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Force and temperature analysis during distinct machining environment using an optimization approach

Anurag Sharma[a], R C Singh[b], Ranganath M Singari[b*] & S L Bhandarkar[c]
[a]Department of Mechanical Engineering, Delhi Technological University, Delhi-110 042 India
[b]Department of Mechanical Engineering, Delhi Technological University, Delhi-110 042 India
[c]Board of Technical Education, Muni Maya Ram Marg, Pitampura, Delhi- 110 088 India

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Cryogenic cooling with liquid nitrogen has a wide field of scientific and engineering applications. The aim of the presented research work is to analyze the impact on cutting force and temperature during the LN_2 single supply at (i) rake face and double supply (ii) rake and flank face of TiN coated carbide cutting tool during turning of AISI D3 steel. Taguchi based S/N ratio was used for Design of Experiments (DoE) of L_{18} orthogonal array. The four control factors were selected. The three factors like speed, feed and depth of cut were varied to three levels. The fourth factor was the machining condition which was varied to two levels. The cutting force and temperature were declined by 32-48% and 34-46% during the double supply of LN_2 at rake and flank face as compared to single supply at rake face. The influence and percentage of contribution of each factor were found out by Analysis of Variance (ANOVA). The double supply method with LN_2 supply at rake and flank face had the highest effect of contribution in the percentage as 77.13% and 87.42% for cutting force and temperature respectively. The values obtained during confirmatory runs were very close to the optimized results within the limits.

Keywords Liquid nitrogen, cutting force, temperature, optimization, ANOVA

1 Introduction

The conventional cutting fluids may not be able to provide sufficient cooling for difficult to cut materials. The process may create problems like splashing, health-related problems for an operator like nausea, itching to eyes and skin infections etc. The dry machining condition could be environmental friendly but the manufacturing rate could be low due to operating at slow cutting parameters[1-5]. The green and clean machining may be supported by using cryogenic cooling with LN_2. The health-related problems may be solved with cleanliness and neatness in the machining process. Liquid nitrogen is non-toxic, odourless and tasteless. The heat removing rate is highly efficient. The boiling point of liquid nitrogen is -196°C[6-9]. Gupta *et al.*[10] performed experiments during dry and cryogenic cooling with LN_2 on AISI 1040 steel. It was found that tool wear and cutting force was reduced to 55.45-65.55% and 61.94-96.6% during cryogenic cooling with LN_2 as compared with dry turning. Shokarani *et al.*[11] used cobalt chromium for machining with LN_2, MQL (minimum quantity lubrication) and flood. It has been found on comparing with LN_2 surface roughness was reduced by 35% and 42% as compared with MQL and flood machining. Flank wear during LN_2 was lowered by 26 times and 17 times as compared with MQL and flood cooling condition. Sartori *et al.*[12] investigated surface morphology of titanium alloy Ti 6Al 4V machine during different machining conditions like dry, wet, MQL, LN_2, CO_2, LN_2(rake)+MQL, LN_2(flank)+ MQL(rake) and CO_2(rake)+MQL(flank). The minimum surface roughness was found during cryogenic cooling with LN_2. Dhanachezian *et al.*[13] used duplex stainless steel 2205 as work piece for analysing the influence of LN_2 during turning. It was found that cutting temperature and cutting force were declined by 53-58% and 30-43% during cryogenic cooling with LN_2 on comparing with dry machining. Sharma *et al.* [14] used cold working die steel AISI D3 as workpiece with TiN coated carbide tool for analysing the effect of LN_2 on machiniability characteristics. It was found that surface roughness, cutting force, flank wear length and temperature were declined by 15-20%, 51-55%, 35-59% and 23-52% respectively on comparing with dry machining condition. The machining operation consists of different machining parameters. The optimization process gives a better combination of parameters for

