

Characterizing the effects of SiC and Al₂O₃ on the mechanical properties of Al6082 hybrid metal matrix composites: An experimental and neural network approach

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ABSTRACT

The use of advanced materials in the field of aerospace and automotive applications has led to use of metal matrix composites (MMC's) due to their excellent mechanical properties. Aluminium metal matrix composite is one of the materials which can be strengthened by reinforcing it with hard ceramic particles. In the current work Al6082 matrix hybrid composites reinforced with silicon carbide (SiC) and aluminium oxide (Al₂O₃) was developed by using stir casting technique. The weight percentage of SiC was varied from 0 wt.% to 8 wt.% and keeping 3 wt.% Al₂O₃ constants. The tensile, hardness, density and impact tests were conducted, and the results obtained revealed that the addition of silicon carbide and Al₂O₃ particles in Al6082 enhances the mechanical properties of the prepared hybrid composites. The artificial neural network (ANN) model, which was trained using a dataset consisting of experimental results, has effectively captured the correlation between the weight percentage (wt.%) of silicon carbide (SiC) and the mechanical properties of the composite material. Through the examination of this model, valuable insights can be obtained regarding the distinct contributions of SiC to the mechanical properties of Al6082.

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1. Introduction

MMCs such as space structures, deck plates, automobile and railway have critical applications in the industrial sector and invited the attention of the brake disc. About 5496 tons to 80000 tons during the period 2012 to 2019 is expected to increase global demand for MMCs, and it is constantly growing. The important feature of MMCs is the properties such as low density, better mechanical properties, thermal expansion and conductivity and high stiffness which are tailor made which enhances the performances. The reinforced particulate composites are getting much attention due to the reduction of weight for many important applications [1-4]. Metal matrix composites

(MMCs) are a type of material that merges the favourable attributes of metals with the augmented mechanical and physical features of reinforcing materials. Metal Matrix Composites (MMCs) are known to exhibit enhanced mechanical properties such as increased strength, stiffness, wear resistance, and thermal stability when ceramic reinforcements are integrated into the metal matrix. This contrasts with conventional metals which lack these desirable attributes. In recent times particulate reinforced metal matrix composites have emerged as important materials due to its characteristics and the low-cost benefits. The important reinforcements used are, mainly the carbides, oxides and nitrides. The various processing techniques have been employed to optimize the properties of the materials required for different applications [5-8]. Mixture of the metals and ceramics grow the required feature in evolving the metal matrix materials. The accumulation of the materials with high modulus and ductile property induces the material with the transitional property between matrix alloy and ceramic reinforcement. When the reinforcement phase in the composite is comprised the transfers of load to them takes place. This transfer depends on the bonding force in between matrix and the reinforcement phase and employed method of fabrication. Stir casting is one of the manufacturing techniques which provide good adhesion between reinforcement and matrix. Al6082 is one of the predominant metals in which selection of right alloy for a given application considering the various properties such as density, tensile strength, ductility, formability, weldability, wear and corrosion resistance. The variety of ceramics are used as reinforcements to aluminium alloy in there MMC's such as Al_2O_3 , TiC, TiB_2 , Al_3Zr , SiC, B_4C [9-13]. The embedded reinforcement particles in hybrid matrix composites will have better properties such as higher stiffness, better toughness lighter weight better toughness and higher wear resistance [14-18]. A frequently researched composite involves the utilization of aluminium alloy, as the matrix material, which is strengthened by the inclusion of silicon carbide (SiC) and aluminium oxide (Al_2O_3) particles. Silicon carbide (SiC) and aluminium oxide (Al_2O_3) are commonly utilized as reinforcement materials owing to their exceptional mechanical characteristics, elevated melting temperatures, and chemical inertness.

