Characterization, machinability studies, and multi-response optimization of AA 6082 hybrid metal matrix composite

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Abstract

This work investigated the effect of carbonized eggshell and fly ash on the microstructure, mechanical properties, and machinability of AA 6082. The fabrication method selected for this study was stir casting. For the hybrid metal matrix composite, the weight fraction was 2.5wt% carbonized eggshell and 2.5wt% fly ash. Density analysis recorded a 10.66% reduction of the cast composite in comparison to the aluminum alloy. Improvements of 12.32%, 21.91%, and 8.30% were recorded for the microhardness, tensile strength, and compressive strength respectively. The wear studies of the cast samples revealed coefficients of friction (CoF) of 0.499 and 0.290 for the base metal and the composite respectively. For the machinability studies, the surface roughness and tool flank wear were the responses under consideration. The design of experiments was conducted using the Taguchi L16 orthogonal array. The input parameters for this investigation were cutting speeds (100 mm/min, 200 mm/min, 300 mm/min, 400 mm/min), feeds (0.1 mm/rev, 0.2 mm/rev, 0.3 mm/rev, 0.4 mm/rev), and depths of cut (0.25 mm, 0.50 mm, 0.75 mm, 1.0 mm). For the multi-response optimization, Taguchi-based grey relational analysis was used. The analysis of variance (ANOVA) of the grey relational grade (GRG) revealed that the feed was the most influential factor on the GRG. The initial optimization showed the optimal cutting speed, feed, and depth of cut as 100 mm/min, 0.1 mm/rev, and 0.25 mm respectively. The confirmatory tests revealed that the optimal combination of factors was 400mm/min, 0.1 mm/rev, and 0.25 mm for the cutting speed, feed, and depth of cut respectively.

Keyword Carbonized eggshells · Fly ash · Machinability · Optimization · Taguchi-based grey relational analysis

1 Introduction

Metal matrix composites (MMCs) have continued to receive adequate attention due to the prospects of improved overall properties making them easily applicable across several industrial sectors not limited to automobiles, aerospace, military, marine, and structural applications. These composites are already poised to replace conventional materials for the purpose already stated. Among the applicable base metals for MMC fabrication, aluminum has received numerous attention because of its corrosion resistance, and strength-to-weight ratio [1]. Research into the fabrication of aluminum matrix composites (AMCs) has yielded noteworthy improvements in the properties under investigation such as research done by Ikumapayi et al [2] who studied the effects of coconut shell ash, cow bone ash, and palm kernel ash on corrosion resistance of AA 7075. The results indicate that reinforcing the aluminum alloy with palm kernel shell ash produced the AMC with the least corrosion resistance. Research done by Rao et al [3] reported refined grain structure, reduction in destiny, and improvements of the hardness and tensile strength of AA 6061 reinforced with particulate fly ash in comparison to the base metal. Kurapati and Kommineni [4] reported improvements in the wear behavior of hybrid AA 2024/fly ash/SiC in comparison to the monolithic metal due to adequate distribution of the reinforcing particulates.

Eight major grades of aluminum alloys are available depending on the alloying elements. Among the aluminum grades available, AA 6082 is one of the most commonly used. AA 6082 is a medium-strength aluminum alloy with good...
Machinability is usually defined based on indices which include surface roughness, tool wear, cutting forces, cutting temperature, material removal rate (MMR) among others. The machinability of a material describes the ease with which a workpiece can be cut [12]. Part of the research into the machinability of MMCs is the need for optimization of certain input parameters such as cutting speed, feed, depth of cut, reinforcement weight fraction, and tool nose radius among others. The need for optimization is necessary to effectively reduce machining cost, waste, and ultimately maximize profit. Certain optimization techniques have been applied to machinability studies of AMCs. Such techniques are illustrated in Fig. 1.

The versatility of these optimization techniques has resulted in their application into other aspects of MMC research including fabrication and tribology optimization [13, 14]. Of these optimization techniques specified in Fig. 1, the Taguchi optimization technique is well applied in MMC machinability analysis owing to its simplicity and its ability for process improvement. The major shortcoming of the Taguchi method of optimization is its inability to optimize multiple responses at a time [15–18]. Research into the machinability studies of selected AMCs include those done in [19] which investigated the effect of bismuth on the surface roughness and cutting forces for the workpiece material Al-Mg2Si. The dry turning test considered the variations in the cutting speed and feed. The results of the study disclosed that the surface roughness and cutting forces decreased with increasing weight fraction of bismuth. Jiang et al. [20] investigated the effect of TiB2 on the machinability of AA 7050. The results of the investigation indicated that the surface roughness decreased with increasing cutting speed while increasing the feed decreased the surface integrity of the AMC. Daniel et al. [21] investigated the machinability of AA7075/TiB2 while varying the cutting speed, feed, depth of cut, and weight fraction of TiB2. The machinability indices under investigation were the cutting forces and surface roughness. It was reported that the surface roughness decreased with increasing cutting speed and TiB2 proportion while increasing the feed and depth of cut caused an increase in the cutting force. The AVOVA results indicated that the TiB2 reinforcements were the highest contributor to the cutting forces and surface roughness. Results reported in [22] showed that the feed has the most influence on the surface roughness of AA 6061 reinforced with rock dust. Joel and Xavier [23] investigated the effect of the cutting speed, feed, and depth of cut on the surface roughness, temperature, tool flank wear, and material removal rate of AA 7075/SiC composite. The results indicate that the feed has the greatest effect on the investigated responses.
Most research efforts including those indicated in the literature review focused on characterization and/or machinability of AMCs fabricated with either synthetic reinforcements or a combination of synthetic reinforcements and sustainable reinforcements. This work involves the examination of the effect of two sustainable reinforcement materials, fly ash and carbonized eggshell, on the microstructure, mechanical properties, tribology, and machinability of AA 6082. Therefore, the basis for the novelty of this work is the study of an innovative sustainable material through comprehensive experimental characterization of the physical, microstructural, mechanical, and machinability properties of the new material.