*Corresponding author: (E-mail id: ranganath@dce.ac.in)

achieving the low (surface roughness, tool wear, cutting force, temperature *etc.*) or high machining response (material removal rate). The resources are used without any wastage. Taguchi Technique was discovered by Genichi Taguchi in 1950. Design of experiments based on Taguchi S/N ratio eliminates unnecessary hit and trial of experiments which reduce the number of experiments to be performed to a definite value. This saves costs associated with workpiece material, tool material, power supply, energy consumption etc. The process is time and economy saving[14, 15]. The optimization process has scientific and engineering applications which are helpful in the design process [16,17]. Gupta *et al.*[18] used Taguchi based optimization in determining the selection of process among dry, wet and LN_2. It was found that cryogenic cooling with LN_2 gave optimum value for surface roughness and cutting force. The different types of steel like EN 47, EN 19, AISI 1045, titanium alloys *etc.* were used by researchers and optimized for machinability characteristics [19-22]. High chromium tool steel alloy AISI D3 (HRC 60) is used in manufacturing blanking & forming dies, forming tools, press tools, punches, bushes and wear-resistant moulds. It is categorised as difficult to machine materials. Cutting parameters for turning of AISI D3 steel alloy is speed 30-260 m/minute, feed 0.05-0.15 mm/revolution and depth of cut 0.2-0.5 mm[14]. The exhaustive literature review shows the combination of AISI D3 workpiece and TiN coated carbide cutting tool is not used during cryogenic turning. in single supply on (i) rake face and double supply at (ii) rake and flank face. In the presented research work AISI D3 was used as workpiece material and TiN coated carbide coated cutting inserts as the cutting tool. The experiments were performed on lathe machine. DoE was Taguchi based on L_{18} [OA]. Two levels of machining condition were proposed. In one condition LN_2 was directly supplied at the rake face of cutting insert and in another condition LN_2 was directly supplied at rake and flank face. The response values of cutting force and temperature were analysed and optimized. The confirmatory runs were performed for checking the response values was in the predicted limit or not.

2 Experimental Processes

2.1 Materials

Round bars of diameter 45 mm and 300 mm long of AISI D3 steel was used in the performance of the experiment. The chemical analysis of workpiece material in the percentage of weight as C(2.01), Si(0.249), Mn (0.426), S(0.018), P(0.021), Cr(11.03), Ni(0.075), Mo(0.08), Co(0.012), Nb(0.22), V(0.037), W(0.088) and Fe (85.929). Carbide cutting inserts with coated TiN in diamond shape were used during performing experiments. The geometry of cutting insert is in accordance with specification DCMT11T308HQ grade PV 20. The thickness is 4mm, end relief angle 11º, front rake angle 0º, nose radius 8 mm. The elements were found as percentage of weight in cutting insert were C(7.06), Co(16.27), Mn(0.29), V(2.06), Nb(5.24), Ni(4.94), W(15.84), Mo(0.67) and Ti(47.64).

2.2 Machining setup

The turning experiments were performed on a lathe machine. The distinct machining environment was created by the direct supply of LN_2 from Dewar container A 55. Uniform flow of air was maintained by an air compressor with a pressure regulator connected to the container. Insulated pipes were connected from container to rake face of cutting insert and in another approach to flank and rake face. Piezo-electric type dynamometer was used for cutting force measurement. Digital infrared non-contact type thermometer was used to measure temperature by the end of the experiment. Every stage of the experiment was started with unused new cutting insert.

2.3 Design of Experiment (DoE)

Turning parameters were selected during the performance of experiments are shown in Table 1. One parameter was related to two distinct machining conditions. Other three parameters were related to 3V', F' and D'. Each was selected with three values in increasing order. Taguchi based orthogonal array [OA] L_{18} saved energy, raw material and operating cost. This may be due to declining the number of experiments for more than 50%.

3 Results

3.1 Probability plot investigations

Probability plots of each response are shown in Fig. 1. The data values were approximately aligned to

Table 1 — Turning parameters during the performance of experiments

Levels	Parameters			
	Mc'	V' (m/min.)	F'(mm/rev.)	D'(mm)
Level 1	LN_2-SJ	50	0.06	0.30
Level 2	LN_2-DJ	70	0.08	0.35
Level 3	-	90	0.10	0.40

the straight central line and normally distributed. The responses were validated by probability plots. This confirms for using data for further analysis.

3.2 Optimization based on Taguchi (Signal to Noise ratio)

Taguchi (S/N) based optimization was used to control the number of experiments to arrive at the targeted outcome. Eq. 1 shows the smaller the better characteristic of continuous response function depending on the optimization principle.

