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Optimization of machining parameters during cryogenic turning of AISI D3 steel

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Abstract. This research paper depicts the process of used liquid nitrogen at the interface of TiN coated carbide cutting tool insert (rake face) and AISI D3 workpiece. Design of experiments (DoE) was planned according to Taguchi L_9 (OA) orthogonal array. The experimental results during machining such as cutting force, machining time and temperature were optimized by Taguchi S/N ratio and analysed by ANOVA. The contribution of machining parameters of (i) speed, (ii) feed and (iii) depth of cut for each response were evaluated. Feed had the highest effect on the percentage of contribution of 57.21% and 52.21% for cutting force and machining time, respectively. Speed had the highest effect on the contribution as 79.57% for the temperature at the interface of insert and workpiece. The predicted values at the optimum level of machining parameters for cutting force, machining time and temperature were 44.49 N, 37.09 sec. and 24.99°C, respectively. Regression models were made. The R-Sq values were 96.59, 89.34 and 96.09% for cutting force, machining time and temperature, respectively. The ratio of an average thickness of generated chip and feed was considered as the chip compression ratio. It was observed that the generated chips during cryogenic turning were thin, discontinuous, long snarled and most of the material had side flow on either side.

Keywords. Cryogenic turning; liquid nitrogen; optimization; ANOVA; Taguchi S/N ratio; AISI D3 steel.

1. Introduction

The modern competitive society is concerned with the global environment to affect, new engineering materials and the fabrication processes involve in manufacturing of the component. There is a challenge for the scientists and researchers to fulfil intrinsic international norms up to the mark for the fabrication. Machining is a common manufacturing process to remove the material from the parent material to have required finished shape and size of the object. The conventional cutting fluid is not eco-friendly during machining operations to get the required finished product [1–4]. Dry machining (without lubricant) could be considered as eco-friendly, but the machining characteristics such as surface roughness, cutting force, temperature, coefficient of friction, tool wear, etc. were almost satisfactory at low machining parameters. This slowed down the manufacturing rate [5–8]. The need for eco- friendly cutting fluid was generated to support machining operations with satisfactory results at low, medium to high levels of machining parameters. Liquid nitrogen could be used during machining. Liquid nitrogen is colourless, tasteless, odourless, non-toxic and having a boiling point of −196°C [9–12]. Health-related issues like breathing, nausea, infection to hands, allergies, etc. for operator, were declined or almost became negligible with the utilisation of LN_2 during machining. Low adhesion and abrasion wear mechanism was found on the cutting tool. Low debris was found on the machined surface. LN_2 improved tool life and surface properties of the workpiece as compared to dry machining [13, 14].

1.1 *Cryogenic cooling*

Liquid nitrogen was used by researchers as direct regulated supply to the interface of cutting tool and workpiece during machining operations. Manimaran *et al* [15, 16] used liquid nitrogen supply at the interface of workpiece (steel) and grinding wheel. It was found that during cryogenic cooling, grinding forces were declined by 32–36% and 13–26% as compared to dry and wet grinding, respectively. Surface roughness was declined by 26–59% and 32–43% as compared to dry and wet grinding. Dhanachnezian *et al* [17] investigated cryogenic turning with a direct regular supply of LN_2 at flank and rake parts of single point cutting insert and found that cutting temperature, cutting force, surface roughness and tool wear were declined by 61–66%, 35–42%, 35% and 39%, respectively during cryogenic turning as compared with flood supply. Sartori *et al* [18]

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Table 1. Chemical analysis of $AISID_3$ steel.

C	Si	Mn	S	P	Cr	Ni	Mo	Co	Nb	V	W	Fe
2.02	0.259	0.430	0.029	0.020	11.00	0.074	<0.10	0.011	0.023	0.038	0.087	85.909

Table 2. Chemical analysis of cutting inserts.

C	Co	Mn	V	Nb	Ni	W	Mo	Ti
7.10	16.25	0.30	2.05	5.23	4.95	15.88	0.69	47.55

studied the tool wear and surface roughness during dry, wet, MQL, CO_2 (rake) + MQL (flank), LN_2, LN_2 (rake) + MQL(flank) and found that surface roughness was low with LN_2. Hong *et al* [19–21] found that friction, cutting force, cutting temperature were low and tool life improved during cryogenic machining as compared to dry machining of titanium alloy. Dhar *et al* [22–25] investigated the influence of cryogenic cooling on steel alloys AISI 1040, E4340C, AISI 4140, AISI 4037 and concluded that the tool wear was low and surface roughness was better as compared to wet and dry machining. The surface produced during cryogenic machining was clean and had a negligible amount of debris. The machined surface had low cracks. The surface profile graph was uniform and within a small range. The chips produced were discontinuous, thin and had clean surface [26–29]. Sun *et al* [30] used LN_2 for cooling down the air and further used chilled air at the interface of the cutting tool and workpiece and found improved surface roughness as compared to dry machining. Chip thickness declined by 9% at cutting speed lower than 50 m/minute. Mia *et al* [31] compared machining characteristics in dry, LN_2 supply at rake face named as single LN_2 jet and liquid nitrogen supply at rake and flank face named as duplex jets and found that surface roughness, cutting force and cutting temperature were low in duplex supply of LN_2.

