Investigation of Cutting Parameters in Sustainable Cryogenic End Milling

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Abstract *Cryogenic machining has attracted significant attention in both academia and industry due to its ability to improve the machinability of difficult-to-machine materials and eliminate adverse environmental and health effects of conventional cutting fluids. Despite the industrial introduction of cryogenic machining systems, there is a considerable research gap in selection of cutting parameters for cryogenic machining. Due to its wide acceptance, Taguchi's process optimisation technique was used to identify the cutting parameters for cryogenic end milling of Ti-6Al-4V alloy. A combination of machining experiments and statistical analyses techniques and methods were undertaken to identify the level of cutting parameters with respect to different machinability metrics, namely surface roughness, tool life, power consumption and specific machining energy. The study indicated that cryogenic cooling facilitates adoption of higher cutting speeds in machining titanium alloy. This results in reduced specific machining energy whilst eliminating the necessity of employing conventional cutting fluids.*

1. Introduction and Background

The unique material properties proffered by titanium and its alloys have resulted in its increased demand and use across many industries including applications in aerospace, biomedical implants and nuclear industries [1]. Titanium has the highest strength to weight ratio among structural materials and is known to possess high yield strength and hardness (even at elevated temperatures), high creep resistance, high corrosion resistivity, high toughness and good biocompatibility [1-3]. On the other hand, machining titanium is considered to be a critical production bottleneck within various industries as it is a notoriously difficult-to-machine material [1].

In machining operations, the high material strength, toughness and hardness of titanium alloys results in the generation of excessive heat at the cutting zone. On the other hand, poor thermal conductivity and high thermal capacity of the material prevents effective heat dissipation through the workpiece and machining chips. As a result, the generated heat accumulates at the cutting zone and results in premature tool failure and poor surface integrity [4]. Using a generous amount of water-based cutting fluids is a common approach in enhancing heat dissipation and improving machinability in machining titanium alloys. However, metal working fluids are commonly considered as environmental and health hazards. Recent studies have raised concerns with regards to the effects of long term exposure to cutting fluids. There is a range of respiratory, skin diseases and even cancer associated with the exposure to cutting fluids [5, 6]. Furthermore, the existence of chemicals such as bactericides, fungicides and germicides in water-based coolants increases their adverse impacts on environment. Therefore, governmental regulations require safe treatment and disposal of cutting fluids [1]. It is noteworthy to mention that preparation, maintenance, treatment and disposal of cutting fluids form a significant portion of machining costs [7].

Using liquefied gases such as liquid nitrogen has been acknowledged by various researchers as an environmentally friendly alternative to the use of conventional water-based cutting fluids [7-9]. In this method, termed cryogenic machining, a liquefied gas at cryogenic temperatures is sprayed into the cutting zone to freeze the cutting zone and alter the material properties of the cutting tool and workpiece whilst controlling cutting temperature. Cryogenic machining is also known to significantly improve machinability of difficult-to-machine materials such as titanium and nickel alloys [10].

There are a significant number of studies reporting that spraying liquid nitrogen into cutting zone in turning operations can favourably control the cutting temperature, increase tool life and improve surface finish of machined workpieces [10]. For instance, Hong and Zhao [11] claimed that using liquid nitrogen resulted in up to a 5 fold improvement in tool life in turning Ti-6Al-4V, whilst Dhananchezian and Kumar [12] concluded that using liquid nitrogen as a coolant significantly reduced tool wear geometry compared with conventional wet machining. Moreover, 36% reduction in surface roughness was achieved through cryogenic cooling. Similar observations were reported by Klocke et al. [13], where using liquid carbon dioxide and liquid nitrogen significantly reduced the flank wear growth rate when compared with conventional flood cooling.

Review of the published literature [10] indicated that there is a significant research gap on selection of cutting parameters for cryogenic machining and there is no published data for solid carbide end milling. This paper presents a study to identify the levels of cutting parameters for cryogenic end milling of Ti-6Al-4V α-β titanium alloy using coated solid carbide end mills. In this paper, the methodology used for machining experiments is explained in detail. Four machinability metrics of surface roughness, tool wear, power consumption and specific machining energy are considered for analysis. The results of the machining experiments together with analysis are also provided. The results are further discussed to identify the effects of various cutting parameters on different machinability metrics in cryogenic end milling of Ti-6Al-4V alloy.

