed model if the desired cost effective results are not achieved then the feedback is given to designer for modifications. The feasible process parameters including cutting speed, feed rate and depth of cut are selected to attain optimum results. Constraints of cutting tool specification, tolerances, cost, time, machining sequence and required surface finish are taken into consideration. Machining of inconel 718 considered for evaluation of sustainability parameters and found that cryogenic machining is more sustainable for machining cost, energy cost, resource consumption, machining cost, CLF cost, waste processing cost, total production cost and part production cost as compared with conventional [15, 16].

It is important to cool down the cutting tool temperature in order to improve the cutting tool life, especially in the case when machining the materials with low thermal conductivity like titanium Ti-6Al-4V [17]. Using the cooling technique of minimal quantity lubrication (MQL), it was found that tool wear is decreased, life of cutting tool is increased and the quality of surface finish was improved as compared the results with conventional and dry machining [18]. Development in lubrication techniques and coolants has a lot of gap for researchers to find optimal cooling systems. In reports it is given that tooling cost is about 4 % of the total machining cost and coolant/lubrication cost is about 15 % of total machining cost [19], therefore huge sustainability gain is possible by avoiding CLF and using high performance coated cutting tools [20]. Reduction in size of chip build up edge and tool wear found in turning of Ti-6Al-4V using cryogenic compressed air [21]. Cryogenic cooling done to study machinability and tool wear effect in end milling of titanium Ti-6Al-4V using coated carbide cutting tools and found that tool wear was slowed down and surface roughness reduced by 11 % and 59 % as compared with dry and wet conditions [22]. Liquid nitrogen used for turning of composite material and found sustainable in reducing surface roughness, tool wear and cutting temperature [23]. Growth of flank wear was significantly reduced by using liquid nitrogen in turning of Ti-6Al-4V [24]. More improvement in tool life and surface integrity was found using cryogenic machining of inconel 718 as compared with conventional [25]. Flank wear, surface finish, cutting power calculated at different combinations by turning Ti-6Al-4V with dry, flood cooling, vegetable oil, cooled air lubrication, cryogenic with LN_2 and vegetable oil mixed with cooled air and it was found that vegetable oil is more sustainable at feed 0.1 mm/min and speed 90 m/min [26]. Cutting forces, machining temperatures, tool wear, machined surface quality, chip formation and energy consumption investigated using end milling of inconel 718 carried under dry, conventional and cryogenic cooling and found that cryogenic cooling is promising for machinability and sustainability improvement as compared to conventional and dry [27].

Presently most of the work reported on sustainable machining of Ti-6Al-4V generally addresses the issue using material in annealed form. In some applications parts are machined after hardening Ti-6Al-4V. Sustainability issue for such condition needs more exploration.

3. Experimental results

Face milling of titanium alloy Ti-6Al-4V was performed in three different conditions of dry, conventional and cryogenic cooling. Initially the alloy was heat treated up to hardness of 55 HRC. DMU-50 CNC milling machine used for face milling with PVD coated carbide inserts "APTM 1135 PDER-M2 VP15TF". Specific values of feed, speed and depth of cut were selected and response of surface finish was checked using perthometer M2 with drive unit Mahr PGK-120. Three levels of cutting speed 20 m/min, 35 m/min and 50 m/min, feed levels of 0.1 mm/tooth, 0.15 mm/tooth and 0.2 mm/tooth, depth of cut having levels of 0.05 mm, 0.1 mm and 0.15 mm were selected. Experiments were designed in RSM for central composite design technique using Design Expert 7.0.0 software. Response values of surface finish were measured for each experiment as shown in Table 1.

3.1 Tool life comparison

The Taylor's tool life equation as given in Eq. 1 used to calculate the cutting tool life. This equation deals in finding tool life for fixed feed and depth of cut.

$$VT^n = C \tag{1}$$

Where n is a constant based on tool material and C is a constant based on tool & work. Value of C expresses the cutting speed of a tool for one minute of tool life. Taking value of C 300 for dry, 507 for conventional and 1142 for cryogenic conditions [28] and value of n taken as 0.5 specified for carbide cutting tools. Tool life calculated for each value of cutting speed V, and is shown in Table 1. Nearly common response values of surface roughness were selected for further comparison of tool life, machining cost calculations and sustainability evaluation using dry, conventional and cryogenic cooling.