The hardness of cutting inserts was increased by cryogenic treatment using liquid nitrogen. Cutting inserts were placed in cryoprocessor. The temperature declined slowly and gradually at approximate 2°C per hour in it. After reaching −196°C, cutting inserts were kept for 12–48 hours. The temperature was increased slowly and gradually to reach room temperature. Tempering was conducted for 2 hours to relieve residual stresses. Grain refinement of tool material took place during the treatment. This might increase hardness and wear resistant property of the material. The number of hours was decided according to the hardness required in the material. The number of hours could be varied from 4 h to 24 h according to the nature of material and extent of hardness was required. Cryogenically treated cutting inserts coated and uncoated could perform better than untreated coated and uncoated cutting inserts for titanium alloys, Nickel-based alloys and AISI D3 alloys and TiN coating with cryogenic treatment gave 20–45% extra tool life [32, 33]. Lal *et al* [34] found that the wear resistance of cryogenically treated cutting inserts was improved by 95.5%.

1.2 *Optimization*

Machining process consisted of various cutting parameters for a definite combination of cutting tool and workpiece. To save energy and decrease in economic aspects it was necessary to know and apply optimum cutting parameters for better surface integrity, lower cutting forces, lower tool wear and lower energy consumption [35]. Optimization was achieved by using multiple desirability function and RSM models to achieve low surface roughness, cutting force, power consumption and high tool life during cryogenic turning with LN_2 [36]. Taguchi technique was discovered in 1950 by Genichi Taguchi. It was based on the signal-to-noise (S/N) ratio. It minimized the practice of hit and trial for selecting the best combination of controlled factors (cutting parameters in machining) for the better conditional output of machining properties [37]. In dry turning of hardened steel alloys AISI D3, AISI4340, AISI H13, EN19, high- alloy white cast iron and magnesium alloy the surface roughness, tool wear, cutting force and cutting temperature were optimized by Taguchi approach [38–50]. The machinability characteristics during cryogenic cooling with LN_2 in turning, milling and grinding were better than dry, conventional cutting fluid, minimum quantity lubrication technique (MQL) with castor oil and frozen CO_2 [51–55].

The review of research papers showed that steel AISI D3 (HRC 60) is used in manufacturing blanking and forming dies, forming tools, press tools, punches, bushes and wear resistant moulds. It is categorised as difficult to machine materials. The combination of TiN coated carbide cutting tool and AISI D3 as workpiece was rarely used during cryogenic turning with LN_2 for the analysis of machinability characteristics. This explored a new dimension for trying experimentation with other noble gases such as frozen CO_2, liquid H_2, liquid Helium, etc. and a hybrid of gases with eco-friendly oils like castor, olive, etc. There is a need for experimental investigation of the parameters in LN_2 environment during turning of AISID3 workpiece and TiN coated carbide cutting insert. To apply the modern tools as Taguchi and ANOVA techniques for human beings and to fulfil the current requirement up to the international standards.

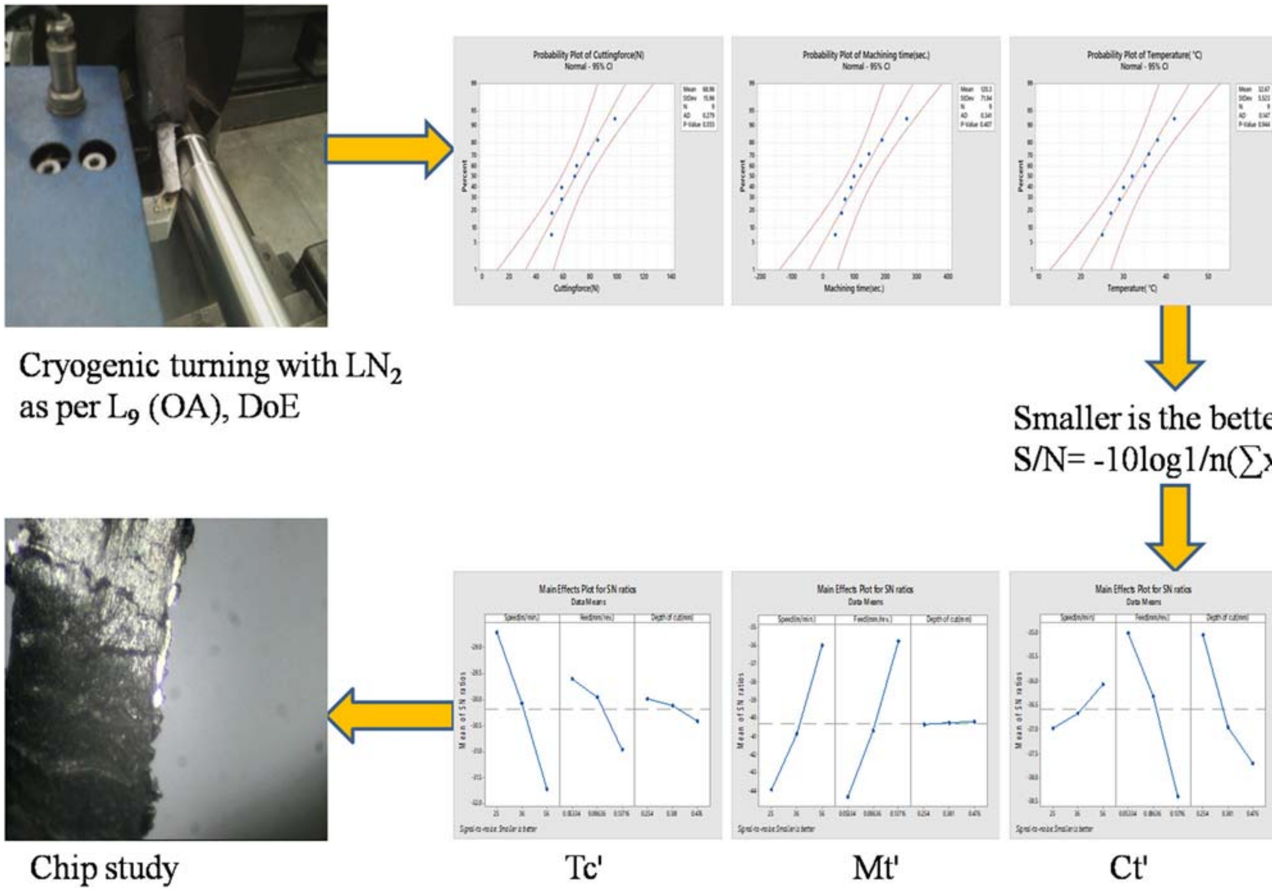

Figure 1. Workflow diagram during turning with LN_2.

