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# Machinability Studies and Multi-Response Optimization of Process Parameters in Turning of T6 Heat Treated Lm25/Al2o3/Graphite Hybrid Composites Using Grey-Based Taguchi Method

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## ABSTRACT

The present work investigated the effects of turning parameters like Cutting speed, Feed, Depth of cut Cutting insert's rake angle on surface quality and tool wear in turning of T6-heat treated LM25/Al2O3/Graphite hybrid composites with coated carbide cutting inserts. Optimisation of turning parameters was conducted using Grey-based Taguchi Method to improve product quality and machining efficiency. Nine machining tests were performed in line with Taguchi's O.A.-L9. Relating to the rank of Grey Relational Grade, optimal process parameters were identified for achieving desired surface quality and minimal tool wear simultaneously. Regression models were established to predict surface roughness and tool flank wear values accurately and were found to be statistically significant and adequate. Finally, the accuracy of multi-response optimization results was proved by confirmatory experiments. Experimental studies reveal that the multi-responses could be improved efficiently with the help of this novel technique.

**Keywords:** CNC turning; surface roughness; tool flank wear; Grey-based Taguchi Method-Optimisation.

## 1. INTRODUCTION

Particulate Aluminium Metal matrix composites (PAMMCs) have continued to receive adequate attention as a result of their significant engineering properties such as enhanced strength-to-weight ratio and higher stiffness at room or higher temperatures and better wear resistance and also due to anisotropic and costly fibre reinforcements. These composites are used for manufacturing some important components such as bearings, liners, piston and rings etc. of automobile and turbocharger impellers. Though high-quality products of Al-MMCs can be produced through different manufacturing techniques like casting or forging etc. but machining has become an integral part of the manufacturing process to achieve desired surface finish and dimensional accuracy for easy and low-cost assembly [1].

Though the hard reinforcements (ceramic particles) such as SiC, $Al_2O_3$etc., will improve strength, hardness and wear behaviour of Al-MMCs, the abrasive nature of these reinforcements makes machining of Al-MMCs very difficult and challenging due to their hardness and stiffness, which cause rapid tool wear during machining, resulting in high machining cost [2]. To improve the machinability of Al-MMCs soft reinforcement like graphite particles can be dispersed in Al matrix along with hard reinforcement with the advantage that these particles act as chip breakers, which result in discontinuous chips, less tool wear, reduced cutting forces and less power consumption but with compromised condition of surface finish [3]. Furthermore, heat treatment of LM25 alloy composite also increases its machinability. It improves its hardness, which, in turn, reduces the formation of BUE on the cutting tool. This results in enhancing surface finish [4].Among the machinability characteristics, Surface finish is significantly considered as an indicator of machinability and also as a necessity for component quality [5]. One more important characteristicis tool wear that determines the economics in metal cutting [6].

In the case of machinability studies of MMCs, it has become an essential need for the optimization of some main turning parameters for improving machinability of Al-MMCs to achieve desired machining characteristics with low machining cost for improving the quality of the product. To meet these requirements, some optimization methods have been applied to machinability studies of Al-MMCs and Steels. Such methods are Taguchi method, Response Surface Methodology, Grey Relational Analysis, Artificial Neutral Network, and Grey-Fuzzy Logic Analysis etc. Among these techniques, the Taguchi method has become more attractive to many researchers in recent years due to its easy application and ability to optimize turning parameters for a single response only at a time with comparatively low cost. But this method is not suitable for the optimization of multi-responses simultaneously. For multi-response, Grey Relational Analysis is found to be the best powerful tool. characteristics [7,8]

## 2. LITERATURE REVIEW

Manna et al. [9] suggested that machining of Al/SiCp MMC with fixed rhombic tooling (uncoated tungsten carbide with positive rake) at lower feed, higher cutting speed, low depth of cut would be economical instead by costly PCD or CBN inserts to accomplish desired surface quality and low tool wear. E. Kilickapet al. [10] proved that machining of Al/SiC- MMC with TiN-coated carbide at high speeds and low feed could produce better surface finish and low tool wear. Optimizations of turning parameters in machining of S45C steel by Yang et al**.** [11] using Taguchi method indicated that tool life and surface quality could be enhanced appreciably during turning operations. They have also reported that the Taguchi Method is found to be quite efficient in identifying the optimal machining parameters, as compared to other optimization techniques. A regression model for flank wear was established by Manna et al**.** [12] using Taguchi method, while machining of Al./SiC-MMC. Confirmation results conclude that the established model was correct for predicting tool flank wear accurately. D. Das et al. [13]employed Grey-based Taguchi Method to perform simultaneous optimization of surface quality, flank wear, flank temperature and MRR in turning of Al 7075/SiCp-MMC. They reported that that the Cutting speed of 154 meter per mt., Feed rate of 0.04 millimetre per revolution and Depth of cut of 0.10 millimetre were achieved as optimal turning parameters. Out of these parameters, feed was reported to be the most significant factor for GRG. N. H. Ononiwu et al. [7] employed Grey Relational Analysis and Taguchi Method to execute multi objective optimization of surface roughness and tool flank wear in turning of AA6082/FA/CES hybrid composite. ANOVA of GRG revealed that the feed was the most significant on surface quality and flank wear. Besides turning operation, Grey-based Taguchi Method has been widely employed also in other operations such as drilling [14], milling [8] and grinding [15], wherein this approach has greatly improved machinability characteristics.

The above reported studies highlight about investigations on improvement of machinability of Al/SiCp composites only in most cases using Grey-based Taguchi method. However, earlier studies on machinability of heat-treated LM25/$Al_2O_3$/Gr. composites have been rarely addressed. Hence the purpose of this study is to analyse and assess the effects of the turning parameters on surface quality and tool life during turning of heat-treated LM25/$Al_2O_3$/Gr composites and subsequently to optimise the turning parameters to achieve minimal surface roughness and tool flank wear using Grey-based Taguchi Analysis.

## 3. MATERIALS AND METHODS

### 3.1 *Work Material*

The LM25 aluminium alloy was selected as metal matrix. Its composition is listed in Table 1. 9 wt.% of $Al_2O_3$ particles of 6-23 µm sizes and 4 wt.% of Graphite particles of 24-94 µm sizes were used as reinforcements. Nine cylindrical composite bars of 27 mm diameter and 115 mm long were casted, using stir casting technique [16]. The cast specimens were rough turned to 25.4 mm in diameter and 110 mm in length. These specimens were later solutionized at 540$^o$ C in an electric furnace for 3 hrs., water quenched and then artificially aged at 180$^o$ C for 4 hrs., followed by air cooling [17]. The mechanical properties of these specimens are tabulated in Table 2.

