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Evaluation of cutting forces, cutting temperature and surface roughness in Cryogenic CO_2 cooling in conventional milling machine using AISI-D2 steel

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Abstract: Metal cutting is the major manufacturing operation today in view of the economic significance. A fundamental knowledge of the metal cutting process is essential to find optimum conditions and develop new cutting equipment. Cutting temperature plays a vital role in the machining of AISI D2 steel. This cutting temperature increasingly important to study how the machining temperature are affected by cutting velocity, feed, and depth of cut and tool wear. Also, wear of tool is also related to cutting forces. Therefore experiments are conducted with cryogenic CO2 involved simultaneous measurement of cutting forces, cutting temperature and surface roughness using milling tool dynamometer, K-type thermocouple and surface roughness tester. The major parameter that is considered for optimization in conventional end milling operation is cutting speed, feed, and constant depth of cut. Results from the experiments are analysed by design of experiment method by using MINI TAB 17 software namely, ANOVA, and Taguchi analysis

Keywords: Cryogenic Machining CO2, Cutting forces, Cutting Temperature, Surface Roughness, ANOVA, Taguchi Analysis,

Introduction

Machining is a term that is related to removal of unwanted material, usually in the form of chips, from a workpiece. This process is used to convert preformed blocks of metal into the desired shape, size and finish specified, often to great precision in order to fulfil design requirements. **Davoodi and Hosseinzadeh (2012)** studied that Accurate temperature measurement is a challenging task to find the effect process parameters involved. Hence, machining processes are often the most expensive. Although the theoretical analysis of the metal cutting process is complex, the application of these processes in the industrial world is widespread. The study of metal cutting focuses on the behaviour of the tool and workpiece material that influence the efficiency and quality of cutting operations. The metal cutting process involves pressing of a cutting tool against the workpiece, with a certain degree of force, resulting in the removal of material from the workpiece, in the form of chips. This results in enormous heat generation at the tool-chip interface. Hence, continuous use of the cutting tool for machining results in tool wears eventually leading to its failure.

In this research work K-Type thermocouple is used, the temperature measuring range of K type is up to 1250 °C and it works on seek effect where the tool acts as a hot junction and workpiece as a cold junction and an electromotive emf establish in between hot-cold junction as discussed by **Sekulic. Gostimirovic et al.(2011)**

HaciSaglam et al (2006) conducted the experiment in the effect of cutting speed on main cutting force and tool tip temperature. In this study, the effects of rake angle and cutting speed on cutting force and the temperature generated on the tooltip is investigated. During the tests, the depth of cut and feed rate were kept constant. The orthogonal arrays as L16 were used with a total of 16 tests. Finally, it was found that the rake angle was effective . While cutting speed was effective on the tooltip temperature.

A lot of research has been conducted on determining the optimal cutting parameters. **Shreemoy Kumar Nayak et al (2014)** conduct the experiment in the influence of machining parameters viz., cutting speed, feed and depth of cut on turning of AISI 304 stainless steel using ISO P30 grade uncoated cemented carbide insert and adopted L27 orthogonal array to measure the characteristics of machinability such as material removal rate (MRR), Cutting force (Fc) and surface roughness (Ra). The machining parameters are optimized using grey relational analysis.

The Analysis of Variance (ANOVA) and Signal-to-Noise ratio are used to study the performance characteristics in a milling operation. Analysis of variance (ANOVA) was introduced by **Sir Ronald Fisher**. (1925). This analysis was carried out for a level of significance of 5%, i.e., for a 95% level of confidence. Taguchi method is a powerful tool for the design of high-quality systems. It provides a simple, efficient and systematic approach to optimize the design for performance, quality and cost.

Bouacha et al. (2014) optimized hard turning operation in respect of cutting speed, feed rate, depth of cut, and machining time. The tool wear, surface roughness, cutting forces, and metal volume removed were the responses, whereas the grey-Taguchi, composite desirability, genetic algorithm, and ANOVA were the optimization and analysis tools. The cutting speed and feed rate were the most significant factors for surface roughness; specifically, the higher cutting speed produced a better surface finish.