Table 3. Machining parameters with different levels.

Levels	Machining parameters		
	Vd′ (m/min.)	Fd′ (mm/rev.)	Dt′ (mm)
Level 1	25	0.05334	0.254
Level 2	36	0.08636	0.381
Level 3	56	0.13716	0.476

2. Experimental procedure

2.1 *Materials and methods*

AISI D3 was used as the material for the workpiece. The shape was cylindrical. The diameter was 28 mm and length was 300 mm. The sample of the material was chemically tested for checking the composition of elements. The percentage of each element in weight was measured and depicted in table 1.

Cutting inserts were used in the shape of a diamond. The material was tungsten carbide with a coating of titanium nitride. ISO specification of cutting insert was DCMT 11T 3087 HQ with a grade of PV20 and tool holder was SDJCR 1212F 11. Tool geometry as per orthogonal rake system was 0°, 0°, 7°, 7°, 60°, 93° and 0.8 mm (λ′, α′, β′, γ′, φ′, θ′ and r′), respectively. The sample of cutting tool insert was examined chemically for checking for the composition of elements available. The percentage of each element in weight was measured and depicted in table 2.

2.2 *Machining set-up and methods*

The experiments were performed on the three-jaw lathe machine. Dewar container with the capacity of 50 kg was used as the storage of liquid nitrogen. The insulated pipe was fitted to container and another free end was fitted at the interface of cutting insert and workpiece. The regulated compressed air supply was maintained by a pressure regulator and pressure relief valve fitted between pipe connected to container and compressor. The temperature was measured by IR thermal image non-contacting thermometer with an accuracy of ±0.05°C of reading. The beam was focused at the interface of cutting insert (rake face) and workpiece. This was done with constant incident angle and distance by using a fixture near the lathe machine. The

Table 4. Taguchi L_9 (OA).

	Coded Values of factors			Un-coded values of factors		
Run	Vd′ (m/min.)	Fd′ (mm/rev.)	Dt′ (mm)	Vd′ (m/min.)	Fd′ (mm/rev.)	Dt′ (mm)
1	1	1	1	25	0.05334	0.254
2	1	2	2	25	0.08636	0.381
3	1	3	3	25	0.13716	0.476
4	2	1	2	36	0.05334	0.381
5	2	2	3	36	0.08636	0.476
6	2	3	1	36	0.13716	0.254
7	3	1	3	56	0.05334	0.476
8	3	2	1	56	0.08636	0.254
9	3	3	2	56	0.13716	0.381

Table 5. Experimental results of responses and respective S/N ratio.

	Responses			S/N ratio of responses		
Run	Ct′	Mt′	Tc′	Ct′	Mt′	Tc′
1	51.5	268.14	25	−34.2361	−48.5672	−27.9588
2	69.8	147.35	27	−36.8771	−43.3670	−28.6273
3	98.2	99.30	30	−39.8422	−39.9390	−29.5424
4	58.8	188.64	29	−35.3875	−45.5127	−29.2480
5	78.4	121.12	32	−37.8863	−41.6643	−30.1030
6	68.6	59.35	35	−36.7265	−35.4684	−30.8814
7	58.8	89.03	38	−35.3875	−38.9907	−31.5957
8	51.2	70.88	36	−34.1854	−37.0105	−31.1261
9	85.3	39.29	42	−38.6190	−31.8856	−32.4650

cutting force was measured by piezo-electric three component dynamometer. The machining time was measured by a dedicated digital stopwatch. Initially, the stopwatch was set at zero reading and started to record time with the start of an experimental run. Stopped with the end of the experimental run. The time shown on stopwatch was noted down. After the completion of each experimental run, worn out used cutting insert was replaced by a new unused cutting insert. Chips were collected for each set of experiment. The chip thickness was measured by optical CNC vision inspection microscope at ten different places. The average value was calculated for getting the final chip thickness value. Figure 1 shows the sequences of stages followed during the experimentation process. Experiments were performed during cryogenic turning with Taguchi based L_9 (OA), DoE. Probability plots were formed for the values obtained for each response (cutting force, machining time and temperature). After checking for acceptance of the null hypothesis with a normal probability distribution, the values were further used for analysis. Mean effect plots were formed. Chips were optically examined for understanding the morphology and compression ratio.

2.3 *Design of experiments (DoE)*

The experiments were performed with three machining parameters such as speed, feed and depth of cut. Each

