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Effect of Process Factors on Cutting Force in DIP Cryogenic Machining of AISI 1040 Steel Using TAGUCHI'S Approach

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ABSTRACT:The efficacy of a machining process is mostly reliant on numerous parameters like surface finish of the product, overall cost, overall time consumed, rate of tool wear and the amount of cutting forces (Fc) produced during shearing. This experiment comprises of turning of AISI 1040 steel under ambient (dry), conventional cutting fluid (wet) and cryogenic condition against high speed steel (HSS) cutting tool. Cutting force values for each of the trials were measured and recorded with the help of a Kistler four component force and torque measuring piezoelectric drilling dynamometer. Taguchi's signal-to-noise (S/N) ratio was introduced to this experiment inorder to determine the significant control factor out of cutting speed, feed rate and depth of cut for all three machining processes in parallel with determining the optimal control factor combinations for procuring minimum cutting force values. An orthogonal array L27 was formed out of the control factors. MINITAB 16 was used to determine the S/N ratio values for all the different interactions by incorporating "smaller the better" characteristic. The investigation resolved feed rate as the significant control factor for ambient (dry) machining and conventional cutting fluid (wet) machining and depth of cut for cryogenic machining. Feed rate of 0.10mm/rev, depth of cut of 0.25mm and cutting speed of 33.92m/min are the optimum control factor combination to be set to procure minimum cutting force values in each of the machining process. The optimum combinations were noticed to be the same for all the machining processes but there was an increase of 23% cutting force in cryogenic machining compared to dry machining and an increase of 9.14% in cryogenic machining was observed in analogous to wet machining for optimum S/N ratio combinations of cutting force. There was a decrease of 53.57% in the surface roughness of cryogenic machining compared to dry and a decrease of 33.92% in cryogenic machining compared to wet for optimum S/N ratio combinations of surface roughness. Even though the cutting force values for cryogenic machining were high, it was condoned with the drastic decrease in surface roughness values. Thus this developed model concludes that the dip cryogenic machining should be adapted in order to procure minimum surface roughness compared to wet machining and dry machining.

KEYWORDS:AISI 1040 steel, dry machining, wet machining, cryogenic machining, cutting force and Taguchi's appraoch.

I. INTRODUCTION

An AISI 1040 steel round bar was dipped in liquid nitrogen (LN2) and turned on lathe machine as an experiment to study the effect on cutting force, surface roughness and chip morphology. The experiment was conducted under ambient (dry), conventional cutting fluid (wet) and LN2 conditions. The results were in favour of LN2 machining but the increasing values of cutting force were discouraging it to be adapted as one of the best machining methods. Thus Taguchi's approach was implemented to determine the control factors which play a significant role in direct variation of cutting force and also to determine the optimum control factor combination that procure minimum cutting force. Fig. 1, fig. 2 and fig. 3 illustrates the variation of cutting force with respect to feed rate for three different conditions of machining at three different values of depth of cut.

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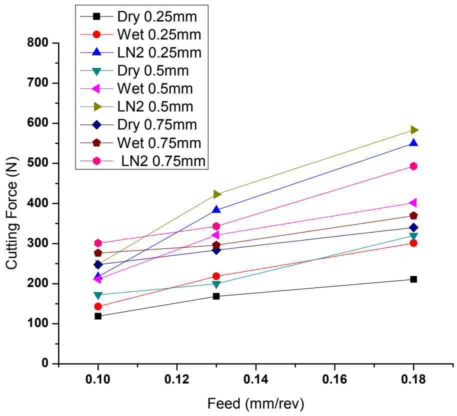

Fig. 1: Cutting force variation with feed rate for a cutting speed of 27.14m/min at various depth of cut.

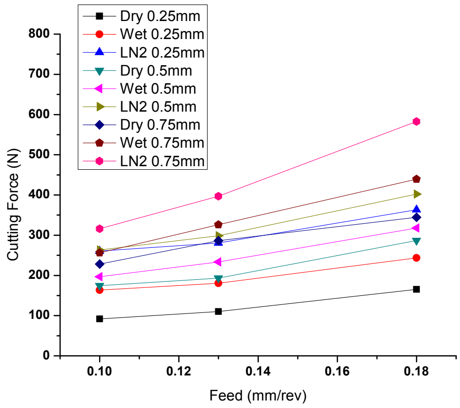

Fig. 2: Cutting force variation with feed rate for a cutting speed of 33.92m/min at various depth of cut.

