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RESEARCH

# Experimental Investigation of Textured Inserts on Machining Performance of Al-MMC Using Taguchi Method

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A B S T R A C T

*Textured inserts coupled with solid lubricant is a good alternative to hydro carbon oil based cutting fluid. In this work, turning process is performed on Aluminium based Metal Matrix Composites (Al-MMC) using different types of textured cutting insert with solid lubrication. Three different types of textured inserts namely micro hole, perpendicular direction and parallel direction textured cutting inserts and Tungsten disulfide ($WS_2$) is used as solid lubricant. Statistical tool such as Taguchi method is used to analyze the experimental results. The following results are noticed that, micro hole textured inserts are given better machining performance than parallel type and perpendicular type pattern textured inserts. The major role of textured inserts with solid lubrication is observed that fracture of $WS_2$, low and stable coefficient of friction during machining. The optimum values are 120 m/min of cutting speed, 0.1 mm/rev of feed rate with micro hole type texture. The result of ANOVA method reveals that the types of texture is the most influencing parameter having value of 40.5% followed by cutting speed and feed rate with 29% and 20% respectively.*



## 1. INTRODUCTION

Cutting fluid is used to remove heat during machining and provides lubrication. However, the application of cutting fluid produces environmental pollution, soil contamination, and ground water pollution, harmful to operator health, disposal and further increasing machining cost. The cost of cutting fluids includes preparation; purchasing, maintenance and disposal are approximately 15% of the machining cost of a product [1]. Due to the above issues, research works are attracted without cutting fluid (dry machining) for reducing the environmental pollution and machining costs. But in dry machining, tool life of the cutting tool inserts were reduced due to high friction and followed by heat produced among tool-chip interface, overheating of the cutting tool, reduction of close tolerance, metallurgical damage on machined surface, chip formation can be detoriate machined surface, unable to wash away, adhesion between tool-chip interface, thermal softening, inducing tensile residual stresses and excessive tool wear [1,2]. To overcome the above issues, researchers are focused in development of new kind of cutting tool inserts for reduction of heat generation by lowering the coefficient of friction, vegetable oil as coolant agent [3], MQL [4] and cryogenic method [5]. However the above methods have some drawbacks which include poor cold flow properties, poor oxidation at high temperature of the vegetable oil [6], embrittlement due to cryogenic treatment [7,8] external supply arrangement of coolant and lubricant in case of MQL and equipment for special Dewer equipment in cryogenic cooling [9,10].

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 coefficient of friction and leads to sustainability in machining. Textured cutting insert with solid lubricant is developing a constant lubricating film around the tool area. This is because of thermal expansion of solid lubricant while heat induced during machining process. This continuous thin lubricated layer is used to decrease of machining zone temperature, cutting forces and reduced friction [11,12]. Various solid lubricants attempted by various researchers are graphite, boric acid, molybdenum disulphide, tungsten disulphide and hexagonal boron nitrite [11-13].

Arulkirubakaran et al. [13] studied that the performance of parallel, perpendicular and cross textured groves on rake face to evaluate force involved in cutting process, temperature in tool-chip interface and chip morphology. Molybdenum disulphide and SAE 40 oil were used to perform machining on Al-MMC. The result indicated that cutting tool with perpendicular texture was performed well. Song et al. [14] 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. Sharma and Pandey [15] 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 CaF2 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. Krishna et al. [12] investigated machining performance using nano boric as solid lubricant in machining process. They have used a device for supply of solid lubricant to the cutting zone. The resulted that nano solid lubricants with coconut oil has shown better resulted in terms of machining performance.