**Table 1. Chemical composition (by weight%) of LM25 Al. alloy**

| Cu | Mg | Si | Fe | Mn | Ni | Zn | Pb | Sn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| <0.20 | 0.20-0.60 | 6.50-7.50 | <0.50 | <0.30 | <0.10 | <0.10 | <0.10 | <0.05 | <0.20 | REM |

**Table 2. Mechanical Properties of T6 treated LM25 Al./ 9wt.% Al2O3/4 wt.% Graphite composite**

| Properties | Ultimate Tensile Strength (N/mm2) | Yield Strength (kN) | Vickers Hardness (HV1) | Compressive Strength (MPa) | Impact Strength (J) | Elongation% (on 24 mm GL) | Coefficient of Friction (μ) |
|---|---|---|---|---|---|---|---|
| Value | 252 | 238 | 168 | 359 | 3.5 | 2.4 | 0.28 |

**Figure 1:** CNC Lathe **se**tup **Figure 2**: Finished samples **Figure 3**: Surf tester **Figure 4**: Stereomicroscope

3.2*Turning parameters and Performance characteristics.*

Turning parameters were selected as Feed, Cutting speed and Depth of cut. Performance characteristics were selected as surface roughness and tool flank wear as per literature review. Range of values of turning parameters was finalized based on pilot experiments and literature review [13].

3.3 *Machine tool and Cutting tool*

A CNC lathe (LT-2XL 500MC) with control FANUC-TC and spindle speed of 4000 rpm maximum was used for conducting the experiments. Figure 1shows CNC Lathe set up. Two different coated carbide cutting inserts were used to analyse their machining performances. The particulars of the inserts are presented in Table 3.

3.4*Design of Experiments*

Experiments were designed in line with Orthogonal array (L9) of Taguchi Method to analyse the whole parametric area with a reduced number of experiments to achieve optimum results with less research efforts, less cost and time. Experiments were performed with the three turning parameters, each at three levels as listed in Table 4.

### 3.5*Experimental Work*

### 3.5a*Machinability Tests*

Experiments for turning operations of cylindrical specimens for machinability tests were performed along with Taguchi's orthogonal array(L9), as presented in Table 5, on a CNC Lathe under dry conditions with two coated carbide rhombic inserts, one with positive and other with negative rake angle, at GTTC, Bangalore.

**Table 3-Particulars of Cutting Tool Inserts used for turning.**

| Types of Cutting Inserts | Cutting Insert-1 | Cutting Insert-2 |
|---|---|---|
| Manufacturer | WIDIA | ISCAR |
| ISO-Code / Designation | VNMG 12T308-WS10PT | VNMG 12T304-NFIC907 |
| Nose radius | 0.8 mm | 0.4 mm |
| Coating layers (PVD) | AlTiSiNTiAlN+TiN | |
| Rake angle | Negative | Positive |
| Included angle | 35º35º | |

**Table 4. Turning parameters with values and levels.**

| Symbol | Parameters | Unit | Levels | | |
|---|---|---|---|---|---|
| | | | 1 | 2 | 3 |
| A | Cutting Speed (v) | m/min. | 70 | 110 | 150 |
| B | Feed rate (f) | mm/rev. | 0.04 | 0.08 | 0.12 |
| C | Depth of Cut (d) | mm. | 0.40 | 0.60 | 0.80 |

Experimental studies were conducted as per ISO 3685 standards. The turning length for all specimens was considered as 45 mm. Finish machined work pieces are shown in the Figure 2.

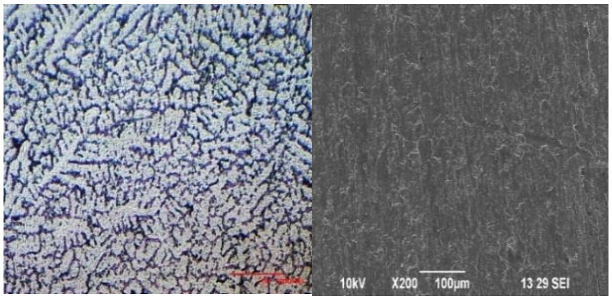
### 3.5b*Measurements*

Surface roughness (Ra) was determined at three places with the help of Mitutoyo surf tester (Japan, Model-SJ-210) with measuring speed range of 0.25-0.75 mm/s. and travel length of 15 mm., as shown in Figure 3. The average value of three readings was considered for data analysis. ISO 4287-1997 standard was followed. Flank wear of each cutting insert was determined by Stereo Microscope, as shown in Figure 4 and average flak wear (Vb) was considered for analysis [1].

## 4. RESULTS AND DISCUSSIONS

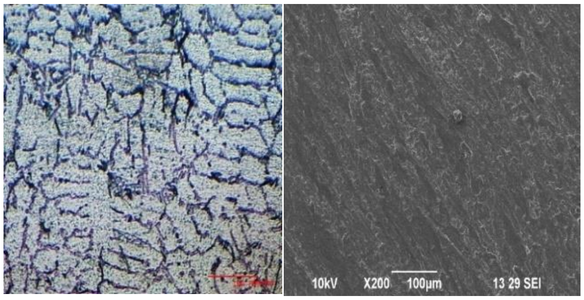
### 4.1*Microstructural analysis*

From Figure 5(a) & (b) the microstructure of the heat-treated LM25 Al. alloy matrix revealed the network of fine dendrites of α-Al and fine precipitates of spheroidized eutectic silicon in the inter-dendritic regions and around the dendrites of α-Al. The structure was fairly identical throughout the section. From Figures 6(a) & (b), microstructure of the heat-treated LM25 Al. composite revealed network of coarser dendrites of α-Al and reinforcements with fine precipitates of spherodized eutectic silicon particles in the inter-dendritic regions and around the dendrites of α-Al. The structure was most identical throughout the section.