Comparison of tool life for all experimental runs of Table 1 is shown graphically in Fig. 1. It describes that the tool life is highest for cryogenic cooling as compared to dry and conventional.

For carrying out further analysis, common response values of R_a and comparison with the tool life is performed which is given in Table 2.

Table 1 Experimental input values, measured response values and calculated tool life

Exp. No.	Input variables			Surface roughness, (R_a) µm			Tool life, min		
	Cutting speed (m/min)	Feed, f_r (mm/min)	Depth of cut (mm)	Dry	Conv.	Cryogenic	For dry	For conv	For cryo
1	20	63.662	0.050	0.89	1.996	0.519	225	643	3260
2	50	159.155	0.050	0.95	1.98	0.569	36	103	522
3	35	167.113	0.016	0.991	1.187	0.63	73	210	1065
4	35	73.530	0.100	0.763	0.681	0.362	73	210	1065
5	35	167.113	0.100	1.727	1.078	0.947	73	210	1065
6	35	167.113	0.100	1.354	1.188	0.3	73	210	1065
7	35	167.113	0.100	1.321	1.349	0.383	73	210	1065
8	35	167.113	0.100	1.195	1.301	0.447	73	210	1065
9	60.227	287.563	0.100	1.61	1.578	1.5	25	71	360
10	20	63.662	0.150	1.043	0.289	0.37	225	643	3260
11	50	159.155	0.150	1.073	0.431	0.339	36	103	522
12	20	127.324	0.050	1.62	0.929	0.5	225	643	3260
13	50	318.310	0.050	1.77	0.587	0.684	36	103	522
14	50	318.310	0.150	2.198	0.929	0.557	36	103	522
15	20	127.324	0.150	2.151	0.853	0.63	225	643	3260
16	35	260.696	0.100	1.916	2.738	2.348	73	210	1065
17	35	167.113	0.184	1.606	1.823	0.905	73	210	1065
18	35	167.113	0.100	---	1.02	0.946	73	210	1065
19	35	167.113	0.100	---	0.98	0.975	73	210	1065

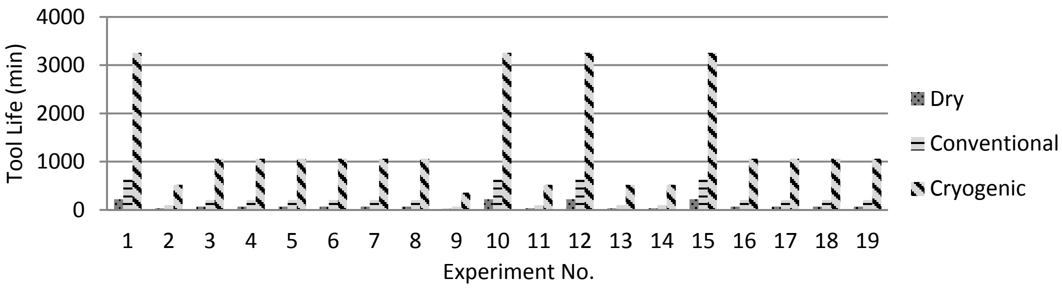

Fig. 1 Comparison of tool life for dry, conventional and cryogenic cooling

The graphical comparison of tool life is given in Fig. 2, and is evident from the comparison of tool life that using cryogenic cooling, the cutting tool will last for more machining time than for conventional and dry. The surface finish obtained is nearly same for these combinations of speed, feed and depth of cut using different cooling combinations however the tool life is greatest in cryogenic conditions.

Table 2 Tool Life for experimental runs having nearly identical R_a

Combination No.	Response, R_a (µm)			Tool life (min)		
	Dry	Conventional	Cryogenic	Dry	Conv	Cryo
1	0.89	0.853	0.905	225	643	1065
2	0.95	0.929	0.947	36	103	1065
3	1.073	1.078	0.975	36	210	1065
			Average	99	318.6	1065

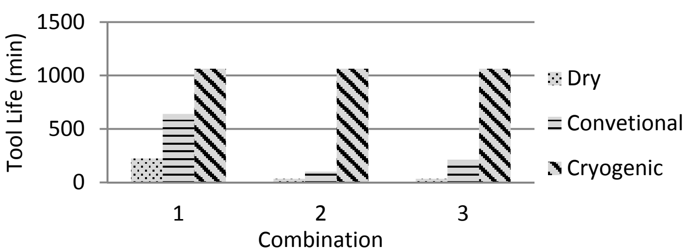

Fig. 2 Tool life comparison based on iso-response values

3.2 Machining cost calculations

Total machining cost (C_m) comprises of multiple associated costs including electricity cost (C_e), overhead cost (C_{oh}), cutting tool inserts cost (C_t) and wasted lubricant/coolant cost (C_{cw}). These calculations are made to compare the cost for selected common response values (R_a) as given in Table 3. Total machining cost in cumulative form can be represented by Eq. 2.

