# TOOL WEAR ANALYSIS DURING TURNING WITH SINGLE AND DUAL SUPPLY OF LN2

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**A Sharma***, Department of Mechanical Engineering, G B Pant DSEU Okhla III Campus, India

* Corresponding author. A Sharma (Email): anuragsharmadtu@gmail.com

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## SUMMARY

In the presented research work, $LN_2$ supplied directly at rake face and in another localised machining condition, $LN_2$ supplied at rake and flank face simultaneously. The DoE of performance of experiments was in accordance with Taguchi S/N ratio $L_{18}$. It was found that flank wear length and crater wear width at $LN_2$ supply at rake & flank face simultaneously declined by 23-38% and 20-30% respectively as compared to $LN_2$ supply at rake face only. ANOVA gave the highest effect of contribution in the percentage to $LN_2$ supply at rake & flank face simultaneously as 76.06% and 77.67%, next in decreasing order followed by speed, feed and depth of cut. SEM images depicted that flank wear length and crater wear width in both machining conditions. Tool wear was low during turning $LN_2$ supply at rake and flank face. Optimized values of each response was confirmed by repeating the experiments.

## KEYWORDS

Liquid nitrogen, Cryogenic turning, Flank face, Rake face, Optimization, ANOVA

## NOMENCLATURE

| | |
|---|---|
| A | Adj SS |
| AM | Adj MS |
| D | DF (Degree of Freedom) |
| DoE | Design of experiments |
| De′ | Depth of cut (mm) |
| E | Error |
| F | F-Value |
| Fe′ | Feed (mm/rev.) |
| FL′ | Flank wear length (µm) |
| $LN_2$ | Liquid Nitrogen |
| $LN_2$-S1 | $LN_2$ at Rake Face |
| $LN_2$-S2 | $LN_2$ at Rake and Flank Face |
| Mg′ | Machining condition |
| P | P-Value |
| RW′ | Crater wear width (µm) |
| S | Source |
| Tu | Turning performance |
| To | Total |
| Vc′ | Cutting speed (m/min.) |
| % | Percentage of contribution |
| $\eta_v$ | S/N ratio calculated at optimized parameters |
| $\bar{\eta}_v$, | An average S/N ratio for all variables at optimized parameters |
| $\overline{Mc}_p$ | An average S/N ratio when machining condition at optimized parameters |
| $\bar{\alpha}_o$ | An average S/N ratio when cutting speed at optimized parameters |
| $\bar{\beta}_o$ | An average S/N ratio when feed at optimized parameters |
| $\bar{\gamma}_o$ | An average S/N ratio when depth of cut at optimized parameters |
| $Z_o$ | predicted responses at optimized parameters |

## 1. INTRODUCTION

The clean and environmental favourable machining condition is the foremost aim of manufacturing. Dry machining is environmentally friendly but the surface roughness and tool wear are low at lower cutting parameter. This slows down the manufacturing rate. The recent development of materials of high hardness like superalloys, difficult to cut materials, composite materials etc. the use of conventional cutting fluid is discouraged [1-8]. This creates health issues related to fumes generated during machining, spilling of cutting fluid, chemical reaction etc. The surface roughness and tool wear during high-speed machining and difficult to machine materials, superalloys & composite materials if used with conventional cutting fluid are not in the proper predicted range. The dry machining is eco-friendly but favourable results are available in low cutting parameters. $LN_2$ is highly efficient in heat removal. This is non-toxic, odourless and tasteless. $LN_2$ has a boiling point of –196°C [9-10]. In machining processes, generally $LN_2$ is used from Dewar container. The regulated and metered amount of air is passed in Dewar. Liquid nitrogen was directly supplied at the tool-workpiece interface. On comparing the difference between dry, flood and cryogenic machining condition, it has been found that surface roughness and tool wear are low in cryogenic machining [11-13]. The significance of $LN_2$ has been analysed on steel specimens and titanium alloys that tool wear and surface roughness are low in comparison with flood and dry machining. The machined surfaces with $LN_2$ have negligible cracks. The chips generated are found to be thin, discontinuous and brittle with ease in breakability [14-17]. Machining process has different levels of control factors. This may be speed, feed, depth of cut, machining condition, dry, flood cryogenic etc. Optimization is performed to run the machine under a decided fixed set of levels of control factors to achieve economical benefit [16-18]. This saves unnecessary wastage of energy, materials of tool and workpiece. Taguchi based S/N ratio is one of the popular technique in optimization. The analysis was performed by Grey analysis or ANOVA techniques. The contributions of factors were calculated. The cryogenic supply with minimum quantity lubricants were performed by researchers and it was found that it gave better results than dry machining processes. The lower localized temperature at tool-workpiece interface emerged as influencing factor in determining various machinability characteristics like surface roughness and tool wear [19-26].

