

Role of Alloying Elements as Reinforcements during Fabrication of Aluminium Metal Matrix Composites

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ABSTRACT

The introduction of alloying elements into steel significantly improves their properties. In this study, an attempt has been made to use alloying elements as reinforcements in Aluminium Metal Matrix Composites (AMMCs). For this purpose, aluminium (LM 25) matrix based MMCs have been developed using stir casting. The composition of the SiC (primary reinforcement) was maintained constant (10 wt. %) in all composite castings, whereas the compositions of the alloying elements (as secondary reinforcements) such as nickel (0, 5 and 10 wt. %), molybdenum (0, 2 and 4 wt. %) and chromium (0, 1.5 and 3 wt. %) were varied and composites were synthesized as per L9 orthogonal array. The microhardness, tensile strength, wear behaviour, scratch hardness and porosity levels of the newly developed composites were determined according to ASTM standards to explore the effect of the type and composition of the particulate reinforcements. A metallographic study was performed using scanning electron microscope (SEM), energy dispersive X-ray spectroscopy (EDS), X-Ray diffraction analysis (XRD) and Optical Microscopy (OM) analyses. Optimization of the composition of secondary reinforcements (viz. Ni, Mo and Cr elements) was performed with the help of Taguchi approach and Grey Relational Analysis (GRA) and a composite containing an optimum value of each property were identified. The results revealed that the composites containing a mixture of secondary reinforcements, several secondary phases were observed, which had a harmful effect on the composite properties. In addition, the reinforcements were scattered throughout the aluminium matrix. The results of GRA shows that a nickel composition of 5% together with 10% SiC, without using molybdenum and chromium is an optimum composition for secondary reinforcements to develop AMMCs.

1. INTRODUCTION

Almost all the materials used to manufacture automobile and aerospace components are being assessed, and the need for lightweight materials is increasing. Light materials such as aluminium, magnesium, and copper have some limitations that restrict their use in many high wear-resistant applications. To overcome these limitations, strong and lightweight composites have been developed by introducing hard reinforcement materials into the base matrix materials. Composites are formed with a mixture of at least two materials with dissimilar properties, in which one is a matrix material and the other is a reinforcement material. However, mixing of the constituents does not occur at the atomic or molecular level [1,2]. Constituent materials in composites retain their microstructures and microscopic properties and do not entirely dissolve in one another. The benefits of using composite materials are light weight, high strength/weight ratio, low TEC, high elastic modulus, corrosion resistance, thermal conductivity, and wear resistance [3,4].

Aluminium and its alloys have many applications in areas such as cooking utensils, automobile bodies, engine components, electrical wires and cables. However, poor hardness, strength, and wear resistance restrict its use in many industrial applications, where wear of material is the predominant factor. The addition of reinforcing materials to the matrix alloy is an effective solution to overcome these limitations. Therefore, it is essential to develop aluminium-based lightweight composites with better mechanical and tribological properties [5-7].

In the last decade, the demand for aluminium matrix composites has increased in the automobile and aerospace industries. Composite materials are formed to combine the favorable characteristics of various materials. Aluminium-based MMCs possess many advantages over aluminium or its alloys, polymer, or ceramic matrix composites. These advantages include high transverse and specific strengths, wear resistance, toughness, good damping properties, and improved ductility. Composites are used in the electrical and electronic industries because of their superior heat and thermal properties [8,9]. Aluminium matrix composites are also used in

the electronic industry owing to their low thermal expansion coefficient [10].

Aluminium matrix composites (AMCs) combine at least two physically and chemically distinct materials: aluminium or its alloy and reinforcing materials such as SiC, B₄C, alumina, graphite, and tungsten. Reinforcements, generally used in AMCs, may be continuous or discontinuous particles, whiskers, or fibers. Nowadays, AMCs are preferred in industrial applications because of their high strength-to-weight ratio, minimum cost, easy accessibility, low density, high resistance against corrosion, and low processing temperature [11]. Moreover, single ceramic/metallic reinforcing AMCs may also have deteriorating effects on several properties such as ductility, toughness and stiffness [12]. These limitations can be avoided using two or more reinforcing materials. Composites constituting at least three materials are known as hybrid aluminium matrix composites (HAMCs). These materials have improved “strength-to-weight ratios, toughness, low temperature sensitivity, high wettability, and machinability. Consequently, HAMCs have numerous applications in aerospace and automotive components” [13].