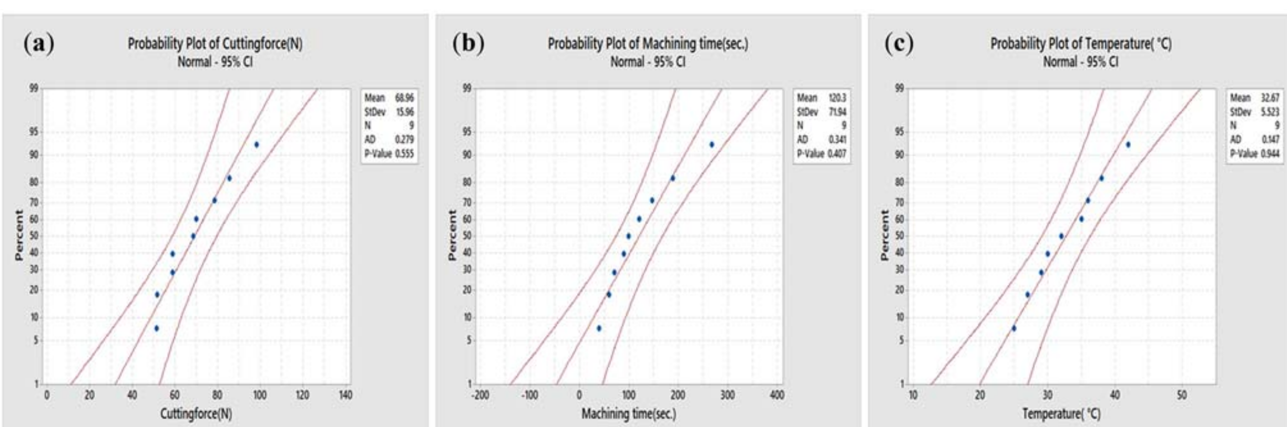

Figure 2. Probability plots for **(a)** cutting force, **(b)** machining time and **(c)** temperature.

Table 6. Response table for mean S/N ratios for (Ct′) cutting force, (Mt′) machining time and (Tc′) temperature.

Response	Level	Vd′ (m/min.)	Fd′ (mm/rev.)	Dt′ (mm)
Ct′	1	−36.99	**−35.00**	**−35.05**
	2	36.67	−36.32	−36.96
	3	**−36.06**	−38.40	−37.71
	Delta	0.92	3.39	2.66
	Rank	3	1	2
Mt′	1	−43.96	−44.36	−40.35
	2	−40.88	−40.68	−40.26
	3	**−35.96**	**−35.76**	**−40.20**
	Delta	8.00	8.59	0.15
	Rank	2	1	3
Tc′	1	**−28.71**	**−29.60**	**−29.99**
	2	−30.08	29.95	−30.11
	3	−31.73	−30.96	−30.41
	Delta	3.02	1.36	0.42
	Rank	1	2	3

Table 7. Response table for means for (Ct′) cutting force, (Mt′) machining time and (Tc′) temperature.

Response	Level	Vd′	Fd′	Dt′
Ct′	1	73.17	**56.37**	**57.10**
	2	68.60	66.47	71.30
	3	**65.10**	84.03	78.47
	Delta	8.07	27.67	21.37
	Rank	3	1	2
Mt′	1	171.60	181.94	132.79
	2	123.04	113.12	125.09
	3	**66.40**	**65.98**	**103.15**
	Delta	105.20	115.96	29.64
	Rank	2	1	3
Tc′	1	**27.33**	**30.67**	**32.00**
	2	32.00	31.67	32.67
	3	38.67	35.67	33.33
	Delta	11.33	5.00	1.33
	Rank	1	2	3

parameter was varied to three levels (Level = 1, 2 and 3). The full factorial design needed 3^3 = 27 experiments for L_9 (OA) orthogonal array. But, according to Taguchi, the total number of experiments reduced to 9. This saved more than 50% of experiments. Table 3 shows the machining parameters with variations. Speed, feed and depth of cut were varied from (25–56 m/min.), (0.05334–0.13716 mm/rev.) and (0.254–0.476 mm), respectively. Table 4 shows coded values of factors with equivalent un-coded factors for the design of experiments. Level 1, 2 and 3 show minimum, medium and maximum value of each machining parameter such as speed, feed and depth of cut.

3. Experimental results and discussion

3.1 *Proability analysis*

Experiments were performed according to Taguchi based S/N ratio L_9 (OA) of DoE. The experimental results of responses with respective values of S/N ratio are shown in table 5. Probability plots were made at 95% confidence level. Each plot showed mean, StDev., AD and P-value. The acceptance or rejection of the null hypothesis with the normal probability distribution was dependent on P-value [44]. Figures 2(a), (b) and (c) showed that response values were approximately inclined to the middle straight line, P-value was greater than 0.01 and AD statistic was low. The experimental data could be used for further optimization, experimental investigation and interpretation.

3.2 *Taguchi based optimization (Signal to Noise ratio)*

Optimization based on Taguchi (S/N) ratio involves a decrease in variability and shifting towards target value. In any process, variability may arise due to factors having no control are termed as uncontrollable factor or noise. The expected value of the response is termed as target or signal. S/N is the ratio of expected target values to unexpected noise [40]. Eq. (1) shows smaller is the better characteristic [44, 58]

$$\frac{S}{N} = -10log\frac{1}{n}\left(\sum x^2\right) \tag{1}$$

Where, x represents the measuring responses (Ct′, Mt′, Tc′). Table 4 shows the coded and un-coded values of factors according to L_9 (OA) orthogonal array (Design of experiments). Table 5 shows the experimental results of responses with the respective S/N ratio. Table 6 shows the description for the mean S/N ratio for each response. Delta was the difference between the maximum and minimum value of each level. On the basis of delta value highest to lowest (rank) was given. This showed a priority given to each control factor. Optimum level value of the factor was evaluated by considering the highest S/N ratio value of a particular factor. Table 7 shows a description for mean values for each response. Optimum level value of the factor was evaluated by considering the lowest value of a particular factor. This was supported by the statistical analysis of variance (ANOVA). Table 8 shows ANOVA which had a degree of freedom (df), adjoint sum of squares (AdjSS), adjoint mean of square (Adj MS), F-Value, P-Value and percentage of contribution. The P-value was defined for the significance level of 5% (confidence level of 95%) for all responses [44, 57, 58].

Table 8. Analysis of variance for means of (Ct′) cutting force, (Mt′) machining time and (Tc′) temperature.

