Investigations on mechanical and wear behaviour of graphene and zirconia reinforced AA6061 hybrid nanocomposites using ANN and Sugeno-type fuzzy inference systems

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Abstract
This research work investigates the mechanical and wear behaviour of graphene (C) and zirconium dioxide (ZrO2) reinforced Aluminium alloy 6061 hybrid nano composites (AMMHNCs) fabricated by ultrasonic-assisted stir casting method. Graphene and ZrO2 are selected as reinforcements for increasing the wear resistance and hardness of the base alloy AA6061. The mixing proportions of graphene and ZrO2 reinforced with AA6061 in weight are 100% AA6061/0% Graphene/0% ZrO2, 98.5% AA6061/0.5% Graphene/1% ZrO2, 97.5% AA6061/0.5% Graphene/2% ZrO2, 98% AA6061/1% Graphene/1% ZrO2, 97% AA6061/1% Graphene/2% ZrO2. Microstructural study was carried out using optical and scanning electron microscopy images to analyse the dispersion of reinforcements in the composite. The results shown that, ultrasonic-assisted stir casting method improves the uniformity in dispersion of reinforcements. The hardness, tensile and wear test were carried out based on ASTM standards to analyse the properties in the proposed composite specimens. It was observed that, the hardness, tensile strength and impact strength are increases by 21.88%, 69.42% and 78.57% respectively and percentage elongation is decreased by 63.52% with the increase of reinforcements. In order to analyse the wear behaviour originality of new composite under wear test parameters, Artificial Neural Network (ANN) and Artificial Neuro Fuzzy Inference Systems (ANFIS) models were used to predict the wear rate for experimented and non-experimented parameters. The prediction analysis was useful in studying the wear behaviour of the composite. Comparative analysis for ANN and ANFIS was performed and the results shown that, ANFIS model predicted with accuracy of R² with 99.9%.

1. Introduction

Aluminium alloys and its composites are inherently possessing characteristics such as light weight, excellent castability compared to other competent alloys and composites enabling intuitive applications in aerospace, automotive and electronic industries [1–4]. Especially Aluminium Alloy 6061 (AA6061) grade finds a typical application in marine applications, tool machinery parts, aircraft parts, trailer structural frames, screw parts, architectural frames, rocket motors and aircraft landing furniture. Moreover, AA6061 combines the characteristics of good corrosion resistivity and good manufacturability. In spite of the characteristics it possesses, exhibits low abrasive wear resistance under different lubricating environment [5, 6]. AA6061 based metal matrix composites are increasingly replaced in various above said applications owing to their tailor-made
mechanical properties. As the development of manufacturing processes continues to expand in the use of these advanced composite materials, the research is still in the growing stage for the past decade [7]. There is a demand for the materials having characteristics such as high strength to less weight ratio without compromising the other qualities of base alloys. Recently, many researchers attempted for producing the composite materials using single reinforcements and multiple reinforcements to enhance the mechanical and tribological properties. To improve the hardness of the base alloy, the ceramic-based reinforcements like Al2O3, SiC, ZrO2, ZrB2, WC, TiC, are used [8]. To enhance the lubricity or increase the wear resistance, the reinforcements like hexagon boron nitride (hBN), Molybdenum Sulphide (MoS2), Graphene (Gr), calcium carbonate (CaCO3), are used [9–12]. In the last decade, the fabrication of aluminium alloy based composite materials with different reinforcement materials in different composition were prepared and analyzed for the enhancement of mechanical and tribological properties for the different field of applications.

The selection of right reinforcement is very much important for the desired intended properties to be enhanced in the composite material. Most of the applications demands the materials having unique properties such as wear resistance and hardness. Therefore, to improve the wear resistance and hardness without compromising the other mechanical properties, suitable reinforcement is to be identified for analysis. For high temperature applications, ceramic reinforced composites show better characteristics to withstand the elevated temperature as it possesses high hardness. The self-lubricating reinforcements improves the wear resistance of the substrate. When two reinforcements combine together, to form a hybrid composite material resulting in tailor-made superior mechanical properties.