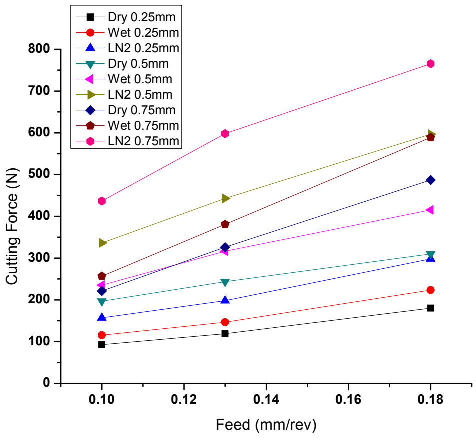

Fig. 3: Cutting force variation with feed rate for a cutting speed of 43.73m/min at various depth of cut.

[2]Aman Agarwal et al. performed CNC turning operation on AISI P-20 tool steel and analysed the power consumption using Taguchi's technique. The results pointed out that the cryogenic machining is the utmost vital factor in abating the power consumption, cutting speed and depth of cut. It was recorded that the effects of feed rate and nose radius proved to be inconsequential in comparison to other process factors.

[3] Anil Gupta et al. turned AISI P-20 steel tool in CNC machine with the help of TiN layered tungsten carbide cutting tool and optimized using Taguchi-fuzzy hybrid approach. It was noticed that the cutting speed at 160m/min, feed rate at 0.1mm/rev, nose radius at 0.8mm and depth of cut at 0.2mm under cryogenic condition were the utmost beneficial cutting factors for high speed CNC turning of the material.

[4] IlhanAsilturk and Harun Akkusperformed turning operation on AISI 4140 (51 HRC) in a CNC turning machine using coated carbide cutting tools. Taguchi's statistical method of signal to noise ratio was applied to examine the effects on surface roughness (Ra and Rz) caused by cutting speed, feed rate, and depth of cut. The outcomes proved feed rate to be highly influential over surface roughness (Ra and Rz).

[5]IlhanAsilturk and SuleymanNeseliturned AISI 304 austenitic stainless workpiece on CNC turning machine using layered carbide insert cutting tool under ambient conditions. Cutting speed, feed rate and depth of cut were the cutting parameters which were designed using Taguchi's method. The results highlighted that the feed rate was the governing

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factor disturbing the surface roughness and its value was obtained to be minimum when the feed rate and depth of cut were set to the lowermost level and when the cutting speed was set to its uppermost level.

[6]TurgayKivark et al. performed a drilling experiment on AISI 316 stainless steel blocks in a CNC vertical machining centre under dry conditions with the help of coated and uncoated M35 HSS twist drills. Taguchi's method was adapted to optimize the experiment. It was inferred from the experiment that cutting tools proved to be a significant factor on surface roughness while feed rate proved to be on thrust force.

[7] Mustafa Gunay et al. carried out a turning experiment on high alloy white cast iron (Ni-Hard) with two different workpieces having Rockwell Hardness Number of HRC 50 and HRC 62 in a CNC lathe using two different cutting tools namely ceramic and cubic boron nitride (CBN). Taguchi's signal-to-noise (S/N) ratio was employed to determine the optimal cutting conditions. It was concluded from the experiment that the cutting speed and the feed rate were the paramount control factors having influence on the surface roughness.

[8] Ashok Kumar Sahoo and Swastik Pradhanturned Al/SiCp metal matrix composite (MMC) under ambient conditions using uncoated tungsten carbide insert. ANOVA and Taguchi's (S/N) ratio methods were used to optimize the process parameters namely cutting speed, feed rate and depth of cut for the flank wear (VBc) and surface roughness (Ra). The optimal combinations for flank wear and surface roughness that were witnessed during the analysis were 60m/min-0.05mm/rev-0.4mm and180m/min-0.05mm/rev-0.4mm respectively.

