Changing Manufacturer's Opinion in Reducing the Use of Flood Coolant when End Milling Titanium

Brian Boswell, Mohammad Nazrul Islam, *Member, IAENG*, Yogie Rinaldy Ginting, *Member, IAENG*

***Abstract*—Titanium alloy has been widely used in the aerospace and automobile industries since the 1960s, and is classified as a hard to machine material. Environmental machining requires the elimination or reduction of coolant use when machining titanium, the exact opposite of flood coolant. Conventional wisdom has determined that copious amount of coolant is required to reduce the chemical reaction between the tool tip and work material, and to extract the heat from the tool interface. If the correct cutting conditions are not used, the tool wear is extreme. The goal of this study is to identify the optimum machining parameters, when traditional coolant is replaced by Cryogenic Liquid Nitrogen or Minimum Quantity Lubrication (MQL). The workpiece test procedure was developed by using the Design-of-Experiment Methodology ensuring robustness of the machining tests, and the results were analysed using the Taguchi method and Pareto ANOVA.**

***Index Terms*—Chemical reactiveness, coolant, wear, cryogenic, Minimum Quantity Lubrication, Taguchi method, tool life, environmental.**

I. Introduction

IT is well established that machining titanium (Ti-6AI-4V) is dependent on the use of cutting fluid to prolong tool life. However, a more environmentally friendly method that can reduce or eliminate the use of traditional coolant and still achieve similar machining quality conditions should be used. Unfortunately, industry seems reluctant to embrace alternatives, such as MQL, which is an environmentally friendlier way of machining. In an effort to eradicate these adverse opinions, this paper will examine the effectiveness of MQL, and Cryogenic Liquid Nitrogen, for a range of machining parameters as given in section III.

Traditional soluble oil coolants or synthetic coolants, directed at the tool interface, have been deemed necessary for high material removal rate (MRR), making the challenges to provide an environmental cooling approach enormous. Liquid coolant is critical in helping extend tool life by dissipating the heat and reducing the chemical reactiveness between the tool and the titanium alloy chip [1, 2]. Considering the high cost of disposal of used liquid coolant, [3-6] gives even more incentive for industrial users to reduce or even eliminate coolant from machining processes. Titanium alloys offer excellent mechanical properties, as well as low thermal conductivity [7-9]. These properties make titanium alloy idea for use in the aircraft and automobile industries [10, 11], particularly when it is 50% lighter with a 30% higher strength than steel [12]. Unfortunately, low conductivity property causes significant problems when machining [13-15], as heat generated by cutting does not dissipate, and concentrates at the tool tip [16-18].

Conventional wisdom limits the cutting speed to less than 60 m/min when a copious amount of cutting fluid is being used [19-21]. Muthukrishnan and Davim [1] reported that wet turning of Titanium Alloy (Ti-6AI-4V) provides a superior surface and increases tool life by 30% relative to dry turning. Islam *et al*. [22] confirmed that the surface finish of the turning process was mostly affected by the feed rate which is the norm for metal cutting. However, the cooling effect was negligible (0.16%) with respect to surface finish. The main benefit in preventing wear when coolant is used is by reducing the effect of adhesion between the tool tip and titanium alloy chip.

II. LITERATURE REVIEW OF COOLING METHODS

Experimental work by Wang *et al*. [23] on the machining forces and cut face reliability, using speeds as high as 400 m/min, found that the optimum cutting speed was 200 m/min, since it produced the lowest cutting force, and provided the best surface finish. However, the high temperature and chemical reaction between the chips and tool leads to tool failure. High cutting force is essential in machining titanium alloys due to the tensile strength, and hardness at high temperature [24, 25]. Priarone *et al*. [26] contrasted the capabilities of MQL, flood cooling and dry cutting for titanium milling and turning processes, it was concluded that MQL was the most environmentally friendly solution. Hashmi *et al.* [27] create a model that can be used to optimize machining parameters in order to produce the desired surface finish. Unfortunately this model is only valid on specific machining conditions, i.e. depth of cut less than 1 mm. In this research traditional flood coolant will be contrasted with MQL, and Liquid Nitrogen cryogenic cooling [28, 29].