Y. Pazhouhanfar et al [13] investigated the Al 6061 composite added with TiB2 were mixed together in various proportions and fabricated by friction stir casting route. The mechanical and microstructure study explains that uniform distribution of base matrix and reinforcements were obtained with little agglomeration. The dimples were found during the fracture test indicate dominant fracture mechanism. The dimples decrease on increase in reinforcements. Mohanavel et al [14] studied the mechanical properties of AA6351 as base matrix with graphite particles as reinforcement. Here reinforcements were added in 0 to 12% in the addition of 4. On inclusion of graphite to the base matrix, the non-homogeneous mixing of materials was identified. The hardness test and tensile strength test results showed the decrease in results values as increase in reinforcement graphite. This was due to this poor bonding in-between the base matrix and reinforcements while examined by scanning electron microscope study. Kumar et al [15] analysed the mechanical properties and characterisation of the aluminium alloy Al6082 as the base matrix and zirconium di-oxide & coconut shell ash as the reinforcement materials. Both the materials are varied from 0 to 10%. The microstructure showed uniform distribution that influence strong bonding at the interface between matrix and reinforcement. The tensile strength and hardness increase as the wt.% of reinforcement increases. Impact strength test shows that increase in reinforcement decreases its strength, due to lubrication effect. Shreyas PS et al [16] analysed the tribological properties of AA6061 reinforced with alumina and zirconia fabricated by stir casting. The frictional properties and wear rate were examined in pin on disk machine. The wear parameters of sliding distance and sliding velocity were considered over different load limits. The test results shows that wear resistance rises with the increase in load. The wt.% of alumina of 2.5 were kept constant and zirconia was varied through 1, 2, 3 and 4%. It was observed that decreases the damage owing to friction.

Amrendra Pratap Singh et al [17] investigated the mechanical properties for aluminium alloy of grade 2024 and Al2O3/ZrO2/Gr reinforced aluminium alloy hybrid composite processed stir casting route. Density of the composite rises with increasing wt.% of reinforcements. Alloy with 4 wt.% Al2O3, 4 wt.% zirconia and 4wt.% graphite showed increased porosity of 10.31%. 158 HV of maximum hardness and 157.36 MPa of tensile strength was shown for AA2024/10 wt% Al2O3/10 wt% ZrO2/10 wt% Gr. Volume fraction of reinforced particles increases with increase in peak intensity. The results proved that the composite significantly enhances the mechanical properties. Rajasekar et al [18] studied the influence of heat treatment on tribological behaviour of Al/ZrO2/flash hybrid composite processed through stir squeeze casting technique. The orthogonal array (L³) of Taguchi method was used to conduct the experiments. The uniform distribution of reinforcement particles was ensured by inverted microscope. It is observed that, the higher micro-hardness was obtained for the 700 °C melting temperature, 7% of zirconia, and heat treatment time of 120 min. The wear resistivity and microhardness of the composite significantly increases with the rise of heat–treating time, reinforcement and the melting temperature. The less wear rate was obtained with 800 °C melting temperature, 6% of zirconia and 60 min heat treatment time. Moreover, wear resistance decreases with the increase of the zirconia and heat-treatment time. Nithin Chakravarthy et al [19] investigated the surface parameters optimization of zirconia reinforced AA7050 alloy in wt.% of 5, 10 nano-sized particles. The machining parameters used were surface harshness impact, feed rate and slicing speed. Two machining strategies of dry turning and wet turning were used to conduct the experiments. Taguchi method and ANOVA were used to predict the surface unpleasantness. The surface unpleasantness effects were expanded by 15.694%, 80.379% and 1.375% for cutting velocity, feed rate and proficiency of cut respectively.
Anjaneyulu et al [20] studied the mechanical and tribological properties of Al₂O₃ and ZrO₂ reinforced ceramic composites fabricated by powder metallurgy route. The material was tested for wear strength, hardness, electrical resistance and linear thermal expansion co-efficient. SEM was used to examine the microstructure. The results shown that the distribution of ultra-nano zirconia was uniform with a slight agglomeration. The mechanical and electrical properties were improved due to the addition of reinforcement. Betul kafkaslioglu Yildiz et al [21] analysed the influence of ZrO₂ content on aluminium composites for bending strength. The different vol.% of 0, 0.5, 1, 3, 5, 10 and 20 were used for analysis. The fracture strength was measured by monotonic equibiaxial flexural strength test. The results shown that the maximum strength was obtained at 20 vol.% zirconia containing 435 ± 78 MPa, which is 24% increase when compared with unreinforced alloy. This is due to the transition of tetragonal to monoclinic phase. Small crack length was identified due to stress induced transition in zirconia.