Smaller is the better characteristic,

$$\frac{s}{n} = -10log\frac{1}{n}\left(\sum x^2\right) \quad \ldots (1)$$

The values of turning performance characteristics & S/N ratio of turning performance characteristics are shown in Table 2. ANOVA means analysis of variance was used for completing and signifying the importance of process parameters contributing factor. The p-value signifies the level of 5% (confidence level of 95%) for all responses.

3.3 Cutting force

It is shown in Fig. 2 that cutting force was more in experiments 1-9 with a directly supplied of LN_2 at (rake face only) than experiments 10-19 with a

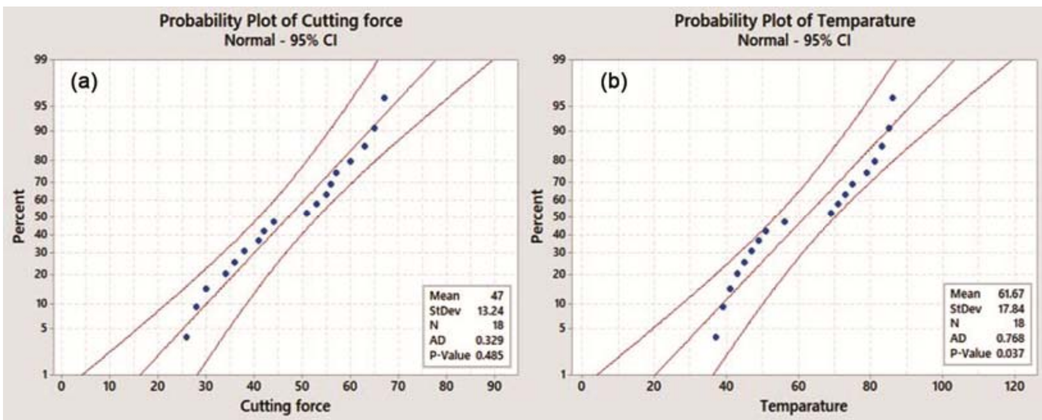

Fig. 1 — Probability plots for (a) cutting forces and (b) temperature

Table 2 — L_{18} Taguchi [OA] DoE with turning parameters and values of each response

Run	Turning parameters				Values of each response		S/N value of each response	
	Machining condition	V' (m/min.)	F' (mm/rev.)	D' (mm)	CF'	TR'	CF'	TR'
1	LN_2-SJ	50	0.06	0.30	67	69	-36.5215	-36.777
2	LN_2-SJ	50	0.08	0.35	65	71	-36.2583	-37.0252
3	LN_2-SJ	50	0.10	0.40	63	73	-35.9868	-37.2665
4	LN_2-SJ	70	0.06	0.30	56	75	-34.9638	-37.5012
5	LN_2-SJ	70	0.08	0.35	57	79	-35.1175	-37.9525
6	LN_2-SJ	70	0.10	0.40	60	81	-35.563	-38.1697
7	LN_2-SJ	90	0.06	0.35	51	83	-34.1514	-38.3816
8	LN_2-SJ	90	0.08	0.40	53	85	-34.4855	-38.5884
9	LN_2-SJ	90	0.10	0.30	55	86	-34.8073	-38.69
10	LN_2-DJ	50	0.06	0.40	44	37	-32.8691	-31.364
11	LN_2-DJ	50	0.08	0.30	41	39	-32.2557	-31.8213
12	LN_2-DJ	50	0.10	0.35	42	41	-32.465	-32.2557
13	LN_2-DJ	70	0.06	0.35	34	43	-30.6296	-32.6694
14	LN_2-DJ	70	0.08	0.40	36	45	-31.1261	-33.0643
15	LN_2-DJ	70	0.10	0.30	38	47	-31.5957	-33.442
16	LN_2-DJ	90	0.06	0.40	26	56	-28.2995	-34.9638
17	LN_2-DJ	90	0.08	0.30	28	51	-28.9432	-34.1514
18	LN_2-DJ	90	0.10	0.35	30	49	-29.5424	-33.8039

directly supplied LN_2 at (rake and flank face) simultaneously. This may be due to better lubrication effect generated by LN_2 at flank and rake face. This reduced the magnitude of cutting force between the cutting tool and workpiece.