[9] K. Venkata Rao et al. conducted boring operation on AISI 1040 steel in order to monitor the cutting tool by analysing the workpiece vibration and metal volume removed using Taguchi method. Feed rate proved to be a significant parameter for affecting surface roughness and metal volume removed by 55.57% and 51.26% respectively.

[10] D. Philip Selvaraj et al. performed the dry turning operation on cast DSS ASTM A 955 grade 5A and grade 4A using TiC and TiCN coated carbide cutting tool inserts. Taguchi's S/N ratio and ANOVA were implemented to optimize the cutting parameters. Cutting speed of 100m/min and a feed rate of 0.04mm/rev gave an outcome of lowest surface roughness values for both the grades of duplex stainless steel. A cutting speed set at 120m/min with a feed rate of 0.04mm/rev secured the lowest cutting force for both the grades of duplex stainless steel.

[11] C.C. Tsao and H. Hochengconducted a drilling operation using candle stick drill on composite material which assisted them in predicting and evaluating the thrust force and surface roughness. Taguchi's method was adapted in this experiment. Results discovered that the feed rate and drill diameter were the most crucial factors disturbing the thrust force. The feed rate and spindle speed contributed the maximum to the surface roughness.

[12] P. Vijian and V.P. Arunachalamused a 3 level orthogonal array inorder to procure the signal to noise ratio. The process parameters affecting the surface roughness of a squeeze casting (is a hybrid metal forming process amalgamated of casting and forging) performed on LM6 aluminium alloy were optimized. The outcomes pointed out that the squeeze cast products procured the ameliorated surface finish due to the squeeze pressure and preheating temperature of the die.

[13] L B Abhang and M Hameedullahturned EN-31 steel alloy against tungsten carbide cutting tool insert. Taguchi's method was implemented to optimize the three control factors namely feed rate, depth of cut and lubricant temperature. Minimum surface roughness values were procured for 0.05mm/rev-0.4mm-10°c combination.

[14]V.N. Gaitondeet al. performed a turning operation on brass against K10 carbide cutting tool. The various factors namely the minimum quantity of lubrication (MQL), cutting speed and feed rate were optimized by Taguchi's method. The optimized values that encouraged in reduction of surface roughness and specific cutting force are 200ml/h for MQL, 200m/min for cutting speed and 0.05mm/rev for feed rate.

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II. EXPERIMENTAL DETAILS

The following are the experimental details followed in order to conduct the experiment:

Table 1:Chemical composition of the AISI 1040 steel, by weight[15]

Material	Carbon	Manganese	Phosphorous	Sulfur
AISI 1040 steel	0.37-0.44	0.60-0.90	0.040	0.050

Table 2: Experimental Conditions

Machine Specification		PSG A141 lathe (2.2 KW)
Work specimen		AISI 1040 steel (Ø24mm and 304.8mm long)
Cutting tool		Single point high speed steel cutting tool
Process Parameters	Feed rate	0.1mm/rev, 0.13mm/rev and 0.18mm/rev
	Depth of cut	0.25mm, 0.5mm and 0.75mm
	Cutting speed	27.14m/min, 33.92m/min and 43.73m/min
Machining Environment		Dry, Wet and Cryogenic conditions

The workpieces used for each of the machining environments (dry, wet and cryogenic) were different but were taken from the same parent material so as to avoid procurement of any aberrant results due to change in chemical composition. The workpiece was immersed in cryogenic liquid (LN2) for a specified duration and then clamped on to the chuck for turning operation as shown in fig.1.

Fig. 4: Cryogenic machining

A.Force measuring instrument.

A tool holder Kistler 9404 was used to hold the cutting tool. A Kistler 4 component force and torque measuring piezoelectric drilling dynamometer was mounted over the toolpost for measuring and recording all 3 forces (cutting, feed, radial).The Kistler used was of type 9272A. A 4 channel charge amplifier 5070A10100 was used and a PC based Dynoware software was used for data acquisition and analysis. Fig. 5 shows the photographic view of the experimental setup.