Reviewing MQL, when turning AISI 4340 high tensile steel, it was found that tool life was increased, and surface finish was improved [30, 31]. Davim *et al*. [32] reported that turning using MQL gave better surface finish results compared to that of flood cooling. Wang *et al*. [33] discovered that MQL could provide a similar cooling effect

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to flood for turning Titanium alloys with low feed rate. Similarly, Pervaiz *et al*. conclude that MQL produces a better surface finish on the turning process of Ti6Al4V alloy due to its ability to provide lubrication to the cutting zone, thereby minimising the interaction between the chips reducing friction [34]. For the milling process, Jiang *et al.* [35] found that MQL was the best cooling method of Ti6Al4V alloy in terms of surface finish.

Liquid Nitrogen cryogenic cooling is considered due to its ability to cool the cutting zone quickly, since high temperatures accelerate the wear mechanisms. It is a significant factor influencing the parameter for tool wear [36-38]. The effect of cryogenic chilling on titanium alloys is known to promote surface hardening, due to its reactiveness to oxygen, hydrogen and nitrogen, as Hong's findings showed [19]. This surface hardening is shown to increase the cutting force as illustrated in this research, and by other researchers [11, 16]. An experiment by Rotella *et al.* [39] demonstrated that turning Ti6Al4V alloy using cryogenic cooling improved surface finish due to grain refinement. When comparing dry, cryogenic and flood, Islam *et al.* [22] showed that cryogenic performance was the best in terms of diameter error, but it produced the worst circularity. Hong and Ding [40] concluded that, when cutting titanium alloy under cryogenic cooling, cutting speed can be increased two-fold compared to flood cooling, while maintaining tool life. Cryogenic cooling maintains the tool temperature below the softening temperature, thereby slowing the tool wear [41, 42].

III. EXPERIMENTAL PROCEDURE AND EQUIPMENT

The 60 mm titanium bar was pre-machined into a workpiece suitable to be clamped onto the Kistler dynometer to measure the real time cutting forces as shown in Fig. 1. The machining process was conducted on the Leadwell V30 milling machine using a 12 mm diameter end mill, to produce slots 1 mm deep on the top of each workpiece.

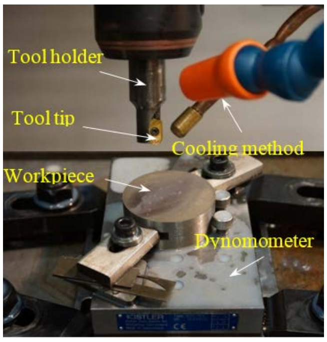

Fig. 1 Workpiece testing set up

The tool parameters were as per Sandvik carbide inserts for titanium machining R390-11 T3 31M PM S40T, used in a tool holder R390-012A16-11L. In order to simplify the milling analysis in this research, a single tool tip was used, and a new insert was inserted for each test. The corresponding real time machine power was measured by Yokogawa CW140 power analyser. The design of experiment methodology was used to define the number of tests performed. Pareto ANOVA was used to show the contribution of the cooling process, machining speed and feed rate parameters, and their interaction with surface roughness, cutting force and machine power requirement [43, 44]. In this study twenty seven tests cuts were completed using different cutting speeds, and feed rates incorporating the three cooling methods: cryogenic, MQL and flood as shown in Fig. 2.

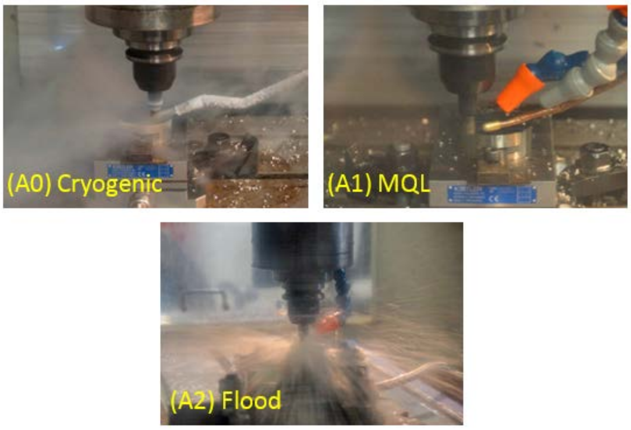

Fig. 2 Coolant method levels used

The maximum value of cutting velocity recommended for cutting titanium alloy under traditional coolant is 80 m/min. These cutting tests will be performed at 20% higher than recommended cutting speed i.e. 100 m/min, as previous research has shown that higher speeds when cutting AISI steel 4340 with MQL produce a better surface finish [31]. Similarly, the speed was increased for machining the Ti-6AI-4V workpiece; the cutting parameters used in these tests can be found in TABLE I.