(a) Optical (100X) (b) SEM (X200)

**Figure 5: Microstructure of Heat-treated LM25Al. matrix**



(a) Optical (100X) (b) SEM (X200)

**Figure 6: Microstructure of Heat-treated LM25Al.comp.**

**Table 5. Experimental Results of Ra and Vb using Insert-1 and Inserts-2**

| | Turning parameters | | | Experimental Results | | | |
|---|---|---|---|---|---|---|---|
| Exp. Run | (A) Cutting Speed v (m/mt.) | (B) Feed f (mm/rev.) | (C) Depth of Cut d (mm) | Insert-1 (-ve rake angle) | | Insert-2 (+ve rake angle) | |
| | | | | Ra (µm) | Vb (mm) | Ra (µm) | Vb (mm) |
| 1 | 70 | 0.04 | 0.40 | 0.412 | 0.180 | 0.346 | 0.145 |
| 2 | 70 | 0.08 | 0.60 | 0.440 | 0.205 | 0.353 | 0.160 |
| 3 | 70 | 0.12 | 0.80 | 0.348 | 0.165 | 0.366 | 0.115 |
| 4 | 110 | 0.04 | 0.60 | 0.260 | 0.180 | 0.213 | 0.190 |
| 5 | 110 | 0.08 | 0.80 | 0.352 | 0.230 | 0.355 | 0.175 |
| 6 | 110 | 0.12 | 0.40 | 0.370 | 0.170 | 0.466 | 0.125 |
| 7 | 150 | 0.04 | 0.80 | 0.240 | 0.152 | 0.208 | 0.110 |
| 8 | 150 | 0.08 | 0.40 | 0.326 | 0.240 | 0.384 | 0.120 |
| 9 | 150 | 0.12 | 0.60 | 0.264 | 0.155 | 0.314 | 0.100 |
| Total mean value | | | | 0.334 | 0.186 | 0.334 | 0.137 |

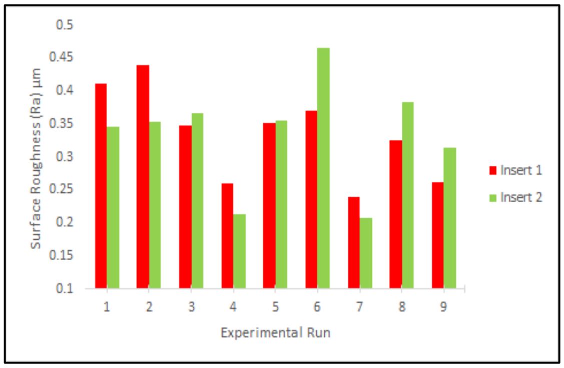


**Figure.7: Performance comparison between Insert-1 and Insert-2 as for Ra**

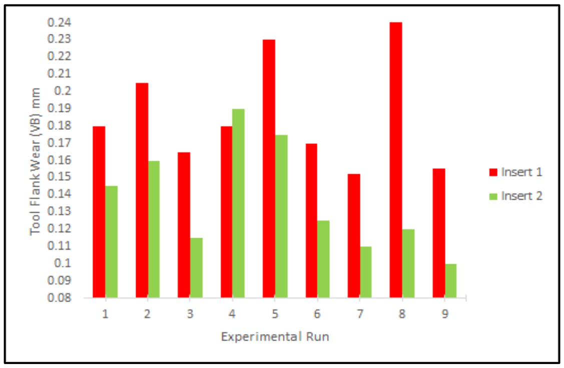


**Figure. 8: Performance comparison between Insert-1 and Insert-2 as for Vb**

4.2*Impact of rake angle on Ra and Vb*

Experimental outcomes for Ra and Vb for both the inserts after each experimental run were measured and are given in Table 5. From Table 5 and Figures 7 & 8, it was observed that the type of rake angle had significant impact on Ra and Vb. It could also been seen from Table 5 that total mean value for surface roughness was more or less same for both the inserts. But the value of minimum surface roughness obtained by positive insert was 0.208 µm, whereas the that obtained by negative insert was 0.240 µm. [18]**.** Incase of flank wear**,** it was observed that total mean value for Vb was 0.137 mm for positive insert and 0.186 mm for negative insert. This showed that the negative rake insert caused more frank wear than the positive rake insert. This may be due to increase in contact area, which increases cutting forces, resulting in higher chip volume and heat generation causing excessive tool wear [19], whereasthe positive rake insert results in lower cutting forces due less contact area, which reduces the risk of vibration and causes a better surface smoothness and less tool flank wear. The results reveal that positive rake insert has more significant impact on the responses than the negative rake insert. Hence it is concluded that positive rake insert is most suitable for machining Al-MMCs.

4.3*Impact of turning parameters on Ra and Vb based on means of Ra and Vb at different factor level*

Experimental outcomes for Ra and Vb recorded while using positive rake insert are tabulated Table 6. From Table 7 & Figure 9, it was observed that Ra reduced when cutting speed increased, but increased when feed increased. It was also noted that Ra reduced when depth of cut increased from 0.40 to 0.60 mm, but increased when depth of cut increased further from 0.60 to 0.80 mm. According to this figure, as the feed increased Ra increased dramatically. However, Ra reduced slightly when cutting speed increased. Therefore, a suitable order of low feed, high speed and medium depth of cut is needed to minimize Ra [20]**.**From Table 7 & Figure 10, it was observed that Vb increased when cutting speed increased from 70 to 110 m/min, but decreased when cutting speed increased further from 110 to 150 m/min. Vb increased, when feed was increased from 0.04 to 0.08 mm/rev., but reduced when feed was increased from 0.08 to 0.12 mm/rev. It was also noted that Vb increased when depth of cut increased 0.40 to 0.60 mm, but reduced on further increase from 0.60 to 0.80 mm. Hence a suitable order of medium speed, low feed and low depth of cut is needed to minimise flank wear in finish turning.[21].

**Table 6. Results with S/N ratios for Ra and Vb using Positive rake insert.**

| Exp. | Turning parameters | | | Surface roughness | | Flank wear | |
|---|---|---|---|---|---|---|---|
| run | Cutting Speed v (m/mt.) | Feed rate f (mm/rev.) | Depth of Cut d (mm) | Ra (µm) | S/N ratio (dB) | Vb (mm) | S/N ratio (dB) |
| 1 | 70 | 0.04 | 0.40 | 0.346 | 09.218 | 0.145 | 16.773 |
| 2 | 70 | 0.08 | 0.60 | 0.353 | 09.045 | 0.160 | 15.918 |
| 3 | 70 | 0.12 | 0.80 | 0.366 | 08.730 | 0.115 | 18.786 |
| 4 | 110 | 0.04 | 0.60 | 0.213 | 13.432 | 0.190 | 14.424 |
| 5 | 110 | 0.08 | 0.80 | 0.355 | 08.995 | 0.175 | 15.139 |
| 6 | 110 | 0.12 | 0.40 | 0.466 | 06.632 | 0.125 | 18.062 |
| 7 | 150 | 0.04 | 0.80 | 0.208 | 13.639 | 0.110 | 19.172 |
| 8 | 150 | 0.08 | 0.40 | 0.384 | 08.313 | 0.120 | 18.416 |
| 9 | 150 | 0.12 | 0.60 | 0.314 | 10.061 | 0.100 | 20.000 |