$$C_m = C_e + C_{oh} + C_t + C_{cw} \tag{2}$$

Electricity cost

The electricity cost calculated using Eq. 3.

$$C_e = C_p \times \frac{P_m}{\eta_m \times 60} \times T_m \tag{3}$$

where C_p is unit energy price in PKR/KWh (20 PKR/KWh at working site), P_m is power of machine in KW (power by main motor and power by coolant pump), η_m is machine efficiency, and T_m is machining time in minutes.

Machine cutting time T_m is calculated using expression of Eq. 4 where cutting length ($L+A$) taken as 100 mm and value of f_r taken from Table 1. Calculated values of machining time (T_m) are given in Table 3.

$$T_m = \frac{L + A}{f_r} \tag{4}$$

Table 3 Machine cutting time for iso-response values of R_a

Combination	Dry		Conventional		Cryogenic	
	R_a (μm)	T_m (min)	R_a (μm)	T_m (min)	R_a (μm)	T_m (min)
1	0.89	1.571	0.853	0.785	0.905	0.598
2	0.95	0.785	0.929	0.314	0.947	0.598
3	1.043	1.571	1.019	2.143	0.946	0.598
4	1.073	0.628	1.078	0.598	0.975	0.598

Eq. 3 has been used for calculating cost of electricity. Here it is notable to mention that the cooling pump is used only in conventional machining so its power consumption is added in calculations. Value of main motor power is 15 KW and power of coolant pump is 0.27 KW. Value of mechanical efficiency (η_m) taken as 0.9 therefore using the values, the electricity cost calculated as given in Table 4.

Fig. 3 shows the graphical comparison of electricity cost against iso-response values of R_a. It is evident that electricity cost is less for the cryogenic cooling as compared to conventional and dry. For second combination, the electricity cost for conventional is less whereas on average basis the electricity cost for cryogenic is less overall.

Table 4 Electricity cost comparison

Combination	Electricity cost, PKR		
	Dry	Conventional	Cryogenic
1	8.73	4.44	3.32
2	4.36	1.78	3.32
3	8.73	12.12	3.32
4	3.49	3.38	3.32
Average	6.33	5.43	3.32

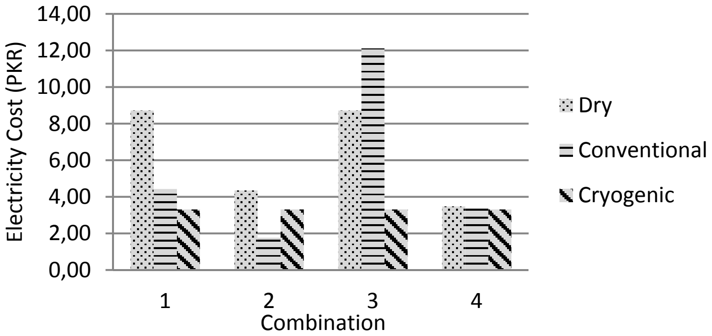

Fig. 3 Comparison of electricity cost

Overhead cost

Overhead cost (C_{oh}) comprises the sum of machine operating cost (C_o), HVAC/lighting cost (C_h) and machine depreciation cost (C_d) as given by following expression:

$$C_{oh} = C_o + C_h + C_d \tag{5}$$

Here machine operating cost will be calculated using Eq. 6.

$$C_o = C_{Lb} \times \sum_{i=1}^{n} Lb_i \times T_i \tag{6}$$

where C_{Lb} is labour unit cost in PKR/hr (208 PKR/hr), Lb_i is number of labours in i^{th} operation, T_i is process time in hours (for i^{th} operation).

By using the machining time from Table 3, the machine operating cost for selected iso-response values of R_a can be calculated as given in Table 5.