2 Material and methods

2.1 Composite fabrication

The elemental composition of AA 6082 used as the matrix material is shown in Table 1. Stir casting was selected as the processing route for the fabrication of the composites. This processing route was preferred because of its ease and cost-effectiveness [24].

The AA 6082 matrix was sourced as sheets from Metal Centre Johannesburg. The as-received sheets were cut and weighed based on the designed weight fractions depicted in Table 2. The type C fly ash was sourced from Ash resources Johannesburg, while the eggshells were sourced from restaurants located in the University of Johannesburg, Auckland Park Campus. The eggshells were cleaned and sundried to eliminate any organic matter. The eggshells were subsequently dried in an electric oven for 2 days to remove any remaining moisture due to humid storage conditions. This step was also taken for the fly ash for the same purpose. The stirrer and steel die were preheated at 350°C ± 20°C. This was done to avoid the effect of the temperature difference between the stirrer and the molten matrix and to ensure uniform fluidity and solidification of the cast. The graphite crucible was preheated at a temperature of 600°C to avoid cracks that could occur as a result of thermal shock. Both reinforcements were charged into a muffle furnace and preheated at a temperature of 300°C for 1 h to ensure adequate wettability between the reinforcements and the matrix. The temperature of the furnace was increased to 760°C ± 5°C to initiate the melting process for the aluminum alloy. One weight percent magnesium was charged into the crucible after the removal of slag and subsequent introduction of the preheated reinforcements to ensure proper wettability and improve the interfacial bonding between the reinforcing phases and the aluminum matrix [24, 25]. The stirring was done to ensure the less dense reinforcements mix evenly in the molten matrix to promote uniform dispersal. The stirring was done for 10 min before casting commenced.

2.2 Microstructural examination

The microstructure of the cast composite was investigated using the TESCAN model type VEGA LMH. This equipment was also used to study the elemental composition of the cast composite via energy dispersive spectroscopy (EDS). The metallographic analysis was done to investigate the level of distribution of the hybrid dispersed phases in the aluminum matrix and also check for the presence of defects usually in the form of voids, agglomerates, and segregation of the reinforcing particulates.

2.3 Mechanical properties and density

This study also attempted to study the effect of the hybrid reinforcements on selected mechanical properties including compressive strength, tensile strength, ductility, and microhardness. The tensile strength and ductility of the samples were obtained via the MKS Universal tensile testing machine with a frame capacity of 1000KN as per the ASTM E8 standard. In the case of the compressive strength, the utilized equipment was the Zwick/Roell Universal tensile testing machine with a maximum applicable load of 250KN. The dimension of the selected samples for the compressive strength test was 2mm × 2mm as per the ASTM standards. As in the case of the tensile strength test, 3 replicates were prepared for each sample for reproducibility of the results. The microhardness test was conducted using the Times Vickers microhardness tester which is equipped with a diamond cone indenter. The applied test force was 300 gF with a dwell time of 15 s per indentation. Five indentations 1mm apart were produced for each sample and the average recorded as the values for the microhardness. All the mechanical tests were conducted at 23°C. The experimental density of the cast samples was obtained via the Archimedes principle.

| Table 1 | Elemental composition of the metal matrix |
|--------|-----------------------------------------|
| Composition | Si | Fe | Cu | Mn | Mg | Cr | Ni | Ti | Al |
| %     | 0.898 | 0.535 | 0.079 | 0.593 | 0.142 | 0.055 | 0.108 | 0.013 | Bal |
2.4 Wear studies

The wear study was conducted to investigate the effect of the carbonized eggshell and fly ash hybrid reinforcements on the aluminum matrix in comparison to the unreinforced aluminum alloy. The wear study was conducted using the Antom Paar ball-on-disc tribometer shown in Fig. 2. The selected load was 10N while the linear speed was 36.04 cm/s. The sliding distance was 440 m. The selected ball for the study was an alumina ball of 6mm diameter.

2.5 Machinability tests

The machinability investigation was undertaken to understand the effect of the hybrid reinforcement on the machinability of the AA 6082 hybrid composite. Joel et al. and Nicholls et al. [23, 24] reported that the inclusion of reinforcements into the aluminum matrix ultimately decreases its machinability. To this effect, this work expressly investigated the machinability of the cast hybrid to determine the effect of the reinforcements. The machinability indices under investigation were the surface roughness and the tool flank wear. The machine tool used for the machinability studies was the Ecoline ctx 3-axi CNC lathe. The specifications of the machine tool are summarized in Table 3.