It is shown in Fig. 3(b) that variation of average CF' that on increasing cutting speed V', cutting force declined and on incrementing feed F' and depth of cut D' cutting force increased. Table 4 shows the respective values of CF' with turning parameters. Variation of average of S/N CF' is shown in Fig. 3(a). Cutting force was optimized at Mc' (level 2 = LN_2-DS), V' (level3 = 90m/min.), F' (level1 = 0.06) and D' (level2 = 0.35mm) as shown in Table 3. The predicted value was calculated from Eqs. 2 & 3. The predicted value of cutting force at an optimum level was 30.93N. It is shown in ANOVA Table 5 that Mc'(machining condition) was highly effective with the percentage of contribution (77.13%). Next followed by V', F' and D' in consecutive decreasing order as 18.74%, 0.48% and 0.07% respectively. F-value depicted relative importance in increasing order of Mc'(machining condition), V'(cutting speed), F'(feed) and D'(depth of cut). p-value was significant for Mc'(machining condition) and V' (cutting speed).

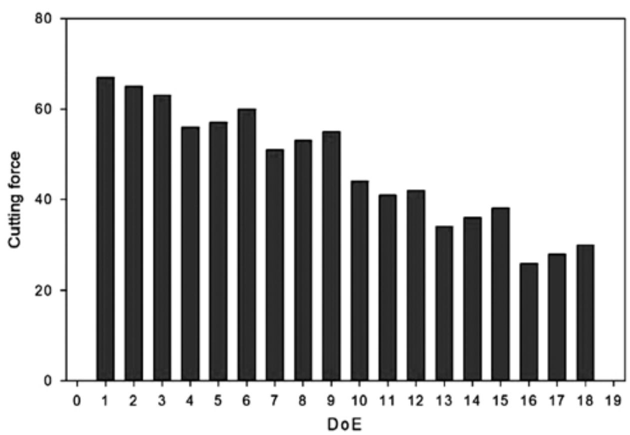

Fig. 2 — Experimental CF' according to DoE

$$\eta_p = \overline{\eta}_p + \left(\overline{Mc_o} - \overline{\eta}_p\right) + \left(\overline{\alpha_o} - \overline{\eta}_p\right) + \left(\overline{\beta_o} - \overline{\eta}_p\right) + \left(\overline{\gamma_p} - \overline{\eta}_p\right) \quad \ldots (2)$$

$$Z_p = 10^{-\frac{\eta_p}{20}} \quad \ldots (3)$$

3.4 Temperature

It is shown in Fig. 4 that temperature measured at the interface of cutting tool and workpiece was more in experiments 1-9 with directly supplied of LN_2 at (rake face only) than experiments 10-19 with a directly supplied of LN_2 at (rake and flank face). This may be due to the high coefficient of heat transfer. The double supply of LN_2 has incremented the faster rate of cooling of the cutting tool. The temperature lowered down and provided betters cooling at the interface of the cutting tool.

It is shown in Fig. 5(b) variation of mean TR' that on increasing cutting speed V' and feed F' was increased and on incrementing depth of cut D' temperature was marginally decreased than increased and respective values are shown in Table 4. Variation of mean S/N, TR' is shown in Fig, 5(a). Temperature was optimized at Mc' (LN2-DS), V' (50m/min.), F' (0.06 mm/rev.) and D' (0.35 mm) as shown in Table 3. The predicted value of temperature at an optimum level by using Eqs. 2 & 3 was 38.99°C. It was shown in ANOVA Table 5 that Mc'(machining condition)