Sofuoğlu et al. [16] investigated that the performance of cutting tool inserts with new design during turning process. The cutting tool was used as textured cutting inserts (dimple and dash) and workpiece was aluminum material. The result revealed that surface quality was enhanced 10 to 18% and surface temperature was reduced 6 to 16% using the textured cutting inserts. Laghari et al. [17] used metahurastic approach (particle swarm optimization) for optimization of process parameters in turning of Al- MMC. The responses such as tool life and surface quality were considered. The result showed that predicted responses and experimental data were matched. Machining performance of Al-MMC was enhanced by optimized process parameters. Prakash et al. [18] conducted a machinability study on Al-MMC. Taguchi based multi objective optimization procedure was used to optimize the process parameters. Rock dust reinforced Al-MMC was used for machinability study. Rock dust and particle size effects on surface quality and rate of material removal were investigated using Taguchi based grey relational analysis. The result observed that improved machining efficiency was obtained by optimized process parameters. Devaraj et al. [19] investigated that the effect of micro textured cutting inserts and its design parameters on machining responses. Design parameters considered were hole diameter, hole depth and pich between the holes. Responses used were surface quality, machining power and flank wear of cutting inserts. The result reveled that design parameters of micro textured cutting inserts were improved machining performance.

Das et al. [20] investigated that cutting tool wear and machining force study while machining of Al-MMC. Cutting tool was considered as carbide tool with titanium nitride coated. ANOVA was used to investigate the significance parameters. The result revealed that machining parameters were significantly affected the machining performance. Swain et al. [21] used coated carbide tool for machining of Al-MMC based nano composite. Machining parameters were optimized using principal Component analysis. Microstructure, surface roughness, micro hardness and tool wear analysis were carried out. Das et al. [22] conducted a machinability study on Al-MMC using uncoated carbide inserts. Surface roughness parameters were analyzed sing statistical approach like S/N ratio, ANOVA. Linear regression model were developed and results concluded that developed models were significant and adequate. Mohanty et al. [23] investigated about machining characteristics of Al-MMC in nano powder mixed spark erosion process. RSM was used to analyze the input and output parameters. The result revealed that nano powder mixed dielectric fluid was used to enhance the process. Mishra et al. [24] optimized process parameters during turning of Al-MMC using Taguchi based multi objective optimization. Machining was carried out using uncoated carbide tools with dry and spray cooling methods. The result revealed that optimized process parameters were matched with industrial requirements. Also, it was noticed that spray cooling method was effective than dry condition.

From the literatures, it is understood that textured inserts with solid lubricant are used to eliminate the conventional cutting fluid. Few researchers are used micro hole, parallel direction and perpendicular direction textured cutting inserts with solid lubricants during machining. Minimum number of research works is reported about comparison of machining performance using two or more different types of textured inserts as well as machinability study on MMC with textured inserts. Supply of solid lubricant to the machining zone is difficult task and not mentioned by most of the researchers. In this work, a specially designed solid lubrication system is fabricated to supply solid lubricants to the machining zone. Hence, machining performance of different textured cutting inserts are compared in terms of surface quality using statistical approach is explored in this work.

## 2. MATERIALS AND METHODS

MMC shows better mechanical properties and can be made near net shape dimensions. Stir casting process also known as vortex technique which is widely used for manufacturing of MMC. Figure 1 shows the setup used for stir casting process. In this work, matrix is selected as Al 6061 alloy and reinforcement is Silicon Carbide (SiC). Based on preliminarily trials and literatures, 93 wt% aluminium alloy, 7 wt% SiC combinations and 1 wt% Magnesium (Mg) are considered. Aluminium alloy (6061) is preferable for wings and fuselages in homebuilt aircraft applications. Silicon Carbide (SiC) is a good abrasive which is used to enhance high thermal conductivity as well as low thermal expansion. The addition of Mg is used to enhance wettability between matrix and the reinforcement. Also, it prevents aluminium oxide coating by binding to the oxygen. The important stir process parameters are preheated temperature of Al alloy (150ºC), melting temperature (700ºC), stir time (20 minutes) and stir speed (500 rpm). The cylindrical rod with dimension of 45 mm diameter and 150 mm length are made to perform experiments [25-29].