A dry turning operation was selected for the investigation. The cast workpiece had an initial dimension of 67mm × 200mm. The need to provide a reference surface was responsible for an initial rough cut on the workpiece. Korloy carbide single-point cutting tool inserts with a nose radius of 0.4 mm were selected for the metal cutting process. The surface roughness was analyzed using the Mitutoyo SJ-201 (0.25 × 5) portable surface roughness tester equipped with a diamond cone stylus which was responsible for taking precise mean surface roughness (Ra) values. To measure the surface roughness, at the end of each run 3 points along the cast workpiece were measured and the mean value recorded. The average tool flank wear (VB) was analyzed using the SEM. At the end of each run, the insert used was changed and stored to measure the tool wear via the scanning electron microscope. The stated equipment for the machinability studies is depicted in Fig. 3.

2.6 Taguchi design of experiments and optimization

The design of experiments (DOE) was conducted via the MINITAB 17 statistical software. The independent variables under consideration for this study were cutting speed, feed, and depth of cut. The process parameters are summarized in Table 4. The L16 orthogonal array DOE selected for this investigation considers 3 process parameters without interaction to be varied at 4 discrete levels. This L16 orthogonal array was designed to run 16 individual experiments to evaluate the tool wear and the surface roughness of the cutting tool inserts and the AA 6082/FA/CES AMC respectively.

Optimization of the responses was done using the signal to noise ratio (S/N) analysis. The S/N analysis is a tool used in the Taguchi response optimization process to ascertain the robustness of the process and evaluate any deviation from the desired values [26]. In this optimization method, greater values of S/N ratios are usually preferred to reduce the effect of uncontrollable factors and noise reduction. For this study, the smaller-the-better S/N ratio criterion was used to optimize the tool wear and surface roughness while the larger-the-better S/N criterion was used to optimize the grey relational grade (GRG). The S/N ratio formulas for the smaller-the-better and larger-the-better criteria are depicted in Eqs. 1 and 2 respectively.

Table 2 Proportions of the cast samples

| Composition                  | Al (wt%) | Carbonized eggshells (wt%) | Fly ash (wt%) |
|------------------------------|----------|----------------------------|---------------|
| AA 6082                      | 100      | -                          | -             |
| AA 6082 + FA + CES           | 95       | 2.5                        | 2.5           |

![Antom Paar ball-on-disc tribometer](image)

Fig. 2 Antom Paar ball-on-disc tribometer
The next step is to obtain the deviation sequence which is done using Eq. 4.

$$\Delta_{ij} = \max(Y_{ij}) - Y_{ij}$$

where $\Delta_{ij}$ is the deviation sequence, $\max(Y_{ij})$ is the maximum normalized value, and $Y_{ij}$ is the reference normalized value.

With the value of the deviation sequence, the grey relational coefficient (GRC) of the individual responses is calculated using Eq. 5.

$$GRC_{ij} = \frac{(\Delta_{\text{min}} + \delta \Delta_{\text{max}})}{(\Delta_{ij} + \delta \Delta_{\text{max}})}$$

where $\Delta_{\text{min}}$ is the minimum deviation sequence, $\Delta_{\text{max}}$ is the maximum deviation sequence, and $\delta$ is the identification coefficient which is defined to be usually set at 0.5 to assign equal weight to each parameter.

The grey relational grade (GRG) is eventually used as a representation of the two responses in the Taguchi optimization. It is obtained via Eq. 6 as:

$$GRG_{i} = \frac{1}{n} \sum_{j=1}^{n} GRC_{ij}$$

### 3 Results and discussion

#### 3.1 Mechanical properties and density

The summary of the results for the density and the investigated mechanical properties is displayed in Fig. 4. The analysis of the microhardness revealed a 12.23% increase in comparison to the base metal. The enhancement of the microhardness is a result of the presence of the hard-reinforcing hybrid particles which work to resist the relative motion between individual grains for any given load applied.

The tensile strength of the cast composite improved by 21.9%. In addition to the uniform dispersal of the fly ash and carbonized eggshell particles, the improvement in tensile strength is brought about by transferring the load from the aluminum matrix to the hybrid reinforcements due to their different elastic constants [27]. The improvement in the tensile strength is also brought about by the presence of the reinforcements at the grain boundaries of the $\alpha$-aluminum phase which
work against the tensile loading of the matrix thereby improving its tensile strength. The reduction in ductility which has also been reported in [11, 28] was also reported in this investigation as being a result of the more brittle reinforcing phases present in the aluminum matrix. In the fabrication of the composite, there is usually a trade-off between tensile strength and ductility. The compressive strength of the composite was generally improved by adding hybrid reinforcements. This improvement is due to the ability of the reinforcements to resist deformation when compressive forces are applied [29].

3.2 Microstructure

The micrograph depicted in Fig. 5 describes the morphology of the cast AMC. The study of the microstructure for this investigation was done to investigate the level of dispersion of the reinforcements in the aluminum matrix and check for defects that could be a result of the composites’ fabrication or the general casting process. The microstructural observation of the cross-section of the cast composites showed the dendritic structure of the α-Al phase and even distribution of the fly ash and eggshell particles. The formation of the dendritic α-Al phase is due to the rapid cooling of the hybrid AMC after casting. The even distribution of the reinforcements in the aluminum phase is a direct consequence of adequate stirring of the melt before casting. The presence of minimal pores is also seen in the micrographs. The formation of the pores is a drawback of stir casting which is formed as a result of trapped small pockets of air during the fabrication process [11]. The reinforcing particles were distributed along the grain boundaries of the AA 6082 matrix. This in turn is responsible for the improvements in tensile strength, compressive strength, and microhardness. Adequate dispersion of the reinforcements could also have been brought about because of the formation of strong interfacial bonds between the hybrid reinforcements.
and the AA 6082 phase due to proper preheating of the reinforcing particles and the addition of 1 wt% magnesium into the melt before casting [30–32]. The formation of minimal fly ash agglomerates is also present in the micrographs. These agglomerates were formed during the solidification of the casts. The energy dispersive spectroscopy (EDS) analysis of the hybrid sample shown in Fig. 6 revealed peaks of aluminum, oxygen, carbon, silicon, and manganese.