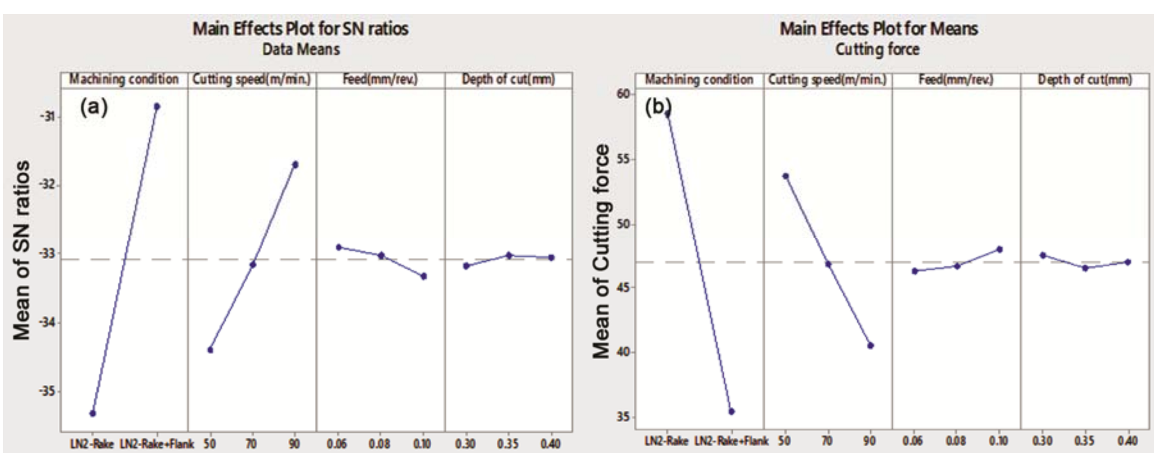

Fig. 3 — (a) Variation of average S/N CF' (b) variation of average CF' with different factors

Table 3 — Turning performance characteristics table for S/N ratio Cutting force (CF') and temperature (TR')

Turning performance characteristics	Level	Machining Condition	V'(m/min.)	F'(mm/rev.)	D'(mm)
CF'	1	-35.32	-34.39	**-32.91**	-33.18
	2	**-30.86**	-33.17	-33.03	**-33.03**
	3	-	**-31.70**	-33.33	-33.05
	Delta	4.46	2.69	0.42	-33.05
	Rank	1	2	3	4
TR'	1	-37.82	**-34.42**	**-35.28**	-35.40
	2	**-33.06**	-35.47	-35.43	**-35.35**
	3	-	-36.43	-35.60	-35.57
	Delta	4.76	2.01	0.33	0.22
	Rank	1	2	3	4

Table 4 — Turning performance characteristics table for means Cutting force (CF') and temperature (TR')

Turning performance characteristics	Level	Machining Condition Mc'	V'(m/min.)	F'(mm/rev.)	D'(mm)
CF'	1	58.56	53.67	**46.33**	47.50
	2	**35.44**	46.83	46.67	**46.50**
	3	-	**40.50**	48.00	47.00
	Delta	23.11	13.17	1.67	1.00
	Rank	1	2	3	4
TR'	1	78.00	**55.00**	**60.50**	61.17
	2	**45.33**	61.67	61.67	**61.00**
	3	-	68.33	62.83	62.83
	Delta	32.67	13.33	2.33	1.83
	Rank	1	2	3	4

was highly effective with the percentage of contribution (87.42%). Next followed by V', F' and D' in consecutive decreasing order as 10.43%, 0.278% and 0.13% respectively. p-value was significant for Mc'(machining condition) and V'(cutting speed).

3.5 Confirmation experiment

Confirmation experiments were performed to check the closeness between predicted values and results during the performance of the experiment at an optimized level. (CI) confidence level was calculated from Eqs. 4 & 5[23]. The range has predicted that values obtained during the performance of the experiment are acceptable or not. The values were in good agreement with the predicted range were acceptable at the optimized level. The reliability of the condition was assumed to be 95%.

$$CI = \sqrt{\left[F(\alpha, 1, fe)Ve\left\{\left(\frac{1}{Ne}\right) + \left(\frac{1}{R}\right)\right\}\right]} \quad \text{... (4)}$$

$$Ne = \frac{N}{(1+Td)} \quad \text{... (5)}$$

Where, $F(\alpha,1,f_e)$ is the F-ratio required for 100(1- α) percent confidence level, fe is DOF for error =10, Ve= AdjMs for error, N = total number of experiment (18), R = number of replications for confirmation of experiments (0) and Td = total degree of freedom associated with mean optimum is (7). From standard statistical table, the value of F ratio for α = 0.05 is F(0.05,1,10) = 4.96. Substituting values from ANOVA Table 6 with the respective responses. CI value of cutting force (CF') was ±0.96N and temperature (T') was ±0.67

3.6 Confirmation tests

Confirmation tests were performed for specified cutting parameters and machining condition to evaluate the degree of accuracy between predicted and experimental values at optimal levels. It has been found that the experimental values of each response were within close range of limits with predicted values. Actual value of cutting force and temperature after performing experiment under optimized conditions were 31.0N and 38.99°C . This was within predicted range of ±0.96N and ±0.67°C.