TABLE I
Cutting parameters

Input parameter	Symbol	Level 0	Level 1	Level 2
Cooling method	A	Cryogenic	MQL	Flood
Cutting speed (m/min)	B	60	80	100
Feed (mm/rev)	C	0.1	0.2	0.3

MQL was delivered externally via a Unist MQL application system, where the flow rate can be precisely set. For the MQL cutting tests the flow rate was set at 80 mL/h. This amount is negligible, compared to 48 L/min of normal coolant flow rate for typical flood milling.

Liquid nitrogen was supplied at a rate of 1.3 L/min to the cutting zone via a nozzle as shown in Fig. 2. A Mitutoyo Surftest with SurfPak-SJ software was used to obtain the surface finish value of each workpiece. The stylus movement along the machined surface was set-up on a 4 add millimeter interval for assessing 9600 points to increase the accuracy of the measurement. In addition, an Olympus Microscope BX51M with Olympus Stream Image Analysis Software was used to examine the surface profiles of the workpiece. Surface finish, together with cutting force and machine power obtained from the machining process, will be utilised to define the optimum grouping of machining conditions and cooling method.

IV. RESULTS AND DICUSSIONS

TABLE II gives the results of the cutting tests and the ratio of the signal to noise (S/N) measurement result, which

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implementing the smaller-the-better quality [46] equation (1). The number of measured observations (n) and y_i is the observed measurement.

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right)\text{[dB]} \quad (1)$$

The response graph for the mean S/N ratio as shown in Fig. 3 verified the Pareto ANOVA analysis result. It showed that parameter C (feed rate) had the most significant contribution to the surface roughness. In order to select the optimum combination of parameters B (cutting speed) and C, a two-way table was developed (to save some space, the two-way tables are not included in this paper). The two-way table showed that B1C0 produced the lowest surface roughness. From TABLE III, MQL cooling (A1) was chosen as the optimum level for cooling method (A).

S/N ratio from Fig. 3 shows that surface finish improved if the machining speed is increased from 60 m/min to 80 m/min. This result is similar to the highest machining speed endorsed by tool tip manufacturers (30-80 m/min) under flood cooling [21]. However, raising the speed to 100 m/min significantly increases the surface roughness value.

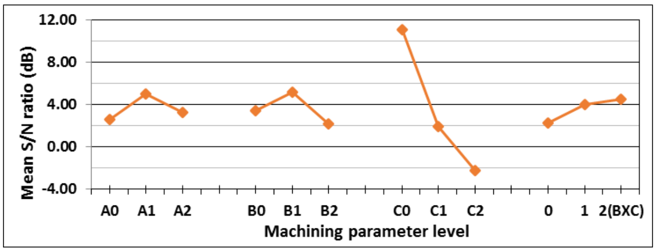

Fig. 3 Surface finish of workpiece

Fig. 4 confirms that the best surface finish is produced by MQL cooling, even though the most influential factor for surface finish is the feed rate. The cooling method is still observed to influence the surface finish; generally MQL provides an excellent surface quality.

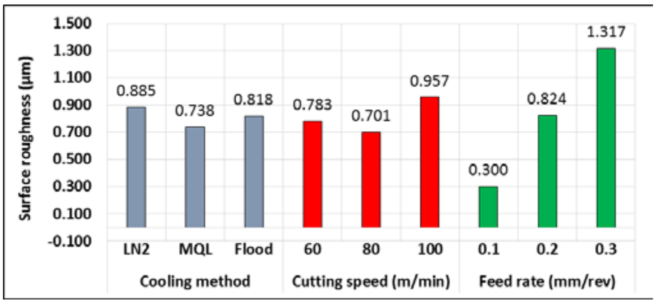

Fig. 4 Average variation of surface roughness for three machining parameters

Pictures acquired by Olympus Microscope BX51M Fig. 5 shows that when using the same cutting speed, 80 m/min (B1) and feed, 0.1 mm/rev (C0), machining with MQL (A1) (R_a = 0.151 µm) gave a better effect on the surface finish compared to flood coolant (A2) (R_a = 0.192 µm). Surface finish produced under flood coolant was only slightly better than that of cryogenic cooling (A0) (R_a = 0.260 µm), with respect to its effect on surface finish. Therefore MQL cooling method is feasible to replace flood coolant in titanium alloy end milling.