Silicon carbide (SiC) is a ceramic material that exhibits remarkable properties such as exceptional hardness, high strength, and excellent thermal conductivity. It is known for its hardness and brittleness. Additionally, it exhibits a diminished coefficient of thermal expansion, rendering it suitable for employment in conjunction with aluminium alloys. Conversely, Al_2O_3 , which is commonly referred to as alumina, exhibits elevated levels of hardness, commendable wear resistance, and exceptional electrical insulation characteristics. The material displays excellent chemical resistance and is capable of enduring elevated temperatures. Incorporating SiC and Al_2O_3 reinforcements into the Al matrix has been observed to substantially augment the composite's mechanical properties. The reinforcing elements function as agents that enhance the strength and stiffness of the composite by hindering the movement of dislocations and obstructing the propagation of cracks. In addition, the inclusion of SiC and Al_2O_3 particles enhances the composite's wear resistance and tribological characteristics, rendering it appropriate for utilization in scenarios necessitating elevated endurance and reduced friction. In addition, the inclusion of SiC and Al_2O_3 particles has the potential to impact the thermal characteristics of the composite material. The thermal conductivity of these reinforcements is exceptional, thereby facilitating the efficient dissipation of heat. The attribute in question holds significant importance in scenarios that necessitate efficient regulation of heat, such as in the context of electronic gadgets, heat sinks, and automotive constituents. The incorporation of SiC and Al_2O_3 reinforcements within Al hybrid metal matrix composites has been observed to confer a variety of advantages, such as heightened mechanical potency. The aforementioned characteristics render them appealing for diverse engineering implementations, encompassing aerospace, automotive, electronics, and thermal regulation systems. The performance attributes and impact of the composite material are subject to various factors such as the distribution, particle size, reinforcement content, and fabrication techniques. These factors require meticulous optimization to attain the intended properties [19, 20]. Artificial Neural Networks (ANNs) have been widely employed in the characterization of material properties owing to their capacity to acquire knowledge of intricate patterns and relationships from empirical data. Artificial neural network (ANN) methodologies have demonstrated their efficacy in the analysis of diverse materials, encompassing metals, polymers, ceramics, composites,

and other such substances. Researchers endeavour to develop a predictive model utilizing Artificial Neural Networks (ANNs) to effectively characterize material properties. The primary objective is to create a model that can accurately estimate material properties by considering input parameters or features [21, 22].

The current investigation centres on the examination of the mechanical characteristics of Al6082 hybrid metal matrix composites. These composites are reinforced with different wt.% of silicon carbide (SiC), in addition to a constant 3 wt.% of aluminium oxide (Al₂O₃). The composite's overall strength and ductility will be evaluated through the implementation of tensile testing. The utilization of hardness measurements can offer valuable insights into a material's capacity to withstand indentation and surface wear. The determination of a composite's stiffness and capacity to endure deformation under load can be facilitated through the utilization of tensile test measurements. Apart from the mechanical properties, the microstructure analysis will be conducted to evaluate other characteristics, such as the distribution of particles and the interfacial bonding between the matrix and reinforcements. The present analysis aims to offer valuable insights into the structural integrity of the composite material and the efficacy of the reinforcement distribution.

The primary objective of this investigation is to enhance the mechanical characteristics of a hybrid metal matrix composite by optimizing the weight proportions of SiC and Al₂O₃ in the Al6082 matrix. The outcomes of this study will enhance the comprehension of the impact of SiC and Al₂O₃ reinforcements on the efficacy of Al6082 composites. This will furnish significant insights for potential applications in industries where augmented mechanical properties hold paramount importance.

2. Materials and methods

2.1 Al 6082

The rationale behind the selection of Al6082 as the matrix material is attributed to its extensive utilization across diverse industrial sectors, owing to its exceptional amalgamation of robustness, anti-corrosive properties, and ease of weld ability. The incorporation of SiC and Al₂O₃ into Al6082 is anticipated to enhance its mechanical characteristics, including but not limited to strength, hardness, stiffness, and wear resistance. Al6082 is an alloy with manganese as the main constituent with good corrosion resistance. Al6082 produces tight coils of chips, when chip breakers are used during machining, this provides good machinability. Table 1 shows the composition of Aluminium 6082.

Table 1 Chemical composition of Al 6082 alloy [23]

Al 6082	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Al
% Composition	0.25	0.1	0.5	1.2	1.0	1.3	0.1	0.2	95.2-98.3

2.2 Aluminium oxide

Al₂O₃ is the budget-friendly and generally used material in the family of engineering ceramics. Its substantial practice is in the manufacture of aluminium metal, even though it is also used as an abrasive on account of its hardness and as a refractory material because of its high melting point. In contrast, aluminium oxide (Al₂O₃) exhibits notable characteristics such as elevated hardness, resistance to wear, and exceptional electrical insulation capabilities. Incorporating Al₂O₃ particles into the composite material can augment its wear resistance and durability. Additionally, aluminium oxide exhibits favourable thermal stability, rendering it appropriate for implementation in scenarios necessitating elevated temperature endurance [24].

2.3 Silicon carbide

Silicon carbide (SiC) is a widely recognized material for reinforcement purposes due to its exceptional mechanical characteristics, which encompass elevated strength, hardness, and thermal conductivity. The properties have the potential to augment the structural integrity and rigidity of the composite material. Moreover, SiC exhibits a diminished coefficient of thermal expansion, rendering it congruous with the aluminium alloy matrix and diminishing the probability of failures

induced by thermal mismatch. The rationale behind selecting Al6082 as the matrix material stems from its extensive application in diverse industrial sectors owing to its exceptional amalgamation of strength, resistance to corrosion. The anticipated outcome of reinforcing Al6082 with SiC and Al_2O_3 is an enhancement in its mechanical characteristics, including but not limited to strength, hardness, stiffness, and wear resistance [25].