**Table 7. Response table for means of Ra and Vb at different factor levels**

| Level | Ra | | | Vb | | |
|---|---|---|---|---|---|---|
| | Cutting Speed | Feed rate | Depth of Cut | Cutting Speed | Feed rate | Depth of Cut |
| 1 | 0.3550 | 0.2557 | 0.3987 | 0.1400 | 0.1483 | 0.1300 |
| 2 | 0.3447 | 0.3640 | 0.2933 | 0.1633 | 0.1517 | 0.1500 |
| 3 | 0.3020 | 0.3820 | 0.3097 | 0.1100 | 0.1133 | 0.1333 |
| Delta | 0.0530 | 0.1263 | 0.1053 | 0.0533 | 0.0383 | 0.0200 |
| Rank | 3 | 1 | 2 | 1 | 2 | 3 |

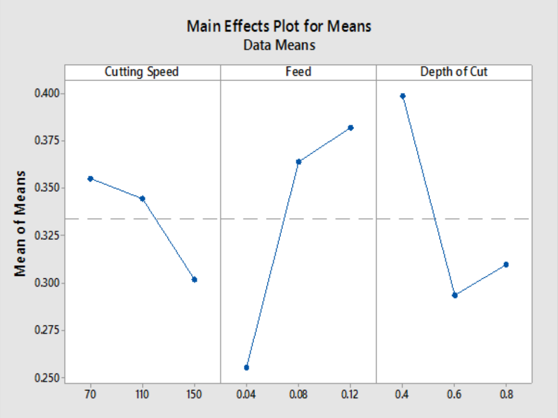


**Figure 9: Main Effects Plot for means of Ra**

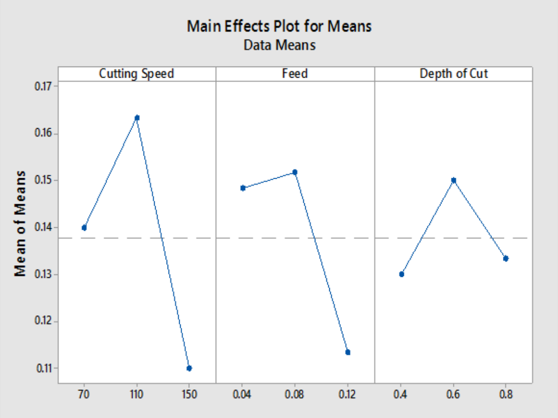


**Figure 10: Main Effects Plot for means of VB**

4.4*Single-response optimization using Taguchi method*

Taguchi method is most suitable for single response optimisation. For both the responses, “the smaller-the-better” type was used for determining S/N ratio in line with Taguchi method, as represented by the Eq. 1. Accordingly, S/N ratios of Ra and Vb values were established by Minitab 17 software and are presented in Table 6. The influences of input parameters were investigated by means of S/N ratios. The optimum level of turning parameter is the level with the maximum mean value of S/N ratio in spite of category of performance features [11].

$$\text{S/N ratio} = -10\log(1/n) \sum (Y_i^2) \qquad (1)$$

Where, n= number of experiments, Yi is response value of ith experiment

4.4a*Response table for S/N ratio*

Table 8 showed the average response characteristics for each level of each factor in the design, which highlights the effect of turning parameters on Ra and Vb. Figure 11 indicated that the optimal combination to minimize Ra were 150 meter per min. (A3), 0.04 millimetre per revolution (B1) and 0.6 millimetre (C2) i.e. A3-B1-C2. Figure 12 indicated that the optimal combination to minimize Vb were 150 meter per min. (A3), 0.12 millimetre per revolution (B3) and 0.4 millimetre (C1) i.e. A3-B3-C1.

**Table 8. Response table for S/N ratios of Ra and VB at different factor levels**

| **Level** | **Ra** | | | **Vb** | | |
|---|---|---|---|---|---|---|
| | **Cutting Speed** | **Feed rate** | **Depth of Cut** | **Cutting Speed** | **Feed rate** | **Depth of Cut** |
| 1 | 8.998 | 12.097 | 8.055 | 17.160 | 16.790 | 17.750 |
| 2 | 9.687 | 8.784 | 10.846 | 15.880 | 16.490 | 16.780 |
| 3 | 10.671 | 8.475 | 10.455 | 19.200 | 18.950 | 17.700 |
| Delta | 1.673 | 3.622 | 2.791 | 3.320 | 2.460 | 0.970 |
| Rank | 3 | 1 | 2 | 1 | 2 | 3 |