It has been found after literature review that very less research work is available with the cold working die steel (AISI D3) and TiN coated cutting tool in presence of single and dual supply of $LN_2$ during turning. Tool wear was investigated by using Taguhi approach and ANOVA. This work can further be extended with different noble gases like $CO_2$, helium, hydrogen. Combine effect of cryogenic cooling with lubrication effect provided by castor oil, vegetable oil etc. (MQL) simultaneously.

## 2. EXPERIMENTAL APPROACH

### 2.1 MATERIALS

The steel used for performing experiments was AISI D3. The chemical composition was checked and found as C, Si, Mn, S, P,Cr, Ni, Mo, Co, Nb, V, W, Fe in % of weight as 2.01, 0.249, 0.018, 0.021, 11.03, 0.075, 0.08, 0.22, 0.037, 0.088, 85.929 respectively. TiN coated carbide cutting inserts were used with chemical composition as C,Co, Mn, V, Ni, W, Mo, Ti, in % of weight as 7.06,16.27, 0.29, 2.06, 5.24, 4.94, 15.84, 0.67 and 47.64 respectively.

### 2.2 MACHINING SET UP

The performance of experiments was carried out on a lathe machine. The different machining environment was developed by $LN_2$ direct supply at the (i) rake face and (ii) rake and flank face simultaneously. This is depicted in Figure 1(a) and (b).

## 3. RESULTS AND DISCUSSIONS

### 3.1 PLOTS OF PROBABILITY

It is depicted in Figure 2 that values of outcome during specified parameters were coordinated towards the central line normally distributed. The outcome values were confirmed by the graphical presentations and could be used for further calculations and analysis.

### 3.1(a) Taguchi Based Optimization (Signal to Noise)

Taguchi (S/N) based optimization is used to control the number of experiments to arrive at the targeted outcome. Eq. (1) shows the smaller the better characteristic