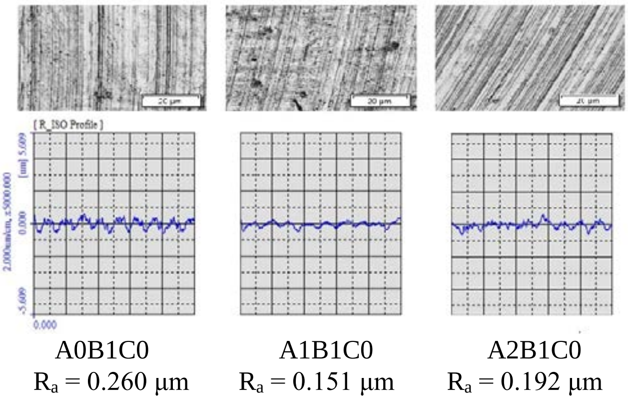

Fig.5 Surface profiles of B1C0 workpiece

The three measured cutting forces (Feed force (F_f), Feed normal force (F_{fN}), and Passive force (F_p)), were measured to calculate the total cutting force required for this alloy titanium milling process by using equation (2).

$$F_{total} = \sqrt{F_f^{\,2} + F_{fn}^{\,2} + F_p^2} \quad (2)$$

The response graph for the mean S/N ratio as shown in Fig. 6 verified the Pareto ANOVA analysis result. The two-way table showed that B0C0 requires the lowest cutting force. From TABLE IV, A1 was chosen as the optimum level for cooling method (A). The best parameters combination that requires the lowest cutting force was A1B0C0, i.e., medium level of cooling (MQL), low cutting speed (60 m/min) and low feed rate (0.1 mm/rev).

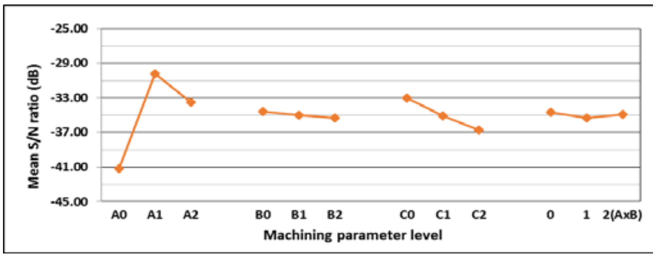

Fig. 6 Mean S/N ratio for cutting forces

The lowest machining temperature was produced from cryogenic cooling, followed by flood cooling, and the last being MQL. Analysis of Fig. 7 shows that reducing the temperature of the workpiece increases the cutting force; machining speed and feed rate had similar trends.

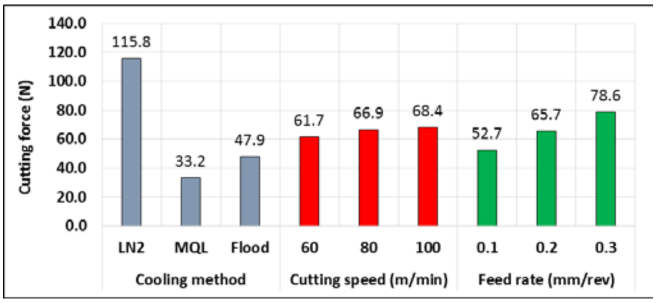

Fig. 7 Average variation of cutting force for three machining parameters

From TABLE V, A1 was chosen as the optimum level for cooling method (A). The best parameters combination that requires the lowest machine power was A1B0C0, i.e.,

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medium level of cooling (MQL), low cutting speed (60 m/min) and low feed rate (0.1 mm/rev). The two-way table showed that B0C0 requires the lowest power. Fig. 8 shows that MQL gave the best performance on required machine power, which was closely followed by cryogenic cooling, while traditional flood required the greatest machine power. This is clearly accountable to the fact that the coolant pump substantially increased the power requirements.