3.7 Discussion

The experiments were performed on lathe machine using LN_2. The design of experiments was based on Taguchi S/N signal to noise ratio. This has reduced the number of experiments to more than 50% of orthogonal array of L_{18}. The liquid nitrogen reduced the cutting force and temperature during double supply at rake and flank face by 55-66% and 53-57% respectively on comparing with a single supply of LN_2 at rake face. The double supply of liquid nitrogen incremented the efficiency in lowering down the temperature. The highly pressurised flow of LN_2 removed the fine debris generated at the interface of cutting insert and workpiece away from the machined surface which reduced the cutting force. The effect of thermal softening was eliminated. This provided the structural stability of the cutting insert. The tool became strong and retained the hardness. The cutting ability increased. The tool life increased. The optimized values were checked for confirmatory runs. It has been found that optimized response values were within the specified range of values. This proved that the performance of experiments was at the 95% confidence of level. The human-related problems like skin infection, nausea etc. were not found during the entire performance of experiments. The process was

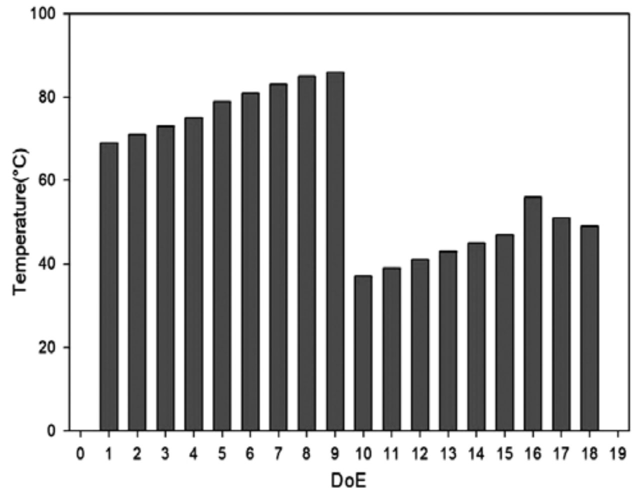

Fig. 4 — Experimental TR ' according to DoE

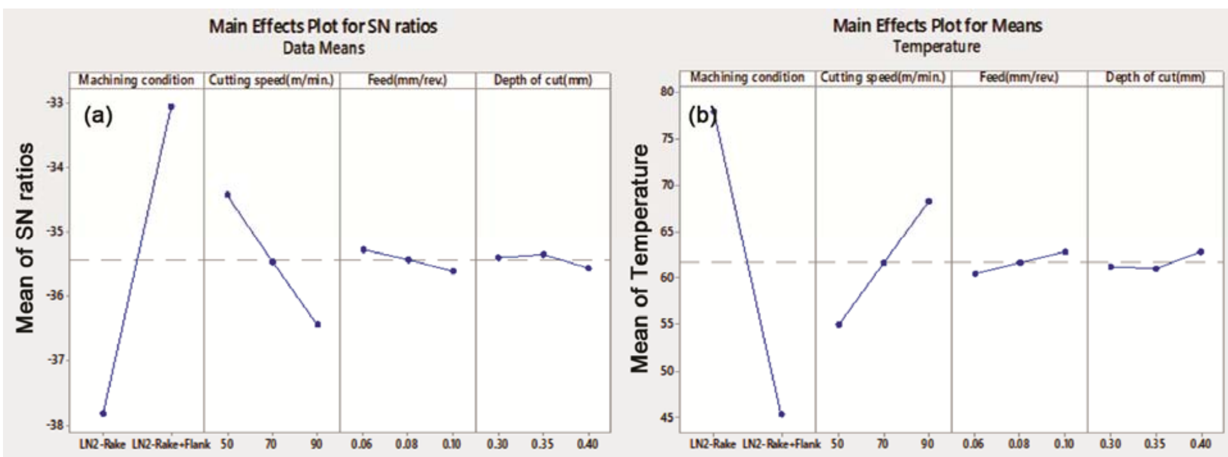

Fig. 5 — (a) Variation of average S/N TR' (b) variation of average TR' with different factors