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Fig. 5: Experimental Setup

B.Taguchi's design of experiment.

The three control factors in the following experiment are cutting speed, feed rate and depth of cut. The three levels considered for all the three control factors are as shown in table no. 1. Each experiment was conducted thrice and the average value of surface roughness was chosen for the Taguchi's S/N ratio analysis. Orthogonal array of L27 (3^{13}) was adapted which consisted of 27 rows corresponding to the different combinations of factor. First column was assigned to cutting speed (m/min), second to feed rate (mm/rev), third to depth of cut (mm) and the remaining columns to the interactions. The analysis was conducted using MINITAB 16 which is the most widely used and accurate software for application of design of experiment.

Table No. 3: Process Parameters and levels used in the experiment.

Levels	(A) Cutting speed (m/min)	(B) Feed rate (mm/rev)	(C) Depth of cut (mm)
1	27.14	0.10	0.25
2	33.92	0.13	0.50
3	43.73	0.18	0.75

The S/N ratio characteristics can be branched into three groups by the three equations given below:

Nominal is the best characteristic

$$\frac{S}{N} = 10 \log \frac{\bar{y}}{s_y^2} \quad (1)$$

Smaller is the best characteristic

$$\frac{S}{N} = - 10 \log \frac{1}{n} (\Sigma y^2) \quad (2)$$

Larger is the best characteristic

$$\frac{S}{N} = - \log \frac{1}{n} (\Sigma \frac{1}{(y)^2}) \quad (3)$$

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Where $\overline{y}$ is the average value of the observed data,
s_y^2 is the variation of y,
n is the number of observations,
y is the observed or recorded data.

III. RESULTS AND DISCUSSIONS.

Cutting force forms a crucial parameter in quantifying the efficacy of a machining method. Larger the cutting force, more the tool wear, more will be the power consumption and vibrations which may lead to deteriorating quality of surface finish. Thus hampering the overall cost and quality of the product being manufactured. In order to avoid the occurrence of such situation this experiment is analysed using Taguchi's (S/N) ratio method to determine the optimum combination of control factor for procuring minimum cutting force value along with determining the prominent control factor. **"Smaller the better"** characteristic (equation no. (2)) was chosen in this analysis so as to determine the optimum cutting force value in all three different machining conditions.