Response	Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cont.
Ct′	Vd′	2	1.3133	0.6567	2.36	0.297	4.28
	Fd′	2	17.5543	8.7771	31.58	0.031	57.21
	Dt′	2	11.2635	5.6317	20.26	0.047	36.70
	Error	20	0.5558	0.2779	–	–	1.81
	Total	26	30.6869	–	–	–	–
Mt′	Vd′	2	97.590	48.7952	21.94	0.044	45.96
	Fd′	2	111.516	55.7581	25.08	0.038	52.21
	Dt′	2	0.035	0.0174	0.01	0.992	0.02%
	Error	20	4.447	2.2236	–	–	2.08
	Total	26	213.589	–	–	–	–
Tc′	Vd′	2	13.7154	6.8577	58.31	0.0.017	79.57
	Fd′	2	3.0005	1.5003	12.76	0.073	17.41
	Dt′	2	0.2863	0.1432	1.22	0.451	1.66
	Error	20	0.2352	0.1176	–	–	1.36
	Total	26	17.2374	–	–	–	–

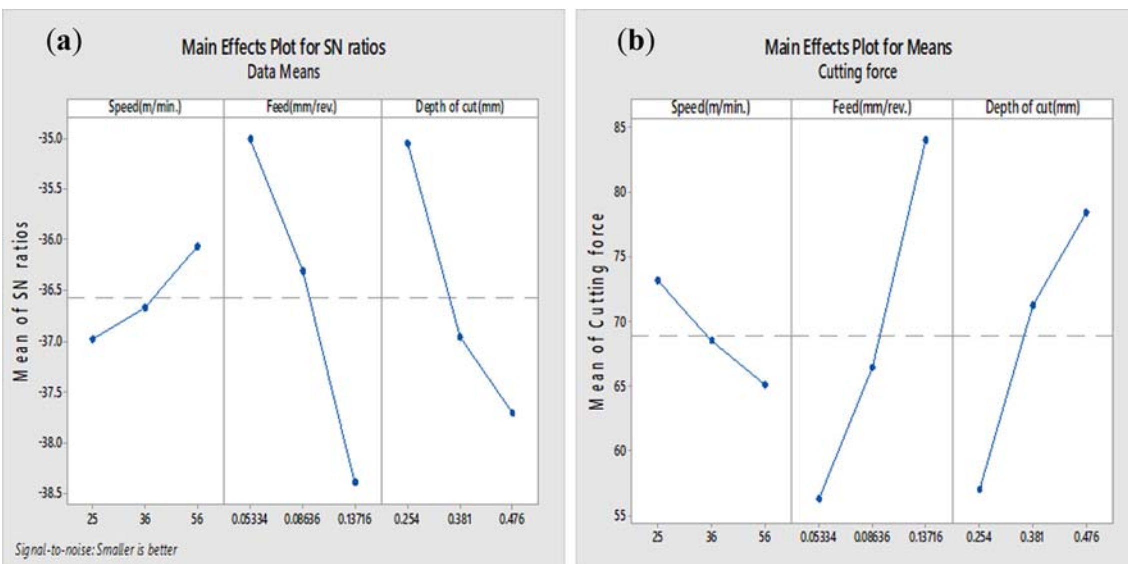

Figure 3. **(a)** Variation of mean S/N ratio Ct′. **(b)** Variation of mean Ct′ with different actor levels.

3.3 *Cutting Force*

Figure 3(a) shows mean effects plot for the mean of S/N ratios of cutting force during cryogenic turning with different levels of machining parameters. Optimum level value of cutting force Ct′ at Vd′ (level 3 = 56 m/min.), Fd′ (level 1 = 0.05334 mm/rev.) and Dt′ (level 1 = 0.254 mm).The predicted value of the response was calculated from Eqs. (2) and (3). d_p was the average S/N ratios of all variables, d_p was predicted response, $\bar{N}_o$ was the average S/N ratio when variable Vd′ (speed) was at optimum level, $\bar{F}_o$ was the average S/N ratio when variable Fd′ (feed) was at optimum level and $\bar{D}_o$ was the average S/N ratio when variable Dt′ (depth of cut) was at optimum level, Ap was predicted responses. Predicted value of cutting force was 44.49 N. (ANOVA) table 8 shows for cutting force, Fd′ had the highest percentage contribution of 57.32% followed by Dt′ and Vd′ in consecutive decreasing order of percentage contribution. F-value showed the relative importance firstly Fd′, secondly Dt′ and lastly was Vd′. P- value was significant at the value of level equal to or less than 0.05. P-value was significant for Fd′ and Dt′. Figure 3(b) shows the variation of mean Ct′ with different factor levels (individual machining parameters). On incrementing cutting speed (Vd′) cutting force declined and on incrementing feed (Fd′) and depth of cut (Dt′) cutting force increased.