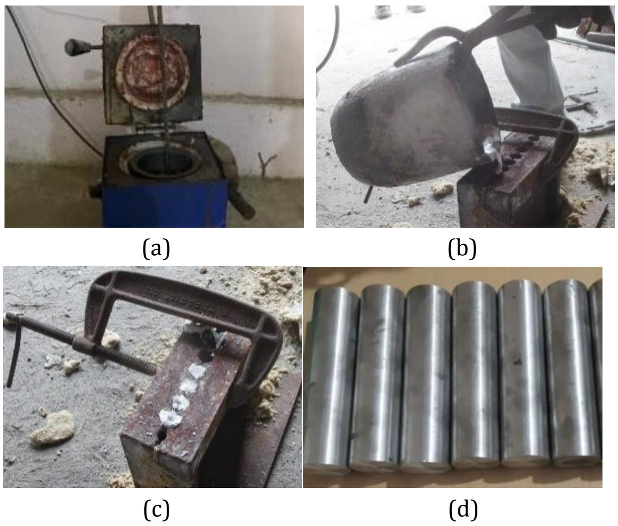


**Fig. 1.** Stir casting setup: (a) Stir casting device, (b) Al-MMC molten metal pouring into die, (c) Solidification of AL-MMC, (d) Al-MMC samples.

**Table 1.** Process parameters and their levels

| **Parameters** | **Levels** | | |
|---|---|---|---|
| | **Level 1** | **Level 2** | **Level 3** |
| Texture type | Parallel | Microhole | Perpendicular |
| Cutting speed (m/min) | 60 | 90 | 120 |
| Feed rate (mm/rev) | 0.1 | 0.15 | 0.2 |

Taguchi $L_9$ orthogonal array is followed to perform experiments. Table 1 shows the selected input parameters and their levels. Turning process is carried out on 15 mm length. Depth of cut is maintained as constant and the value is 0.5 mm. The Pride Jaguar CNC lathe is used 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 LASER (Micro hole) and Wire cut EDM (parallel and perpendicular directions). Figure 2 shows the tungsten carbide cutting tool with different types of textures. The dimensions of the micro hole texture, parallel and perpendicular directions texture are mentioned in Table 2 and 3. Depth of cut is maintained as constant throughout the experiment and the value is 0.6 mm. Tungsten disulfide $WS_2$ is used as solid lubricant which is mixed with SAE 40 oil in the ratio of 80 to 20 by weight. A separate solid lubricant supply system is used to supply this lubricant to the machining zone. Figure 3 shows the CNC setup with solid lubrication supply.

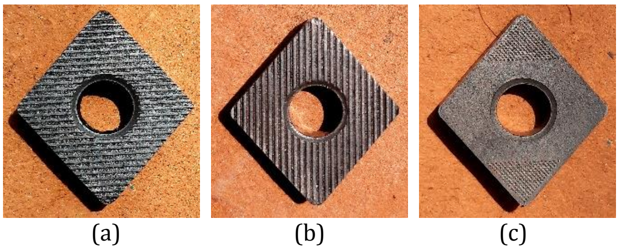


**Fig. 2.** Tungsten carbide cutting inserts with different textures: (a) Parallel direction, (b) Perpendicular direction, (c) Micro hole texture.

**Table 2.** Micro hole textured inserts dimension

| Sl. No | Parameters | Dimensions |
|---|---|---|
| 1 | Micro hole depth | 200 µm |
| 2 | Edge distance | 150 µm |
| 3 | Micro hole diameter | 150 µm |

**Table 3.** Parallel and perpendicular direction textured inserts dimension

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

Average surface roughness ($R_a$) of the machined profile is measured using Mitutoyo SJ 210 surface roughness testing machine (Figure 4). This $R_a$ leads to important indication on machinability factor and leads to good functional life. Average results of $R_a$ for Taguchi study is obtained by measured three to five places on machined area. 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 4 presents the result of experiments.