This paper intends to provide a benchmark for industries willing to adopt cryogenic machining for their subtractive machining processes. Furthermore, this paper provides a baseline for selecting cutting parameters for further studies in modelling and optimisation of cutting parameters for various machinability metrics.

2. Methodology for Cryogenic Machining Experiments

In order to study the effects of using liquid nitrogen (LN_2) on the machinability of heat-resistant alloys in CNC end milling operations, a cryogenic cooling system has been designed and manufactured. Figure 1 illustrates a pictorial view of the system, which consists of a cryogenic Dewar, a series of vacuum jacketed pipes and cryogenic valves and a cryogenic nozzle. The nozzle is designed as such it can be retrofitted to an existing conventional Bridgeport vertical CNC milling machine. The aim of the design is to spray a controlled stream of LN_2 at -197°C along the cutting tool into the cutting zone, freezing the cutting zone without significant effect on the workpiece material.

For the purpose of this study, four input parameters of cutting speed (V_c), chip load (f_z), depth of cut (a_p) and cryogenic flow rate ($\dot{m}$) were identified at three levels as shown in Table 1. An L9 Taguchi orthogonal array design was selected as an appropriate design of experiment in order to develop a meaningful combination of cutting parameters at various levels whilst reducing the number of experimental runs. Taguchi's design of experiments (DoE) is one of the most widely used and well known approaches for process optimisation which was developed by Genichi Taguchi, a Japanese engineer [14]. His approach has had a prominent influence in the adaptation of the DoE in industry by introducing a low resolution orthogonal array design. This design is derived from fractional factorial design and significantly reduces the number of experimental runs, resulting in its popularity [14, 15].

Table 2 illustrates the process parameters and specifications of the DoE used for this study. Four machinability metrics were selected as monitoring parameters and includes surface roughness (Ra), tool life, power consumption (P) and specific machining energy (SE).

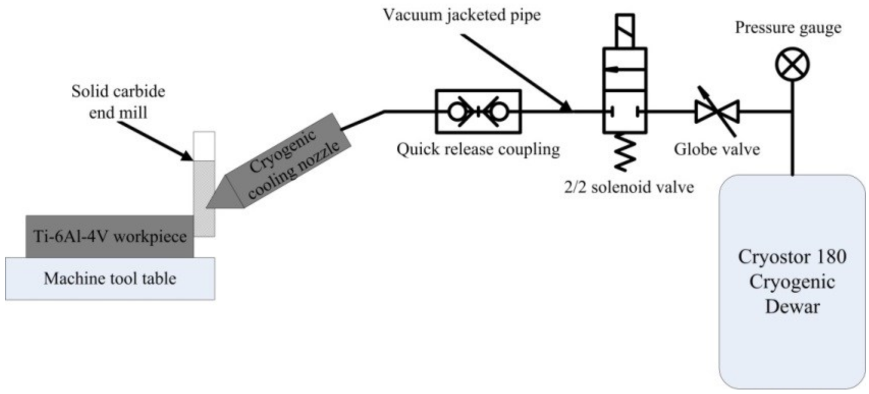

Figure 1, Schematic presentation of the cryogenic cooling system used for machining experiments

Table 1, Machining parameters and the associated levels used for machining experiments

	Parameter	Level -1 (lower)	Level 0 (medium)	Level 1 (higher)
A	Cutting speed (m/min)	30	115	200
B	Chip load (mm/tooth)	0.01	0.055	0.1
C	Depth of cut (mm)	1	3	5
D	Flow rate (kg/hr)	10	20	30

Table 2, Taguchi's L9 orthogonal array design of experiments

ID	A- Cutting speed (m/min)	B- Chip load (mm/tooth)	C- Depth of cut (mm)	D- Flow rate (kg/hr)
1	30	0.01	1	10
2	30	0.055	3	20
3	30	0.1	5	30
4	115	0.01	3	30
5	115	0.055	5	10
6	115	0.1	1	20
7	200	0.01	5	20
8	200	0.055	1	30
9	200	0.1	3	10

The machining experiments were conducted on a Bridgeport VMC 610xp vertical CNC milling centre shown in Figure 2. This was equipped with the developed cryogenic cooling system and a HIOKI HiTester 3169-20 power demand analyser. The machining experiments consisted of end milling with a 12mm PVD TiAlN coated solid carbide cutter, with a 30° helix angle and a 12° rake angle. In order to minimise variations in experiments, the tool overhang and radial depth of cut (a_p) were kept constant at 40mm and 4mm respectively throughout the experiments. Furthermore, each experiment was repeated three times and the mean value of the results were used for analysis.