Table 5 — Analysis of variance for means of Cutting force (CF') and Temperature (TR')

Turning performance characteristics	Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Cont.
CF'	Machining Condition	1	89.463	89.4630	215.96	0.000	77.13
	V'(m/min.)	2	21.728	10.8642	26.23	0.000	18.74
	F'(mm/rev.)	2	0.561	0.2803	0.68	0.530	0.48
	D' (mm)	2	0.081	0.0403	0.10	0.908	0.07%
	Error	10	4.143	0.4143	-	-	-
	Total	17	115.975	-	-	-	-
TR'	Machining Condition	1	101.846	101.846	503.53	0.000	87.42
	V'(m/min.)	2	12.146	6.073	30.03	0.000	10.43
	F'(mm/rev.)	2	0.324	0.162	0.80	0.476	0.278
	D'(mm)	2	0.162	0.081	0.40	0.680	0.13
	Error	10	2.023	0.202	-	-	-
	Total	17	116.502	-	-	-	-

neat and green. The chips generated could be readily used as direct scrape for raw material. This further reduced the cost related to the handling of debris and chips. The process can be considered for sustainable green production.

Conclusions

Taguchi based L_{18} DoE was used in the presented analysing research work. The two machining conditions were selected. One is with LN_2 at (i) rake face and second was with LN_2 at (ii) rake and flank face. The responses like cutting force and temperature were optimized and check for accuracy by performing confirmation tests. The following conclusions have been made on the basis of above-mentioned research work.

1. LN_2 supply at rake and flank faces was significant and gave a better cooling than LN_2 supply at rake face.
2. LN_2 absorbed heat and evaporated quickly which formed a fluid layer between the cutting tool and workpiece. Dual supply (rake and flank face) reduced cutting force as compared to a single supply (rake face).
3. LN_2 reduced the temperature due to the effective and efficient property of heat-carrying capacity. Dual supply (rake and flank face) reduced temperature as compared to a single supply (rake face).
4. Cutting force was optimized at MC' (-DJ), V' (50 m/min.), F' (0.06 mm/rev.) D' (0.30 mm). The predicted value was 30.93N.
5. Machining condition with LN_2 supply at flank and rake face simultaneously has the highest contribution the percentage (77.13%). The value of cutting force after confirmation test is 31 N. The CI range limit was $\pm$ 0.96.
6. The temperature at the interface of cutting insert was optimized at MC' (LN_2-DJ), V' (50 m/min.), F' (0.06 mm/rev.) D' (0.35 mm). The predicted value was 38.99 °C.
7. Machining condition with LN_2 supply at flank and rake face simultaneously has the highest contribution the percentage (87.42%). The value of cutting force after confirmation test was 40 °C. The CI range limit was $\pm$0.67.
8. LN_2 was efficient and eco-friendly. This may be suitable for green machining

List of Symbols

V' : Cutting speed (m/min.)
F' : Feed (mm/rev.)
D' : Depth of cut (mm)
CF' : Cutting force (N)
TR' : Temperature (°C)
Mc' : Machining condition
LN_2-SJ : LN_2 at Rake Face
LN_2-DJ: LN_2 at Rake and Flank Face
LN_2 : Liquid Nitrogen,
DoE : Design of experiments
η_p : S/N ratio calculated at optimized parameters
$\overline{\eta}_p$: mean S/N ratio for all variables at optimized parameters
$\overline{Mc_o}$: mean S/N ratio when machining condition at optimized parameters
$\overline{\alpha}_p$: mean S/N ratio when cutting speed at optimized parameters
$\overline{\beta}_p$: mean S/N ratio when feed at optimized parameters
$\overline{\gamma}_p$: mean S/N ratio when depth of cut at optimized parameters

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