Different types of composite formulation processes such as solid state-casting processes (friction stir processing, powder metallurgy, etc.), liquid-state casting processes (stir casting, ultrasonic cavitation, pressure/pressureless infiltration, spray forming, etc.), semisolid state casting processes (thixoforming) and in-situ processes have been used by various researchers. [14,15]. However, the liquid-state casting process especially stir casting process is the simplest technique with the lowest production cost and is suitable for mass production [16]. Moreover, it is the most suitable technique for developing aluminium metal matrix composites, especially hybrid aluminium matrix composites. A large casting of upto 500 kg can be produced via a single route using this process. Therefore, it is a widely used fabricating aluminium-matrix composites. In this process, the reinforcement(s) are combined with the molten metal/alloy and mechanically stirred under precise conditions [17].

Grey relational analysis is a multiple criteria decision-making technique that is used to

optimize multi-objective optimization problems. In this approach, all responses are converted into grey relational grades (GRG) which are further optimized using the Taguchi approach. GRA was successfully used to optimize the process parameters of cylindrical grinding and electric discharge machining. The consequences obtained through this route indicate process improvement [18,19]. Mitra et al. [19] evaluated the output parameters of the ECM of AMCs using the GRA technique. Garg et al. [20] successfully explored the impact of ECM process parameters on the responses using this technique. Wei Bing et al. [21] used this technique for the multiple response optimization of heating system schemes. Mitra and Kumar [22] and Kolhapure et al. [23] geometrically optimized the "strain gauge force transducer" using the same route and obtained fruitful results using this technique.

In this investigation, AMMCs were fabricated through liquid vortex casting to explore the impact of the addition of secondary reinforcements (alloying elements such as Ni, Mo, and Cr) in the base Al-SiC composite. For comparison purposes, the weight percent of the SiC was fixed, while the weight percent of the secondary reinforcements was varied, and a total of nine composites were fabricated according to the L9 orthogonal array and characterized according to ASTM standards. Optimization of the composition of the secondary reinforcements was also carried out using the Taguchi approach and Gray Relational Analysis.

2. MATERIALS AND METHODS

2.1 Materials

The reinforcement affects the characteristics of the base aluminium alloys in their ways. Therefore, the selection of appropriate reinforcement materials for a particular aluminium alloy is a complex task for researchers. In this study, AMMCs were developed to evaluate the influence of the

reinforcement content on the properties of the base aluminium alloy.

2.1.1 Matrix Material

In this study, an aluminium-silicon alloy purchased from S.S. Moulding Industries, Jagadhari, Haryana, India was chosen as the base matrix. The selected aluminium-silicon alloy and its composites possess many applications in automobile parts like "pistons, engine blocks, piston rings, connecting rod, brake disc," etc., where high wear resistance and strength/weight ratio is required [24-26]. The SEM and optical micrograph of the base aluminium alloy showed a dendritic structure as shown in Fig. 1.

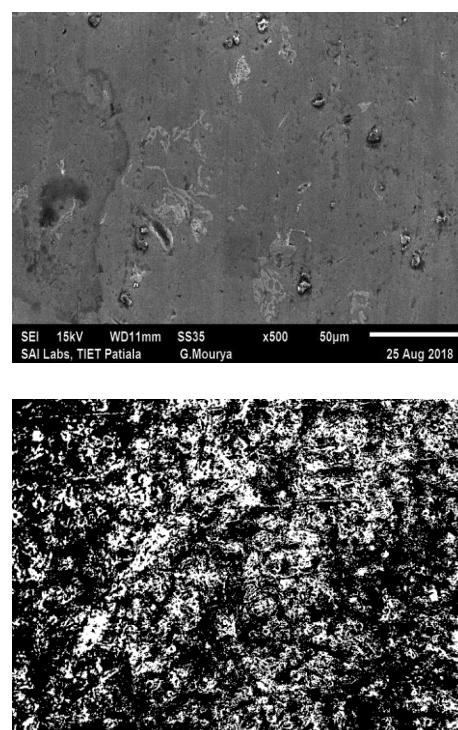


Fig. 1. SEM and Optical Micrograph of the base Al (LM25) alloy.

The composition of the base aluminium alloy was determined using a spark spectrometric analyzer according to the ASTM: E 1251-11 standard [27]. Table 1 lists the composition of the aluminium alloy.

Table 1. Chemical composition of aluminium-silicon alloy.