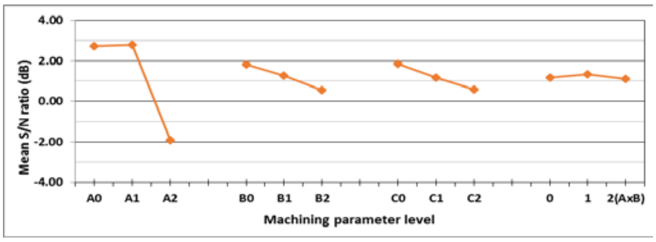

Fig. 8 Mean S/N ratio for machine power

For cryogenic cooling, commercial production of 1 kg of liquid nitrogen requires energy of approximately 0.5 kWh [47]. The evaporating liquid nitrogen during the machining process needs to be taken into account when calculating the total energy used for cryogenic cooling. This energy requirement of liquid nitrogen needs to be considered when evaluating the sustainability advantage between MQL. The machine power for speed and feed rate in Fig. 9 generally indicated that the cutting velocity on machine power to be higher than that of the feed rate.

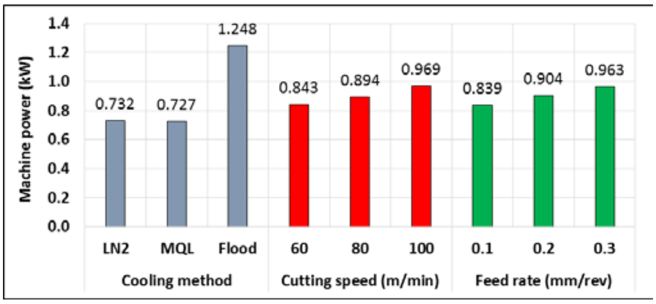

Fig. 9 Average variation of power requirement for three machining parameters

Analysis of Fig. 9 also shows that, on average, MQL cooling requires less energy compared to cryogenic and traditional coolant. Feed rate and cutting velocity show a similar trend, where the power requirement increases when feed rate and cutting velocity increase. Indicating that MQL cooling is more sustainable compared to cryogenic cooling in terms of energy requirement.

V. DISCUSSION

As expected, the lower feed rates provided the better surface finish of all cooling methods, and the rate (C) has a dominant effect on surface roughness, with a contribution ratio (*P* = 86.50%), followed by cutting speed (B) (*P* = 4.12%) and then cooling method (A) (*P* = 2.88%). The most significant interaction is BxC (*P* = 2.60%). Optimisation of surface irregularity through the selection of input machining conditions becomes easier, particularly the feed rate, since the total contribution of the main effects is 93% compared to 7% total contribution of the interaction effects. It is worth noting that for the feed rate of 0.1 mm/rev and 0.3 mm/rev, MQL cooling provides a better surface finish for all cutting speeds. In addition, to beneficially influence the surface finish, MQL also gave reduced measurement of the cutting force.

The Pareto ANOVA analysis for the cutting force TABLE IV shows that cooling method (A) gave the most significant effect on cutting force with a contribution ratio (*P* = 88.87%), followed by feed rate (C) (*P* = 9.90%) and then cutting speed (B) (*P* = 0.37%). The most significant interaction is AxB (*P* = 0.34%). MQL significantly lowered the cutting force compared to that of flood, and much lower when compared to that of cryogenic cooling, primarily due to the lubricating function, reducing the frictional forces between the tool and the workpiece. The workpiece temperature remains high, making it more plastic and reduces the efforts for cutting. MQL provides this better lubrication effect due to the consistent bond of lubricant with the surface of the workpiece [29]. It was found that when cryogenic cooling is used, the tool requires significantly greater cutting force, and is far greater compared to the other two cooling methods. Fig. 9 and TABLE IV show that the effect of cutting speed in terms of cutting force, is consistent with Ernst and Merchant who disregarded cutting speed in calculating cutting force [48].

The Pareto ANOVA analysis for machine power requirement Table V shows that cooling method (A) gave the most significant effect on cutting force with a contribution ratio (*P* = 89.74%), followed by cutting speed (B) (*P* = 4.90%) and then feed rate (C) (*P* = 4.84%). The most significant interaction is AxB (*P* = 0.15%). Optimisation of cutting force through the selection of input parameters becomes relatively uncomplicated, especially the cooling method, since the total contribution of the main effects is approximately 99%, compared to 1% of the total contribution of the interaction effects.