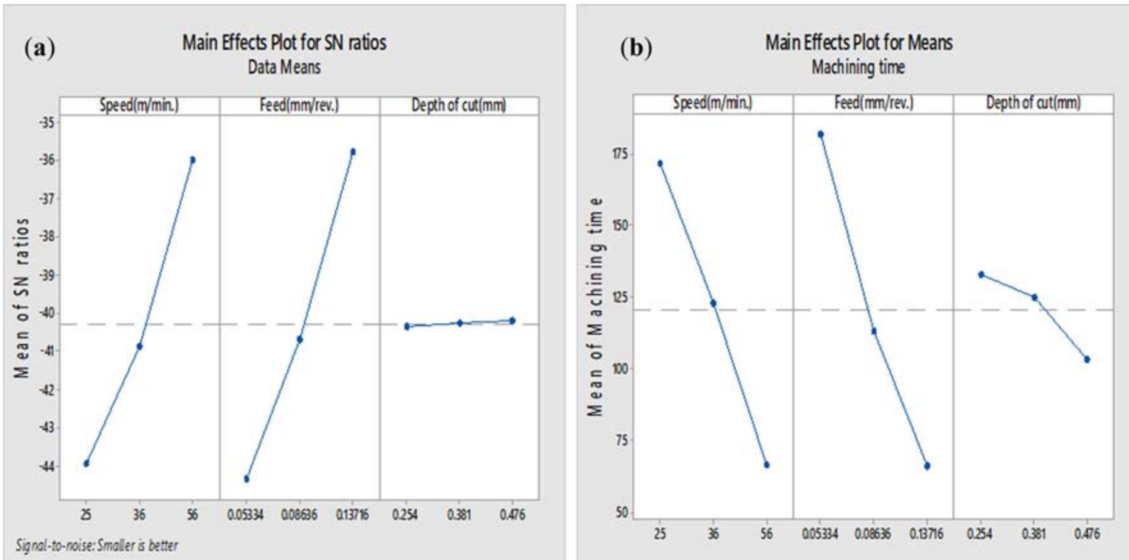

Figure 4. **(a)** Variation of mean S/N ratio Mt′. **(b)** Variation of mean Mt′ with different factor levels.

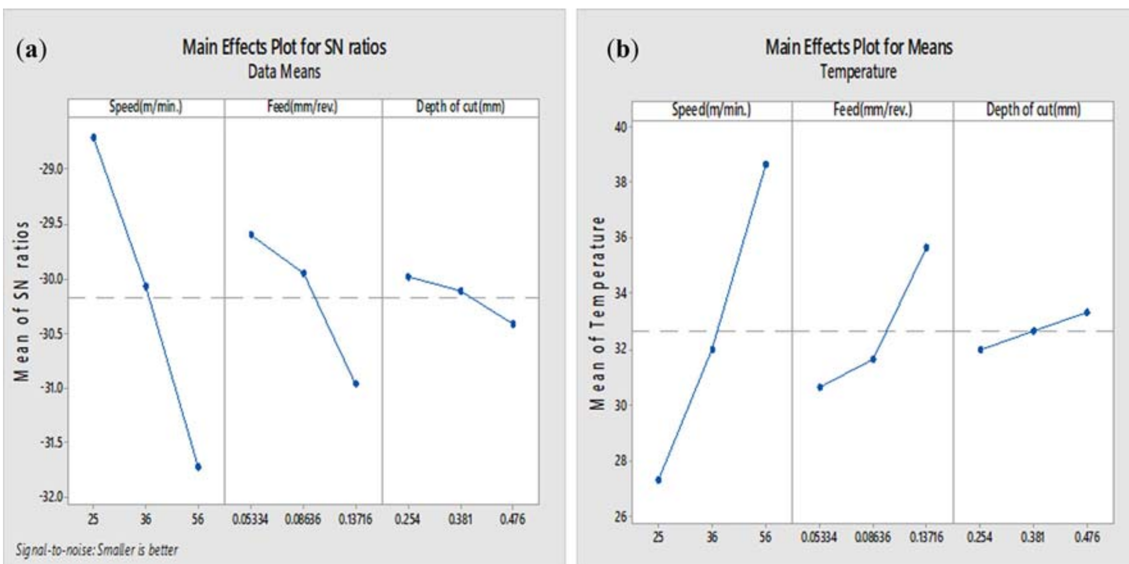

Figure 5. **(a)** Variation of mean S/N ratio Tc′. **(b)** Variation of mean Tc′ with different factor levels.

Table 9. Confirmation test results.

Response	Predicted value of response	Confidence Level(CI)	Actual value of response at experimental (optimized level)
Ct′	44.49 N	±0.85 N	45 N
Mt′	37.09 sec.	±2.39 sec.	37 sec.
Tc′	24.99°C	±0.55°C	25°C

Table 10. Regression models and R-Sq values for the experimental results.

	Regression Models	R-Sq%
Ct′	12.16 − 0.2499 Speed (m/min.) + 331.4 Feed (mm/rev.) + 97.1 Depth of cut (mm)	96.59
Mt′	422.1 − 3.125 Speed (m/min.) − 1345 Feed (mm/rev.) − 130 Depth of cut (mm)	89.34
Tc′	10.70 + 0.3617 Speed (m/min.) + 61.3 Feed (mm/rev.) − 5.96 Depth of cut (mm)	96.99

$$d_p = \overline{d_p} + \left(\overline{N_o} - \bar{d}_p\right) + \left(\overline{F_o} - \bar{d}_p\right) + \left(\overline{D_o} - \bar{d}_p\right) \quad (2)$$

$$A_p = 10^{-d_p/20} \quad (3)$$

3.4 *Machining time*

Machining time was measured in seconds as the time taken by tool travelling from the start of cut to end of cut in each experiment. Figure 4(a) shows mean effects plot for mean of S/N ratios for machining time during cryogenic turning with different levels of cutting parameters. Table 6 shows the optimum level of Mt′ was at Vd′ (level 3 = 56 m/min.), Fd′(level 3 = 0.13716 mm/rev.) and Dt′(level 3 = 0.476 mm). Predicated value of machining time was calculated from Eqs. (2) & (3) as 37.09 seconds. ANOVA table 8 shows Fd′ had the highest effect on the percentage of contribution (52.2%) followed by Vd′ and Dt′ in consecutive decreasing order of percentage contribution.