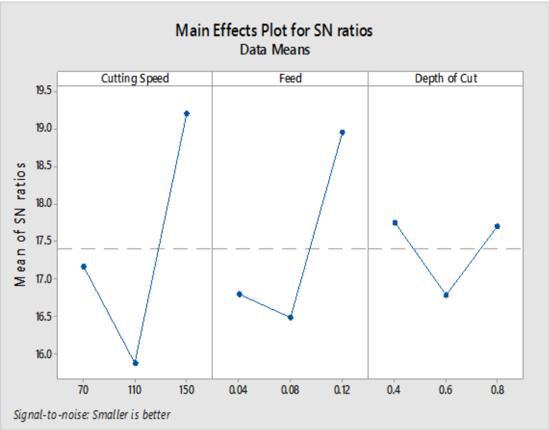


**Figure 11: Main effects plots for S/N ratios of Ra**

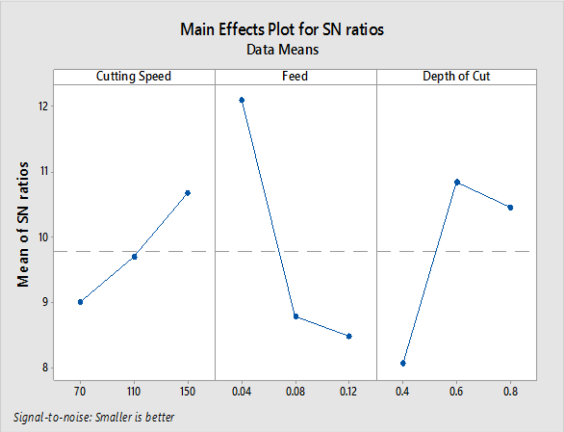
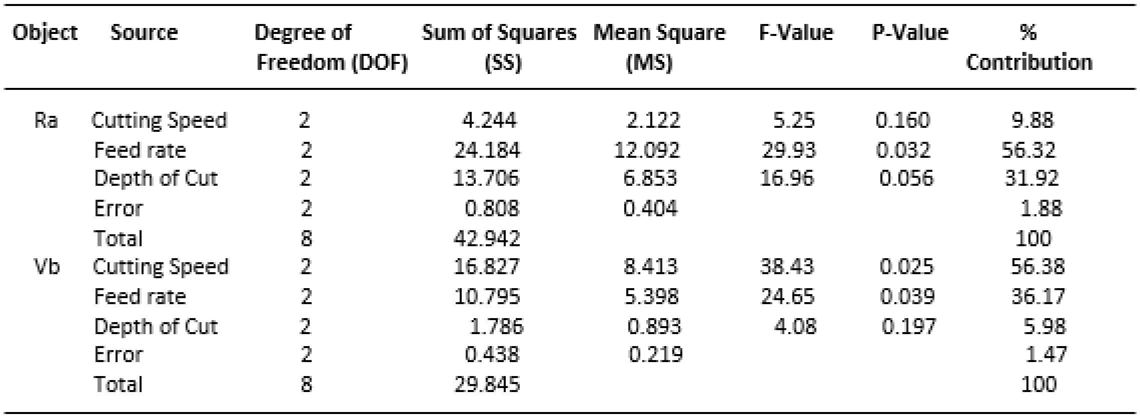


**Figure 12: Main effects plots for S/N ratios of Vb**

4.4b*ANOVA*

Results for Ra and Vb, as given in Table 6, were analysed with ANOVA for a confidence level of 95% to get % Contribution of each turning parameter considered towards Ra and Vb [22]. From Table 9, it was observed that feed rate was the highest significant factor affecting Ra, whereas the cutting speed was the highest significant factor affecting Vb.

**Table 9. ANOVA for S/N ratios of Ra and Vb**



| Object | Source | Degree of Freedom (DOF) | Sum of Squares (SS) | Mean Square (MS) | F-Value | P-Value | % Contribution |
|---|---|---|---|---|---|---|---|
| Ra | Cutting Speed | 2 | 4.244 | 2.122 | 5.25 | 0.160 | 9.88 |
| | Feed rate | 2 | 24.184 | 12.092 | 29.93 | 0.032 | 56.32 |
| | Depth of Cut | 2 | 13.706 | 6.853 | 16.96 | 0.056 | 31.92 |
| | Error | 2 | 0.808 | 0.404 | | | 1.88 |
| | Total | 8 | 42.942 | | | | 100 |
| Vb | Cutting Speed | 2 | 16.827 | 8.413 | 38.43 | 0.025 | 56.38 |
| | Feed rate | 2 | 10.795 | 5.398 | 24.65 | 0.039 | 36.17 |
| | Depth of Cut | 2 | 1.786 | 0.893 | 4.08 | 0.197 | 5.98 |
| | Error | 2 | 0.438 | 0.219 | | | 1.47 |
| | Total | 8 | 29.845 | | | | 100 |

4.4c*Regression mathematical models*

Regression mathematical models for Ra and Vb have been established by non-linear regression using Minitab 17 and represented in terms of coded values of turning parameters by Eqns. (2) and (3) respectively. The values of coefficient of determination ($R^2$) as obtained are greater than 90% and closer to 100%, which confirm that the developed models are adequate and reliable [23].

$$Ra = 0.659 + 0.00156 \text{ x } v + 6.10 \text{ x } f - 2.047 \text{ x } d - 0.000010 \text{ x } v^2 - 28.23 \text{ x } f^2 + 1.521 \text{ x } d^2 \quad (2)$$

$R^2$ = 98.54%, $R^2$ (adj) = 94.16%, $R^2$ (pred) = 70.42%

$$Vb = -0.2775 + 0.004896 \text{ x } v + 1.646 \text{ x } f + 0.558 \text{ x } d - 0.000024 \text{ x } v^2 - 13.02 \text{ x } f^2 - 0.458 \text{ x } d^2 \quad (3)$$

$R^2$ = 97.81%, $R^2$ (adj) = 91.23%, $R^2$ (pred) = 55.60%

4.4d*Comparison of experimental and predicted values*

To confirm accuracy of the established mathematical models, the absolute error (AE%) between experimental result and predicted value for each sample's data and the mean absolute errors (MAE%) for all the samples' data were calculated using Eq. (4) and displayed in Table 10.

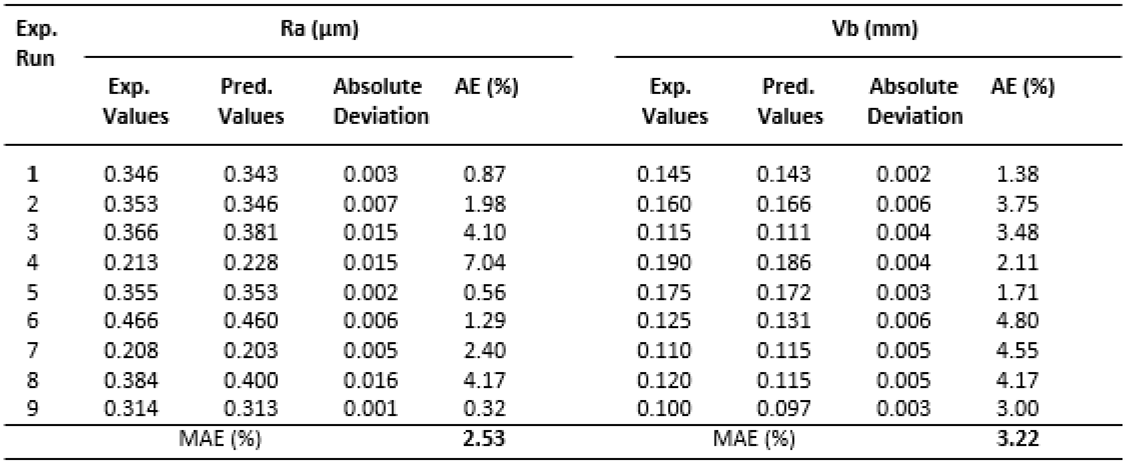
$$AE\ (\%) = [|Exp.\ results - Pred.\ results| \text{ X } 100] / Exp.\ results \quad (4)$$

Comparative study showed that experimental and predicted results were very close to each other for both the responses. As seen from the Table 10, MAE (%) for Ra and Vb were 2.53 % and 3.22 % respectively. Errors (%) between experimental and predicted results were found to be within the acceptable range (±7 %). Finally, these results proved that the developed mathematical models were more reliable and adequate and hence, can be used for the prediction of Ra and Vb with high accuracy within the considered range of conditions [20].