Ghanbariha et al [22], investigated the effect of zirconia on nano-mechanical properties and wear behaviour of AlCoCrFeNi-ZrO₂ high entropy alloy composites. The material was processed through mechanical alloying and spark plasma sintering method. Microstructural examination showed that the specimen consists of BCC and FCC phases, which are enhanced by 10% addition in wt. % of monoclinic ZrO₂. Wear rate is improved by the 5 wt.% addition of zirconia. Wear mechanism such as abrasive, adhesive, oxidation and delamination were identified in all specimens. Eligiusz Postek et al [23] studied the impact of alumina and zirconia reinforced composite by determining impact damage development and role of phase content present in it. The impact damage analysis was performed in three dimensions. The damage at higher level is occurred in mid-depth of the cross-section whereas the lowest is lying on the surface of the plate. The growth of the damage is analysed in terms of percentage during impact test. The analysis shows that the material with higher amount alumina exhibits less damage resistant than with high amount of zirconia. Juanjuan Chen et al [24] investigated the elevated temperature wear behaviours of ZrO₂/h-BN/SlC composite under vacuum and air exposed environments. The results indicates that the wear and friction behaviour are highly sensitive of temperature and testing environment. The composite material possesses excellent lubricity in vacuum and it is very negligible of 0.3 of coefficient of friction at 800 °C. The material is detrimental to wear resistance at elevated temperature.

Jigar Suthar et al [25] investigates the optimization of significant parameters such as stir time, stir speed, temperature for stir casting hybrid composite while preheating and quantity of reinforcement were found to be the most important parameters for acquiring high ultimate tensile strength and reduced porosity. This article shows with less porosity and maximum ultimate tensile strength at 650 rpm speed with 12 min stirring time. Using of permanent mould, surface roughness value decreases to less than 3 μm, contrasted to conventional green sand-casting process. Porosity decreased underneath 3% by degassing and fluxing. Al/SlC composite in vehicle enterprises are utilized to fabricate connecting rods, pistons, liners and so on, while Al/Al₂O₃ composites are utilized for piston rings, engine blocks and connecting rods which is reasonable for our project as well. Hardness, ductility and ultimate tensile strength diminish with increment in graphene content. Utilization of graphite material is basic to enhance the wear strength properties.

From the extensive literature review, it is understood that, the effect of graphite on aluminium alloys increases the lubricity resulting in increasing the wear strength. zirconia increases the hardness, tensile strength and impact strength for the enhancement of mechanical properties. In this present research, the tribological and mechanical behaviour of nano sized zirconium di-oxide and graphene reinforced AA6061 hybrid metal matrix composite material were studied and proposed the enhanced properties in addition to the normal base AA6061.
The novelty in the present work is the use of both graphene and zirconia combination as nano-sized particles to improve the strength of the composite materials.

2. Experimental details

2.1. Materials

The base matrix used is AA6061 as ingot of diameter 70 mm and the reinforcements used are ZrO$_2$ and graphene in nano sized irregular shaped particles of average size 200 nm as depicted in figures 1(a) and (b) respectively. Tables 1 and 2 highlights the chemical composition and mechanical properties of AA6061. Table 3 highlights the
mechanical properties of ZrO$_2$. Figures 2(a) and (b) shows the Electron dispersive spectroscopy (EDS) of graphene and ZrO$_2$.