A 150mmx100mmx50mm block of Ti-6Al-4V α-β titanium alloy was used for each machining experiment. To ensure consistency of the material properties, the blocks were sourced in one batch and were annealed prior to the experiments to reduce variability in material properties. The average material hardness for the titanium blocks were 298VH with 5% standard deviation. For each test, a new cutting tool was used and linear paths of 150mm length and 4mm width were machined along the length of the workpiece blocks. Moreover, the power consumption of the machine tool was monitored in real time.

The machining experiments were continued until the cutting tool reached the criterion indicated by ISO 8688-2:1989 [16]. During the experiments, the machining operation was interrupted at various intervals and the tool wear was measured using a high resolution digital tool maker's microscope. Based on ISO 8688-2:1998 [16], the tool life criterion for this experiment was defined as max 300μm flank wear. Other tool wear phenomenon e.g. notching, chipping, staircase flank wear, etc. were treated as flank wear. The standard suggests expressing tool life in terms of time, however due to the changes in the cutting speed and feed rate of the machining experiments, machining time does not provide a meaningful comparison for the tool life. Therefore in this study the tool life was represented in terms of machining length (ML) and the volume of machined material (VMM).

The arithmetic surface roughness (Ra) of the machined surface was measured using a Proscan 2000 optical profilometer with 10nm resolution. The methods outlined in BS EN ISO 4288:1998 were strictly followed for measuring the surface roughness of each sample [17].

Furthermore, the machine tool's energy consumption during material cutting was calculated from the power consumption. Subsequently, the energy consumption per unit volume of machined material was calculated by dividing the machine tool's energy consumption by the machined volume for each machining experiment to represent specific machining energy.

Figure 2, Bridgeport CNC milling centre used for machining experiments equipped with cryogenic cooling system

3. Results and Discussion

Four output parameters, namely surface roughness, tool life, power consumption and specific machining energy were measured for this study. Taguchi introduced using Signal to Noise (SN) ratio, instead of standard deviation, as a measure for process improvement [18]. The SN ratio is classified into three categories of [18]:

Eq. 1 Nominal-is-best

SN = $10\ log_{10}(\frac{\bar{Y}^2}{\sigma^2})$ when response mean and variance are related

or SN = $-10\log_{10}\sigma^2$ where mean and variance can be treated independently

Eq. 2 Smaller-is-better SN = $-10\log_{10}(\frac{\sum y^2}{n})$

Eq. 3 Larger-is-better SN = $-10\log_{10}(\frac{1}{n}\sum\frac{1}{y^2})$

where, for a sample *y*, $\bar{Y}$ is the sample mean; σ^2 is the variance and *n* is the sample size for one experiment. For this study the values of Ra, P and SE are to be minimised and the ML and VMM are to be maximised. Thus, Eq.2 was used to calculate the SN values for Ra, P and SE whilst Eq.3 was used to compute the SN value for tool life, namely ML and VMM. Table 3 presents the average measured values for each of the machinability metrics.

Table 3, Experimental results for various machinability metrics

ID	Average Measured Values				
	Ra (µm)	**ML (mm)**	**VMM (mm^3)**	**P (W)**	**SE (J/mm^3)**
1	0.25	600	2400	1291	811.2
2	0.5	1650	19800	1332	51.1
3	1.5	278	5557	1495	18.9
4	0.33	750	9000	1311	71.4
5	0.52	1650	33000	1556	10.4
6	0.68	900	3600	1361	22.7
7	0.26	4650	93000	1478	28.1
8	0.51	750	3000	1511	27.7
9	0.76	349	4194	2037	6.8

Based on the measured results for each experiment, the mean SN ratio was computed for each parameter at different levels. Table 4 shows the calculated mean SN ratio for different levels of each parameter for surface roughness (Ra), tool life (ML and VMM), power consumption (P) and specific machining energy (SE), respectively. Taguchi recommends a visual approach to identify the effect of each parameter and its optimum level by plotting the mean SN ratio against each level and then identifying the parameters which appear to be most significant. Consequently, this approach suggests the level with the highest SN ratio is the desired level for a particular output parameter.