Element	Al	Si	Mg	Cu	Fe	Mn	Zn	Ti	Cr	Ni	Pb
Wt.%	85.1	10.3	0.261	1.87	0.980	0.134	0.951	0.040	0.0247	0.096	0.058
Element	Be	Ca	Sn	Ga	Cd	Ag	V	Bi	Zr	In	Hg
Wt.%	0.0001	0.001	0.0391	0.0119	0.001	0.0022	0.0058	0.005	0.0076	0.01	0.003

2.1.2 Primary reinforcing Material (Silicon Carbide)

Silicon carbide (SiC) is a very hard and light ceramic material that can withstand high temperature owing to its tetrahedral structure.

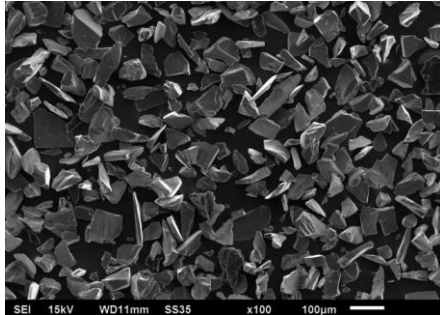


Fig. 2. SEM image of the primary reinforcing material (SiC powder).

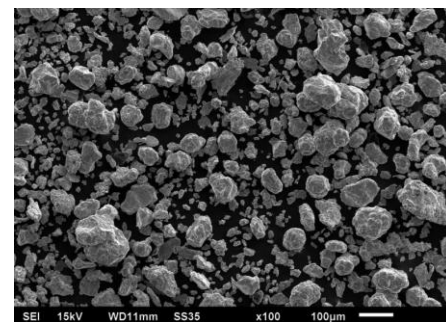
Therefore, in this study, a chemically pure green to bluish-black fine silicon carbide, supplied by “S.D. Fine-Chem Limited Mumbai, Maharashtra, India”, was chosen as the primary reinforcing material and its composition was kept constant (10% by weight) for all composites. Fig. 2 shows the SEM image of the SiC powder taken at 100x magnification.

2.1.3 Secondary Reinforcing Materials

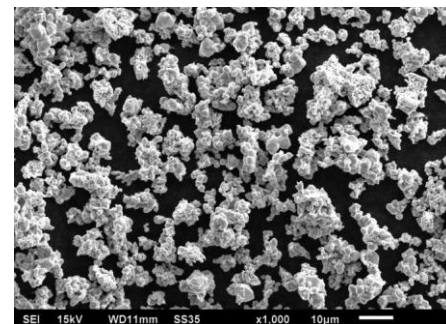
Nickel (Ni) materials possess excellent corrosion resistance even at high temperature, good electrical and thermal conductivity [28], high hardness and strength. Based on these characteristics, Ni has been used to strengthen many alloys. When nickel is added to an aluminium matrix, it retains its ductility and improves its properties [29,30]. Ni is a transition metal group of materials. Molybdenum is used as an alloying element in certain steel grades and its properties are significantly improved. It possesses the highest melting point among the pure elements after tungsten and tantalum. Molybdenum, when added to aluminium or its alloys enhances ductility [31]. Therefore, molybdenum was selected as a secondary reinforcement to investigate its influence on the properties of the base Al-SiC composite. Chromium is a lustrous, hard, and brittle metal that hardens steel when used as an alloying element. It is also used in stainless steel to make it rust-free. The use of chromium as a reinforcement material in AMMCs may improve

their properties, but a limited study in this area has hitherto been reported.

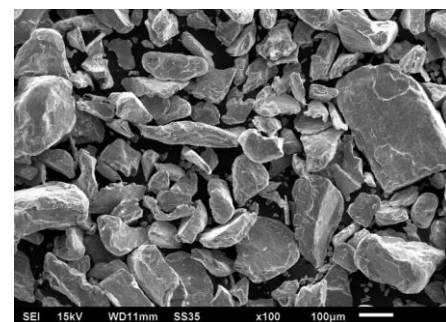
Considering this, Ni, Mo, and Cr were selected as secondary reinforcing materials and their SEM images are shown in Fig. 3. Nickel was purchased in the form of greyish black powder containing 99.5% purity from “LOBA Chemie Pvt. Ltd. Mumbai, Maharashtra, India”. Silver-gray metallic chromium powder (99% purity) and gray molybdenum (99.9% purity) were purchased from “S.D. Fine-Chem Limited Mumbai, Maharashtra, India”. The weight percentages of the reinforcing materials varied during the stir casting.



Ni



Mo



Cr

Fig. 3. SEM images of secondary reinforcing materials (Ni, Mo and Cr powders).

The characteristics of the ingredients used in the aluminium-metal matrix composites are listed in Table 2.