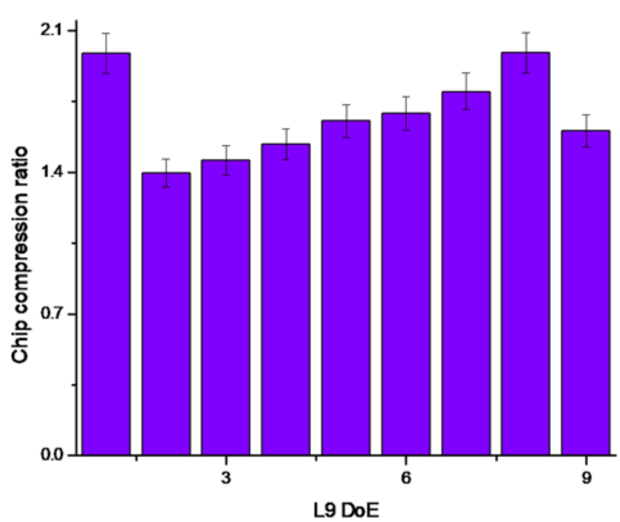

Figure 6. Chip compression according to experiments L_9 DoE.

F-value showed the relative importance firstly Fd′, secondly Vd′ and lastly was Dt′. P-value was significant for Vd′ and Fd′. Figure 4(b) shows the variation of mean Mt′ with different factor levels (cutting parameters). On incrementing cutting speed (Vd′), feed (Fd′) and depth of cut (Dt′) machining time declined.

3.5 *Temperature*

Temperature at the interface of tool and workpiece influences surface integrity of the machined component. This affects service providing the life period of the machined component. Figure 5(a) shows mean effects plot for the mean of S/N ratios for temperature during cryogenic turning with different levels of cutting parameters. Table 6 shows the optimum level of Tc′ was at Vd′ (level 1 = 25 m/min.), Fd′(level 1 = 0.05334 mm/rev.) and Dt′ (level 1 = 0.254 mm). Predicated value of temperature was calculated from Eqs. (2) & (3) as 24.99°C. ANOVA table 8 shows Vt′ had the highest effect on the percentage of contribution (79.57%), followed by Fd′ and Dt′ in consecutive decreasing order of percentage contribution. F-value showed the relative importance firstly Vd′, secondly Fd′ and lastly was Dt′. P-value was significant for Vd′. Figure 5(b) shows the variation of mean Tc′ with different factor levels (cutting parameters). On incrementing cutting speed (Vd′), feed (Fd′) and depth of cut (Dt′) temperature increased.

3.6 *Confirmation Experiment*

In Taguchi method confirmation experiments were performed to calculate the difference between actual values and predicted values of response at optimum levels. If the reliability of the condition was assumed to be 95%, then the confidence level (CI) was calculated from Eq. (4) [56]

$$CI = \sqrt{\left[F(\alpha, 1, f_e)V_e\left\{1/N_{eff} + (1/R)\right\}\right]} \quad (4)$$

$$N_{eff} = N/\left(1 + T_{dof}\right)Neff = N \quad (5)$$

Where, $F(\alpha,1,f_e)$ is the F-ratio required for 100(1 − α) percent confidence level, f_e, DOF for error = 20, Ve = AdjMs for error, N = total number of experiment(9 × 3 = 27), R = number of replications for confirmation of experiments (3) and T_{dof} T_f = total degree of freedom associated with mean optimum is (2 × 3 = 6). From standard statistical table, the value of F ratio for α = 0.05 is F(0.05,1,20) = 4.351. Substituting values form respective tables 6, 7 and 8.

CI value for cutting force was ±0.85, machining time was ±2.39 and temperature was ±0.5. The predicted optimal ranges of cutting force, machining time and temperature were $43.49 \leq Ct' \leq 45.34$, $34.7 \leq Mt' \leq 39.48$ and