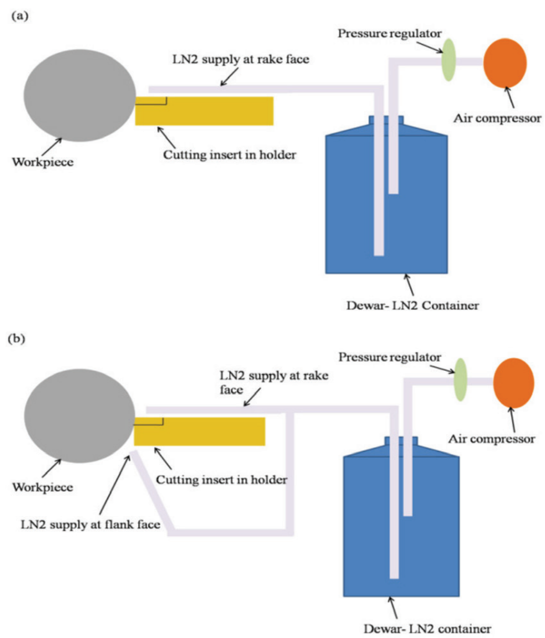


Figure 1. (a) Shows a schematic experimental setup of $LN_2$-S1 (b) $LN_2$-S2

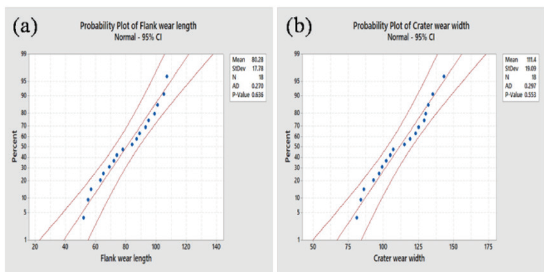


Figure 2. Probability plots for (a) Flank face-wear length (b) Rake face-crater width

 

of continuous response function depending on the optimization principle [3,4].

Smaller is the better characteristic

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

$L_{18}$ Orthogonal array based on Taguchi was used for experimentation machining operations. Table 1 depicts the process parameters and machinability characteristics FL′, RW′ and S/N FL′, RW′ respectively.

The highest S/N ratio value is selected for optimizing the particular level of factors. ANOVA means analysis of variance 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 [1]. Table 2 depicts S/N values for the 18 runs. Table 3 depicts S/N values of all parameters.

### 3.2 FLANK WEAR LENGTH

It is shown in Figure 3 that flank wear length is more in experiments 1-9 with $LN_2$ directly supplied at (rake face only) than experiments 10-19 with $LN_2$ directly supplied at (rake and flank face) simultaneously. This may be due to the high efficiency of $LN_2$ in heat removing capacity from contact heat zone of cutting insert. Secondly, the supply of $LN_2$ at both faces of cutting tool incremented the better cooling. From Fig. 4 shows flank wear length 101 µm at $LN_2$- S1 and Figure 5 shows flank wear length as 78 µm at $LN_2$-S2. The surface of cutting insert is better clean and smooth. It is shown in Figure 6(b) shows different average values of Fl′ at turning parameters. Table 4 shows variation of average values Fl′ at turning parameters. On increasing Vc′ (cutting speed), Fe′(feed) and De′ (depth of cut) flank wear length increased. Variation of average S/N Fl′ is shown Fig. 6(a). Flank wear length is optimized at Mg′ ($LN_2$-S2), Vc′ (50 m/min.), Fe′ (0.06) and De′ (0.30 mm).

Table 1. L18 Turning parameters on Taguchi based approach

| Run | Turning parameters | | | |
|---|---|---|---|---|
| | Mg′ | Vc′ | Fe′ | De′ |
| 1 | $LN_2$-S1 | 50 | 0.06 | 0.30 |
| 2 | $LN_2$-S1 | 50 | 0.08 | 0.35 |
| 3 | $LN_2$-S1 | 50 | 0.10 | 0.40 |
| 4 | $LN_2$-S1 | 70 | 0.06 | 0.30 |
| 5 | $LN_2$-S1 | 70 | 0.08 | 0.35 |
| 6 | $LN_2$-S1 | 70 | 0.10 | 0.40 |
| 7 | $LN_2$-S1 | 90 | 0.06 | 0.35 |
| 8 | $LN_2$-S1 | 90 | 0.08 | 0.40 |
| 9 | $LN_2$-S1 | 90 | 0.10 | 0.30 |
| 10 | $LN_2$-S2 | 50 | 0.06 | 0.40 |
| 11 | $LN_2$-S2 | 50 | 0.08 | 0.30 |
| 12 | $LN_2$-S2 | 50 | 0.10 | 0.35 |
| 13 | $LN_2$-S2 | 70 | 0.06 | 0.35 |
| 14 | $LN_2$-S2 | 70 | 0.08 | 0.40 |
| 15 | $LN_2$-S2 | 70 | 0.10 | 0.30 |
| 16 | $LN_2$-S2 | 90 | 0.06 | 0.40 |
| 17 | $LN_2$-S2 | 90 | 0.08 | 0.30 |
| 18 | $LN_2$-S2 | 90 | 0.10 | 0.35 |