VI. CONCLUSIONS

Interestingly, the coolant was shown to have little effect with respect to feed rate on the surface finish of the workpieces. When MQL is being used as the coolant, the cutting forces were the lowest, which is a positive when trying to define the optimum sustainable cutting method. Cooling cryogenically does not allow the material to soften, therefore requiring more cutting force to shear the titanium workpiece. In addition, the liquid nitrogen increases the hardness of titanium alloy due to the formation of nitrides [49].

A summary of the key points of this work are:

- MQL when compared to cryogenic cooling and flood cooling has been proven more environmentally friendly
- MQL produces a better surface finish due to its ability to provide lubrication at the tool interface
- MQL reduced cutting force
- MQL provides the best surface finish with the highest cutting speed as recommended for flood cooling 30-80 m/min
- MQL requires no cooling pump power only a convenient compressed air supply
- Cryogenic cooling requires substantial energy in providing the liquid nitrogen

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It has been established that MQL is the best replacement for flood end milling of titanium alloy, as it is an environmentally friendly cooling method, and needs less energy in the making of the coolant. Compared to liquid nitrogen which needs additional plant to make it, using it, can be hazardous to the operator. Tool wear could not be verified in these tests as the length of time needed was not sufficient to produce observed wear on tool tip.

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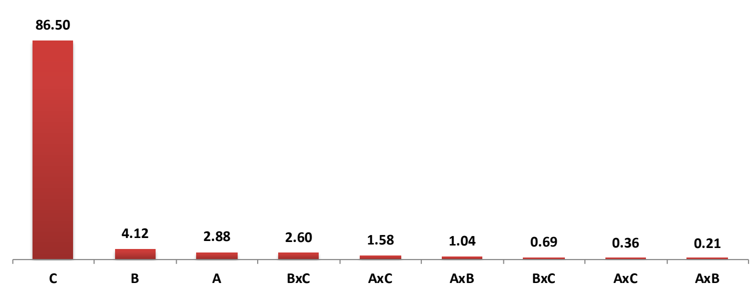
TABLE II
Measured parameters and their corresponding S/N ratios

Experiment No	Cutting Parameters	Measured Parametrs			Calcultaded S/N Raio		
		Surface Rougness (μm)	Cutting Force (N)	Machine Power (kW)	Surface Rougness (dB)	Cutting Force (dB)	Machine Power (dB)
1	A0B0C0	0.373	76.66	0.63	8.558	-37.699	4.006
2	A0B0C1	0.922	103.72	0.68	0.705	-40.324	3.343
3	A0B0C2	1.326	137.85	0.74	-2.450	-42.795	2.608
4	A0B1C0	0.260	99.93	0.67	11.693	-40.001	3.471
5	A0B1C1	0.978	121.54	0.74	0.193	-41.701	2.608
6	A0B1C2	1.058	140.7	0.75	-0.518	-42.973	2.492
7	A0B2C0	0.417	106.15	0.72	7.590	-40.526	2.846
8	A0B2C1	0.686	122.47	0.79	3.267	-41.768	2.040
9	A0B2C2	1.941	133.42	0.87	-5.762	-42.512	1.202
10	A1B0C0	0.313	25.08	0.61	10.097	-27.992	4.286
11	A1B0C1	0.704	34.99	0.67	3.017	-30.887	3.471
12	A1B0C2	1.227	41.28	0.71	-1.778	-32.323	2.968
13	A1B1C0	0.151	23.61	0.66	16.400	-27.470	3.602
14	A1B1C1	0.522	32.79	0.73	5.647	-30.323	2.726
15	A1B1C2	1.056	40.99	0.79	-0.471	-32.261	2.040
16	A1B2C0	0.181	24.14	0.71	14.856	-27.661	2.968
17	A1B2C1	0.857	33.28	0.79	1.340	-30.451	2.040
18	A1B2C2	1.631	42.73	0.87	-4.251	-32.622	1.202
19	A2B0C0	0.308	37.90	1.13	10.148	-31.579	-1.069
20	A2B0C1	0.600	45.29	1.19	4.441	-33.127	-1.518
21	A2B0C2	1.270	52.80	1.23	-2.077	-34.459	-1.805
22	A2B1C0	0.192	40.01	1.18	14.318	-32.050	-1.445
23	A2B1C1	1.149	46.64	1.23	-1.209	-33.383	-1.805
24	A2B1C2	0.942	55.47	1.30	0.519	-34.888	-2.286
25	A2B2C0	0.503	40.69	1.24	5.968	-32.198	-1.876
26	A2B2C1	0.999	50.13	1.32	0.006	-34.01	-2.419
27	A2B2C2	1.400	62.49	1.41	-2.921	-35.923	-2.992