2.4 Preparation of Al 6082 – Al_2O_3 – SiC hybrid composites

Stir casting is employed in the present investigation to fabricate aluminium hybrid metal matrix composite with Al6082 as base metal, SiC and Al_2O_3 as reinforcement material (Table 2). Initially, the particles are preheated at 300 °C – 400 °C for 2 hours to eradicate the volatile substances and the particle temperature is maintained nearer to melting temperature of about 750 °C. The pre-heating give rise to the artificial oxidation of the particle surface forming SiO_2 layer in SiC and this SiO_2 layer thus formed in turn helps in refining the wettability of the particles. Next, the Al6082 ingots were charged into the furnace and melting was allowed to continue till an even temperature of 700 °C is attained, subsequently a degassing agent (Hexachloroethane) was supplemented into the molten metal for elimination of dissolved gas to control the porosity in the cast. The melt was then permitted to cool till 600 °C to a semi-solid state. At this point, the SiC and Al_2O_3 mixture was added to the melt and manual stirring of the slurry was performed for 20 min. After the manual stirring, the composite slurry was reheated and maintained at a temperature of 700 °C $\pm$ 10 °C and then mechanical stirring was performed. The stirring was done for 10 min at an average stirring rate of 350 rpm. Finally, the molten metal at a temperature of 710 °C was then poured into the mould of diameter 25 mm and height 250 mm, which was preheated at 300 °C and then permitted to solidify [26, 27].

Table 2 Wt.% of reinforcement in Al6082

Samples	Wt.% of Al	Wt.% of SiC	Wt.% of Al_2O_3
M	100	-	-
M1	95	2	3
M2	93	4	3
M3	91	6	3
M4	89	8	3

2.5 Testing of composites

The testing of composites for density, tensile strength, hardness and impact were carried out as per ASTM standards. The density of material is evaluated using Archimedes principle. Rockwell hardness tester was employed for determining hardness. The tensile strength of the specimen prepared were evaluated using UTM of 50-ton capacity. A notched sample of Al 6082 was used to calculate the impact strength. The scanning electron microscope with a resolution of 3.0 nm at 30kV and magnification of 5X to 1000X was used to study the clear microstructure of the specimens. The specimen was highly polished by using bluffing machine and high-quality emery papers [28-34].

3. Results and discussions

3.1 Microstructural studies

The SEM micrographs of the analysed composites are depicted in Fig. 1. The micrographs presented herein offer a comprehensive depiction of the cross-sectional morphology of SiC and Al_2O_3 particles within the Al6082 matrix. The images depict microstructures that exhibit the ceramic phase of silicon carbide, displaying a range of luminosity in shades of grey. Upon analysis of the micrographs, it is evident that the microstructure layer is impacted by the composition of the composites. The microstructure layer undergoes a shift as a result of the incremental incorporation of reinforcement materials, namely SiC and Al_2O_3 , which leads to modifications in their respective percentages. The micrographs provide valuable information regarding the dispersion, shape, and interfacial properties of SiC and Al_2O_3 particles in the matrix.