Table 2. Output values of FL′ , RW′ and S/N FL′ , RW′ respectively

| Run | Turning performance characteristics | | S/N value of Turning performance characteristics | |
|---|---|---|---|---|
| | FL′ | RW′ | FL′ | RW′ |
| 1 | 84 | 115 | –38.4856 | –41.214 |
| 2 | 87 | 125 | –38.7904 | –41.9382 |
| 3 | 89 | 129 | –38.9878 | –42.2118 |
| 4 | 93 | 119 | –39.3697 | –41.5109 |
| 5 | 95 | 123 | –39.5545 | –41.7981 |
| 6 | 99 | 130 | –39.9127 | –42.2789 |
| 7 | 105 | 132 | –40.4238 | –42.4115 |
| 8 | 107 | 143 | –40.5877 | –43.1067 |
| 9 | 101 | 135 | –40.0864 | –42.6067 |
| 10 | 52 | 81 | –34.3201 | –38.1697 |
| 11 | 55 | 84 | –34.8073 | –38.4856 |
| 12 | 57 | 86 | –35.1175 | –38.69 |
| 13 | 63 | 93 | –35.9868 | –39.3697 |
| 14 | 65 | 99 | –36.2583 | –39.9127 |
| 15 | 69 | 97 | –36.777 | –39.7354 |
| 16 | 72 | 102 | –37.1466 | –40.172 |
| 17 | 74 | 105 | –37.3846 | –40.4238 |
| 18 | 78 | 107 | –37.8419 | –40.5877 |

The predicted value of flank wear length at an optimum level by using Eqs. (2) and (3) is 54.70 µm. It is shown in ANOVA Table 8 that machining condition is highly effective with the percentage of contribution (76.06%). Next followed by Vc′, Fe′ and De′ in consecutive decreasing order as 20.65%, 1.09% and 0.08% respectively. F-value depicts relative importance in increasing order of Mg′ (machining condition), Vc′ (cutting speed), Fe′ (feed) and De′ (depth of cut). p-value is significant for Mg′ (machining condition) and Vc′ (cutting speed) [27-28].

$$\eta_v = \bar{\eta}_v + \left(\overline{Mc_p} - \bar{\eta}_v\right) + \left(\overline{\alpha_o} - v\right) + \left(\overline{\beta_o} - \bar{\eta}_v\right) + \left(\overline{\gamma_o} - \bar{\eta}_v\right) \tag{2}$$

Table 3. S/N ratio for flank wear length (FL′) and crater wear width (RW′)

| TC | Level | Mg′ | Vc′ | Fe′ | De′ |
|---|---|---|---|---|---|
| FL′ | 1 | –39.58 | **–36.75** | **–37.62** | **–37.82** |
| | 2 | **–36.18** | –37.98 | –37.90 | –37.95 |
| | 3 | – | –38.91 | –38.12 | –37.87 |
| | Delta | 3.40 | 2.16 | 0.50 | 0.13 |
| | Rank | 1 | 2 | 3 | 4 |
| RW′ | 1 | –42.12 | **–40.12** | **–40.47** | **–40.66** |
| | 2 | **–39.51** | –40.77 | –40.94 | –40.80 |
| | 3 | – | –41.55 | –41.02 | –40.98 |
| | Delta | 2.61 | 1.43 | 0.54 | 0.31 |
| | Rank | 1 | 2 | 3 | 4 |

Table 4. Average value of flank wear length (FL′) and crater wear width (RW′)

| TC | Level | Mg′ | Vc′ | Fe′ | De′ |
|---|---|---|---|---|---|
| FL′ | 1 | 95.56 | **70.67** | **78.17** | **79.33** |
| | 2 | **65.00** | 80.67 | 80.50 | 80.83 |
| | 3 | - | 89.50 | 82.17 | 80.67 |
| | Delta | 30.56 | 18.83 | 4.00 | 1.50 |
| | Rank | 1 | 2 | 3 | 4 |
| RW′ | 1 | 127.89 | **103.33** | **107.00** | **109.17** |
| | 2 | **94.89** | 110.17 | 113.17 | 111.00 |
| | 3 | - | 120.67 | 114.00 | 114.00 |
| | Delta | 33.00 | 17.33 | 7.00 | 4.83 |
| | Rank | 1 | 2 | 3 | 4 |