Ghani et.al (2004**)** established that the conceptual S/N ratio and ANOVA approach for data analysis in end milling uses at the high cutting speed of 355 m/min, the low feed rate of 0.1mm per tooth and low depth of cut of 0.5 mm. Application of Taguchi's method for parametric design has been carried out to determine an ideal feed rate and desired force combination, the experimental results showed that surface roughness decreases with a slower feed rate and larger grinding force.

Hamdan et al. (2012) had approached the lubrication modes and cutting variables to optimize the surface roughness. The Taguchi L9 orthogonal array and ANOVA revealed that the feed was the most dominating factor followed by cutting speed and axial depth of cut, while lubrication modes contributed the least. The confirmation test manifested 41.3 % better result.

Dinesh et al. (2015) concluded that the effects of cryogenic cooling on cutting temperature, force, and surface roughness; the drawn conclusion is that around 60 % temperature is reduced compared to dry turning.

The industry is therefore dominated by small and medium-sized enterprises. Cryogenic machining companies offer a range of services, including cryogenic nitrogen and CO_2 method liquefied gases are directed into the cutting zone and absorb the heat and finally evaporate into the atmosphere. the experiments are analysed by design of experiment method by using MINI TAB 17 software namely, ANOVA, and Taguchi analysis.

2. Experimental procedure

Conventional end milling test was performed using HMT M1TR conventional milling machine attached with DRO. In this study, AISI D2 Steel is used as a work pice material and CVD TiN coated carbide insert based tool is used. In this study, work material have the dimensions of 150x50x50mm. The table 1 and 2 shows the properties of AISI D2 steel and figure 1 shows the SANDWICH make CVD TiN coated carbide insert which is used in this experiment. Cryogenic CO_2 was delivered by the copper nozzle at a required pressure of 10bar.This cryogenic CO_2 liquified gases directed to the cutting zone and absorb the heat and finally.it evaoprates as shown in fig 2

Fig 1. Photographic view-cutting tool insert

Table: 1 Chemical Composition of AISI D2 Steel

Element	Amount (%)
Carbon	1.50%-1.70%
Silicon	0.1%-0.35%
Manganese	0.25%-0.50%
Chromium	11%-13%
Molybdenum	0.80% max
Vanadium	0.80% max
Iron	Balance

Table: 2 Mechanical properties of AISI D2 Steel

Mechanical Property	Metric Value
Hardness Rockwell C	62
Density	7.7x1000 Kg/m^3
Poisson ratio	0.27-0.30
Elastic modulus	190-210Gpa
Thermal conductivity	20 W/mK

Fig 2 Cryogenic Machining CO_2

In the current study cutting force, cutting temperature, and surface roughness have been measured in the end milling operation on AISI H13 steel and CVD TiN coated carbide insert under dry, wet and cryogenic CO_2 condition. The cutting force prompt during end milling operation can be divided into three components (1) Feed Force (F_X) (2) Normal force (F_Y) and (3) Axial force (F_Z). These three cutting forces are measured by using milling tool dynamometer under dry wet and cryogenic CO_2 condition. Similarly cutting temperature and surface roughness was measured by using K-Type thermocouple and surface roughness tester. The results obtained are listed in table 3, under dry, wet and cryogenic CO2 environment.