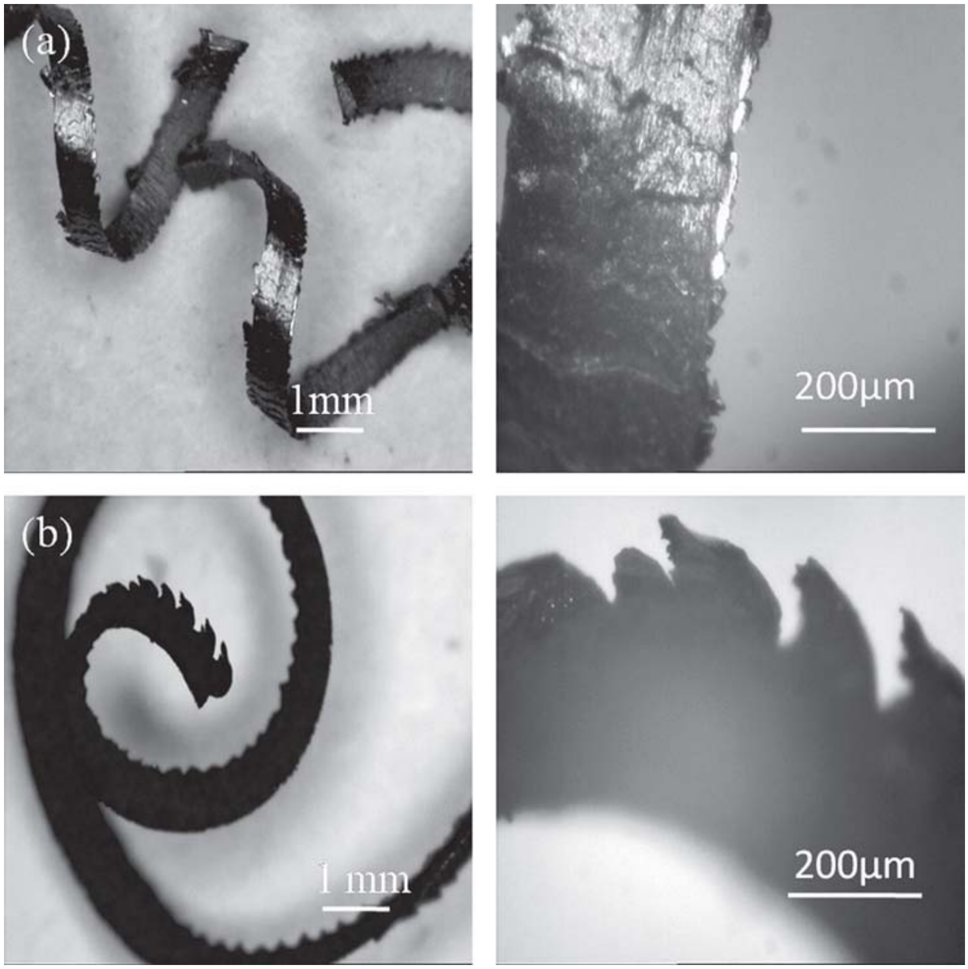

Figure 7. **(a)** Optical images of chip at Vd′ 25 m/min., Fd′ 0.05334 mm/rev. and Dt′ 0.254 mm. **(b)** Vd′ 56 m/min., Fd′ 0.13716 mm/rev. and Dt′ 0.381 mm.

$24.44 \leq Tc'25.54$ respectively. The confirmatory tests were performed for the optimum level of parameters for cutting force, machining time and temperature. It was found that response values were 45 N, 37 seconds and 25°C, respectively. This was within the range of the confidence interval (CI) (table 9).

3.7 *Confirmation test results*

The experiments were conducted again for validating the predicted values obtained for each response. It was found that the values obtained after performing experiments at the optimum level were within the predicted range.

Regression models were developed for studying the relationship between machining parameters and the correlation between independent and dependent parameters. From table 10, it was observed that R-Sq value was greater than 89–97% and approaching 100% and a good correlation was obtained between cutting parameters and experimental outputs.

3.8 *Chip compression ratio*

The chips were collected during cryogenic turning. The ratio of deformed chip thickness to undeformed chip thickness is defined as the chip compression ratio by utilizing Eq. (6).

$$CR = \frac{t_d}{t_u} \tag{6}$$

Chip compression ratio showed the frictional condition on the tool surface. Generally, at a low cutting speed of less than 30 m/minute, the chip compression ratio was low due to discontinuous chips. Chip compression ratio decreased with increased cutting speed, feed and depth of cut for cryogenically treated cutting inserts due to increase in hardenability and wear resistance created in the cutting inserts [32]. From figure 6 it was found that chip compression ratio was less than 2 for experiments performed under cryogenic turning with LN_2 and with the increase in cutting parameters at experiment performance of 9 of L_9 DoE chip compression ratio was less than at lower cutting parameter at experiment performance at 1 of L_9DoE. This may be due to the low temperature created at the interface of cutting insert and workpiece. The effect of thermal softening of the tool was declined. The tool became hard with low wear rate.

The chips generated during cryogenic turning were analysed by optical images as shown in figure 7(a) and (b). It was observed that they were staggered and most of the material had one sided flow. Chips were found discontinuous, brittle, easily breakable and long snarled. The low temperature created by a liquid nitrogen environment played an important role for such chip formation.

4. Conclusions

The exhaustive literature survey was conducted on machining for humankind and found that there was the need for experimental investigation during cryogenic turning in LN_2 environment at the mating zone of TiN coated cutting insert and AISI D3 workpiece. The experiment was carried out on lathe in created LN_2 environment. The following conclusions were drawn.

1. Chips generated during cryogenic turning were staggered and most of the material had one sided flow. The chip thickness increased with the increase of the machining parameters (speed, feed and depth of cut).
2. Chips were discontinuous, brittle, and easily breakable. The chips were long snarled. This may be due to the cooling effect created by the liquid nitrogen environment.
3. Taguchi based design of experiments [orthogonal array] was applied to reduce the number of the experimental run. This saved energy, raw materials for workpiece and cutting tool.
4. During analysis, the optimized value of cutting force was found at speed (56 m/min.), feed (0.05334 mm/rev.), and depth of cut (0.254 mm). According to mean effect plot, it was found that cutting force was inversely proportional to the speed and directly proportional to feed and depth of cut.
5. According to mean effect plot, it was found that the machining time was directly proportional to speed, feed and depth of cut. This may be due to the faster tool movement and reduction in friction between the cutting tool and workpiece. LN_2 absorbed heat generated between the cutting tool and workpiece and built a fluid layer which reduced friction. The optimized value of machining time was found at speed (56 m/min.), feed (0.13716 mm/rev.), and depth of cut (0.476 mm).
6. The optimized value of temperature was found at speed (25 m/min.), feed (0.05334 mm /rev.) and depth of cut (0.254 mm). According to mean effect plot, it was found that the temperature was directly proportional to speed, feed and depth of cut. This may be due to increasing friction at the interface of cutting tool and workpiece.

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Nomenclature

Ct'	Cutting Force during cryogenic turning with LN_2
Mt'	Machining time during cryogenic turning with LN_2
Tc'	Temperature during cryogenic turning with LN_2
Vd'	Speed (m/min.)
Fd'	feed (mm/rev.)
Dt'	Depth of cut (mm)
λ'	Inclination angle
α'	Orthogonal rake angle
β'	Orthogonal clearance angle of principal flank
γ'	Auxiliary orthogonal clearance angle
φ'	Auxiliary cutting edge angle
θ'	Principal cutting edge angle
r'	Nose radius (mm)
OA	Orthogonal array
DoE	Design of Experiment
LN_2	Liquid Nitrogen
CO_2	Frozen Carbon dioxide
AD	Anderson-Darling value

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