### 3.3 Tribology studies

The wear resistance study was conducted based on the coefficient of friction analysis. The results are summarized in Fig. 7. From these results, it is shown that the cast composite exhibits higher wear-resistant properties due to the relatively lower coefficient of friction in contrast to the matrix. The average CoF of the base metal and composite are 0.499 and 0.293 respectively. It is shown that the CoF of the AMC is lower than that of the matrix which indicates improved wear resistance. The improved wear resistance is because of the hard-reinforcing particles which work to resist the relative motion of the alumina ball on the surface of the cast hybrid composite samples. The reduction of the CoF with increasing sliding distance for both the base metal and the composite could be due to the transition of the wear mechanism from adhesive to abrasive. From the results, it is shown that the CoF for both samples decreased with increasing sliding distance. This could also be attributed to the \( Al_2O_3 \) formation on the surface of the cast samples which acts as a lubricating film thereby reducing the effect of friction [33].

The formation of the oxide layer forms a barrier that reduces the contact between the alumina ball and the aluminum counterface thereby improving the wear resistance of both samples under consideration. The decline in the CoF with increasing sliding distance could also be due to the formation of wear debris on the surface of the cast samples. This debris decreases the wear rate of both the matrix and the hybrid AMC by reducing the contact between the alumina ball and the counterface of the samples. Another reason for the improved wear resistance of the cast AMC is the adequate interfacial bonding between the hybrid reinforcements and the aluminum matrix which resists the pull-out of the hybrid reinforcements during the relative movement between the ball and the counterface [33].

The analysis of the wear tracks as seen in Fig. 8 obtained with the aid of SEM shows the presence of predominantly abrasive wear for both the base metal and the hybrid reinforcement, evident by the presence of grooves and delamination. There was also the presence of adhesive wear as confirmed by the presence of aluminum debris deposited on the surface of the cast samples. The presence of abrasive wear in both samples is evident by the presence of grooves formed as the alumina ball moves along the face of the cast samples due to the application of the normal load. The movement of the alumina ball along the surface of the cast samples led to a rise in temperature which aids the plastic deformation of the counterface. The wear debris indicated in the wear tracks is a result of the cutting action of the deformed aluminum which stuck to the alumina ball. The reduction in the CoF as evident from the wear tracks presented in the micrographs in Fig. 8 is also a result of the conversion of the wear mechanism from adhesive to abrasive wear [30, 34].

### 3.4 Design of experiments

Using the Taguchi DOE, 16 distinct experiments were developed from the L16 orthogonal array. These experiments were designed using the MINITAB 17 statistical analysis software. The experiments were conducted based on the designed experiments to obtain the tool wear of the carbide tool inserts and the surface roughness of the AA 6082/FA/CES hybrid composite. The L16 orthogonal array is shown in Table 5.

### 3.5 ANOVA

The analysis of variance (ANOVA) is a statistical tool utilized for different applications to determine the significance of 2 or more independent variables as they affect the response or
group of responses. For this study, the ANOVA of the tool wear, surface roughness, and the grey relational grades (GRG) obtained through the utilization of Eqs. 3–6 are shown in Tables 6, 7, and 8 respectively. This was done to determine the significance of the input parameters on the associated responses.

The ANOVA analysis of the tool wear indicates that all the independent variables have $p$-values $< 0.05$ which indicates that they all have a significant effect on the cutting tool wear while machining the cast hybrid AMC. Further analysis of the significance of the independent variables on the tool wear indicates that the cutting speed has the most contribution of 66.41% on the tool wear. The feed and depth of cut have contributions of 20.90% and 10.96% respectively. The ANOVA of the surface roughness also revealed that the cutting speed has the highest contribution of 72%. This result is in tune with research done in [35, 36]. The $p$-values of all the factors were 0.00, 0.00, and 0.002 for the cutting speed, feed, and depth of cut respectively making them significant factors that influence the surface roughness. These $p$-values as in the case of the ANOVA analysis of the tool wear indicates that the cutting speed is the significant factor that influences the surface roughness of the AA6082/FA/CES composite. The percentage contribution of the feed was 23.25% which also indicates that the feed is a major contributor to the surface roughness. The depth of cut had a contribution of 4.27% indicating little to negligible contribution on the surface roughness.

Fig. 7 Coefficient of friction for the matrix and hybrid AMC

Fig. 8 Micrographs of the wear mechanism for a AA 6082 and b AA 6082/FA/CES
The ANOVA of the grey relational grade was also conducted to investigate the effect of the cutting speed, feed, and depth of cut on the tool wear and surface roughness. The $p$-values of the independent variables were all $\leq 0.05$ indicating that they are all significant on the combined responses (tool wear and surface roughness). In the case of the contribution of the factors on the GRG, the feed had a contribution of 72.78%, while the cutting speed and depth of cut have contributions of 4.58% and 20.66% respectively. The AVOVA analysis revealed that the feed has the most influence on the combined responses while machining the AA6082/FA/CES hybrid composite.