Table 3. Experimental results for Cryogenic CO_2 machining -AISI D2 Steel material Cutting Forces, cutting Temperature and Surface Roughness parameters measurements reading

Sl.No	Cutting Velocity m/min	Feed mm/rev	Cutting Forces in N			Temperature Measured in °C	Surface Roughness R_a
			Feed Force F_X	Normal force F_Y	Axial force F_Z		
1	17.84	0.034	175	160	125	28	0.42
2	17.84	0.074	180	170	105	28	0.5
3	17.84	0.150	180	165	105	27	0.58
4	45.24	0.034	160	180	130	28	0.5
5	45.24	0.074	170	170	120	29	0.51
6	45.24	0.150	155	180	110	29	0.52
7	70.37	0.034	155	150	105	28	0.36

8	70.37	0.074	155	145	100	29	0.42
9	70.37	0.150	140	145	90	28	0.41

3. Results and Discussion

3.1 Cutting Forces:

3.1.1 ANOVA for cutting forces:

The measured cutting forces are shown in table 3. It is necessary for analyze the cutting forces to increases the process capability and increase the productivity in the production cycle. In order to evaluate the significant factor that tends to affect the desired output parameter, ANOVA is performed. ANOVA is a mathematical technique which based on the least square approach. The experimental results are based on the analysis of variance. Table of ANOVA shows the degrees of freedom (DF), the sum of squares (SC), mean squares (MS), F-values (F) and probability (P) in addition to the percentage contribution (Cont. %) of each factor and different interactions dry. A low P value (≤ 0.05) indicates statistical significance for the source on the corresponding response. The analysis was run using the Minitab software with the General Linear Model Technique with a confidence level of 95%. This method identified the important parameters and also compute the percentage of influence of each parameter on different responses. From table 4,5,and 6 we can observe that cutting speed (cont ≈ 81.113 %, 91.1143% and 55.1284) have great influence on the feed force (F_X), Normal force (F_Y) and Axial Force (F_Z) Obtained that is Cutting Speed contributes the most for the cutting force when compared to feed rate.

Table 4. Analysis of Variance for Feed Force F_X for cryogenic CO_2 machining

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cont
Cutting Speed	2	1216.7	608.33	18.25	0.010	81.113%
Feed	2	150.0	75.00	2.25	0.221	10.00%
Error	4	133.3	33.33			8.886%
Total	8	1500.0				

Table 5. Analysis of Variance for Normal Force F_Y for cryogenic CO_2 machining

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cont
Cutting Speed	2	1372.22	686.111	21.48	0.007	91.1143%
Feed	2	5.56	2.778	0.09	0.918	0.36929%
Error	4	127.78	31.944			8.4872%
Total	8	1505.56				

Table 6. Analysis of Variance for Axial Force F_Z for cryogenic CO_2 machining

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cont
Cutting Speed	2	716.67	358.33	21.50	0.007	55.1284%
Feed	2	516.67	258.33	15.50	0.013	39.7438%
Error	4	66.67	16.67			5.1284%
Total	8	1300.00				

3.1.2 Signal Noise Ratio : (S/N ratio)

Taguchi proposed three categories of performance characteristics in the analysis of the S/N ratio, that is, the smaller the better, the higher the better, and the nominal the better. Since the objective of this work is to reduce the selected response (Cutting force), So Smaller the better characteristics of the S/N ratio is selected in MINITAB 17 software. The S/N ratios were computed for Feed force F_X, Normal force F_Y and axial force Fz using the Minitab 17 data analysis software.

Table 7 Signal noise ratio value for Feed force (F_X) for cryogenic CO_2 machining

Level	Cutting Speed m/min	Feed mm/rev
1	-45.02	-44.25
2	-44.17	-44.51
3	-43.51	-43.94
Delta	1.51	0.56
Rank	1	2