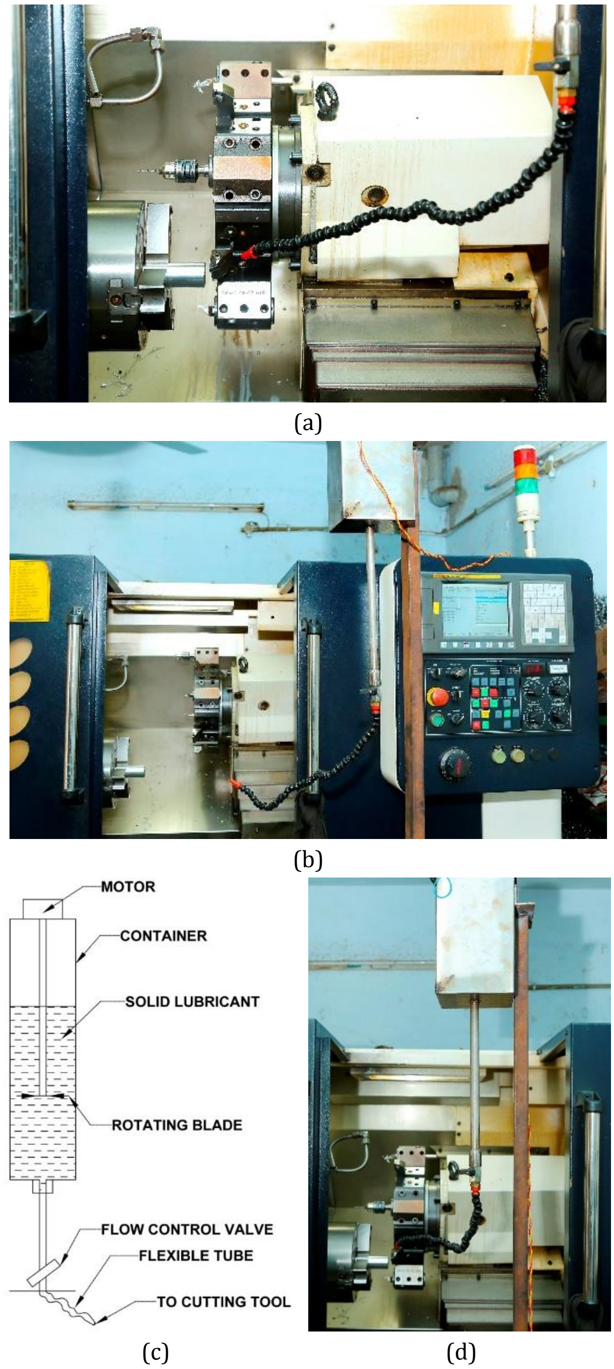


**Fig. 3.** CNC setup with solid lubrication supply: (a) CNC machine, (b) CNC setup with solid lubrication device, (c) Solid lubrication device (layout), (d) Solid lubrication device (actual).

**Table 4.** Experimental results

| Sl . No | Types of texture | Cutting speed (m/min) | Feed rate (mm/rev) | Surface roughness $R_a$ (μm) | S/N ratio |
|---|---|---|---|---|---|
| 1 | Parallel textured | 60 | 0.10 | 4.1 | -4.165 |
| 2 | Parallel textured | 90 | 0.15 | 3.7 | -3.295 |
| 3 | Parallel textured | 120 | 0.20 | 4.8 | -4.690 |
| 4 | Micro hole textured | 60 | 0.15 | 3.9 | -3.533 |
| 5 | Micro hole textured | 90 | 0.20 | 3.2 | -2.647 |
| 6 | Micro hole textured | 120 | 0.1 | 2.6 | -1.735 |
| 7 | Perpendicular textured | 60 | 0.2 | 4.9 | -4.102 |
| 8 | Perpendicular textured | 90 | 0.1 | 3.2 | -2.647 |
| 9 | Perpendicular textured | 120 | 0.15 | 2.8 | -2.013 |

(a)

(b)