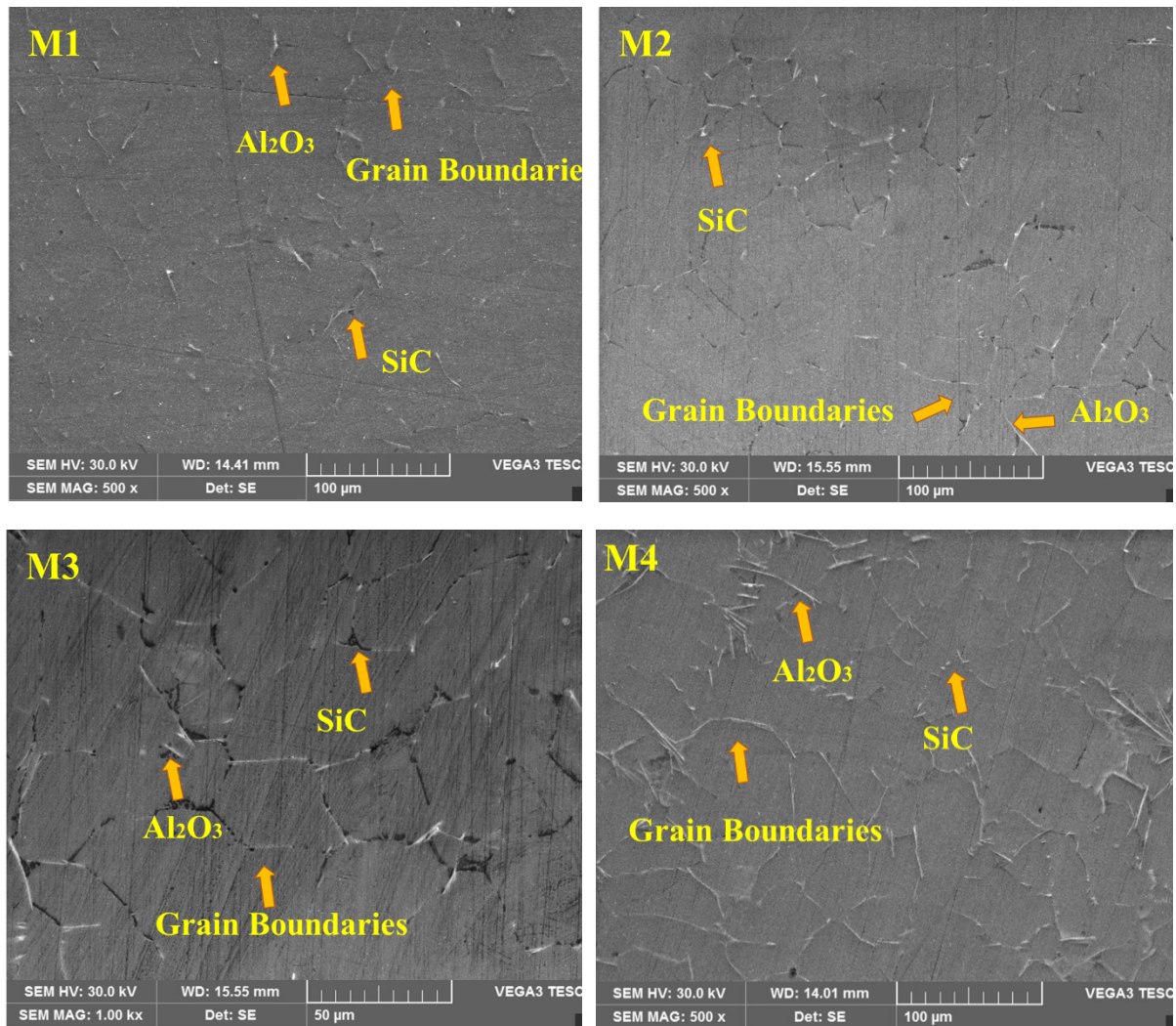


Fig. 1 SEM micrographs of the hybridized composites

3.2 Density measurement

The parameter of density holds significant importance in the examination of composite materials, as it offers valuable insights into their composition and overall performance. The present investigation aimed to examine the density fluctuations among various reinforcement material compositions (namely SiC and Al₂O₃) within the Al6082 matrix. The graphical representation depicted in Fig. 2 showcases the correlation between the density of the composites and the proportion of SiC reinforcement. The plot's results suggest that the density of the composite materials exhibits a positive correlation with the percentage of SiC reinforcement. As the silicon carbide content within the composite material is augmented, the overall density of the material is correspondingly elevated. The observation is in accordance with the established fact that SiC (3.1 g/cm³) and Al₂O₃ (3.95 g/cm³) possess a higher density in comparison to the unadulterated Al6082 matrix (2.71 g/cm³). The elevated densities of the hybrid composite specimens, in contrast to those of pure Al6082, can be ascribed to the incorporation of SiC and Al₂O₃ reinforcements. The incorporation of reinforcements with higher densities than the matrix material results in a notable elevation of the composite's overall density. This occurrence is anticipated and represents a prevalent attribute of composite materials.