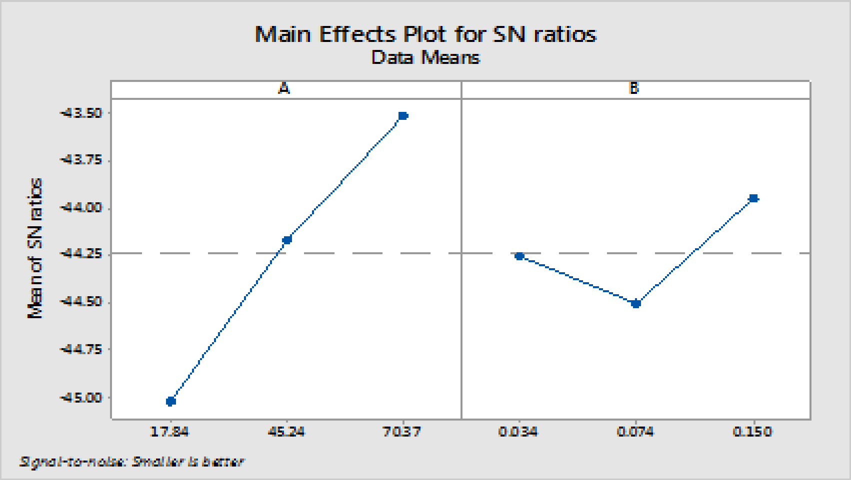

Fig 3. S/N ratio for Feed force F_x in Cryogenic CO_2 machining

Table 8 Signal noise ratio value for Normal force (F_Y) for cryogenic CO_2 machining

Level	Cutting Speed m/min	Feed mm/rev
1	-44.35	-44.24
2	-44.94	-44.15
3	-43.33	-44.23
Delta	1.61	0.09
Rank	1	2

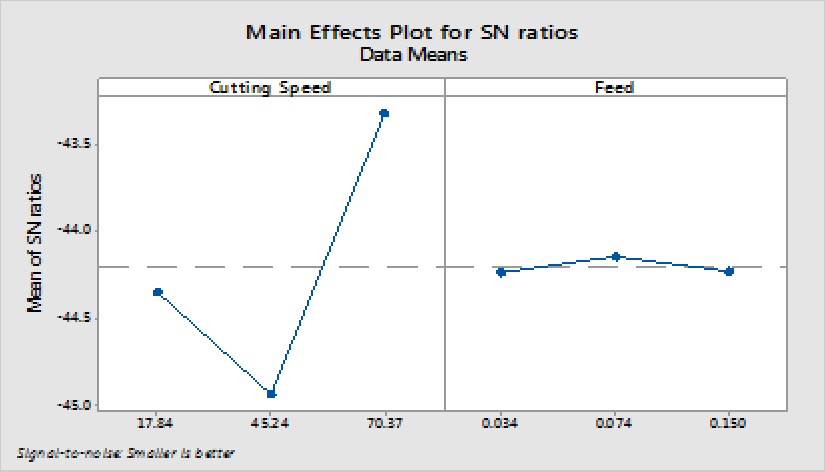

Fig 4. S/N ratio for Normal Force F_Y in Cryogenic CO2 machining

Table 9 Signal noise ratio value for Axial force (F_Z) for cryogenic CO_2 machining

Level	Cutting Speed m/min	Feed mm/rev
1	-40.93	-41.55
2	-41.56	-40.67
3	-39.84	-40.11
Delta	1.73	1.43
Rank	1	2