**Fig. 4.** Machined sample and Surface Roughness tester: (a) Machined samples , (b) Testing of surface roughness.

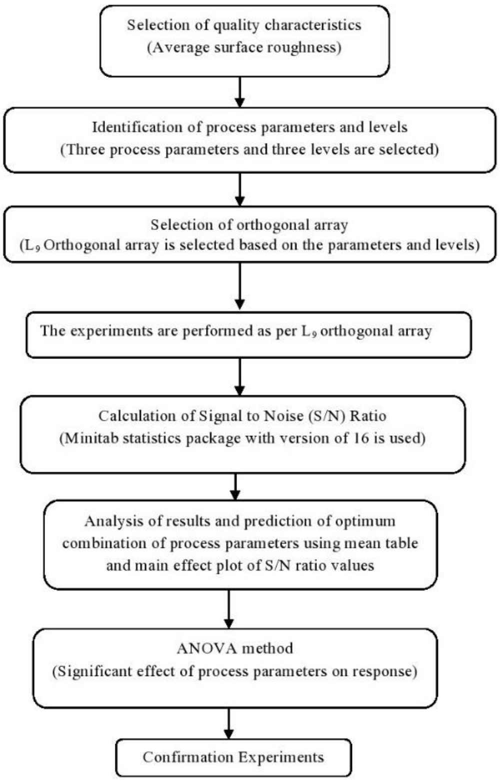


**Fig. 5.** Flow chart for steps involved inTaguchi method.

## 3. METHODOLOGY

Taguchi method involves orthogonal array, Signal to Noise (S/N) ratio and ANOVA method. 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 [30]. The deviation between the experimental value and actual value can be estimated by S/N ratio. ANOVA method 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. The following are the steps that adopted for analyzing and optimizing the results using Taguchi method [30]. Fig. 5 explains the steps involved in Taguchi method graphically.

*Step: 1 Establishment of quality characteristics*

In this study, average surface roughness ($R_a$) is selected as quality characteristic. This characteristic is minimization objective which is important machinability characteristic and directly influence the functional characteristics.

*Step: 2 Selection of process parameters and their level*

The selection of process parameters and their level are applied to design the experiments to be performed. The important process parameters considered for the experiments are texture type, cutting speed and feed rate. Table 1 shows the selected process parameters and their level.

*Step: 3 Selection of the appropriate orthogonal array*

In the present work, three levels of process parameters and levels are considered; hence, $L_9$ Taguchi orthogonal array is one of the suitable designs. An appropriate orthogonal array is used to minimize the experimental run to be performed. It leads to reduce the labor cost involved in machining and time consumption.

*Step: 4 Experimental run*

Experimental runs are conducted using $L_9$ orthogonal array and the results are displayed in Table 4.

*Step: 5 Estimation of Signal to Noise (S/N) ratio*

Three types of S/N ratio are available such as smaller-the-better, larger-the-better and nominal-the-better. It is observed with the experiment that the selected quality characteristic is surface roughness which is a minimization type objective. The following equation is executed for estimation of S/N ratio for minimization objective.

Smaller-the-better

$$\frac{S}{N} = -10log_{10}\left(\frac{1}{n}\sum_{1=1}^{n} {y_{ij}}^2\right)$$

*Step: 6 Investigation of results and prediction of optimum process parameters*

The results from the S/N ratio estimation are considered to form mean table as well as main effects plot. This can be applied to predict the optimum combination of process parameters.

*Step: 7 ANOVA method*

The significant effect of process parameters on surface roughness in terms of percentage distribution can be determined by ANOVA method.

*Step: 8 Confirmation experiments*

The confirmation experiments are used, to validate the optimum process parameters obtained from the result analysis.

## 4. RESULTS AND DISCUSIIONS

In this work, hydrocarbon oil based cutting fluid is avoided by introducing surface texturing with solid lubricant on cutting tool inserts. Micro hole type textures are produced using LASER and parallel direction and perpendicular direction are produced by WEDM process. Tungsten disulfide is used as solid lubricant. The input parameters considered are types of textures, cutting speed and feed rate and output parameter is surface roughness ($R_a$).