### 3.6 Single-objective optimization

For both responses (tool wear and surface roughness), the experimental data were converted to the S/N ratio. Also, the most influential independent variables were identified via the generated response table of the S/N ratio shown in Tables 9 and 10. Since the objective for both the tool wear and surface roughness was to be minimized, the smaller-the-better criterion was utilized.

#### Table 5 L16 Orthogonal array and results

| Experimental Runs | Cutting speed (mm/min) | Feed (mm/rev) | Depth of cut (mm) | Tool wear (μm) | Surface roughness (μm) |
|-------------------|------------------------|---------------|------------------|----------------|------------------------|
| 1                 | 100                    | 0.1           | 0.25             | 2.53           | 1.69                   |
| 2                 | 100                    | 0.2           | 0.5              | 17.76          | 1.80                   |
| 3                 | 100                    | 0.3           | 0.75             | 113.86         | 1.91                   |
| 4                 | 100                    | 0.4           | 1.0              | 232.45         | 2.02                   |
| 5                 | 200                    | 0.1           | 0.5              | 41.12          | 1.58                   |
| 6                 | 200                    | 0.2           | 0.25             | 57.13          | 1.63                   |
| 7                 | 200                    | 0.3           | 1.0              | 279.15         | 1.82                   |
| 8                 | 200                    | 0.4           | 0.75             | 295.33         | 1.85                   |
| 9                 | 300                    | 0.1           | 0.75             | 206.40         | 1.47                   |
| 10                | 300                    | 0.2           | 1.00             | 325.44         | 1.58                   |
| 11                | 300                    | 0.3           | 0.25             | 238.33         | 1.57                   |
| 12                | 300                    | 0.4           | 0.50             | 357.71         | 1.68                   |
| 13                | 400                    | 0.1           | 1.00             | 371.59         | 1.37                   |
| 14                | 400                    | 0.2           | 0.75             | 387.42         | 1.47                   |
| 15                | 400                    | 0.3           | 0.50             | 403.29         | 1.42                   |
| 16                | 400                    | 0.4           | 0.25             | 419.69         | 1.52                   |

The delta values for the surface roughness depicted in Table 9 shows the ranks of the individual responses based on the S/N ratios obtained via the Taguchi orthogonal array. The analysis showed that the cutting speed was assigned a rank of 1 with a delta value of 2.1571 signifying that it is the predominant factor that affects the surface roughness of the cast composite. The feed and the depth of cut were assigned second (1.245) and third (0.391) ranks respectively. The result is in tune with Fig. 9 which shows the main effects plot for the S/N ratio for the surface roughness. The main effect plot indicates that the optimal combination of the factors to minimize the surface roughness of the AA6082/FA/CES hybrid composite are 400 mm/min for the cutting speed, 0.1 mm/rev for the feed and 0.25 mm for the depth of cut. The surface roughness increases steadily with an increase in the depth of cut. This could be owing to an increase in chatter produced due to the vibration of the workpiece caused by cutting through larger sections of the workpiece after each cutting pass. The increased surface roughness could also be due to either the pull out of the harder reinforcing particles or the migration of the particles brought about by the thermal softening of the

#### Table 6 ANOVA for tool wear

| Source       | DF | Seq SS  | Contribution (%) | Adj SS  | Adj MS  | $F$-value | $p$-value |
|--------------|----|---------|------------------|---------|---------|-----------|-----------|
| Cutting speed| 3  | 211,910 | 66.41            | 211,910 | 70,636.80 | 76.94     | 0.000     |
| Feed         | 3  | 66,704  | 20.90            | 66,704  | 22,234.60 | 24.22     | 0.001     |
| Depth of cut | 3  | 34,990  | 10.96            | 34,990  | 11,663.20 | 12.70     | 0.005     |
| Error        | 6  | 5509    | 1.73             | 5509    | 918.1    |           |           |
| Total        | 15 | 319,113 | 100              | $S = 30,3006$ | $R^2 = 98.27\%$ | $R^2_{adj} = 95.68\%$ |
workpiece due to increased heat generation during the cutting operation. The surface roughness decreases with an increase in cutting speed thereby improving the surface integrity of the cast AMC. Increased cutting speed improves the surface roughness of the cast composites due to the lesser generation of built-up edges during cutting [37]. At lower cutting speeds, the fracture of the chips generated increases the surface roughness of the workpiece.

The response table for the S/N ratio for the optimization of the tool flank wear is depicted in Table 10. The table shows that the cutting speed as in the case of the surface roughness S/N ratio analysis had the rank of 1. This also suggests that it is the predominant factor that affects the cutting tool wear.

The depth of cut is ranked 3rd while the feed is ranked 2nd based on the delta value obtained via the S/N ratio analysis. The delta values of the independent factors are shown in the response table for the S/N ratio of the tool wear. The table also suggests that for the cutting speed, feed, and depth of cut levels 1, 1, and 1 respectively have the maximum S/N ratio which makes them the optimal combinations of the S/N ratio for the optimization of the tool wear. This is further validated by the main effects plot for the S/N ratio of the tool wear depicted in Fig. 10. Based on the plot, the optimal combination of the factors to optimize the tool flank wear is 100 mm/min, 1.0 mm/rev, and 0.25 mm for the cutting speed, feed, and depth of cut respectively.

The analysis also suggests that increasing the feed and depth of cut during the turning of the hybrid AMC also increases the tool wear considerably.