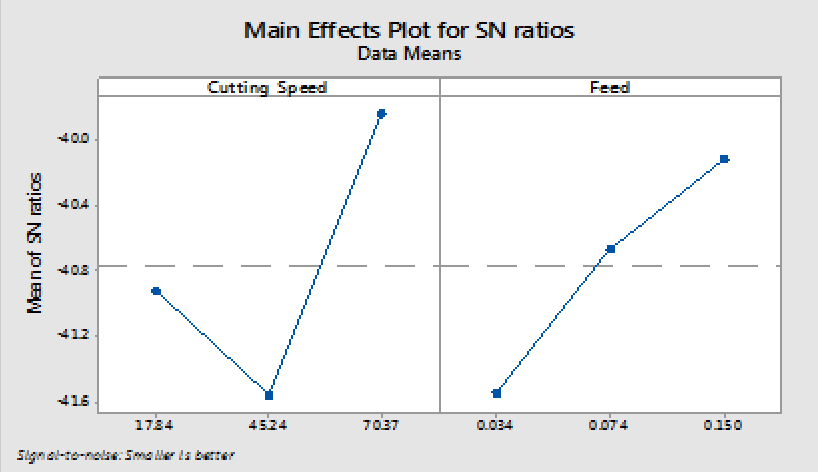

Fig 5. S/N ratio for Axial Force F_Z in Cryogenic CO2 machining

Fig 3,4 and 5 shows an S/N ratio for the feed force Fx, Normal Force F_Y, and Axial force F_Z, with respect to feed and cutting speed levels chosen for the experimentation. It is clear that cutting speed is dominating parameter in all the three forces (F_X, F_Y, and F_Z). Infeed force, F_X fig 3 observed that as a cutting speed increases cutting forces decreases and lowest value of cutting force is observed at cutting speed 70.37 m/min. Similarly, as a feed rate increases cutting force increases and lowest value of cutting force are observed at the feed rate is 0.150 mm/rev, but in the normal force, F_Y as a cutting speed increases cutting forces decreases and lowest value of cutting force is observed at cutting speed 70.37 m/min. Similarly, as a feed rate increases cutting force increases and lowest value of cutting force is observed at the feed rate is 0.075 mm/rev. In an identical way in axial force, F_Z as a cutting speed increases cutting forces decreases and lowest value of cutting force is observed at cutting speed 70.37 m/min. Similarly, as a feed rate increases cutting force increases and lowest value of cutting force are observed at the feed rate is 0.150 mm/rev hence cutting speed of 70.37 m/min is considered as the optimum speed, when compared to other cutting speeds used in this study.

3.1.3 Confirmation test for cutting forces:

After the selection of the optimal combination of parameters, the final stage is to predict and verify the improvement of the quality characteristics for the cryogenic CO_2 machining of AISI D2 steel material. It is observed that optimal combination of the minimum value of Feed force, Normal force and axial force value is closely related as shown in table 10.

Table 10. Confirmation test results for cutting forces for cryogenic CO_2 machining

S.l No	Predicted Cutting Forces in N			Experimental Cutting Forces in N		
	Feed Force F_X	Normal force F_Y	Axial force F_Z	Feed Force F_X	Normal force F_Y	Axial force F_Z
1	177.77	165.55	121.67	175	160	125
2	182.77	163.89	110.00	180	170	105
3	174.44	165.55	103.34	180	165	105
4	161.11	177.22	130.00	160	180	130
5	166.11	175.55	118.34	170	170	120
6	157.77	177.22	111.67	155	180	110
7	151.11	147.22	108.33	155	150	105
8	156.11	145.56	96.66	155	145	100
9	147.77	147.22	90.00	140	145	90

3.2 Cutting Temperature:

3.2.1. ANOVA for Cutting Temperature :

In order to see the effect of Machining parameters on Cutting Temperature, experiments were conducted using L9 Orthogonal Array. Table 11 shows the analysis of variance for cutting temperature for cryogenic CO_2 machining. It can be seen that cryogenic CO_2 cooling has maximum contribution of 95% followed by cutting speed 43.75% and feed rate 25% in optimizing the multi-response characteristics. That is Cutting Speed contributes the most to the cutting force when compared to feed rate.

Table 11. Analysis of Variance for Cutting Temperature for cryogenic CO_2 machining

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Cont**
Cutting Speed	2	1.5556	0.7778	2.80	0.174	43.75
Feed	2	0.8889	0.4444	1.60	0.309	25.00
Error	4	1.1111	0.2778			31.25
Total	8	3.5556				