Taguchi method is used to investigate the experimental data with the help of S/N ratio and ANOVA method. Experimental results obtained using $L_9$ orthogonal array are shown in Table 4. 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. Tables 5 shows the response table of mean S/N ratio for surface roughness. Figure 6 shows the mean S/N graph. From the main effects plot (Figure 6), minimum surface roughness value can be obtained using the following combinations. The optimum combinations are micro hole texture, cutting speed of 120 m/min and 0.1 mm of feed rate.

**Table 5.** Response table of mean S/N ratio for surface roughness.

| Sl. No | Parameters | Mean S/N Ratio | | |
|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 |
| 1 | Types of texture | -4.050 | -2.638 | -2.921 |
| 2 | Cutting speed | -3.933 | -2.863 | -2.813 |
| 3 | Feed rate | -2.849 | -2.947 | -3.813 |

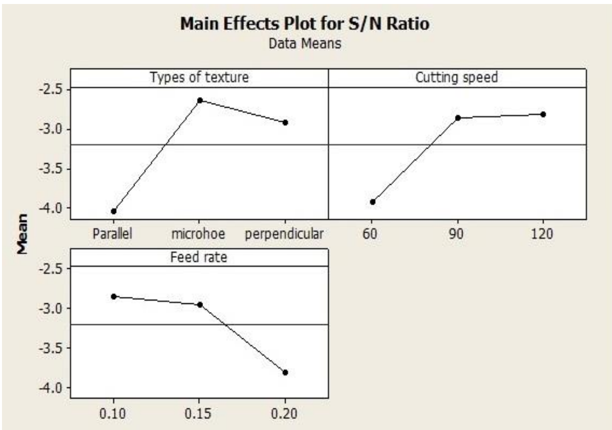


**Fig. 6.** Main effects plot for S/N ratio.

Various direction textures are available namely parallel, perpendicular, cross type and micro hole texture [10,15,31]. The introduced surface textures on rake face of the cutting tool inserts are used to store the lubricants which are used to promote lubricity as well as anti-adhesive effect in between the tool-chip interface [32]. This micro grooved cutting inserts are provided aerodynamic lubrication effect due to creation of air pockets between tool rake face and chip back surface [33,34]. Hence, micro hole textures with solid lubrication, minimizes frictional behavior at the tool-chip interface. This is the reason good surface finish is achieved. Generally, the direction of chip flow during machining is not predictable. It is difficult to cut chip in one direction in case of parallel type pattern and perpendicular type pattern textured inserts. Texturing with micro holes are consist of the following characteristics such as independent with directions, shape with closed nature and enclosed with convex surfaces. Micro hole textures are used to break the long continuous chip produced during the process and serve as chip breaker. It leads to high localized pressure to chip flow and reduced tool-chip contact length [31,35]. The pattern of textured cutting tool insert was significantly affected in terms of machining performance. The lower value of cutting force values were employed during turning process with perpendicular type textured pattern due to the chip flow direction rather than parallel type pattern. In parallel type pattern, adhesion between the tool and chip interfaces was observed. It is also observed that increased coefficient of friction value was mention due to turn over of the chip. Hence, parallel type pattern had some negative effect compared to perpendicular pattern [13,15].