Table 5 Machine operating cost for iso-response values of R_a

Combination	Machine operating cost, PKR		
	Dry	Conventional	Cryogenic
1	5.45	2.72	2.07
2	2.72	1.09	2.07
3	5.45	7.43	2.07
4	2.18	2.07	2.07
Average	3.95	3.33	2.07

It is evident from Fig. 4, that the machine operating cost is less for cryogenic machining as compared with dry and conventional. For 2nd combination, the machine operating cost is less for conventional however on average basis, the machine operating cost is less for cryogenic cooling. Lightening, HVAC cost and machine depreciation cost is nearly same for all therefore their effect can be neglected for specific case.

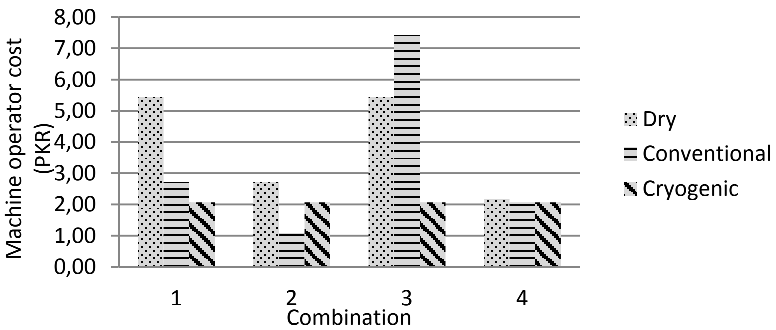

Fig. 4 Machine operating cost comparison

Cutting tool cost

Cost of a cutting tool insert (C_t) is PKR 500 (1US$=107 PKR). Cutting tool's cost is dependent upon the tool life. Shorter the tool life will need more tools in a complete operation. Considering data of tool life presented in Table 1 & Table 2 it is clear that minimum tool life is 36 min for dry, 103 min for conventional and 1065 min for cryogenic therefore the number of cutting tools will be higher for dry machining as compared with conventional and cryogenic. Here the cutting inserts cost was taken as for two inserts in each scenario.

The calculation of machining time is based on work piece length of 100 mm. As far as the work piece machining length will be increased, the machining time will also be increased accordingly, therefore requirement of cutting inserts will be increased for each scenario based on their tool life resulting that machining cost in dry machining will increase more rapidly.

Cost of wasted coolant

Coolant used in conventional machining is "Shell macron 221 CM-32" having cost (C_c) of 500 PKR per litre. Flow rate (Q_c), for coolant was measured as 3 litres per min. This coolant is re-used by circulating through pumping action and filtration system. Some of the coolant quantity is wasted in cleaning process which is taken as 0.05 litre per min. This wasted quantity (Q_w), has direct impact on cost burden in the calculation of coolant cost.

Therefore the cost of coolant wasted during machining (C_{cw}) is calculated using Eq. 7 and is given in Table 6.

$$C_{cw} = C_c \times Q_w \times T_m \tag{7}$$

For cryogenic machining, the cost of liquid nitrogen is 6 PKR per litre. The estimated consumption rate of liquid nitrogen was 0.5 litres per min. Machining time for cryogenic is taken from Table 3 and calculated the cost of liquid nitrogen against each combination as given in Table 6.

Table 6 Cost of coolant for iso-response values of R_a

Combination	Coolant cost, PKR		
	Dry	Conventional	Cryogenic
1	0	19.625	1.8
2	0	7.85	1.8
3	0	53.575	1.8
4	0	14.95	1.8
Average	0	24	1.8

Cost of coolant found very less for cryogenic cooling as compared with the conventional machining for iso-response values of surface finish. It is about 13 times cheaper from conventional coolant on average basis.

3.3 Machining cost comparison

Using the values of electricity cost (C_e), overhead cost (C_{oh}), cutting tool cost (C_t) and wasted coolant cost (C_{cw}) in Eq. 2, the Machining cost was calculated for each scenario of dry, conventional and cryogenic cooling and shown in Table 7.