4.4e*Confirmatory tests*

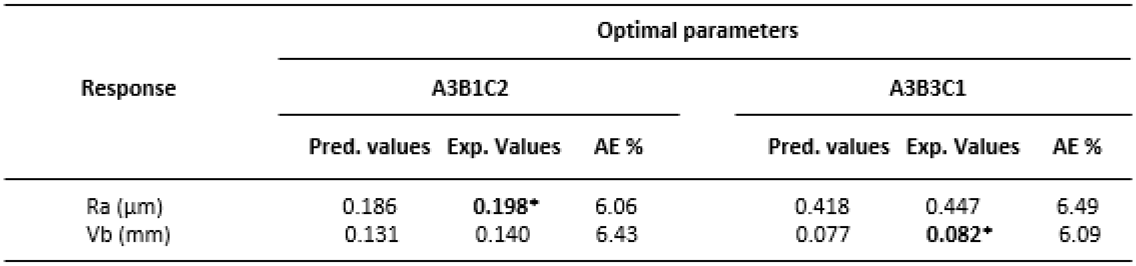
As seen from the Table 11, absolute error % was within the acceptable range (±7 %). Table 11indicated that the optimal combination of parameters i.e. A3B1C2 could achieve minimum Ra value of 0.198 µm but caused higher Vb value of 0.140 mm. whereas the optimal order of parameters i.e. A3B3C1 could achieve minimum Vb value of 0.082 mm but led to a higher Ra value of 0.418 µm. This led to a confusion in the selection of optimum setting of parameters, which could satisfy both the responses. To solve this multi-response problem, Grey-Taguchi Method was used.

**Table 10. Comparison of experimental and predicted results**



| Exp. Run | Ra (µm) | | | | Vb (mm) | | | |
|---|---|---|---|---|---|---|---|---|
| | Exp. Values | Pred. Values | Absolute Deviation | AE (%) | Exp. Values | Pred. Values | Absolute Deviation | AE (%) |
| 1 | 0.346 | 0.343 | 0.003 | 0.87 | 0.145 | 0.143 | 0.002 | 1.38 |
| 2 | 0.353 | 0.346 | 0.007 | 1.98 | 0.160 | 0.166 | 0.006 | 3.75 |
| 3 | 0.366 | 0.381 | 0.015 | 4.10 | 0.115 | 0.111 | 0.004 | 3.48 |
| 4 | 0.213 | 0.228 | 0.015 | 7.04 | 0.190 | 0.186 | 0.004 | 2.11 |
| 5 | 0.355 | 0.353 | 0.002 | 0.56 | 0.175 | 0.172 | 0.003 | 1.71 |
| 6 | 0.466 | 0.460 | 0.006 | 1.29 | 0.125 | 0.131 | 0.006 | 4.80 |
| 7 | 0.208 | 0.203 | 0.005 | 2.40 | 0.110 | 0.115 | 0.005 | 4.55 |
| 8 | 0.384 | 0.400 | 0.016 | 4.17 | 0.120 | 0.115 | 0.005 | 4.17 |
| 9 | 0.314 | 0.313 | 0.001 | 0.32 | 0.100 | 0.097 | 0.003 | 3.00 |
| | MAE (%) | | | **2.53** | MAE (%) | | | **3.22** |

**Table 11. Confirmatory tests for optimal turning parameters for Ra and VB**



| Response | Optimal parameters | | | | | |
|---|---|---|---|---|---|---|
| | A3B1C2 | | | A3B3C1 | | |
| | Pred. values | Exp. Values | AE % | Pred. values | Exp. Values | AE % |
| Ra (µm) | 0.186 | **0.198*** | 6.06 | 0.418 | 0.447 | 6.49 |
| Vb (mm) | 0.131 | 0.140 | 6.43 | 0.077 | **0.082*** | 6.09 |

* Optimised responses

### 4.5*Multi-Response Optimization*

Grey Relational Analysis is widely used and most economical to achieve a common set of optimal parameters for multi-response optimisation. The highest GRG is assigned as a common set of optimum parameters for multi-responses [24].

The procedural steps for multi-response optimization are detailed below.

Step1: Results of Ra and Vb are normalised to values lying between zero and unity by Eq. (5). The criterion selected for both the responses is “lower-the-better” as the intent of present study is to minimise both responses.

$$x_i^*(k) = [\max x_i^o(k) - x_i^o(k)] / [\max x_i^o(k) - \min x_i^o(k)] \qquad (5)$$

Where, $x_i^*(k)$ is the normalised data for i^th experimental result, max $x_i^o(k)$ is the maximum experimental result, $x_i^o(k)$ is the i^th experimental result and min $x_i^o(k)$ is the minimum experimental result.

Step 2: From the normalized data, absolute deviation sequence ($\Delta o_i(k)$) is determined by Eq. (6)

$$\Delta o_i(k) = |x_o^*(k) - x_i^*(k)| \qquad (6)$$

Where, $x_o^*(k)$ = the reference sequence, $x_i^*(k)$ = the comparability sequence

Step 3: Grey relational Coefficient ($\xi(k)$) is calculated by Eq. 7

$$\xi(k) = [\Delta\min + \xi.\Delta\max] / [\Delta o_i(k) + \xi\Delta\max] \qquad (7)$$

Where, Δ max =1, Δmin =0 and $\xi$ is the distinguishing coefficient. In the present study, $\xi$=0.5 was considered.

Step 4: Grey relational grade (ϒi) is calculated by averaging the Grey relational coefficients of all the performance characteristics by Eq. (8)

$$\Upsilon i= (1/n) \sum^{0}_{i=1}\xi_{i}(k) \qquad (8)$$

where ϒi is the GRG for the ith experiment and n is the number of performance characteristics. $\xi_i(k)$ is sum of Grey relational coefficients of all the performance characteristics.

