EFFECT OF VARIOUS SOLID LUBRICANTS ON SURFACE QUALITY IN TURNING OF INCONEL 718

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Abstract

Metal cutting or machining is a backbone of manufacturing industries. In machining process, heat is generated and it must be removed with the help of cutting fluid. Generally, hydrocarbon oil based cutting fluid is used, but it leads to environmental pollution and as well as operator’s ill health. Solid lubrication is a good alternative to hydro carbon oil based cutting fluid. In this work, turning process is carried out on Inconel 718 with perpendicular direction textured cutting insert filled with different solid lubricants. Solid lubricants as lubricant materials, which are basically solid but become soft due to frictional heat at the point of contact. In this work, Molybdenum disulfide (MoS₂) and Graphite solid lubricants are used. Experiments are performed as per L₉ orthogonal array and the effect of each process parameter is determined through the Analysis of Variance (ANOVA). The result revealed that solid lubricant with textured tool produces a continuous lubricating layer on the surface of the tool due to the thermal expansion of heat produced during machining. This thin layer may reduce friction in the machining zone. Perpendicular direction textured cutting inserts are used to reduce friction and good surface finish is obtained. Compared with MoS₂, graphite has shown better results in terms of surface finish due to its low shear strength properties.

Keywords: Turning, Solid Lubrication, Surface finish, Taguchi

I. Introduction

It is a well known fact that large amount of heat is generated between tool and work piece during metal cutting process. Cutting fluid is used to improve the cutting conditions and conventional one is hydrocarbon oil based. It affects both
environment as well as the health of the operator. Some other alternative methods are also available such as dry machining, Minimum Quantity Lubrication (MQL), vegetable oil as cutting fluid, cryogenically treated tool and solid lubricants. Few drawbacks with alternative methods namely, dry machining affects metallurgical changes and releases more heat, vegetable oil depends on its properties, Cryogenic treatment and MQL method need special equipment [I-IV]. Solid lubrication is one of the easiest way and good alternative to hydrocarbon oil based cutting fluid. Texture on cutting tool inserts is used to reduce co-efficient of friction and leads to sustainability in machining. Application of solid lubricant on the textured tool is leaving a constant solid lubricating layer on the tool surface which is due to thermal expansion by heat produced during machining. This continuous thin layer led to decrease of machining zone temperature, cutting forces and reduced friction [V]. Various solid lubricants attempted by various researchers are graphite, boric acid, molybdenum disulphide, tungsten disulphide and hexagonal boron nitrite [VI-XII].

II. Literature Review

Song et al. [VI] compared conventional cutting tool with textured tool filled with graphite and concluded that tool embedded with graphite exhibited lower friction coefficient, reduced rake face wear and also improvement in surface quality of work piece. Song et al. [VII] used micro hole textured tool with CaF$_2$ powder burnished into the micro holes and studied the wear and friction characteristics of tool and result reported that CaF$_2$ filled textured tool performed better at higher temperatures. Shuting lei et al. [VIII] has studied the friction force and friction coefficient of micro dimple, micro groove and flat texture on rake face of cutting tool with oil, solid lubricant (tungsten disulphide) and dry machining. The result showed that cutting force, friction coefficient and tool-chip contact length were minimized when machining is done with textured cutting tools with lubrication. Arulkirubakaran et al. [IX] studied that the performance of parallel, perpendicular and cross textured groves on rake face to evaluate machining forces, cutting temperature and chip morphology. Semi solid lubricant of molybdenum disulphide and SAE 40 oil were used to perform machining on Ti-6Al-4V alloy. The result indicated that cutting tool with perpendicular texture was performed well. Sharma et al. [X] reported that cutting insert with perpendicular texture and multiple circular holes (hybrid texture) has reduced the tool chip contact area and hence cutting forces, when machined with CaF$_2$ as solid lubricant when compared with cross, parallel and multiple textured inserts. The performance of all textured tools is better when compared with non textured tools. Padmini et al. [XI] has performed turning operation on AISI 1040 steel using two nano solid lubricants mixed with sesame oil and coconut oil and resulted that nano solid lubricants with coconut oil has shown better resulted in reducing the tool flank wear, surface roughness, cutting forces and cutting temperature in comparison with sesame oil. Yılmaz et al. [XII] used external chip breaker to break the continuous chip while machining of Inconel 718 and reported that external chip breaker has improved the machining performance.