Table 4, Response table for average SN ratio for different machinability metrics

Machinability Metric	**Cutting Parameter**	**Mean of SN** Level -1	0	1	**δ**
Ra	V_c	4.9	6.3	6.7	1.8
	F_z	11.2	5.9	0.7	10.5
	a_p	7.1	6.1	4.6	2.6
	$\dot{m}$	6.69	7.06	4.00	3.06
VMM	V_c	76.1	80.2	80.5	4.3
	F_z	82.0	82.0	72.8	9.2
	a_p	69.4	79.1	88.2	18.8
	$\dot{m}$	76.81	85.48	74.51	10.97
ML	V_c	56.3	60.3	60.6	4.3
	F_z	62.1	62.1	52.9	9.2
	a_p	57.4	57.6	62.2	4.8
	$\dot{m}$	56.93	65.59	54.63	10.97
P	V_c	-62.7	-63.0	-64.4	1.7
	F_z	-62.7	-63.3	-64.1	1.5
	a_p	-62.8	-63.7	-63.6	0.9
	$\dot{m}$	-64.08	-62.85	-63.14	1.23
SE	V_c	-39.3	-28.2	-24.8	14.5
	F_z	-41.4	-27.8	-23.1	18.3
	a_p	-38.1	-29.3	-24.9	13.1
	$\dot{m}$	-31.85	-30.09	-30.55	1.76

The calculated values were used to generate the plots in Figure 3, which illustrates the underlying effects of each parameter on the machinability metrics. Inspection of these plots facilitated the calculation of delta (δ), the difference between the minimum and maximum values of SN ratio for each parameter. δ serves as a measure of the significance level of one particular parameter with respect to the others.

The analysis of SN ratio graphs for all the machinability metrics evaluated, indicated that cryogen flow rate of 20kg/hr has the highest value of mean SN ratio and thus is the most desirable level to achieve improved machinability. Visual inspection of the mean SN ratio graphs, shown in Figure 3, identifies that using lower level of chip load (0.01mm/tooth) and depth of cut (1mm) and the higher level of cutting speed (200 m/min) facilitates improved surface roughness. Considering the plots in conjunction with the delta values shown in Table 4, it can be seen that the most significant parameters affecting surface roughness are chip load followed by cryogen flow rate and depth of cut. The plots indicated that increasing the chip load exacerbates surface roughness. A similar relationship can be extracted from the mean SN ratio graphs of surface roughness for depth of cut.