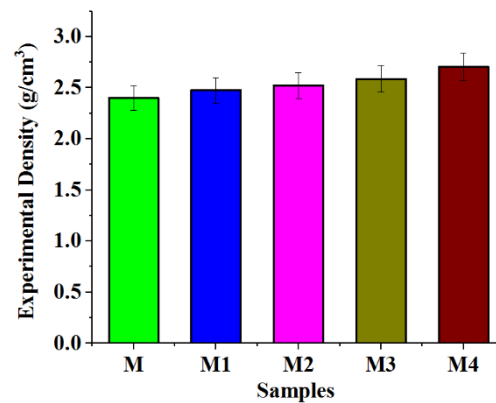


Fig. 2 Density measurement

3.3 Tensile strength

The findings depicted in Fig. 3 demonstrate that the Al6082 hybrid composite (M4) containing 3 wt.% Al₂O₃ and 8 wt.% SiC exhibits greater tensile strength in comparison to the remaining compositions. The observed enhancement in the tensile strength can be ascribed to the ceramic properties of the SiC particles and their interplay with the matrix substance. The incorporation of ceramic SiC particles is a critical factor in enhancing the strength of the composite material, because of their intrinsic high strength and hardness properties. The inclusion of SiC within the matrix of a composite material serves as a reinforcing agent, thereby augmenting its strength. The incorporation of SiC particles serves to impede the movement of dislocations and hinder the propagation of cracks, leading to an improvement in the composite's tensile strength as its entirety. The findings indicate that the Al-SiC chemical reaction leads to a slight change in silicon concentration, which in turn enhances the interfacial bonding between the matrix and SiC particles. The enhancement of interfacial bonding is a significant factor in facilitating stress transfer between the matrix and the reinforcement, thereby resulting in a rise in tensile strength. Furthermore, Fig. 4 illustrates the fluctuation of percentage elongation in relation to the SiC content. The data indicates that the percentage of elongation exhibits an initial increase, rising from 10.54 % at 0 wt.% SiC to 12.45 % at 4 wt.% SiC composition. The observed rise in elongation values suggests an enhancement in the composite's ductility. The inclusion of SiC particles has the potential to enhance the plastic deformation characteristics of a material, thereby impeding premature failure by furnishing additional energy-absorbing locations within the material.

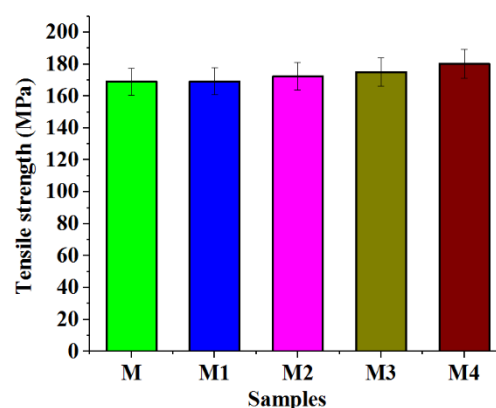


Fig. 3 Tensile strengths of samples

Nevertheless, when the SiC content is elevated to 8 wt.%, the percentage of elongation experiences a reduction to 8.16 % (M4). The observed decline in elongation indicates a reduction in the material's ductility as the concentration of SiC increases (Fig. 4). The presence of a greater amount of SiC may result in an increased number of stress concentration sites, thereby restricting the material's capacity to undergo plastic deformation and elongation. The incorporation of SiC and Al₂O₃ reinforcements into the Al6082 matrix results in an enhancement of the material's tensile

strength. The utilization of SiC particles in ceramic form leads to an improvement in the interfacial bonding with the matrix, thereby causing a rise in the tensile strength. The percentage of elongation exhibits an initial increase as the SiC content is augmented, thereby signifying an enhancement in ductility. However, at elevated SiC concentrations, the percentage of elongation experiences a decline. The discoveries underscore the intricate correlation among reinforcement content, interfacial bonding, and mechanical characteristics, underscoring the necessity for meticulous optimization of composite composition to achieve the intended performance.

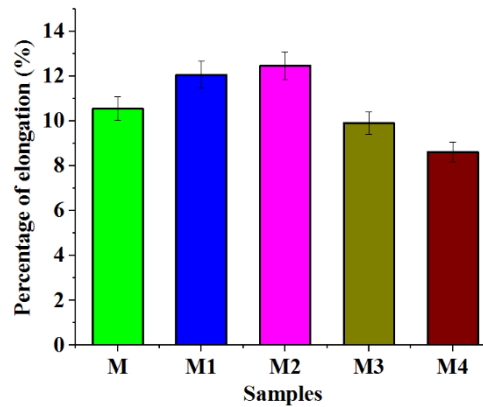


Fig. 4 Percentage of elongation of samples

3.4 Impact Strength

The findings illustrated in Fig. 5 indicate that the impact strength of Al6082 hybrid composites exhibited fluctuations in response to the varying proportions of SiC and Al₂O₃ reinforcements. The impact strength values pertaining to various compositions are presented as follows: The interfacial shear strength values for SiC concentrations of 2 wt.%, 4 wt.%, 6 wt.%, and 8 wt.% were found to be 30.2 N/m, 36.5 N/m, 40.3 N/m, and 46.9 N/m, respectively. These values were obtained while maintaining a constant 3 % Al₂O₃ content. The graphical representation unambiguously demonstrates that the impact strength of the composite material reinforced with 8 wt.% silicon carbide and 3 wt.% aluminium oxide was superior in comparison to the composite material reinforced with 2 wt.% silicon carbide and 3 wt.% aluminium oxide. The observation implies that the augmentation of SiC content has a beneficial effect on the impact strength of the hybrid composite. The enhanced impact strength of Al6082 can be ascribed to the incorporation of SiC and Al₂O₃ reinforcements into its matrix. Ceramic materials such as SiC and Al₂O₃ exhibit exceptional hardness and strength characteristics. Upon integration into the matrix, these entities function as fortifying agents and facilitate the prevention of crack propagation under conditions of impact loading.