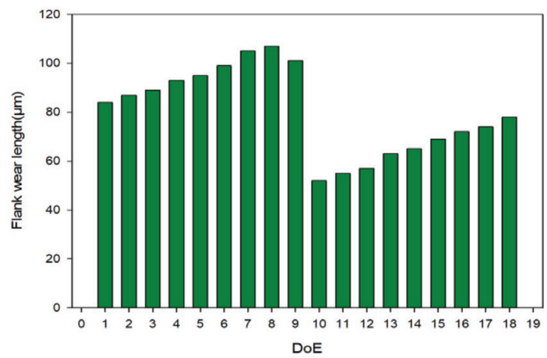


Figure 3. Experimental FL′ according to DoE

$$Z_o = 10^{-\frac{\eta_v}{20}} \tag{3}$$

## 3.3 CRATER WEAR WIDTH

It is shown in Figure 7 that crater wear width is more in the experiments 1-9 with $LN_2$ directly supplied at (rake face

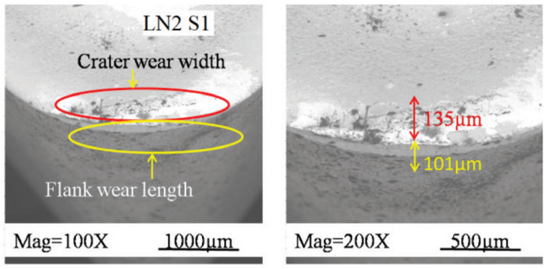


Figure 4. SEM image of cutting insert used at Vc′ = 90 m/min., Fe′ = 0.10 mm/rev. and De′ = 0.30 mm at $LN_2$-S1

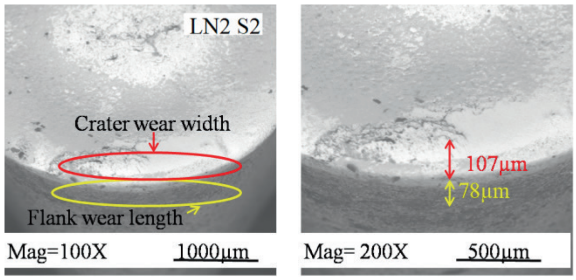


Figure 5. SEM image of cutting insert used at Vc′ = 90 m/min., Fe′ = 0.10 mm/rev. and De′ = 0.35 mm at $LN_2$-S2

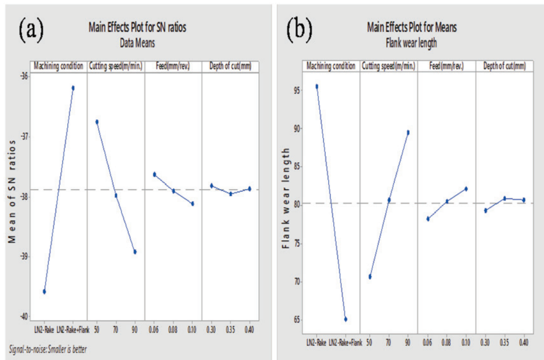


Figure 6. (a) Variation of average S/N FL′ (b) variation of average FL′ with turning parameters

only) than experiments 10-19 with $LN_2$ directly supplied at (rake and flank face) simultaneously. This may be due to the high efficiency of $LN_2$ in heat removing capacity from contact heat zone of cutting insert. Secondly, supply of $LN_2$ at both faces of cutting tool incremented the better cooling. From Figure 4 shows crater wear width as 135 µm at $LN_2$-S1 and Figure 5 shows crater wear width as 107 µm at $LN_2$-S2. The surface of cutting insert is better clean and smooth.