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From the literature it is concluded that textured tools with solid lubricants are used to eliminate the conventional cutting floods. Few researchers have used micro hole, micro groove, parallel, perpendicular and cross textured cutting inserts along with solid lubricants to study their performance during machining. Most of the literature not mentioned about the supply of solid lubricants to the machining zone. In this work, the effort has been taken for perpendicular direction textured inserts with two solid lubricants (MoS$_2$ and graphite) and their performance on surface roughness with solid lubrication supply system.

### III. Experimental Setup

Inconel 718 is considered as work piece material which is widely used where high temperature and corrosion resistance are required. Turning process is performed on 25mm in diameter with 45mm in length. The CNC lathe of make and model (Pride and Jaguar) is used to perform turning process. The cutting tool insert used in this work is uncoated tungsten carbide with grade CNMA 120408 (make WEDIA). The texture is produced on the rake face of the tool insert using Wire cut EDM. The dimensions of the perpendicular direction texture are mentioned in Table 1. Figure 1 shows the tungsten carbide cutting tool with perpendicular direction texture. Molybdenum disulphide and Graphite are the solid lubricants used in this work which are mixed with SAE 40 oil in the ratio of 80 to 20 by weight. A distinct solid lubricant supply system is used to supply this lubricant to the machining zone. Figure 2 and 3 shows the solid lubrication supply setup and machined samples.

| Sl. No | Parameters       | Dimensions |
|--------|------------------|------------|
| 1      | Width of groove  | 300 µm     |
| 2      | Depth of groove  | 100 µm     |
| 3      | Pitch of groove  | 200 µm     |

| Symbol | Cutting parameters | Level 1 | Level 2 | Level 3 |
|--------|--------------------|---------|---------|---------|
| A      | Cutting speed (m/min) | 91      | 116     | 141     |
| B      | Feed rate (mm/rev)  | 0.1     | 0.15    | 0.2     |
| C      | Depth of cut (mm)   | 0.5     | 1       | 1.5     |
Surface roughness of the machined sample is measured using SJ-210 surface roughness tester. The average surface roughness ($R_a$) is measured for three times on each machined work piece and the average values are used for further studies. Surface roughness is an important machinability characteristic and indication of machinability. It is indicated by area between the roughness profile and its centre line while measurement. It is followed that ISO 4287:1997 with a cut-off length of 0.8 mm and sampling length of 5 mm. Table 3 presents the result of experiments.

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| Sl. No | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Surface Roughness (µm) |
|--------|-----------------------|--------------------|------------------|-----------------------|
|        |                      |                    |                  | MoS₂                  | Graphite              |
| 1      | 91                   | 0.1                | 0.5              | 0.83                  | 0.77                  |
| 2      | 91                   | 0.15               | 1                | 1.19                  | 0.9                   |
| 3      | 91                   | 0.2                | 1.5              | 1.28                  | 1.06                  |
| 4      | 116                  | 0.1                | 1                | 0.62                  | 0.52                  |
| 5      | 116                  | 0.15               | 1.5              | 0.73                  | 0.64                  |
| 6      | 116                  | 0.2                | 0.5              | 1.18                  | 0.97                  |
| 7      | 141                  | 0.1                | 1.5              | 0.6                   | 0.59                  |
| 8      | 141                  | 0.15               | 0.5              | 0.89                  | 0.91                  |
| 9      | 141                  | 0.2                | 1                | 1.16                  | 0.85                  |

### IV. Methodology

Taguchi method involves orthogonal array, S/N ratio and ANOVA study. The most important statistical tool for design of experiments which reduces the number of test required, time of the experiments and cost is orthogonal array. Moreover it is also used to observe the consequence of each process parameters on the responses [XIII]. The deviation between the experimental value and actual value can be estimated by S/N ratio. ANOVA is the best method to observe the effect of each process parameter with percentage contribution on the output which cannot be achieved by Taguchi method.

Steps involved in Taguchi method

1. Selection of quality characteristics

   The quality characteristic considered in this work is surface roughness.