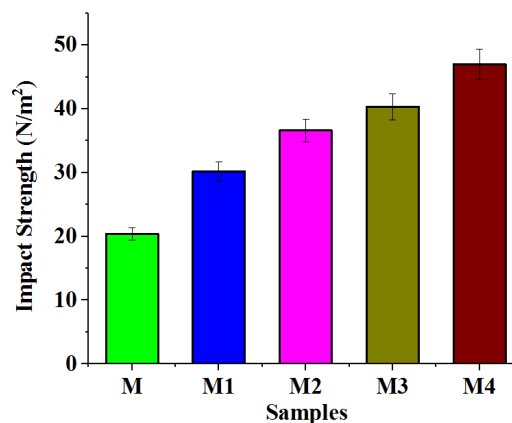


Fig. 5 Impact Strength of samples

The enhanced impact strength of the composite containing 8 weight percent SiC and 3 wt.% of Al₂O₃, in comparison to the composite comprising 2 wt.% of SiC and 3 wt.% of Al₂O₃, can be ascribed to the amplified volume fraction and dispersion of the reinforcing particles. An increase in the SiC content leads to a greater number of reinforcing particles that hinder the propagation of cracks, thereby enhancing the material's impact resistance. Furthermore, it is noteworthy that the hybrid composite specimens exhibit greater impact strength in comparison to the pure Al6082. The incorporation of SiC and Al₂O₃ reinforcements into the composite material presents a noteworthy benefit in terms of enhancing its impact strength. The data suggests that the hybrid composite material exhibits enhanced energy absorption and impact load resistance, rendering it a viable option for scenarios where impact resistance is of paramount importance.

3.5 Hardness test

As depicted in Fig. 6, it is evident that the hardness value of pure Al6082 is comparatively low. The present study reveals that there is an increase in the hardness value of hybrid composites with varying compositions of SiC and Al₂O₃. The composite containing 8 wt.% SiC and 3 % Al₂O₃ exhibits a greater hardness value in comparison to the composite containing 2 wt.% SiC and 3 % Al₂O₃. The observed trend suggests that the incorporation of SiC and Al₂O₃ reinforcements results in an augmentation of the hardness of the Al6082 matrix. The inclusion of SiC and Al₂O₃, which are classified as ceramic materials, exerts a substantial impact on the hardness characteristics of the composite. The composite material containing 8 wt.% of silicon carbide (SiC) and 3 wt.% of aluminium oxide (Al₂O₃) exhibits greater hardness in comparison to the composite material containing 2 wt.% of SiC and 3 wt.% of Al₂O₃. The present study's results indicate that an elevated SiC reinforcement content correlates with a rise in the hardness of the hybrid composite. The augmented level of hardness can be ascribed to the existence of the ceramic phase within the matrix alloy. The introduction of SiC and Al₂O₃ reinforcements results in a modification of the microstructure of the composite material. The ceramic particles function as reinforcing agents by impeding the movement of dislocations and offering supplementary resistance to plastic deformation. This phenomenon is a contributing factor to the overall augmentation in hardness. The composite material comprising Al6082 metal exhibits enhanced strength characteristics when reinforced with 8 wt.% SiC and 3 wt.% Al₂O₃. The observed phenomenon can be ascribed to the rising proportion of the ceramic phase present in the matrix alloy. The composite material's augmented hardness and strength render it appropriate for utilization in scenarios that necessitate enhanced mechanical properties and resilience against deformation.

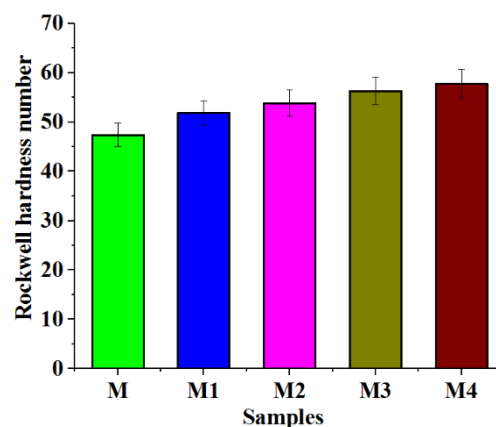


Fig. 6 Rockwell hardness number of samples

4. Mechanical property characterization of hybrid composites using artificial neural networks (ANN)

Artificial Neural Networks (ANNs) are a computational model that draws inspiration from the structural and functional characteristics of the human brain. Artificial neural networks (ANNs) are extensively employed in the field of machine learning and have demonstrated their efficacy in