A. Dry machining

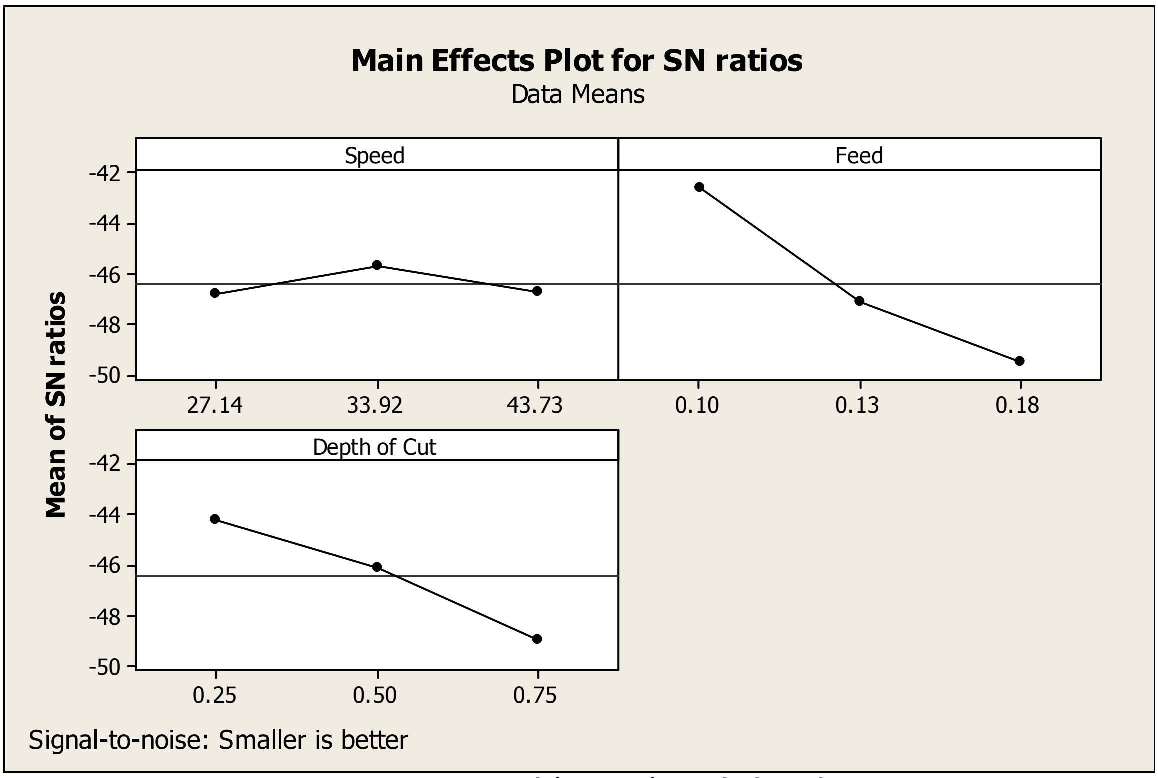

Figure 6: Mean S/N ratio graph for cutting force under dry machining.

Table No. 4: Response table for signal to noise ratios of cutting force obtained during dry machining (Smaller the better)

Level	Cutting speed	Feed rate	Depth of cut
1	-46.77	-42.55	-44.17

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2	-45.69	-47.11	-46.09
3	-46.70	-49.50	-48.91
Delta	1.07	6.96	4.74
Rank	3	1	2

Dry machining was conducted on AISI 1040 steel to study the effects. Its increasing demand in industries that work with this metal under ambient condition brought the metal in limelight for Taguchi's analysis inorder to enhance the machining method. Fig. 6 shows S/N ratio vs. cutting force graphs under dry condition and table 4 shows the response table for the same. For dry machining, it was observed that the feed rate obtained the first rank followed by cutting speed and depth of cut which were second and third respectively. The signal to noise ratio value secured for lowest feed rate was the minimum of all the values obtained in dry machining. The S/N ratio values for cutting force increased with the increase in feed rate but there was no proportional increase observed. The S/N ratio values for cutting speed and depth of cut increased with the increase in cutting speed and depth of cut but except for the lowest cutting speed. Feed rate of 0.10mm/rev, depth of cut of 0.25mm and cutting speed of 33.92m/min are the optimum combination of control factor that must be adapted to procure minimum cutting force values under dry machining of AISI 1040 steel.