2. Identifying factors and levels

   The main effect of process parameters that is cutting speed, feed rate and depth of cut on response is analyzed. The process parameters and their levels are shown in Table 2.

3. Selection of an orthogonal array

   Three levels of process parameters are selected; hence minimum experiments are required as per $L_9$. 

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4. Perform the experiments
Experiments are carried out as per L₀ orthogonal array recommendation.

5. Calculation of Signal-to-Noise (S/N) ratio
Major types of S/N ratio are smaller-the-better and larger-the-better. Equations (1) and (2) are used to analyze the results for maximization and minimization of output parameters respectively.

Larger-the-better
\[ \frac{S}{N} = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_{ij}^2} \right) \]  \hspace{1cm} (1)

Smaller-the-better
\[ \frac{S}{N} = -10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} y_{ij}^2 \right) \]  \hspace{1cm} (2)

Table 4: S/N ratio values

| S.No | MoS₂  | Graphite |
|------|-------|----------|
| 1    | 1.618 | 2.270    |
| 2    | -1.510| 0.915    |
| 3    | -2.144| -0.506   |
| 4    | 4.152 | 5.679    |
| 5    | 2.733 | 3.876    |
| 6    | -1.437| 0.264    |
| 7    | 4.436 | 4.582    |
| 8    | 1.012 | 0.819    |
| 9    | -1.289| 1.411    |

6. Analyze the results
Mean table and main effects plot are used to study the outcome of experiments and to predict the optimum combination of input process parameters for machining.

7. Confirmation experiments
V. Results and Discussion

In this work, conventional cutting fluid is avoided and solid lubrication is attempted. Solid lubricants used in this work include MoS\(_2\) and graphite. Process parameters are taken based on their prior experiments and literature. The input parameters considered in this research are cutting speed, feed rate and depth of cut and output parameter is surface roughness (R\(_a\)). Experimental results obtained using L\(_9\) orthogonal array are shown in table 3. Taguchi method is used to investigate the experimental data with the help of S/N ratio and ANOVA. In this experimental study R\(_a\) is taken as minimization type output parameter. Hence smaller-the-best concept is used for minimization objective to achieve optimum process parameters.

Textured inserts with solid lubricants produces a thin lubricating layer and it is used to minimize the friction and temperature in the cutting zone [V]. Basically these solid lubricants are soft in nature. In MoS\(_2\) solid lubricant, there is a chance of sulphides gets oxidation and may lose lubricating property at working temperature. Hence, graphite serves better than sulphides with wider range of working temperature. Also, graphite has hexagonal lamellar structure with low shear strength [XIV]. This is might be the reason for better surface finish of work piece when machined with graphite as solid lubricant than MoS\(_2\) as solid lubricant. Various direction textures are available namely parallel, perpendicular, cross type and dimple texture [VI-XII]. Among these methods, perpendicular direction textures are used to reduce friction and tool-chip contact length during machining [IX]. Due to these reason, good surface finish is achieved with perpendicular direction textured cutting inserts. Tables 5 and 6 shows the response table of mean S/N ratio for surface roughness .Figure 3 and 4 shows the mean S/N graph of MoS\(_2\) and graphite. Generally in most of the literature is not mentioned about solid lubricant supply system to the machining zone. In this work, a specially designed solid lubrication supply system is used. This work attempts towards eco friendly machining and to solve issues related to mineral oil based cutting fluid.

To observe the significant effect of process parameters and to evaluate the experimental results ANOVA is used [XV]. The effect of process parameters in terms of their percentage, error variance in the process and significant effects for controlling the responses are determined by ANOVA. In this investigation feed rate is the major process parameter which is affecting the response. The conformation tests are carried out to confirm the optimal process parameters attained during the investigation. A2B1C3 is an optimum combination of process parameters for MoS\(_2\) as solid lubricant and it is A2B1C2 for graphite as solid lubricant obtained using Taguchi method in turning operation. Therefore, above optimum process parameters are considered for validation analysis. The optimum combination of process parameters (v=116 m/min, f=0.1 mm/rev and d=0.5 mm) are used, the validation
experiments gives the $R_a$ of 0.63 µm and 0.52 µm for MoS$_2$ and graphite as solid lubricants respectively.