addressing intricate challenges across diverse domains such as image and speech recognition, natural language processing, and data analysis. Artificial neural networks (Fig. 7) consist of interconnected nodes referred to as artificial neurons or perceptrons. The neurons within the system are arranged in a hierarchical structure, consisting of distinct layers, namely the input layer, one or more hidden layers, and the output layer. The input layer is responsible for receiving the input data, which undergoes processing and transformation as it traverses through the hidden layers. Ultimately, the output layer generates the intended output or prediction. Every individual neuron within an Artificial Neural Network (ANN) is responsible for receiving input signals, undergoing a specific transformation process, and subsequently generating an output signal. In the typical scenario, the inputs are subjected to a process of weighting, wherein each input is multiplied by an associated weight value. Subsequently, the neuron performs a computation by aggregating the weighted sum of its inputs and subsequently applying an activation function to ascertain its output. The utilization of an activation function in the model introduces non-linearity, thereby facilitating the acquisition of intricate patterns and relationships within the dataset. Training an artificial neural network (ANN) entails the utilization of a technique known as backpropagation. This technique facilitates the adjustment of neuron weights by considering the discrepancies between the predicted output and the observed output. The iterative process persists until the performance of the model attains a level that can be considered satisfactory. Artificial neural networks (ANNs) offer a robust framework for constructing intelligent systems capable of emulating specific facets of human cognition. This capability empowers machines to execute intricate tasks and generate precise predictions by leveraging available data.

The experimental and artificial neural network (ANN) prediction plots of all samples with density and UTS are depicted in Fig. 8 indicates that there is a reasonable level of concurrence between the outcomes obtained from the experiment and those derived from the artificial neural network (ANN). The Artificial Neural Network (ANN) was utilized to forecast the density and UTS phenomenon via comparison with experimental outcomes. The results indicated a favourable match with a regression coefficient of $R^2 = 0.974$ & 0.988 (as shown in Fig. 9) and a relative error of 0.003.

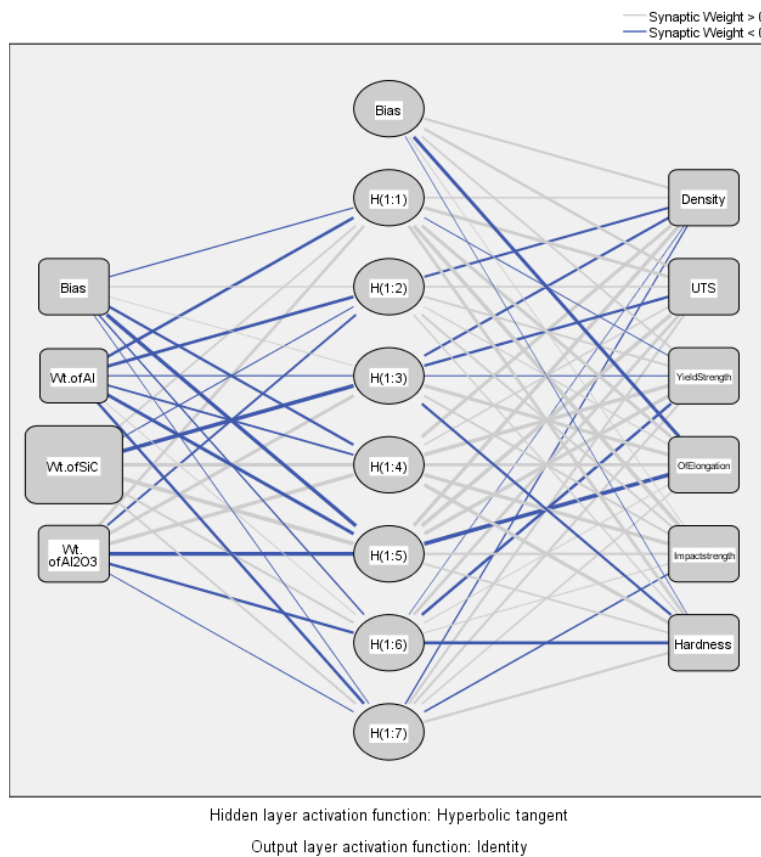


Fig. 7 ANN architecture

The experiment and artificial neural network (ANN) prediction plots of all sample with impact strength and hardness are depicted in Fig. 9. illustrates that the empirical findings are in concurrence with the artificial neural network (ANN) outcomes. The Artificial Neural Network (ANN) was utilized to forecast the impact strength and hardness phenomenon by means of a comparative analysis with experimental outcomes. The results of this analysis demonstrated a strong correlation with a regression coefficient of $R^2 = 0.941$, as depicted in Fig. 10 and a relative error of 0.050.