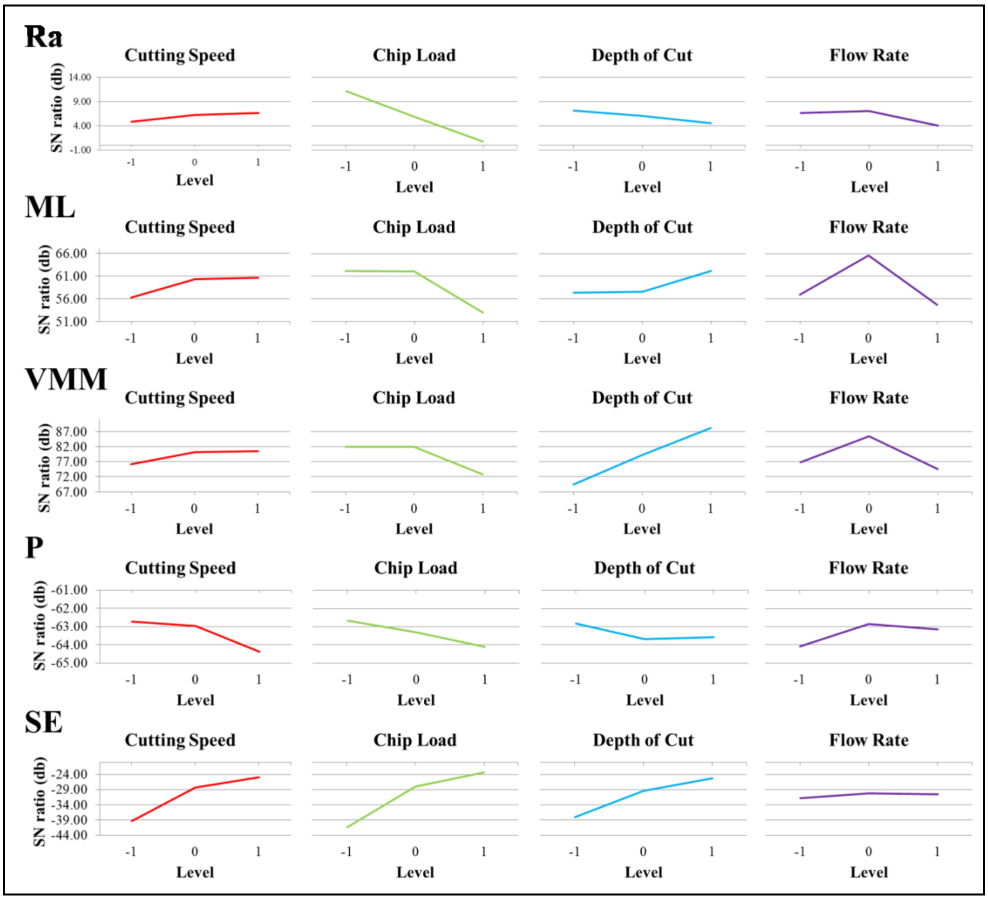

Figure 3, Mean SN ratio graphs for various machinability metrics

As can be seen in Table 4 and through inspection of the mean SN plots for tool life (Figure 3), extended tool life (ML or VMM) requires the use of higher level cutting speeds and depths of cut. The analysis shows that the effect of chip load on tool life is limited at 0.01mm/tooth and 0.055mm/tooth but it significantly reduces tool life at higher chip loads. The experiments revealed that initially the cutting tools suffer from mechanical wear mechanisms such as abrasion, flaking, chipping and notching resulting in exposure of carbide substrate. The exposure of carbide substrate facilitates abrasion wear and also thermally induced tool wear mechanism such as crater wear, built up edge and diffusion. For instance, in experiment 6, as shown in Figure 4a and 4b, abrasion and flaking exposed the carbide substrate after 450mm of machining length. The exposure of carbide substrate facilitated the growth of crater wear and subsequently weakening of the cutting edge as shown in Figure 4c after 750mm of machining. Further machining resulted in chemical reaction between the cutting tool and workpiece material. Flow of cutting chips over the rake face and thus deeper crater wear together with abrasion of flank face resulted in tool failure (Figure 4d).

Comparison of δ for depth of cut in ML and VMM reveals that depth of cut is more crucial when the volume of machined material is of interest. This can be explained by the fact that the VMM is a product of ML multiplied by radial and axial depths of cut. Whilst the radial depth of cut was kept constant for all machining experiments, multiplying ML by axial depth of cut significantly increases the effect of depth of cut on the VMM resulting in higher level of significance.

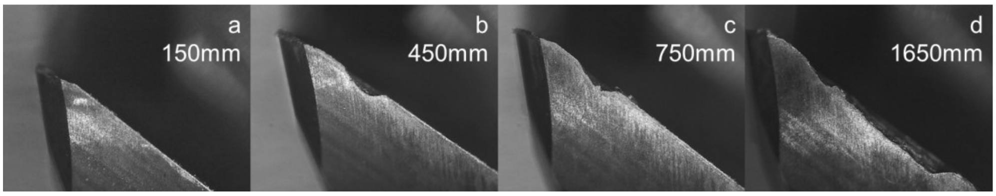

Figure 4, Microscopic images of the cutting tool used for experiment 6 after various machining length

δ shows that flow rate is the most significant parameter affecting ML and the second most significant in VMM only after depth of cut, indicating the importance of cryogenic cooling on tool life. Within the selected levels of machining parameters, the analysis shows that chip load is the second most significant parameter affecting the ML, followed by depth of cut and cutting speed respectively. Furthermore, the latter was recognised as the least significant parameter for tool life.

As shown in Table 4 and illustrated in Figure 3, the study of the SN ratio for power consumption demonstrated that in order to reduce the power consumption of the machine tool, a low level of cutting speed (30 m/min), chip load (0.01 mm/tooth) and depth of cut is preferred. In contrast, the analysis suggests using higher levels of cutting parameters in order to minimise specific machining energy. Energy consumption of the machine tool may be defined as the integration of power consumption with respect to time.

Eq. 4 SE $= \int_{t_0}^{t_f} P \, dt$

where P is power consumption and t is machining time

This metric has broader application in the field of manufacturing as it defines the energy cost of machining a part. The time is directly affected by cutting speed and chip load, therefore these parameters must be maximised to reduce the energy consumed in the manufacture of a part. It is known that the energy required to run the machine tool significantly outweighs that required to remove material, hence the importance of reducing process times is of paramount importance. Furthermore, specific machining energy is the energy consumption of a machine tool for removing a unit volume of workpiece material. Thus, increasing the material removal rate through selection of higher depth of cut can have significant effect on SE. The SN ratio analysis supported this observation as higher levels of cutting speed, chip load and depth of cut were recommended in the case of minimising SE. Moreover, comparing δ value for SE suggests that chip load is the most significant parameter affecting SE being followed by cutting speed and depth of cut respectively.