3.2.2. Signal Noise Ratio for Cutting Temperature : (S/N ratio)

The present study was performed to understand and evaluate the K-Type thermocouple based temperature measurements during metal cutting and to consider the practical difficulties. The experimental results are shown in table 3. In order to see the effect of machining parameters on tool tip temperature. Taguchi experiments were conducted using L9 Orthogonal Array. The goal of this research is low temperature can be achieved in the cryogenic CO_2 machining. Thus observed temperature was set to be minimum. This means the objective function, S/N ratio is based on Smaller the better characteristics.Table 12 shows the signal-noise ratio for cutting temperature for cryogenic CO_2 machining. Fig 6 observed that Cutting speed is the significant parameter for cutting temperature when compared to feed rate. It can be seen that lowest value of cutting temperature is observed at a cutting speed of 17.84m/min and feed rate of 0.034 mm/rev.

Table 12. Signal noise ratio value for Cutting Temperature (°C) for cryogenic CO_2 machining

Level	Cutting Speed m/min	Feed mm/rev
1	-28.84	-28.94
2	-29.15	-29.15
3	-29.04	-28.94
Delta	0.31	0.21
Rank	1	2

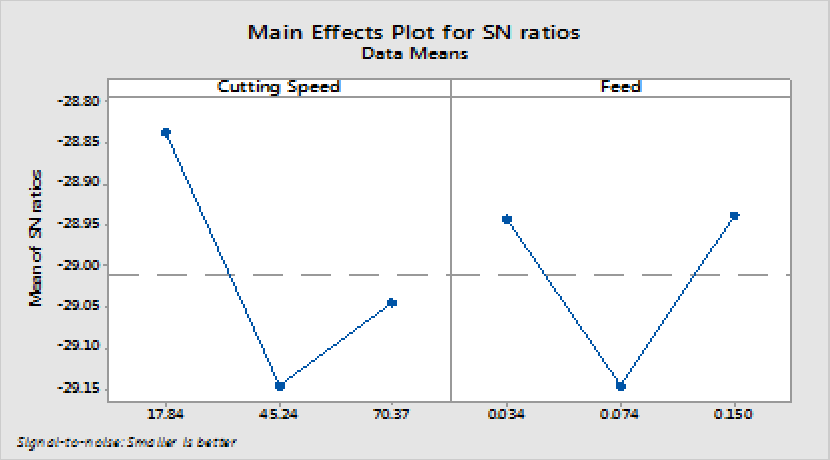

Fig 6. S/N ratio for Cutting Temperature in Cryogenic CO2 machining

3.2.3 Confirmation test for cutting Temperature (in °C)

The final step is to verify and predict the optimal level of machining parameter. The below table 13. shows experimental cutting temperature for cryogenic CO_2 machining and predicted cutting temperature values are closely related

Table 13. Confirmation test results for cutting forces for cryogenic CO_2 machining

Sl.No	Predicted Cutting Temperature in °C	Experimental Cutting Temperature in °C
1	27.4	28
2	28.1	28
3	27.4	27
4	28.4	28
5	29.1	29
6	28.4	29
7	28.1	28
8	28.8	29
9	28.1	28

3.3 Surface Roughness:

3.3.1. ANOVA for Surface Roughness :

By way of a superior effective deed of an implemented section as in friction, tool wear, coolant as well as accuracy of dimension been notably subordinated upon the surface assets, the surface roughness constraint plays an essential part in manipulation. As well as enumerated by the finalized generalization aspect. Table 14 shows the main effects of the cutting speed and feed rate are significant with respect to Surface roughness (R_a). A P-Value less than 0.05 indicates that the parameter is significant at 95% confidence level.therefore from table 14 cutting speed 61.056% and feed rate 23.49%, further error contribution from ANOVA is 15.45% which intelligibly shows that the interaction effects of process parameter are imperceptible for concurrently minimizing R_a

Table 14. Analysis of Variance for Surface Roughness for cryogenic CO_2 machining

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cont
Cutting Speed	2	0.023622	0.011811	7.90	0.041	61.056
Feed	2	0.009089	0.004544	3.04	0.157	23.49
Error	4	0.005978	0.001494			15.45
Total	8	0.038689				