### 3.7 Multi-objective optimization

The Taguchi-based grey relational analysis was employed to perform the multi-objective optimization of the cutting tool flank wear and surface roughness of the cast AMC. The “larger the better” criterion was selected because the objective of the study was to maximize the GRG. The results obtained from experimental data provided in Table 6 were processed to obtain the grey relational grade populated in Table 11.

Prior to optimizing the GRG using the Taguchi optimization method, the initial optimization using the grey relational analysis confirmed the initial optimum parameters based on the conducted experimental runs was the 1st experimental run. This experimental run suggests that the initial optimum combination of parameters was 100 mm/min, 0.1 mm/rev, and 0.25 mm for the cutting speed, feed, and depth of cut respectively. The response table for the S/N ratio tabulated in Table 12 was used to initiate the optimization of the input parameters. The response table indicates that the feed was the predominant factor influencing the responses under investigation and was ranked 1st. The cutting speed and depth of cut were ranked 3rd and 2nd respectively. Further analysis of the response table for the S/N ratio indicated that level 4, level 1, and level 1 for the cutting speed, feed, and depth of cut respectively were the combinations of optimum factors to maximize the grey relational grade and by extension optimizing the surface roughness and tool wear. This is also evident in

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**Table 7** ANOVA for surface roughness

| Source          | DF | Seq SS  | Contribution (%) | Adj SS   | Adj MS   | F-value | p-value |
|-----------------|----|---------|------------------|----------|----------|---------|---------|
| Cutting speed   | 3  | 0.375500| 72.00            | 0.375500 | 0.125167 | 300.40  | 0.000   |
| Feed            | 3  | 0.121250| 23.25            | 0.121250 | 0.040417 | 97.00   | 0.000   |
| Depth of cut    | 3  | 0.022250| 4.27             | 0.022250 | 0.007417 | 17.80   | 0.002   |
| Error           | 6  | 0.002500| 0.48             | 0.002500 | 0.000417 |         |         |
| Total           | 15 | 0.521500| 100              |          |          |         |         |

bold values reflect how good the model is

**Table 8** ANOVA for GRG

| Source          | DF | Seq SS   | Contribution (%) | Adj SS   | Adj MS   | F-value | p-value |
|-----------------|----|----------|------------------|----------|----------|---------|---------|
| Cutting speed   | 3  | 0.009153 | 4.58             | 0.009153 | 0.003051 | 4.62    | 0.053   |
| Feed            | 3  | 0.145450 | 72.78            | 0.145450 | 0.048483 | 73.40   | 0.000   |
| Depth of cut    | 3  | 0.041289 | 20.66            | 0.041289 | 0.013763 | 20.84   | 0.001   |
| Error           | 6  | 0.003963 | 1.98             | 0.003963 | 0.000661 |         |         |
| Total           | 15 | 0.199855 | 100              |          |          |         |         |
the main effect plot of the S/N ratio of the GRG depicted in Fig. 11. Using the Taguchi prediction tool in MINITAB 17, based on the optimal combination of factors obtained in the response table for the GRG, the predicted S/N ratio was obtained as 0.984 dB, while the mean was predicted as 0.7731. Since these values are larger than the S/N ratios and GRG for all the experiments shown in Table 11, the optimal combinations are considered valid.

### 3.8 Regression analysis

A regression model is used to make a correlation between the factors and the desired responses. For this investigation, 2nd order regression models were developed to adequately predict the effect of the input parameters on the tool wear, surface roughness, and GRG. The model generated in Eq. 7 was adequate to predict the tool wear owing to the $R^2$ value of 99.49% and a $p$-value of 0.000. For the surface roughness, the model generated has an $R^2$ value of 99.12% and a $p$-value of 0.000. For the GRG, which was developed to conduct a multi-objective optimization study, the regression model developed for this response had an $R^2$ value of 95.59% and a $p$-value of 0.002. The $p$-values for all the regression models are ≤0.05 showing that they are significant suggesting that at least one of the coefficients is different from zero. The $R^2$ value for all the models which are all higher than 0.90 shows the ability to explain >90% of the variance in all the responses under investigation. The 2nd order regression models developed for the tool flank wear, surface roughness, and GRG are expressed in Eqs. 7, 8, and 9 respectively.

$$GRG = 0.956 - 0.000974v - 0.761f - 0.072d - 0.000002v^2 - 0.00066vf + 0.000011vd + 0.321f^2 - 0.134fd - 0.075d^2$$  \(7\)

$$SR = 0.7293 - 0.001491v + 0.88f + 0.079d - 0.000341vf + 0.000136vd + 0.018fd$$  \(8\)

### Table 9: Response table for surface roughness S/N ratio

| Level | Cutting speed | Feed | Depth of cut |
|-------|---------------|------|-------------|
| 1     | -5.348        | -3653| -4.089      |
| 2     | -4.666        | -4.167| -4.158     |
| 3     | -3.936        | -4.422| -4.414     |
| 4     | -3.191        | -4.898| -4.480     |
| Delta | 2.1571        | 1.245| 0.391       |
| Rank  | 1             | 2    | 3           |

where SR is the surface roughness, VB is the tool flank wear, GRG is the grey relational grade, and $v$, $f$, and $d$ are the cutting speed, feed, and depth of cut respectively.