TABLE III
Pareto ANOVA analysis for surface roughness

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	23.28	30.66	32.39	31.44	99.63	24.58	33.37	32.95	20.50
1	44.86	46.57	25.76	35.83	17.41	41.04	28.10	37.64	36.11
2	29.19	20.09	39.18	30.06	-19.71	31.71	35.86	26.74	40.72
Sum of squares of difference (S)	746.13	1065.84	270.29	54.42	22379.32	408.86	94.22	179.38	673.58
Contribution ratio (%)	2.88	4.12	1.04	0.21	86.50	1.58	0.36	0.69	2.60



Cumulative contribution	86.50	90.62	93.50	96.11	97.69	98.73	99.43	99.79	100.00
Check on significant interaction		BxC two-way table							
Optimum combination of significant factor level		A1B1C0							

TABLE IV
Pareto ANOVA analysis for cutting force

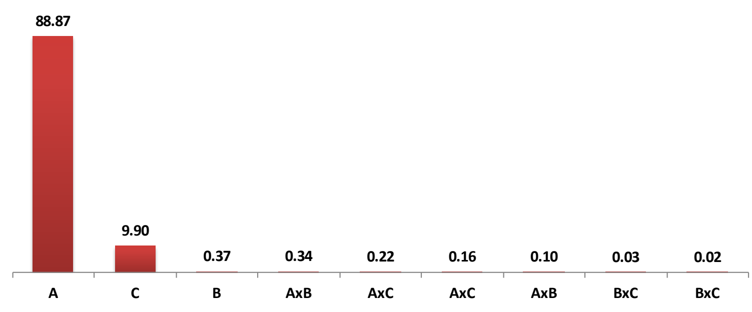
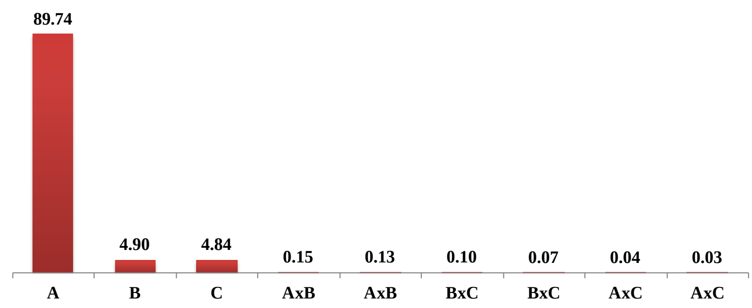
Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	-370.30	-311.19	-311.87	-313.00	-297.17	-315.95	-315.16	-313.62	-313.74
1	-271.99	-315.05	-318.01	-314.57	-315.97	-312.19	-316.83	-314.92	-314.84
2	-301.62	-317.67	-314.02	-316.33	-330.76	-315.77	-311.92	-315.37	-315.33
Sum of squares of difference (S)	15259.62	63.83	58.13	16.60	1699.71	27.03	37.28	4.94	3.99
Contribution ratio (%)	88.87	0.37	0.34	0.10	9.90	0.16	0.22	0.03	0.02
									
Cumulative contribution	88.87	98.77	99.14	99.48	99.69	99.85	99.95	99.98	100.00
Check on significant interaction		AxB two-way table							
Optimum combination of significant factor level		A1B1C0							

TABLE V
Pareto ANOVA analysis for machine power

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	24.62	16.29	10.63	11.04	16.79	10.79	11.48	11.13	10.17
1	25.30	11.40	12.01	10.39	10.49	11.76	9.81	10.34	11.48
2	-17.21	5.01	10.06	11.28	5.43	10.15	11.42	11.24	11.06
Sum of squares of difference (S)	3558.11	191.87	6.01	1.27	194.37	3.96	5.35	1.45	2.70
Contribution ratio (%)	89.74	4.84	0.15	0.03	4.90	0.10	0.13	0.04	0.07
									
Cumulative contribution	89.74	94.64	99.48	99.63	99.76	99.86	99.93	99.97	100.00
Check on significant interaction		AxB two-way table							
Optimum combination of significant factor level		A1B0C0							

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