Further to SN ratio analysis, Pareto ANOVA was performed in order to identify the significance level of each input parameter on various machinability metrics. This tool is a simplified ANOVA, which does not require the F-test to be performed and has previously been used by researchers [19, 20] to identify the contribution percentage of parameters on the desired quality measures. In this method the sum of squares of the results obtained for each parameter is calculated and then used to identify its contribution percentage. Based on the calculated results, a Pareto diagram is generated, which also shows the accumulative contribution of the parameters for the desired quality measure. Prior to performing the analysis, the data was tested for normality and a Box-Cox power transformation was used to normalise the data. Figure 5 illustrates the Pareto diagrams for the results generated from the sum of squares of the measured results for each machinability metric. The Figure shows the contribution percentage of each input parameter on controlling the selected machinability metric. As shown in Figure 5, input parameters are ordered from higher influence on the left to the lower on right hand side of each diagram.

The Pareto ANOVA analysis confirms the δ results obtained from SN ratio analysis. Furthermore, it quantifies the contribution of each input parameter. For instance, whilst it has been found that chip load is the most significant parameter affecting surface roughness, Pareto ANOVA demonstrated that the selection of chip load contributes to more than 80% of the resultant surface roughness. Similarly, as shown in Figure 5, accumulated contribution of flow rate and chip load forms more than 80% of ML tool life whilst it is depth of cut and flow rate for VMM tool life.

4. Conclusions

The experimental results and analysis indicated that cryogenic cooling using liquid nitrogen is a viable method to improve machinability of titanium alloy whilst reducing the adverse environmental impacts of using conventional cutting fluids. Nitrogen is an inert, odourless and colourless gas which forms almost 78% of atmosphere [10]. The analysis indicated that cryogenic cooling can facilitate employing higher cutting speeds hence increasing material removal rate whilst improving machinability through improved surface roughness and tool life. Whilst the analysis revealed that cryogen flow rate has a very limited impact on machine tool energy consumption, by realising higher cutting speeds, cryogenic cooling has potential to significantly reduce the energy consumption for removing a unit volume of workpiece material.

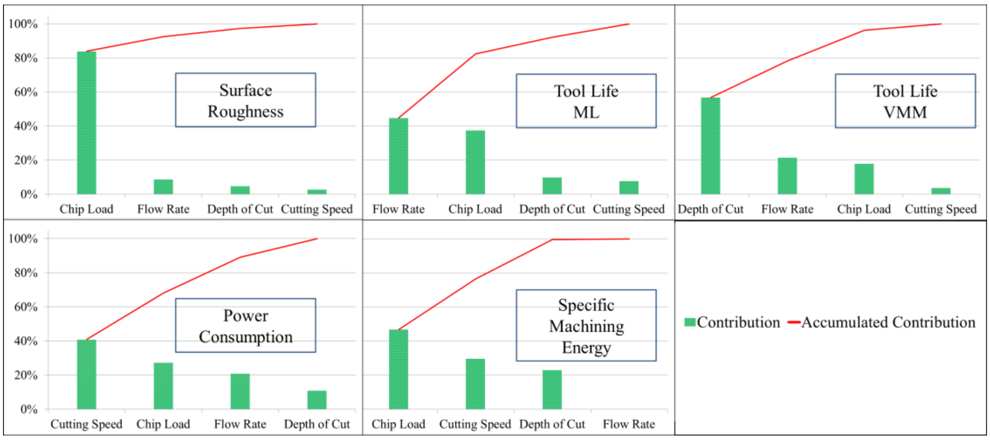

Figure 5, Pareto ANOVA analysis of the results for various machinability metrics

The analysis indicated that medium level of cryogen flow rate (20kg/hr) is the most favourable amount of liquid nitrogen for improving all machinability metrics considered in this study. Furthermore, higher levels of cutting speed are recommended to achieve improved surface roughness and tool life. Further studies are required to statistically and mathematically model different machinability metrics based on cutting parameters and to identify optimised values for each parameter.

5. References

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