Textured inserts with solid lubricants produces a thin lubricating layer and it is used to minimize the friction and temperature in the cutting zone [12]. In general, solid lubricants are called soft materials. $WS_2$ is used as solid lubricant and it has the following characteristics of less value of shear strength, lower brittleness and very thin in nature. This is the reason, it is immediately gets smeared and generates layer of thin lubricating film. Also, the texture II, structure with hexagonal layer and minimum coefficient of friction of $WS_2$ solid lubricant is observed as better lubricity. The other significant advantages are good lubricious in nature, resistance to high temperature and oxidation. During machining process, solid lubricants are generate thin lubricated layer because of heat development and followed by thermal expansion. This continuous thin lubricated layer is used to decrease co-efficient of friction in the tool-chip region. The above natures of $WS_2$ solid lubricant are performed better during machining process [11]. Tool flank wear analysis is carried out on low (0.24 μm), middle (0.34 μm) and maximum (0.42 μm) value of $R_a$ value which is measured using tool maker's microscope. It is understood that tool flank wear influences the surface roughness ($R_a$) value. The value of $R_a$ is increased when the tool flank wear value is in increasing trend. This is may be temperature increases due to rapid rubbing action between tool flank side and machined surface. This temperature rise may increase wear of flank face. But in textured with solid lubrication provides effective lubrication between tool-chip interface, reduction of friction and wear hence smooth sliding and low friction reduces the cutting tool from rapid wear.

**Table 6.** Result of ANOVA method for surface roughness.

| Source of variation | DOF | Sum of Squares | Mean Square | P Value | Contribution % |
|---|---|---|---|---|---|
| Texture type | 2 | 3.347 | 1.673 | 0.3319 | 40.57 |
| Cutting speed | 2 | 2.403 | 1.20 | 0.7608 | 29.13 |
| Feed rate | 2 | 1.688 | 0.844 | 0.4130 | 20.46 |
| Error | 2 | 0.810 | 0.405 | | 9.82 |
| Total | 9-1=8 | 8.248 | | | 100 |

**Table 7.** Confirmation test.

| | Initial cutting Parameters | Optimal cutting parameters | |
|---|---|---|---|
| | | Prediction | Experiment |
| Level | A2B2C2 | A2B1C3 | A2B3C1 |
| surface roughness (μm) | 3.4 | --- | 2.42 |
| S/N ratio (dB) | -2.919 | -1.735 | -1.473 |
| Improvement of S/N ratio | 1.446 | | |

To observe the significant effect of process parameters and to evaluate the experimental results ANOVA method is used [30] .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 method. The result of ANOVA method of the surface roughness is shown in Table 6. It is observed that types of textured insert have highest contribution followed by cutting speed and feed rate.

The conformation tests are carried out to confirm the optimal process parameters attained during the investigation. A2B3C1 is an optimum combination of process parameters using Taguchi method in turning operation. Therefore, above optimum process parameters are considered for validation analysis. The optimum combination of process parameters (texture type as micro hole, v=120 m/min, f=0.1 mm/rev) are used, the validation experiments gives the $R_a$ of 2.42 μm. The conformation test (Table 7) is performed to find the optimum parameters during the experimentation.

## 5. CONCLUSION

Stir casting process is used to make MMC. Three kind of textured inserts are used and their machining performance is compared. Experiments are performed as per $L_9$ orthogonal array and the effect of each process parameter is analyzed through the S/N ratio and ANOVA method. Optimization of process parameters in turning of Al-MMC by the application of Taguchi is conducted as the method of study. The major conclusions are obtained from this study.

- The optimum process parameter values are determined using main effect plot and the performance table. The optimum values are 120 m/min of cutting speed, 0.1 mm/rev of feed rate with micro hole type texture. The result of ANOVA method reveals that the types of texture is the most influencing parameter having value of 40.5% followed by cutting speed and feed rate with 29% and 20% respectively. The validation test is conducted to validate the optimum results are obtained.
- Textured inserts with solid lubrication is a kind of self lubricated cutting inserts which promotes anti-adhesive and lubricity. Chip flow during machining is very difficult to predict. Hence, texture on insert must be not direction dependent. The result revealed that micro hole type of texture is not direction dependent compared with parallel and perpendicular types of textures.
- $WS_2$ solid lubricant consists of texture II and structure with hexagonal layer and gives good lubricious nature, oxidation and corrosion resistance.
- Textured cutting inserts eliminate conventional cutting fluid and solid lubrication leads to sustainability in turning process.

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