2.2. Fabrication of composite
As the reinforcement particles used are in nano size, the particle dispersion becomes a challenging task. This is due to the large surface area to volume ratio resulting in clustering and agglomeration in one particular region. This affects the resulting properties such as poor wettability which in turn to produce with inferior mechanical properties. In order to overcome this, the composite material is fabricated through ultrasonic-assisted stir casting method in which the ultrasonic probe helps to uniformly disperse the particles all over the casting [26, 27]. The process uses the subsystems such as resistance heating furnace, feeding mechanism for nano-particle, inert gas environment for protecting the molten metal from contamination and an ultrasonic system. The ultrasonic system consists of a transducer, an ultrasonic probe, and power source. The ultrasonic waves generally used of frequency between 18 and 20 kHz. When these waves propagate through the liquid medium, alternating dilation and compression cycles are produced. At the end of alternating cycles, the high intensity ultrasonic waves make the air bubbles of micro size to grow in the liquid. Once the saturated volume is reached, they can no longer absorb enough energy which results in violent imploding. During implosion, very high temperatures and pressures are reached inside these bubbles. At the end of the cavitation cycle, collapse of micro bubbles produces transient micro hot spots that can reach very high temperatures and pressures. Implosive cavitation impact is sufficient to break down the agglomeration and forming of clusters for uniform dispersion in the metal matrix.
AA6061 material and the die was first polished using emery sheet of grade 40 to remove dirt, rust and foreign particles. Secondly, the alloy was placed in crucible made of stainless-steel grade SS304 and heated using electrical resistance furnace at 950 °C. Thirdly, the reinforcements were bagged into aluminium foil separately as shown in the figure 3 to disperse them uniformly and preheated to 200 °C to remove the moisture and reduce the cracking of casting material. Fourthly, the preheated reinforcements were mixed with melted alloy, followed by mechanical stirring process carried out at 500 rpm for 15 min. The ultrasonic probe was then inserted inside the molten metal and the vibration was carried out for 10 min in 40 kHz at 4 s interval, which helps the molten material in suspension to ensure the uniform dispersion and homogenous mixture. After the sonification process, again the mechanical stirring was carried out for 10 min. The molten material is then poured into preheated die at 400 °C and dismantled after solidification for 2 h \cite{28, 29}. The ultrasonic-assisted casting set-up is depicted in figures 4 and 5. The fabricated composite of different composition in weight percentage shown in table 4 was machined into specimens for various tests such as hardness, tensile, impact and wear according to ASTM standards. Figures 6 and 7 depicts the specimens before and after test for microstructure evaluation, hardness, tensile and impact.

### Table 4. Weight percentage of AA6061-T6, Graphene and ZrO₂.

| Specimen No.  | AA6061 | Graphene | ZrO₂ |
|---------------|--------|----------|------|
| Pure AA6061-T6 | 100    | 0        | 0    |
| AMMHNC1       | 98.5   | 0.5      | 1    |
| AMMHNC2       | 97.5   | 0.5      | 2    |
| AMMHNC3       | 98     | 1        | 1    |
| AMMHNC4       | 97     | 1        | 2    |

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### 3. Results and discussion

#### 3.1. Microstructure evaluation

The optical and SEM images of Al6061 alloy and AMMHNCs are depicted in figures 8(a)–(h). From the images, it is clearly evident that, the grain structure in the form of dendrite regions for graphene and ZrO₂
Table 5. Design of experiment and wear rate results.