The plots for the Normal probability plots were developed as outputs of the regression models to assess if the data sets are approximately normally distributed. The assessment of the normal probability plots for the tool flank wear depicted in Fig. 12a shows that the data points were approximately normal distribution as evident by the closeness of the data points to the regression line. The normal probability plot for the tool wear also suggests that the error terms are normally distributed about the regression line. Figure 12 b shows the normal probability plots for the surface roughness. The analysis of the plot for the surface roughness suggests a fairly normal distribution of the data points. However, the plots showed the presence of outliers for experimental run 14 and 15. These possible outliers could be described as unusual observations. The normal probability plots for the GRG in Fig. 12c suggest an approximately normal distribution of the data points proving the validity of the developed regression model. No presence of outliers of skewness of the data points was observed for the model. The comparison between the experimental results and predicted values of the tool flank wear, surface roughness, and GRG was done to show the closeness between the two sets of results. The results are summarized in Fig. 13. The plots show that the developed 2nd order regression models are capable of adequately predicting the responses under consideration with negligible error.

Contour plots were used in this investigation to show the relationship between 2 categorical factors as they affect the selected response. The contour plots showing the relationship between the cutting speed and feed on the tool wear showed the maximum tool wear occurred at cutting speeds of 300 mm/min to 400 mm/min. The plots also suggested that the feed has little effect on the tool wear. It was evident from the contour
plots in Fig. 14a that the zones to machine the hybrid AMC to obtain tool wear less than 100 μm is between cutting speed of 100 mm/min to 236.44 mm/min and feed of 0.10 mm/min and 0.28 mm/rev. Examining the contour plots for the tool wear vs the cutting speed and depth of cut in Fig. 14b, it is evident that increasing the cutting speed with the depth of cut increases the tool wear. Although the maximum tool wear (greater than 400 μm) occurs at 390 mm/min to 400 mm/min and depth of cut of 0.25 mm to 0.55 mm. From the plots, the region to machine the hybrid AMC to minimize the tool wear is at cutting speeds of 100 mm/min to 225 mm/min and depth of cut 0.25 mm to 0.17 mm. The contour plots showing the effect of the feed and depth of cut on the tool wear depicted in Fig. 14c show that the minimum tool wear of the carbide inserts occurs at a feed range of 0.1 mm/rev and 0.25mm/rev, and depth of cut of 0.1 mm and 0.58 mm.

The contour plots for the effect of the input parameters on the surface roughness shown in Fig. 15a–c suggest that the ideal surface roughness while machining the hybrid AMC should be less than 1.4 μm. Figure 15 a shows that the best surface roughness occurs at a tight region of cutting speed of 371 mm/min to 400 mm/min and feed of 0.10 mm/rev and
0.11 mm/rev. The contour plots also indicate that the surface roughness of the hybrid AMC decreases with increasing cutting speed while an increase in feed increases the surface roughness of the machined AMC. The contour plots of the surface roughness vs cutting speed and depth of cut shown in Fig. 15b suggest that increasing the depth of cut increases the surface roughness of the machining AMC. The best region to obtain the least surface roughness is at depth of cut of 0.96 mm to 1 mm. The contour plots shown in Fig. 15c were used to evaluate the effect of the feed and depth of cut on the surface roughness. The plot suggests 2 regions as the best to obtain the least surface roughness. The regions are 0.3 mm/rev to 0.35 mm/rev, 0.33 mm to 0.48 mm, and 0.1 mm/rev to 0.18 mm/rev, 0.77 mm to 1.0 mm for the feed and depth of cut respectively.

The contour plot for the effect of the cutting speed and depth of cut on the GRG is depicted in Fig. 16a–c. The plot shows that the maximum GRG is achieved at lower cutting speed and feed. It is also evident from the plots in Fig. 16a that increasing the feed and cutting speed results in lower values of the GRG and by extension increased tool wear and surface roughness. The best region for the maximum GRG (greater than 0.75) is between cutting speeds of 100 mm/min to 157.6 mm/min and feed of 0.10 mm/rev to 0.14 mm/rev. Figure 16b depicts the contour plots for the GRG vs the cutting speed and depth of cut. This plot suggests that lower cutting speeds and depth of cut are required to obtain GRG values greater than 0.75. Further analysis of the contour plots for the effect of the cutting speeds and depth of cut suggests 100 mm/min to 202.07 mm/min and 0.25 mm to 0.49 mm as the regions to obtain the maximum GRG. The contour plots for the effect of the feed and depth of cut on the GRG depicted in Fig. 16c show that the boundary for the maximum GRG is located at 0.1 mm/rev to 0.11 mm/rev and 0.25 mm to 0.32 mm for the feed and depth of cut respectively.

### 3.9 Confirmatory test

The Taguchi-grey relational analysis method was used to obtain the ideal combination of the investigated input parameters to optimize the cutting tool wear and surface roughness of the cast hybrid AMC. The last phase of the GRA is to verify the optimum condition for the multi-objective quality characteristics through confirmatory tests [15]. The confirmation test was done using Eq. 8 to validate the multi-objective optimization process.

\[
\beta = \beta_t + \sum_{i=0}^{n}(\beta_i - \bar{\beta}_i)
\]  

(10)

where \(\beta_t\) is the total mean of the grey relational grade, and \(\beta_i\) is the average of the grey relational grade of the optimum factors.