**Table 5: Response table mean S/N Ratio for MoS$_2$**

| Symbol | Cutting parameters | Mean S/N Ratio |
|--------|--------------------|----------------|
|        |                    | Level 1 | Level 2 | Level 3 |
| A      | Cutting speed      | -0.678  | 1.816   | 1.386   |
| B      | Feed rate          | 3.402   | 0.744   | -1.623  |
| C      | Depth of cut       | 0.397   | 0.450   | 1.675   |
|        |                    | 3.121   | 3.011   | 1.438   |

**Table 6: Response table mean S/N Ratio for Graphite**

| Symbol | Cutting parameters | Mean S/N Ratio |
|--------|--------------------|----------------|
|        |                    | Level 1 | Level 2 | Level 3 |
| A      | Cutting speed      | 0.893   | 3.273   | 2.271   |
| B      | Feed rate          | 4.177   | 1.870   | 0.390   |
| C      | Depth of cut       | 1.117   | 2.668   | 2.651   |
|        |                    | 6.188   | 7.812   | 5.312   |

**Fig. 3:** The mean Single-to-noise graph for surface roughness when machined with MoS$_2$
Fig. 4: The mean Single-to-noise graph for surface roughness when machined with Graphite

Table 7: Result of ANOVA for MoS$_2$

| Source of variation | DOF | Sum of Squares | Mean Square | F Ratio  | Contribution % |
|---------------------|-----|----------------|-------------|----------|----------------|
| Cutting speed       | 2   | 10.675         | 5.3377      | 19.904   | 20.41          |
| Feed rate           | 2   | 37.935         | 18.967      | 70.732   | 72.55          |
| Depth of cut        | 2   | 3.135          | 1.5677      | 5.8462   | 5.99           |
| Error               | 2   | 0.5363         | 0.2681      | 1.025    | 1.025          |
| Total               | 9-1=8 | 52.283         |             | 100      |                |

Table 8: Result of ANOVA for Graphite

| Source of variation | DOF | Sum of Squares | Mean Square | F Ratio  | Contribution % |
|---------------------|-----|----------------|-------------|----------|----------------|
| Cutting speed       | 2   | 8.571          | 4.285       | 13.469   | 23.92          |
| Feed rate           | 2   | 21.861         | 10.930      | 34.356   | 61.02          |
| Depth of cut        | 2   | 4.756          | 2.3780      | 7.474    | 13.27          |
| Error               | 2   | 0.636          | 0.3181      | 1.77     | 1.77           |
| Total               | 9-1=8 | 35.825         |             | 100      |                |
Taguchi technique determines the effect of individual parameters for entire process using ANOVA. The ANOVA table contains the degrees of freedom (DOF), sum of squares (SS), mean square (MS) and percentage contribution (P) of process parameters. The result of ANOVA of the surface roughness is shown in Table 7 and 8. It is observed that from both solid lubrication conditions, feed rate has highest contribution. From the result of confirmation test (Table 9 and 10) surface roughness is decreased by 2.17 times in MoS$_2$ and 1.76 times in graphite conditions. The confirmation test is performed to find the optimum parameters during the experimentation.

### Table 9: Confirmation test MoS$_{2}$ as solid lubricant

| Initial cutting Parameters | Optimal cutting parameters |
|---------------------------|----------------------------|
|                          | Prediction | Experiment |
| Level                    | A2B2C2     | A2B1C3     | A2B1C3     |
| surface roughness (µm)   | 1.37       | 0.631      |
| S/N ratio (dB)           | -2.734     | 5.211      | 3.999      |
| Improvement of S/N ratio |             | 6.733      |

### Table 10: Confirmation test Graphite as solid lubricant

| Initial cutting Parameters | Optimal cutting parameters |
|---------------------------|----------------------------|
|                          | Prediction | Experiment |
| Level                    | A2B2C2     | A2B1C2     | A2B1C2     |
| surface roughness (µm)   | 0.861      | 0.501      |
| S/N ratio (dB)           | 1.299      | 5.828      | 6.003      |
| Improvement of S/N ratio |             | 4.703      |

### VI. Conclusions

Optimization of process parameters in turning of Inconel 718 steel by the application of Taguchi is conducted as the method of study. The major conclusions are obtained from this study.