| S. No. | Material composition (wt. %) | Wear rate (mm$^3$ s$^{-1}$) | Predicted result by ANN | Predicted result by ANFIS | Predicted Error |
|--------|------------------------------|-------------------------------|--------------------------|---------------------------|----------------|
|        | AA6061 C ZrO$_2$ Load (N) Speed (rpm) Exp. result |                              |                          |                           |                |
|        |                               | Exp. result                   | Predicted result by ANN  | Predicted result by ANFIS |                |
| 1      | 100 0 0 10 500                | 8.2039                        | 8.203 899 999            | 8.204                     | 8.53E-10 −0.000 22 |
| 2      | 100 0 0 10 750                | 8.2103                        | 8.210 299 994            | 8.210                     | 6.13E-09 −0.000 13 |
| 3      | 100 0 0 20 500                | 8.7993                        | 5.859 122 58             | 8.799                     | 2.940 177 42 0.000 04 |
| 4      | 100 0 0 20 750                | 8.9427                        | 8.942 700 006            | 8.943                     | −6.18E-09 0.000 34 |
| 5      | 100 0 0 30 500                | 10.3523                       | 6.320 304 559            | 10.352                    | 4.031 995 441 0.000 00 |
| 6      | 100 0 0 30 750                | 10.3832                       | 10.383 200 01            | 10.383                    | −1.39E-08 −0.000 08 |
| 7      | 98.5 0.5 1 10 500            | 5.9933                        | 6.338 318 446            | 5.993                     | −0.345 018 446 −0.000 01 |
| 8      | 98.5 0.5 1 10 750            | 6.0841                        | 6.675 169 197            | 6.084                     | −0.591 069 197 −0.000 02 |
| 9      | 98.5 0.5 1 20 500            | 6.9394                        | 6.939 999 998            | 6.939                     | 2.04E-09 0.000 05 |
| 10     | 98.5 0.5 1 20 750            | 7.0512                        | 7.051 200 023            | 7.051                     | −2.32E-08 0.000 10 |
| 11     | 98.5 0.5 1 30 500            | 7.8051                        | 7.805 999 992            | 7.805                     | 7.69E-09 −0.000 07 |
| 12     | 98.5 0.5 1 30 750            | 7.8145                        | 8.319 593 045            | 7.814                     | −0.305 093 045 −0.000 20 |
| 13     | 97.5 0.5 1 10 500            | 5.3689                        | 5.368 959 369            | 5.369                     | 3.81E-10 −0.000 03 |
| 14     | 97.5 0.5 1 10 750            | 5.3564                        | 5.356 400 001            | 5.357                     | −1.36E-09 0.000 10 |
| 15     | 97.5 0.5 1 20 500            | 6.0782                        | 6.078 199 997            | 6.078                     | 2.71E-09 −0.000 04 |
| 16     | 97.5 0.5 1 20 750            | 6.0835                        | 5.219 920 207            | 6.084                     | 0.863 579 793 0.000 08 |
| 17     | 97.5 0.5 1 30 500            | 6.8841                        | 6.884 999 984            | 6.884                     | 1.57E-08 0.000 05 |
| 18     | 97.5 0.5 1 30 750            | 6.8918                        | 6.891 800 006            | 6.892                     | −6.13E-09 −0.000 02 |
| 19     | 98 1 1 10 500                | 4.0146                        | 4.014 599 999            | 4.015                     | 7.57E-10 −0.000 01 |
| 20     | 98 1 1 10 750                | 4.0189                        | 4.018 899 999            | 4.019                     | 9.76E-10 −0.000 07 |
| 21     | 98 1 1 20 500                | 4.4982                        | 4.620 870 587            | 4.498                     | −0.122 670 587 −0.000 04 |
| 22     | 98 1 1 20 750                | 4.5127                        | 4.512 700 003            | 4.513                     | −3.41E-09 0.000 05 |
| 23     | 98 1 1 30 500                | 5.0365                        | 5.036 499 983            | 5.036                     | 1.72E-08 −0.000 14 |
| 24     | 98 1 1 30 750                | 5.0841                        | 5.084 100 002            | 5.084                     | −2.19E-09 0.000 15 |
| 25     | 97 1 2 10 500                | 3.4923                        | 3.492 299 989            | 3.492                     | 1.08E-08 0.000 03 |
| 26     | 97 1 2 10 750                | 3.4568                        | 3.456 800 006            | 3.457                     | −6.00E-09 0.000 01 |
| 27     | 97 1 2 20 500                | 3.7537                        | 3.028 302 626            | 3.754                     | 0.725 397 374 −0.000 08 |
| 28     | 97 1 2 20 750                | 3.8416                        | 4.445 827 982            | 3.841                     | −0.604 227 982 −0.000 14 |
| 29     | 97 1 2 30 500                | 4.0062                        | 4.545 989 213            | 4.006                     | −0.539 789 213 0.000 03 |
| 30     | 97 1 2 30 750                | 4.0157                        | 4.015 700 006            | 4.016                     | −7.49E-11 −0.000 10 |
Figure 8. Optical images (a)–(d) at 200X magnification and SEM images (e), (f), (g) & (h) at 500X magnification displaying microstructures of AMMHNCs.
reinforcements are seen scattered, which ensures that the dispersion of particles is uniform throughout the matrix materials due to the ultra-sonification process. There is no porosity and less agglomeration identified and hence strong intermolecular bonding between the matrix and nano-sized reinforcement materials. The uniform dispersion obstructs the dislocation movements due to dispersion strengthening mechanism resulting in improving the mechanical behaviour of nano composites.

3.2. Hardness

The Brinell’s hardness testing machine was used to determine the hardness of AMMHNCs based on ASTM standards. 250 kg of load using 5 mm ball was applied during the test. For each specimen, three trials were conducted. The average of three observed values presented in table 5 were considered to plot the graph. From the graphical representation depicted in figure 11, it is clearly evident that the hardness increases to 2% with the rise of ZrO₂ owing to the higher hardness and density of ZrO₂ particles through toughening transformation. The percentage improved for the hardness from 0% to 2% is 21.88%.