## 3.4 VERIFICATION EXPERIMENTS

Verification 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 is calculated from Eqs. (4) and (5). The

 

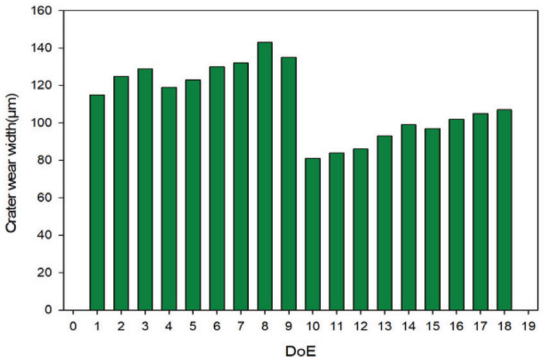


Figure 7. Experimental RW′ according to DoE

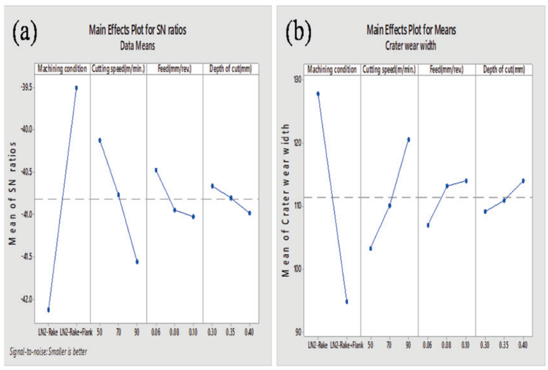


Figure 8. (a) Variation of average S/N RW′ (b) variation of average RW′ with different factors

range predicts that values obtained during the performance of the experiment are acceptable or not. The values in good agreement with the predicted range are acceptable at the optimized level. The reliability of the condition is assumed to be 95%. [27].

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

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

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 5 with the respective responses. CI value of Flank wear length (FL′) is ±0.56 µm and crater wear width (RW′) is ±0.83µm.

Table 5. Analysis of variance for means of flank wear length (FL′), crater wear width (RW′)

| Tu | S | D | A | AM | F | P | % |
|---|---|---|---|---|---|---|---|
| FL′ | Mg′ | 1 | 51.87 | 51.87 | 359.7 | 0.00 | 76.06 |
| | Vc′ | 2 | 14.08 | 7.04 | 48.84 | 0.00 | 20.65 |
| | Fe | 2 | 0.74 | 0.37 | 2.59 | 0.12 | 1.09 |
| | De′ | 2 | 0.05 | 0.02 | 0.19 | 0.82 | 0.08 |
| | Er | 10 | 1.44 | 0.14 | - | - | - |
| | To | 17 | 68.21 | - | - | - | - |
| RW′ | Mg′ | 1 | 30.75 | 30.75 | 232.1 | 0.00 | 77.67 |
| | Vc′ | 2 | 6.18 | 3.09 | 23.32 | 0.00 | 15.61 |
| | F′e | 2 | 1.04 | 0.52 | 3.94 | 0.05 | 2.63 |
| | D′ | 2 | 0.29 | 0.14 | 1.11 | 0.36 | 0.74 |
| | Er | 10 | 1.32 | 0.13 | - | - | - |
| | To | 17 | 39.60 | - | - | - | - |

The experiments were performed in the specified optimized parameters and found that values were in the range calculated range.

## 4. CONCLUSIONS

The experiments were performed on lathe machines with single and dual supply of $LN_2$ and following conclusions were summarized

1. Liquid nitrogen in dual supply (Rake and Flank Face) gave better and improved results as compared to single supply (Flank face only).
2. Dual supply of $LN_2$ gave highest contribution in percentage of (76.06%). The flank wear length was 54.0µm and CI range was ±0.56.
3. Crater wear width was 83.00 µm and CI range was ±0.83.
4. The environment wad clean without any emergance of toxic fumes.
5. The scrape devepoled could be easily recycle because no traces of oil, lubricants etc. were found as compare to conventional cutting fluids.

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