| Table 11 | Ranks of grey relational grade and S/N ratios |
|----------|----------------------------------------------|
| Experimental run | Cutting speed | Feed | Depth of cut | GRG | S/N ratio for GRG | Rank |
| 1 | 100 | 0.1 | 0.25 | 0.75193798 | -2.47636 | 1 |
| 2 | 100 | 0.2 | 0.5 | 0.68120739 | -3.33441 | 2 |
| 3 | 100 | 0.3 | 0.75 | 0.51385921 | -5.78312 | 8 |
| 4 | 100 | 0.4 | 1 | 0.40450019 | -7.86163 | 16 |
| 5 | 200 | 0.1 | 0.5 | 0.72567464 | -2.78516 | 2 |
| 6 | 200 | 0.2 | 0.25 | 0.67406469 | -3.42620 | 5 |
| 7 | 200 | 0.3 | 1 | 0.43017408 | -7.32712 | 14 |
| 8 | 200 | 0.4 | 0.75 | 0.4096926 | -7.74709 | 15 |
| 9 | 300 | 0.1 | 0.75 | 0.63520783 | -3.94168 | 6 |
| 10 | 300 | 0.2 | 1 | 0.4996026 | -6.02129 | 12 |
| 11 | 300 | 0.3 | 0.25 | 0.54421034 | -5.28466 | 9 |
| 12 | 300 | 0.4 | 0.5 | 0.44089558 | -7.11329 | 13 |
| 13 | 400 | 0.1 | 1 | 0.68054498 | -3.34286 | 4 |
| 14 | 400 | 0.2 | 0.75 | 0.5580213 | -5.06604 | 8 |
| 15 | 400 | 0.3 | 0.5 | 0.60448573 | -4.37228 | 7 |
| 16 | 400 | 0.4 | 0.25 | 0.50877193 | -5.86954 | 11 |

| Table 12 | Response table for S/N ratio for grey relational grade |
|----------|-------------------------------------------------------|
| Level | Speed | Feed | Depth of cut |
| 1 | -4.864 | -3.137 | -4.264 |
| 2 | -5.321 | -4.462 | -4.401 |
| 3 | -5.590 | -5.692 | -5.634 |
| 4 | -4.663 | -7.148 | -6.138 |
| Delta | 0.928 | 4.011 | 1.874 |
| Rank | 3 | 1 | 2 |
The results of the confirmatory tests identified level 4 for the cutting speed, level 1 for the feed and level 1 for the depth of cut which directly translates to 400 mm/min, 0.1 mm/rev, and 0.25mm for the cutting speed, feed, and depth of cut respectively. The calculated grey relational grade via Eq. 9 is 0.78904. This value is approximately equal to the predicted

![Main Effects Plot for SN ratios](image1)

![Normal Probability Plot](image2)

![Normal Probability Plot](image3)

Fig. 11 Main effects plots for GRG S/N ratios

Fig. 12 Normal probability plots for a tool wear, b surface roughness, and c GRG
Fig. 13  Comparison between the actual and predicted for a tool wear, b surface roughness, and c GRG

Fig. 14  Contour plots for tool wear a cutting speed and feed, b cutting speed and depth of cut, and c depth of cut and feed
value obtained via the Taguchi prediction tool highlighted earlier. Table 13 summarizes the comparison between the initial and the optimum machining parameters. The Taguchi-based grey relational analysis as an optimization tool showcases its ability to adequately optimize multiple responses simultaneously. In comparison to the initial optimized
parameters, the optimal optimized parameters suggested that the cutting speed be increased from 100 mm/min to 400 mm/min while leaving the feed and depth of cut unchanged.

4 Conclusion

From the investigation of the effect of fly ash and carbonized eggshells on the microstructure, density, mechanical properties, and machinability of AA 6082, the following conclusions can be made.

1. The analysis of the microstructure revealed that the reinforcements were homogeneously dispersed in the aluminum matrix. The presence of the hybrid reinforcements was responsible for the decrease in the density from 2.72 g/cm³ for the base metal to 2.43 g/cm³ for the cast composite.

2. The studies of the mechanical properties revealed that the microhardness improved from 63.23 HV to 71.02 HV. The tensile strength improved from 141.60 MPa to 172.63 MPa while the compressive strength improved from 121.23 MPa to 131.29 MPa. The existence of the reinforcing particles in the aluminum matrix resulted in a decrease in the ductility of the composite from 8.5% for the base metal to 2.62%.

3. The wear studies showed an improvement in wear resistance evident from the reduction of the CoF in comparison to the base metal. The predominant wear mechanism for both samples was abrasive and adhesive wear.

4. The experimental runs were designed using Taguchi L₁₆ orthogonal array.

5. The ANOVA analysis for the tool wear and surface roughness showed that the cutting speed was the most influential factor, while the feed was the most influential factor for the grey relational grade.

6. The single objective optimization of the individual responses showed that the optimal combination of factors was 400 mm/min, 0.1 mm/min, and 0.25 mm/min for the cutting speed, feed, and depth of cut respectively.

Availability of data and material Not applicable

Code availability Not applicable

Declarations

Ethics approval No data, theory, or test from this work has been presented elsewhere. Proper acknowledgements to other work have been made.

Consent to participate Not applicable

Consent for publication Not applicable

Conflict of interest The authors declare no competing interests.

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Table 13 Results of the confirmatory test

|                | Initial design parameters | Predicted design parameters |
|----------------|---------------------------|----------------------------|
| Level          | v1 f1 d1                  | v4 f1 d1                   |
| Surface roughness | 1.26                      | 0.74815                    |
| Tool wear      | 145.39                    | 0.78904                    |

Table 13

Int J Adv Manuf Technol (2021) 116:1555–1573

1571
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