3.3. Tensile strength

The tensile specimens were sized using lathe machine with ASTM standards as shown in figure 9. The test was conducted at room temperature. The reinforcement effects from 0% to 2% is depicted in figure 12. From the figure, it is understood that the increase in reinforcement leads to an increase in tensile strength of AMMHNCs. The tensile strength is improved by 69.42% in AMMMHC4 (1% graphene and 2% ZrO₂), when compared to AA6061 alloy. The increase in tensile strength is firstly due to the homogenous distribution of the reinforcement in the base matrix and the presence of graphene particles. Secondly, due to the sonification process, the longer diffusion of atomic particles is seen at bonding interface between the base alloy and the reinforcements.

3.4. Percentage elongation

With increasing reinforcement, all the properties of the AMMHNCs improves and elongation decreases with rise in reinforcement. Figure 13 depicts reduction in weight proportion of AMMHNCs elongation with increase of strengthening from 0 to 2%. This is due to higher hardness of ZrO₂ particles which decreases the ability of super-plasticity behaviour. This decrement in elongation is an advantageous, due to the material will exhibit rigidity during its elevated temperature. The percentage elongation is decreased by 63.52%. These determinations are comparable to those of researchers attempted with the competitive materials [30, 31].

3.5. Impact strength

The impact strength of the AMMHNCs was determined using Charpy Impact testing machine based on ASTM standards as shown in figure 10. The specimen size of 10 mm × 10 mm × 55 mm and un-notched type at room temperature of 24°C was used. Figure 14 depicts the effect of reinforcements on impact strength. The results show that, the impact strength increases with the rise of graphene and ZrO₂ particles from 0% to 2%. The elevated temperature maintained at 950 °C during casting, resulting in precipitation process and the mixture were cooled very slowly. The percentage improvement for impact strength from 0% to 2% is 78.57%.

3.6. Wear behaviour

The wear specimens of size 8 mm diameter and 30 mm length was prepared from casted samples according to the ASTM G99 standards. The pin on disc machine set up was used to conduct the experiments. The specimens were cleaned using acetone and polished using 518 emery grade sheets for the required track radius of 60 mm. The test was conducted at three different loads of 10, 20 and 30 N with constant disc speed of 500 rpm for 900 s to determine the best composition of the composite.
Figures 15–17 shows the plot between wear and time for different wt.% compositions of AMMHNCs at 10 N, 20 N and 30 N loads. It is evident that, AMMHNC4 is obtained with less wear rate compared with other wt.% in all the load conditions. The wear decreases with increase in ZrO2 particles. This is due to the combined effect of characteristics that the higher hardness of ZrO2 particles which resist the wear and graphene have the tendency of slipperiness which leads to reduce the coefficient of friction [32]. Secondly, Due to the increase in temperature at the interface of the surface layer between the rotating disk and specimen after the sliding time rises, the composite becomes softer resulting in less wear. Comparing the three plots for 3 different loads, there is an increase in the wear as the load increases. This is due to the hardness properties which are proportional to wear rate behaviour.

Figure 18 shows the variation of wear loss for different wt.% of reinforcements. The wear loss decreases as the reinforcements increases for all the load conditions of 10 N, 20 N and 30 N. Compared to pure alloy, the composite has considerable wear resistance that can be attributed to higher values of hardness possessed by ZrO2.
particles and slipperiness produced by the higher temperature at the wear interface due to the applied load [33–36]. Figure 19 depicts the SEM images of worn surface during wear tests for different compositions. It is clearly evident that, 97% AA6061/1% Graphene/2% ZrO₂ (AMMHNCs) is seen with less delamination and there is no lamination compared to other compositions.

3.7. Wear prediction model using ANN and ANFIS
The wear load considered for analysing the wear resistance was 10, 20, and 30 N and speed was 500 rpm. In order to understand the originality of the wear behaviour for the various levels of wear loads and disk speed, 30...
experimental runs were conducted according to multi-level design methodology, and their results are shown in table 5 [37–39]. A wear prediction model using Artificial neural network (ANN) and Adaptive neuro-fuzzy inference systems (ANFIS) was constructed to predict the wear behaviour. Many soft computing techniques such as probabilistic reasoning, machine learning, fuzzy logic, etc are available for computing the predictions.
Apart from conventional techniques, these soft tools are pre-dominant in ceratinities, precision and consistency in obtaining the approximate solutions [40].