Step 5: GRG value is converted to S/N ratio based on “larger-the-better” (LB) criterion by Eq. (9)

$$S/N\ ratio = -10\log (1/n) \sum (1 / Y_i^2) \qquad (9)$$

Where, $Y_i$ is $i^{th}$ GRG value.

As per the procedural steps as stated above, the data obtained for Ra and Vb, as presented in Table 6, were processed to obtain the Grey Relational Grades as given in Table 12.

**Table 12. Grey relational grade table with ranks and S/N ratios**

| Exp. Run | Responses | | Grey Relational Generation | | Evaluation of Δoi | | Grey relational Coefficient | | Grey Relational Grade (GRG) | S/N ratio (LB) | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ra (µm) | Vb (mm) | Ra | Vb | Ra | Vb | Ra | Vb | | | |
| 1 | 0.346 | 0.145 | 0.4651 | 0.5000 | 0.5349 | 0.5000 | 0.4831 | 0.5000 | 0.4916 | -6.1686 | 6 |
| 2 | 0.353 | 0.160 | 0.4380 | 0.3333 | 0.5620 | 0.6667 | 0.4708 | 0.4286 | 0.4497 | -6.9415 | 8 |
| 3 | 0.366 | 0.115 | 0.3876 | 0.8333 | 0.6124 | 0.1667 | 0.4495 | 0.7499 | 0.5997 | -4.4413 | 4 |
| 4 | 0.213 | 0.190 | 0.9806 | 0 | 0.0194 | 1 | 0.9627 | 0.3333 | 0.6480 | -3.7685 | 3 |
| 5 | 0.355 | 0.175 | 0.4302 | 0.1667 | 0.5698 | 0.8333 | 0.4674 | 0.3750 | 0.4212 | -7.5102 | 9 |
| 6 | 0.466 | 0.125 | 0 | 0.7222 | 1 | 0.2778 | 0.3333 | 0.6428 | 0.4881 | -6.2298 | 7 |
| 7 | 0.208 | 0.110 | 1 | 0.8888 | 0 | 0.1112 | 1 | 0.8181 | 0.9091 | -0.8278 | 1 |
| 8 | 0.384 | 0.120 | 0.3178 | 0.7778 | 0.6822 | 0.2222 | 0.4229 | 0.6923 | 0.5576 | -5.0735 | 5 |
| 9 | 0.314 | 0.100 | 0.5891 | 1 | 0.4109 | 0 | 0.5489 | 1 | 0.7745 | -2.2196 | 2 |
| | | | | | | | Mean value of GRG = **0.5933** | | | | |

**Table 13. Response table for Means of GRG and S/N ratios of GRG at different factor levels**

| Level | Means of GRG | | | S/N ratios of GRG | | |
|---|---|---|---|---|---|---|
| | Cutting speed | Feed rate | Depth of cut | Cutting speed | Feed rate | Depth of cut |
| 1 | 0.5137 | 0.6829 | 0.5124 | -5.8505 | -3.5883 | -5.8240 |
| 2 | 0.5191 | 0.4762 | 0.6241 | -5.8362 | -6.5084 | -4.3099 |
| 3 | 0.7504 | 0.6208 | 0.6433 | -2.7070 | -4.2969 | -4.2598 |
| Delta | 0.2367 | 0.2066 | 0.1309 | 3.1435 | 2.9201 | 1.5642 |
| Rank | 1 | 2 | 3 | 1 | 2 | 3 |

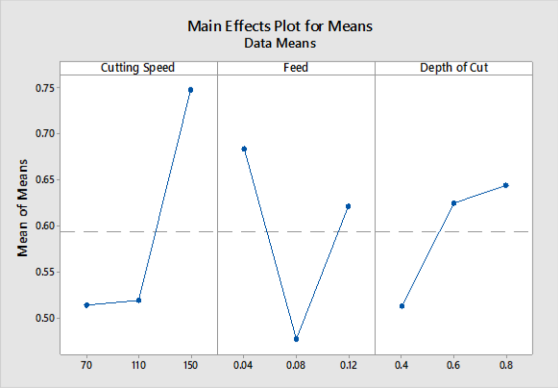


**Figure 13: Main Effects Plot for Means of GRG**

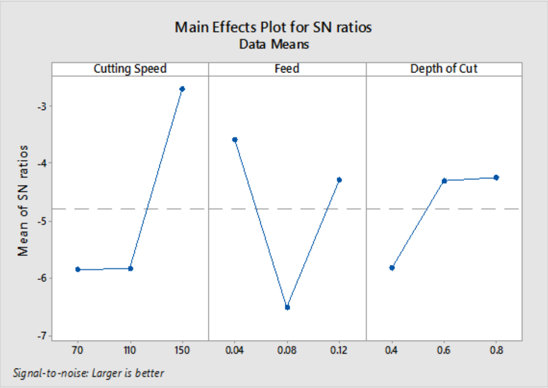


**Figure 14: Main Effects Plot for S/N ratios of GRG**

### 4.5a*Response table for GRG*

Table 13, Figures 13 and 14 exhibited that Cutting speed was the most dominant factor affecting the responses and was ranked as 1st. Feed rate and depth of cut were ranked as 2nd and 3rd respectively. Furthermore, from the response Table for S/N ratios, Level 3 for cutting speed, Level 1 for feed rate and Level 3 for depth of cut constituted a common set of optimal turning parameters for maximizing GRG value as well as for minimizing the Ra and Vb. This set of optimal parameters corresponded to 7th experimental run, which indicated highest GRG and S/N ratio and assigned with rank of 1. The recommended set of optimal parameters were speed as 150 meter per min., feed as 0.04 millimetre per revolution and 0.80 millimetre i.e., v3-f1-d3.

**Table 14. ANOVA for GRG**

| Source | Degree of Freedom (DOF) | Sum of Squares (SS) | Mean Square (MS) | F-Value | P-Value | % Contribution |
|---|---|---|---|---|---|---|
| Cutting Speed | 2 | 0.106474 | 0.053237 | 23.30 | 0.041 | 51.06 |
| Feed rate | 2 | 0.067508 | 0.033754 | 14.77 | 0.063 | 32.37 |
| Depth of Cut | 2 | 0.029968 | 0.014984 | 6.56 | 0.132 | 14.37 |
| Error | 2 | 0.004570 | 0.002285 | | | 2.19 |
| Total | 8 | 0.208520 | | | | 100 |

**Table 15. Results for Confirmatory experiments**

| | Initial parameters | Optimal parameters | | | % Improvement |
|---|---|---|---|---|---|
| | | Prediction | Experiment | % Absolute Error | |
| Level | *v1-f1-d1* | *v3-f1-d3* | *v3-f1-d3* | | |
| Ra (µm) | 0.346 | 0.200 | 0.208 | 3.85 | 39.88 |
| Vb (mm) | 0.145 | 0.115 | 0.110 | 4.55 | 24.14 |
| GRG | 0.4916 | 0. 8900 | 0.9091 | 2.10 | 84.93 |
| Increase in GRG = 0.9091 – 0.4916 = **0.4175** | | | | | |

### 4.5b*ANOVA for GRG*

Table 14 showed that Cutting speed (51.06%) was the highest dominating factor affecting Ra and Vb. It also showed that Depth of cut had least impact on responses.