Table 7 Calculated machining cost

Combination	Machining cost, PKR		
	Dry	Conventional	Cryogenic
1	1014.18	1027	1007.19
2	1007.08	1010.8	1007.19
3	1014.18	1073.7	1007.19
4	1005.67	1020.56	1007.19
Average	1010.278	1033.015	1007.19

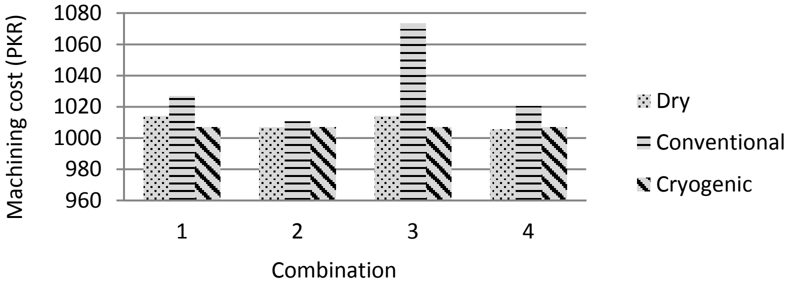

Fig. 5 Machining cost comparison

In calculated values of machining cost of Table 7, the effect of cutting tool cost (C_t) was for two inserts in each case. While machining time is increased, the cutting tools for dry machining will more rapidly wear as compared to conventional and cryogenic cooling. Therefore the cutting tools cost for dry machining will increase rapidly.

Machining cost comparison given in Fig. 5, shows that machining cost is less for cryogenic as compared with dry and conventional.

3.4 Tool wear analysis

Cutting inserts used in machining were analysed to check wear and damage using SEM. In dry machining the cutting tool nose tip was damaged by a length of 1250.68 μm and cutting edge by 1453.91 μm as shown in Fig. 6. Maximum flank wear of 338.82 μm was observed as shown in Fig. 7(a). Cutting tool using coolant was slightly damaged by 68.27 μm as shown in Fig. 7(b), whereas no tool wear was observed in cryogenic cooling as shown in Fig. 7(c).

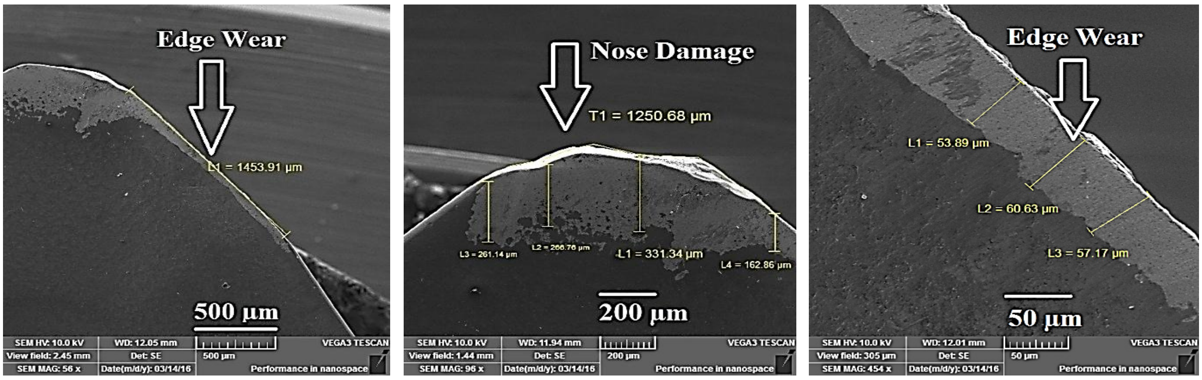

Fig. 6 Tool wear in dry cutting

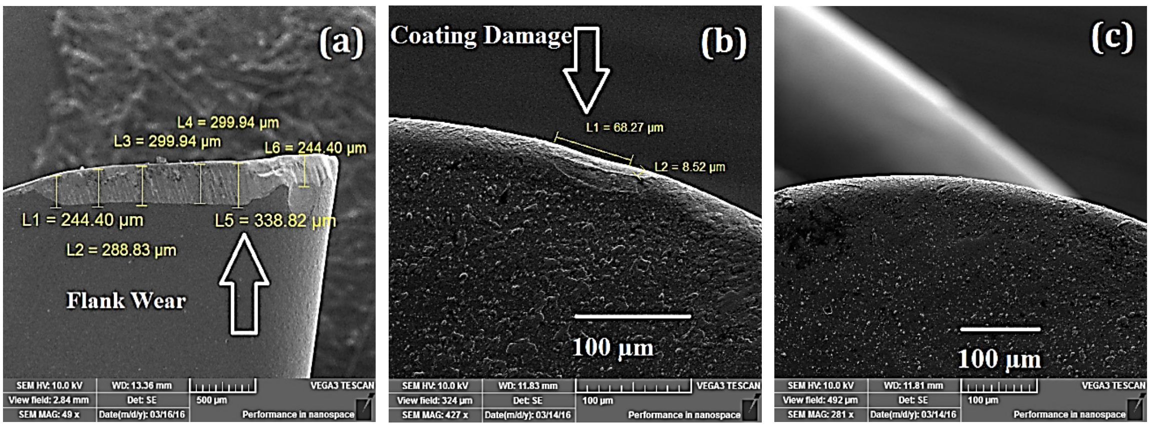

Fig. 7 Flank wear in dry cutting (a), Tool wear using coolant (b), Cutting tool wear using cryogenic cooling (c)