Based on the findings presented in Fig. 10, it can be concluded that the wt.% of SiC holds the highest degree of influence among the composition. The Artificial Neural Network (ANN) was utilized to forecast the mechanical properties phenomenon through a comparative analysis with experimental outcomes.

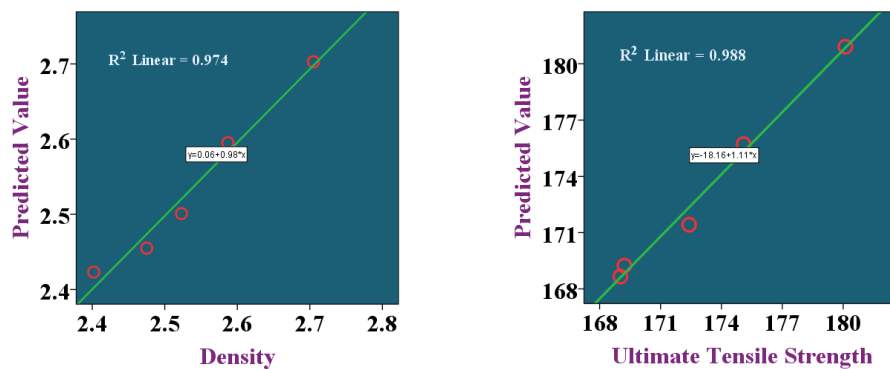


Fig. 8 Experimental vs. predicted values of the samples.

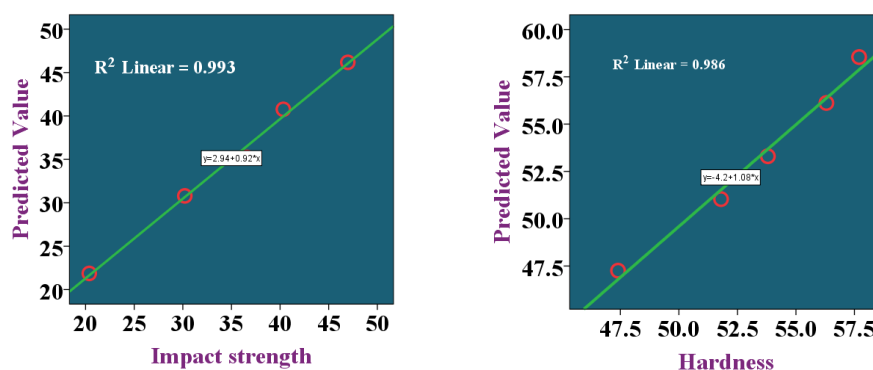


Fig. 9 Experimental vs. predicted values of the samples

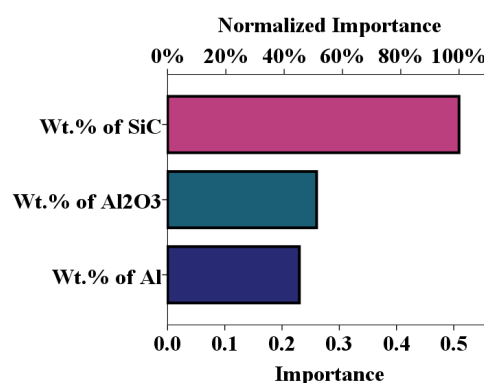


Fig. 10 Normalized factor importance

5. Conclusions

In the current study, Al₆₀₈₂/SiC/Al₂O₃ nanocomposites obtained by the method of stir-casting and the impact of nano-Al₂O₃ and nano-SiC particle on mechanical properties of the MMCs were investigated. The conclusions could be concised as follows.

- The experimental density values improved with the rise in proportion of SiC particles as reinforcement.
- The increase in wt. % of SiC enhanced tensile and impact strength of all the casted composite materials.
- The increment in weight percentage of SiC by keeping the load constant of 100 kg improved the hardness. The extreme hardness value was observed with the composites having 8 % wt. of SiC, while the minimum was seen in the composites having 2 % wt. of SiC.
- From the SEM analysis we observed that SiC and Alumina was uniformly distributed in Al6082 metal matrix.
- The implementation of Artificial Neural Network (ANN) analysis has provided confirmation that the weight percentage (wt.%) of silicon carbide (SiC) plays a substantial role in the observed improvement of mechanical properties in Al6082 alloy.

Thus, the experimental results clearly indicate that the Al6082 properties gets better with rise in the weight percentage of SiC reinforcement. Therefore, the integration of SiC and Al₂O₃ in Al6082 produces improved outcomes than pure Al6082.

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