- Textured cutting inserts eliminate conventional cutting fluid and solid lubrication leads to sustainability in turning process
Solid lubricants are having low coefficient of friction and graphite gives minimum surface roughness compared to molybdenum disulphide.

Optimum process parameters levels are determined using main effect plot and the performance table. The optimum process parameter values are cutting speed of 116 m/min, feed rate of 0.1 mm/rev and depth of cut of 1.5 mm.

The significant effect of process parameters are found by ANOVA. The result of ANOVA reveals that the feed rate is the most influencing parameter having value of 72.5% with MoS₂, and 61% with graphite solid lubricants followed by the cutting speed with the value for MoS₂ as 20.4 % and 23.9% for graphite solid lubricants. The verification tests are conducted to confirm the optimum process parameters.

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References

I. Debnath, S., Reddy, M.M. and Yi, Q.S., 2014. Environmental friendly cutting fluids and cooling techniques in machining: a review. *Journal of cleaner production*, 83, pp.33-47.

II. Lawal, S.A., Choudhury, I.A. and Nukman, Y., 2012. Application of vegetable oil-based metalworking fluids in machining ferrous metals—a review. *International Journal of Machine Tools and Manufacture*, 52(1), pp.1-12.

III. Ghosh, S. and Rao, P.V., 2015. Application of sustainable techniques in metal cutting for enhanced machinability: a review. *Journal of Cleaner Production*, 100, pp.17-34.

IV. Sharma, V. and Pandey, P.M., 2016c. Recent advances in turning with textured cutting tools: A review. *Journal of Cleaner Production*, 137, pp.701-715.

V. Krishna, P.V. and Rao, D.N., 2008. Performance evaluation of solid lubricants in terms of machining parameters in turning. *International Journal of Machine Tools and Manufacture*, 48(10), pp.1131-1137.

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Divya Ch. et al
VI. Song, W., Wang, Z., Wang, S., Zhou, K. and Guo, Z., 2017. Experimental study on the cutting temperature of textured carbide tool embedded with graphite. The International Journal of Advanced Manufacturing Technology, 93(9-12), pp.3419-3427.

VII. Song, W., Wang, S., Lu, Y. and Xia, Z., 2018. Tribological performance of microhole-textured carbide tool filled with CaF2. Materials, 11(9), p.1643.

VIII. Lei, S., Devarajan, S. and Chang, Z., 2009. A comparative study on the machining performance of textured cutting tools with lubrication. International Journal of Mechatronics and Manufacturing Systems, 2(4), pp.401-413.

IX. Arulkirubakaran, D., Senthilkumar, V. and Kumawat, V., 2016. Effect of micro-textured tools on machining of Ti–6Al–4V alloy: an experimental and numerical approach. International Journal of Refractory Metals and Hard Materials, 54, pp.165-177.

X. Sharma, V. and Pandey, P.M., 2016. Comparative study of turning of 4340 hardened steel with hybrid textured self-lubricating cutting inserts. Materials and Manufacturing Processes, 31(14), pp.1904-1916.

XI. Padmini, R., Krishna, P.V. and Mohana Rao, G.K., 2015. Performance assessment of micro and nano solid lubricant suspensions in vegetable oils during machining. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 229(12), pp.2196-2204.

XII. Yılmaz, B., Karabulut, Ş. and Güllü, A., 2018. Performance analysis of new external chip breaker for efficient machining of Inconel 718 and optimization of the cutting parameters. Journal of Manufacturing Processes, 32, pp.553-563.

XIII. Singaravel, B. and Selvaraj, T., 2016. Application of desirability function analysis and utility concept for selection of optimum cutting parameters in turning operation. Journal of Advanced Manufacturing Systems, 15(01), pp.1-11.

XIV. Wenlong, S., Jianxin, D., Hui, Z. and Pei, Y., 2010. Study on cutting forces and experiment of MoS 2/Zr-coated cemented carbide tool. The International Journal of Advanced Manufacturing Technology, 49(9-12), pp.903-909.

XV. Singaravel, B. and Selvaraj, T., 2016. Application of Taguchi method for optimization of parameters in turning operation. Journal for Manufacturing Science and Production, 16(3), pp.183-187.

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