The cutting tools made of tungsten carbide used for experimentation have coating layer of (Ti, Al) N processed by technique of physical vapour deposition (PVD). This layer prolongs tool life when compared to cemented carbide under same cutting conditions. This coating layer was damaged in dry machining as shown in EDX analysis given in Fig. 8. The base tool material which is tungsten carbide found exposed by 60 %. Coating was damaged in tools used for dry machining only whereas no damage was observed for tools used in conventional and cryogenic machining.

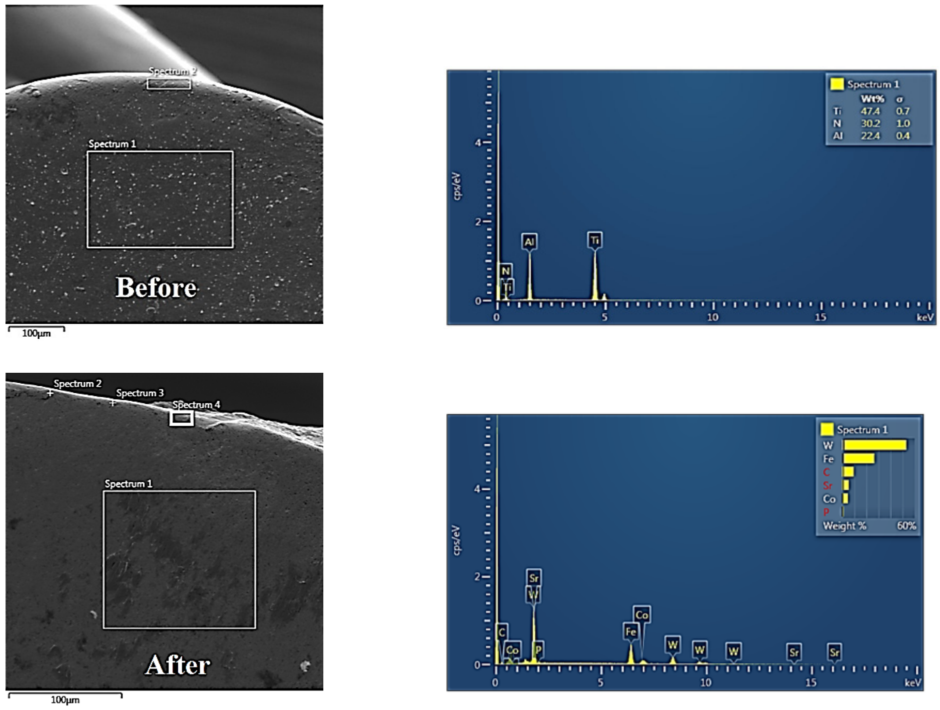

Fig. 8 EDX analysis of coating layer on cutting tool used in dry machining

4. Energy, waste, environmental, and social impacts

Cutting power and material removal rate are calculated for iso-response values of surface finish given in Table 3. Fig. 9 shows results obtained from the analysis and are related to sustainable machining:

Cutting Power: It was found that the cutting power required in cryogenic machining is 61.9 % less than cutting power required in dry machining.

Machining Cost: It is found that 47.55 % less electricity cost as compared with dry and 14.22 % less as compared with conventional machining.

Adverse effects of CLF: The adverse effects of conventional coolants are reduced by replacing the coolant with N_2 gas. Corresponding cutting power and machining cost are also reduced.

Machining time: Machining time for cryogenic is 15.12 % less than dry and conventional machining 12.51 % less than dry case.

Material Removal Rate: The material removal rate is 81.12 % more for cryogenic than dry machining.

Tool Life: Cutting tools life is 10.76 times more for cryogenic cooling which indicates that the waste in the form of damaged tools is reduced. On the other hand tool life is increased, productivity is enhanced by increasing the material removal rate and effective utilization of resources is ensured by reducing the machining times as shown in Fig. 9. Comparison of cutting power, cutting time, electricity cost, coolant cost, machine operating cost, material removal rate and tool life on average basis is presented in Table 8.