### 4.5c*Confirmatory experiment*

Once the set of optimal machining parameters is selected, the final step is to predict and verify the enhancement of the performance characteristics using the set of optimal machining parameters. The predicted GRD ($\Upsilon_p$) can be calculated by Eq. (10)

$$\Upsilon_p = \Upsilon_m + \sum_{i=1}^{q} (\Upsilon i - \Upsilon_m) \qquad (10)$$

Where, $\Upsilon_m$ = Total mean of the grey relational grade,
$\Upsilon i$ = Mean of the grey relational grade at the optimum level and
Q = Number of machining parameters that significantly affects the multiple performance characteristics.

Using Eq. (10) the predicted GRD was calculated as 0.8900. For initial setting of parameters during machining tests, first levels of all the turning parameters were considered. As seen from the Table 15, Confirmatory tests indicated a good agreement between the experimental and predicted values and an increase of 0.4175 or 84.93% in GRG. The results also revealed that the surface roughness (Ra) was decreased by 39.88% and flank wear (Vb) was decreased by 24.14%. Thus, it can be concluded that the performance characteristics can be effectively improved by Grey-based Taguchi method [25].

## 5. CONCLUSIONS

Outcomes of the present studies are summarised as follows:

- Experimental trials on heat-treated LM25/Al2O3/Gr. Composites were performed with positive rake and negative rake coated carbide inserts to compare their performances. The results revealed that positive rake insert was most suitable for better machining performance.
- Abrasion wear was dominant in finish turning operation.
- Number of experimental runs were reduced from 27 to 9, while using Taguchi's Orthogonal Array (L9).
- S/N ratio of Taguchi Method was applied to minimise all responses.
- Set of optimal turning parameters to minimize Ra (0.198 µm) was achieved as cutting speed of 150 meter per min, feed rate of 0.04 millimetre per revolution, and depth of cut of 0.6 millimeter. Moreover, set of optimal turning parameters to minimise Vb (0.082 mm) was achieved as cutting speed of 150 meter per min., feed rate of 0.12 millimeter per revolution and depth of cut of 0.4 millimeter.
- The developed mathematical models for Ra, and Vb were verified. Predicted values were found to be very close to experimental values. The results showed that Mean Absolute Error % for Ra and Vb were 2.53% and 3.22% respectively.
- The recommended set of optimal turning parameters, to get minimum Ra (0.208 µm) and Vb (0.110) simultaneously, were as cutting speed (150 meter per min.), feed rate (0.04 millimeter per revolution and depth of cut (0.80 millmeter).
- The % Absolute Error between predicted and experimental values of the GRG was almost within 2.10%.
- The increase in GRG from the initial set of parameters to optimal set of parameters is 0.4175 (i.e., 84.93%).
- Finally, it was concluded that multi responses can be effectively enhanced through Grey-based Taguchi Method.

## REFERENCES

Seeman M, Ganesan G, Karthikeyan R and Velayudham A 2010 *Int. J. Adv. Manuf. Technol*. **48** 613
Bansal P and Upadhyay L 2016 *ICIAME* 2016 **23** 304
Basavarajappa S and Davim J P 2013 *Materials Research* **16** 990
Tash M, Samuel F H, Mucciardi F, Doty H W and Valtierra S 2006 *Mat. Sci. Eng.A* **434** 207

Benardos P G and Vosniakos G C 2003 *Int. J. of M/C Tools and Manuf.* (Greece-ResearchGate) p 1
Suthar J and Patel K M 2018 *Materials and Manufacturing Processes***33** 499
Ononiwu N H, Ozoegwu C G, Madushee N and Akinlabi E T 2021 *Research Square* (South Africa)
Rahman A M, Rob S M A and Srivastava A K 2021 Procedia Manufacturing **53** 204
Manna A and Bhattacharaya B 2003 *J. Mat. Pro. Tec.* **140** 711
Kılıckap E, Cakır O, Aksoy M and Inan A 2005 *J. Mat. Pro. Tec.* **164** 862
Yang W H and Tarng Y S 1998 *J. Mat. Pro. Tec.***84** 122
Manna A and Bhattacharyya B 2006 *IJMMM* **1** 448
Das D, Routara B C, Nanda B K and Chakraborty S 2019 *IJITEE* **9** 81
Ay M, Altunpak Y and Hartomacioglu S 2017 *Int. Congress Exhibition* Maslak**131** 551
Thiagarajana C, Ranganathan S and Shankar P 2015 *Applied Mechanics and Materials***813** 388
Rao A V, Suresh B S, Murthy H N N, Krishna M and Somashekar H M 2020 *AJMME***4** 1
Zulkamal N A M, Nasir L M M and AnasyidaA S 2018 *Journal of Physics*: *Conf. Series* **1082** 1
Karim Z, Azuan S A S and Yasir M S A 2013 *Aust. J. Basic & Appl. Sci.***7** 46
Gunay M, Korkut I, Aslan E and Seker U 2005 *J. Mat. Pro. Tec.***166** 44
Rafighi Md. 2021 J*ournal of Polytechnic***24** 1295
Xavier J F,Ravi B,Balakrishnan D J, Ezilarasan C, Jayaseelan V and Elias G 2021 *Journal of Nanomaterials* **2021** 1
Basmaci G 2018 *Int. Adv. Appl. Phy. Mat. Sci.***134** 260
Wang Z and Li L 2021 *Advances in Mechanical Engineering***13** 1
Ficko M, Begic-Hajdarevic D, Hadziabdic V and Klancnik S 2020 *Int. J. Simul Model***19** 547
Nayak S K, Patro J K, Dewangan S and Gangopadhyay S 2014 *Procedia Materials Science***6** 701