3.3.2. Signal Noise Ratio forSurface Roughness: (R_a)

For surface roughness (Ra), the smaller the better criterion was also selected for better surface quality. Table 15. shows the experimental results and corresponding Signal noise ratios for surface roughness. From Table 15, it shows that Cutting speed was ranked 1, and feed rate 2, according to the significance of the parameters. The same approach was adopted to determine the optimum result of Ra. From Fig 7. The highest S/N ratio was obtained at level-3 for cutting speed, and level-1 for feed rate respectively. Therefore, the optimal combination of process parameter was found as cutting speed of 70.37 m/min and feed of 0.034 mm/rev.

Table 15. Signal noise ratio value for Surface Roughness (R_a) for cryogenic CO_2 machining

Level	Cutting Speed m/min	Feed mm/rev
1	6.096	7.477
2	5.850	6.468
3	8.051	6.052
Delta	2.201	1.425
Rank	1	2

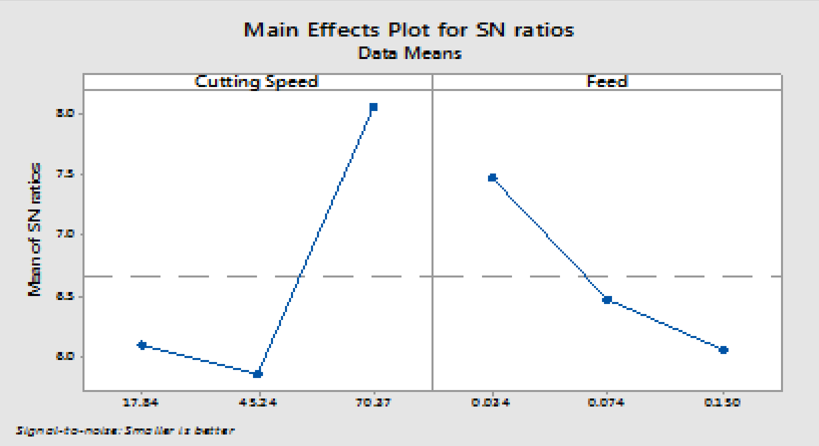

Fig 7. S/N ratio for Surface roughness in Cryogenic CO2 machining

3.3.3 Confirmation test for Surface Roughness

The final step is to verify and predict the optimal level of machining parameter. The below table 16. shows experimental surface roughness for cryogenic CO_2 machining and predicted surface Roughness values are closely related.

Table 16. Confirmation test results for surface roughness for cryogenic CO_2 machining

Sl.No	Predicted Surface Roughness	Experimental Surface Roughness
1	0.4577	0.42
2	0.5077	0.5
3	0.5344	0.58
4	0.4677	0.5
5	0.5177	0.51

6	0.5444	0.52
7	0.3544	0.36
8	0.4044	0.42
9	0.4311	0.41

4. Conclusion

This paper analyzed an application of the Taguchi method for optimizing the cutting parameters in cryogenic CO_2 cooling for conventional milling operation. As confirm in this study, the Taguchi method provides a systematic and efficient methodology for the design and optimization of cutting parameters with far less effort than would be required for most optimization techniques. It has been prove that cutting force, cutting temperature, and surface roughness were reduced significantly for milling operation by conducting experiments at the optimal parameter combination and also by analyzing S/N ratio. The conformation experiments were also conducted to verify the optimal combination of parameters obtained. Good agreement between the predicted and cryogenic CO_2 actual values for Force, temperature and surface roughness has been observed.

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Competing interests

The authors declare that they have no competing interests.

Author’s Contribution Section:

V.Balaji conducted experiments and collected the data and wrote the paper and presented discussion. Dr S.Ravi and Dr P.Naveenchandran scientific supervisors, who guided and supported this work and contributed with their expertise and advice. All authors have prepared, analyzed and approved the final manuscript.

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