B. Conventional cutting fluid (wet) machining

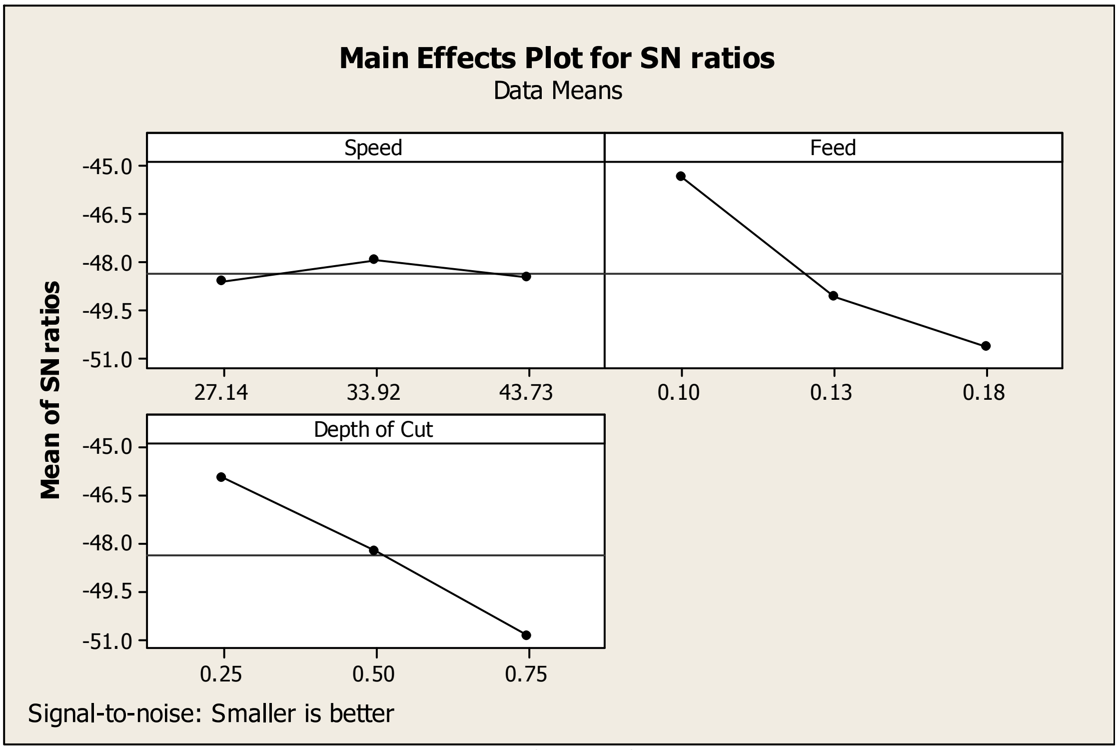

Figure 7: Mean S/N ratio graph for cutting force under wet machining.

Table No. 5: Response table for signal to noise ratios of cutting force obtained during wet machining (Smaller the better)

Level	Cutting speed	Feed rate	Depth of cut
1	-48.64	-45.35	-45.96
2	-47.97	-49.09	-48.23

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3	-48.51	-50.68	-50.93
Delta	0.68	5.33	4.97
Rank	3	1	2

AISI 1040 steel was turned against high speed steel cutting tool under influence of pressurized soluble oil which forms one of the conventional cutting fluid used to absorb the heat at cutting zone temperature. Thus this form of machining also had to be studied and analysed as a part of the experiment. Fig. 7 shows the signal to noise ratio graphs obtained for cutting force under conventional cutting fluid (wet) machining of AISI 1040 steel and table no. 5 shows the response table for the same. It was certain from the above graphs and response table that feed rate secured the first rank and thusproved to be the prominent control factor in terms of wet machining followed by depth of cut and cutting speed which were second and third respectively. Lowest feed rate procured the least signal to noise ratio value that is -45.35. This was imminent as lower the feed rate more the time for cutting fluid to enter the interstitial spaces inorder to remove the metal chips which when stuck on cutting tool tip causes increase in the value of cutting force. 0.10mm/rev-0.25mm-33.92m/min are the optimum combination of control factor that procured the least cutting force values under wet machining.