Table 8 Average response values calculated for nearly identical R_a

Sr.	Response	Units	Dry	Conventional	Cryo
1	Cutting power	KW	6.33	5.43	3.32
2	Cutting time	min	0.959	0.839	0.814
3	Electricity cost	PKR	6.33	5.43	3.32
4	Coolant cost	PKR	0	24	1.8
5	Machine operating cost	PKR	3.95	3.33	2.07
6	Material removal rate	mm^3/min	1.578	3.247	2.858
7	Tool life	min	99	318.6	1065

It is learnt that nitrogen gas is not harmful for the workers and environment, whereas the coolant used in the conventional machining had its adverse effects on the environment. This advocates use of cryogenic as more sustainable for machining and help workers life.

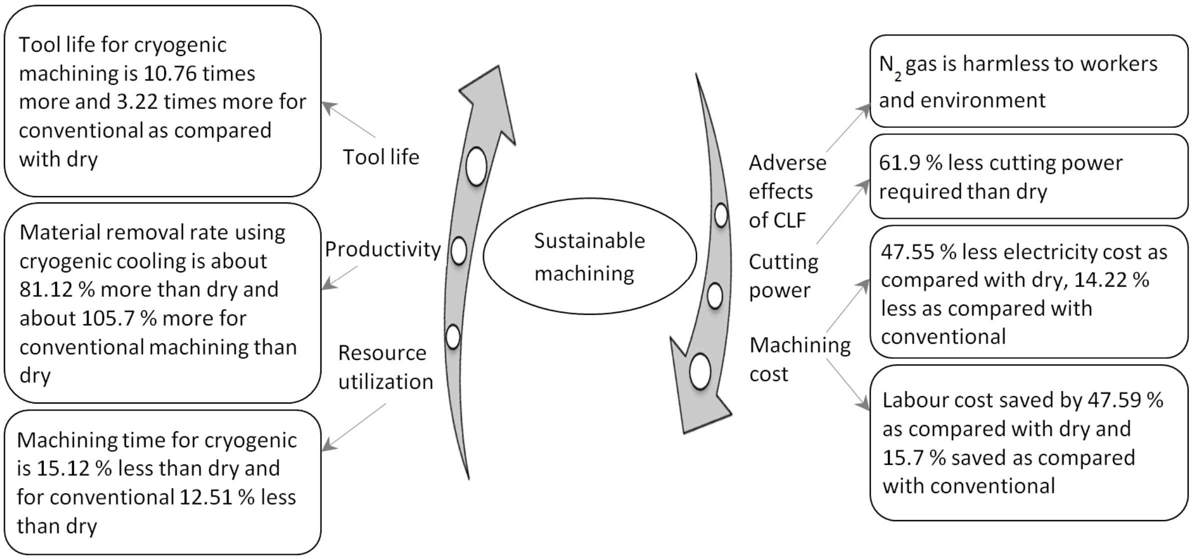

Fig. 9 Sustainable machining results using cryogenic cooling

5. Conclusion and future study

Findings of the experimental work using iso-response technique of evaluation are summarized as below:

- Tool life calculated for nearly identical response values of R_a and fond that maximum tool life for dry machining is 225 min, for conventional it is 643 min and for cryogenic it is 1065 min. On average Basis, the tool life for cryogenic machining is about 10.76 times more than that for dry and 3.22 time more for conventional than for dry. Also in overall comparison of dry & conventional it was found that tool life is maximum for cryogenic. Due to the increased tool life, the cost for the cutting tools is also reduced and productivity is increased. Waste in the form of worn tools is also reduced.
- Machining cost including the electricity consumption cost by machine and operating cost are based on time of machining operation; it is found that the time of machining is less in cryogenic cooling mode as compared with dry and conventional therefore overall cost is less for cryogenic cooling.
- Overall impact of machining cost including electricity cost, labour cost, cutter tools cost resulted that cryogenic machining is cheapest of all and hence sustainable. Nitrogen gas is harmless for workers and environment.

For future study, the technique of iso-response value can be applied for sustainability assessment of other difficult-to-machine materials. Process of machining other than face milling may be considered for evaluation. Cutting force may be introduced as response value and effect of different tool nose radii may also be investigated.

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