ANN and sugeno-type fuzzy inference systems (SFIS) were used to analyse the wear behaviour of composite materials. The architecture of ANN and the membership function for this analysis are shown in figures 20 and 21 respectively. The input parameters for the model used are material composition (alloy wt.%, ZrO₂ wt.% and
graphene wt.%, load (10, 20, 30 N) and speed (500 and 750 rpm) and the output variable as wear rate. The computing model was constructed in MATLAB R2020a using the neural network tab. Among 30 experimental data sets, 25 were used for training and the remaining 5 for test. The error values are computed and shown in the table 5. ANFIS uses neural network and fuzzy inference systems for solving nonlinear complex problem through if-then rules set. The parameters can be modified using training technique based on Takagi-Sugeno model and it utilizes least squares method for modelling a trained data set. The model was constructed using five inputs (wt. % of AA6061, graphene and ZrO2) and one output (wear rate). Gaussian membership characteristic function presented in equation (1) was used to explore the distribution of each input parameter. ANFIS includes the input parameter fuzzification, implementation of fuzzy operator (AND or OR), determination of consequent rules, output distribution and defuzzification.

\[
gaussmf \left( x; \sigma, c \right) = e^{-\frac{(x-c)^2}{2\sigma^2}}
\]  

Figure 21. Fuzzy gaussian membership function.

The input—output data set of total 120 were used to form the network and the ANFIS model was trained using the data sets and gaussian membership function and simulated using the script file created in MATLAB R2020a.

3.8. Analysis of ANN and ANFIS model

The whole dataset was divided into 3 sets viz., 80% of data set for training, 10% for validation and the remaining 10% for testing purpose. The test data were evaluated based on membership function for the determination of accuracy level. The results were compared to the experimental data set using cross-correlation coefficient R² to validate the wear parameter determination quality. The process parameter effects on wear behaviour of composites were examined using a feed forward back-propagation [41–43]. The best performance of ANN structure developed and trained by Levenberg-Marquardt (LM) algorithms are illustrated in figure 22. It is evident from the graph that, the variation of the pattern for validation and test curve shows the training fairness,
resulting in best validation accuracy with the value of 3.5945 obtained at 4th epoch. The gradient value is declined monotonically with the rise of epochs and reaching close to zero at 5th epoch as depicted in figure 23.

In ANFIS model, the fuzzy linguistic input parameters were used to explore the gaussian membership functions for transforming the input values into fuzzy values. Figure 24 shows the predictive performance between experimental and predictive results. The correlation coefficient (R) for the model obtained was 0.92255 which indicates the outstanding relationship between the experimental result and network response. Figure 25 represents the error histogram with 20 bins between target values and predicted values after training a feedforward neural network. It indicates the error range between $-0.4836$ and $3.046$ in which zero error line lies between $-0.1121$ and $0.07363$ with 20 samples of training data set. Figure 26 indicates the training and checking errors between root mean square error RMSE and epoch that both are exactly coinciding with each other. So it is
Figure 24. Cross-correlation of predicted and experimental values of wear rate.

Figure 25. Error Histogram with 20 Bins.

Figure 26. Error curves between RSME and Epochs.
evident that there is no variation in training and checking function in the computing process. Figure 27 depicts the comparison between experimental and ANFIS predicted result. It indicates that the values are coinciding with each other for all data sets. So it is understood that, the predicted wear rate values for non-experimented parameters are accurate. Figure 28 depicts the comparison between experimental, ANN and ANFIS results which indicates that the ANFIS are more closer and accurate compared to ANN. The correlation coefficient ($R^2$) of ANN and sugeno-type ANFIS models are 77.9% and 99.9%, which indicates that ANFIS model predictions are more accurate. It is observed that, the predicted wear rate values for the non-experimented parameters found to be within the limit range of the experimented parameters.

### 4. Conclusion

- The inclusion of graphene and zirconia combination in AA6061 alloy strongly influenced the mechanical, microstructural and tribological characteristics. The optical and SEM examination ensured the uniform distribution of reinforced particles with base alloy.
• The hardness, tensile and impact are increases with the increase of reinforcement by 21.88%, 69.42%, 78.57% and percentage elongation is decreased by 63.52% with the increase of reinforcements.

• Wear resistance increases with the increase of reinforcements. ANN and ANFIS models predicted the wear rate for experimented and non-experimented parameters. Among the two models, Sugeno-type ANFIS predicted with accuracy of R² with 99.9%.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration of competing interest

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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