C. **Cryogenic machining**

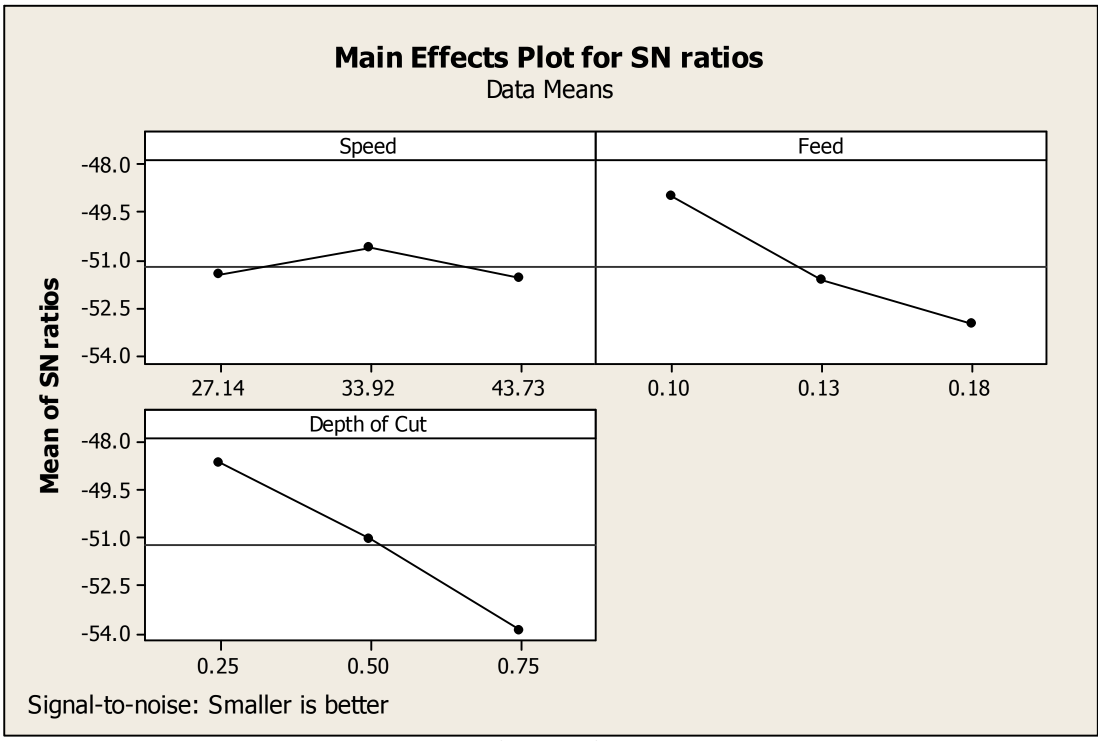

Figure 8: Mean S/N ratio graph for cutting force under cryogenic machining.

Table No. 6: Response table for signal to noise ratios of cutting force obtained during cryogenic machining (Smaller the better)

Level	Cutting speed	Feed rate	Depth of cut
1	-51.46	-49.00	-48.69
2	-50.64	-51.63	-51.08
3	-51.59	-53.05	-53.92

Delta	0.95	4.05	5.23
Rank	3	2	1

Fig. 8 illustrates the signal to noise ratio graphs acquired for surface roughness under cryogenic machining and table no. 6 shows the response table for the same. There has been several sorts of cryogenic machining done such as spraying LN2 directly at the shear zone with an external tube or rake cooling of cutting tool with the help of LN2 or spraying LN2 at shear zone which is sent from the gap between the cutting tool insert and cutting tool body. Dipping in cryogenic liquid LN2 and then turning was all together a new method of machining which has never been tried earlier especially for metals. Thus this calls for all the attention which could possible change the existing machining scenario of metals for a betterment. Depth of cut was discovered to be the utmost substantial control factor for cutting force values proceeded by feed rate and cutting speed which were ranked second and third respectively. 0.10mm/rev-0.25mm-33.92m/min are the optimum combinationof control factor that procured least cutting force values under cryogenic machining. In cryogenic machining, the lowest value of depth of cut procured the minimum signal to noise ratio value that is -48.69 in analogous to all the possible outcomes of cryogenic machining.

Table No. 7: Percentage variation of optimum surface roughness and cutting force S/N ratio values.

Cryogenic machining compared to	Cutting force	Surface roughness
Dry	Increase of 23%	Decrease of 53.57%
Wet	Increase of 9.14%	Decrease of 33.92%

IV. CONCLUSIONS

- In dry and wet machining, feed rate acquired the position of most significant control factor proceeded by depth of cut and cutting speed. In cryogenic machining, depth of cut acquired the first rank of significance of control factor lined up by feed rate and cutting speed which secured second and third rank respectively.
- The optimum combinations of control factor (feed rate-depth of cut-cutting speed) for acquiring minimum cutting force in each of the machining condition are 0.10mm/rev-0.25mm-33.92m/min.
- The increase in optimum S/N ratio values of cutting force in cryogenic machining compared to dry was 23% and in comparison with wet was 9.14%. The decrease in optimum S/N ratio values of surface roughness in cryogenic machining was 53.57% compared to dry and in comparison to wet it was 33.92%. Although the cutting force values for cryogenic machining were higher compared to dry and wet but the extreme decline in the surface roughness value instigated dip cryogenic machining to be adapted as one of the best machining methods to procure minimum surface roughness for the product.

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