Table 2. Properties of the ingredients used in AMCs.

Property	Approximate values				
	Al alloy	SiC powder	Ni powder	Mo powder	Cr powder
Average particle size	-	67 μm	64 μm	74 μm	72 μm
Density	2.685 g/cm ³	3.21 g/cm ³	8.9 g/cm ³	10.89 g/cm ³	7.12 g/cm ³
Melting point	650oC	2730oC	1453oC	2617oC	1907oC
Tensile strength	174 MPa	230 MPa	345 MPa	485 MPa	370 MPa
Hardness on mohs scale	2.75	9	4	5.5	8.5

Magnesium (Mg) is the most soluble material in aluminium after zinc. This material has the ability to improve wettability and strengthen metallurgical bonding between the constituents of AMCs [12,32]. However, high Mg content may have a negative effect on the properties of AMCs. Therefore, Mg in the form of silvery white powder (density 1.74g/cm³), was also used in this study. It was purchased from LOBA Chemie Pvt. Ltd. Mumbai, Maharashtra, India, and However, the composition of Mg was kept constant (1% by weight) in all the aluminium matrix composites.

2.2 Fabrication of Composites

Aluminium-based MMCs were fabricated using a liquid-vortex process (stir-casting). The weight percent of SiC was fixed (10% by weight), while composition of the nickel (0, 5, and 10% by weight), molybdenum (0, 2, and 4% by weight) and chromium (0, 1.5, and 3% by weight) were varied according to Taguchi's L₉ orthogonal as shown in Table 4. This study aims to explore the combined effect of secondary reinforcements on composite properties such as microhardness, tensile strength, elongation, wear rate, friction coefficient, porosity and traction force of the base composite. Table 3 lists the reinforcing materials and their weight percentage used in this study.

Liquid vortex casting is simple, less expensive, and economically used to develop AMCs, particularly hybrid composites [33]. Fig. 4 shows the setup used to fabricate the AMMCs. The weights of aluminium, silicon carbide, nickel, chromium, molybdenum, and magnesium were calculated according to the charge calculations. The required quantitative amount of the constituting elements was measured using a precise weighing machine with the minimum least count of 0.05 mg. the reinforcements were

made moisture free by preheating them at approximately 200 °C. The matrix was melted at 630±20 °C in a ceramic crucible in an electric furnace. The temperature of the furnace was then lowered to the semi-solid form of the melt and stirred slowly with a graphite stirrer.

Table 3. The contents of the Secondary Reinforcement Contents as per L₉ Orthogonal Array.

Casting No.	Variation of secondary reinforcements together with 10% SiC		
	Ni wt. %	Mo .wt. %	Cr wt. %
1	0	0	0
2	0	2	1.5
3	0	4	3
4	5	0	1.5
5	5	2	3
6	5	4	0
7	10	0	3
8	10	2	0
9	10	4	1.5



Fig. 4. Stir Casting Setup used for Composite Casting.

The required amounts of the preheated reinforcements were poured into the melt and stirred for 10-12 minutes at a speed of 400 ± 20 rpm. A continuous inert gas environment was maintained around the molten surface to prevent atmospheric contamination. Instantaneously, the mild steel mould was heated to 250°C in a separate furnace. Subsequently, the semi-solid slurry was discharged into the M.S. mold. After solidification, the test specimens were obtained from the defect-free region of the castings using the wire-EDM process, and testing was performed according to different ASTM standards.

2.3 Testing of composites

Characterization is an important part of the development of composite materials, as it ensures the suitability of the newly developed material for a particular application. Characterization refers to determining the properties, microstructural behaviour and additional compounds formation within the composite resulting from internal reactions. After fabrication, the samples were prepared with wire-EDM according to ASTM standards such as ASTM-G99, ASTM-384, ASTM-1624, and ASTM-E8. Samples were then tested according to the advanced testing methods like "SEM, XRD, EDS, OM, microhardness test, tensile test, wear test, scratch test and porosity analysis" and the results are presented. Therefore, the characterization of the newly developed composites was performed as per various ASTM standards with the help of advanced testing techniques and the procedure is explained as under:

2.3.1 Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS)

The newly developed AMCs were composed of a light aluminium matrix, in which dense reinforcement particles were introduced. Owing to the density difference between the constituents, regular dispersion of the reinforcing phase within the aluminium matrix is a significant challenge. The irregular distribution of the reinforcements harms the composite properties. Therefore, a study of the reinforcement dispersion in the base matrix is required. Keeping in view of this, SEM and EDS of the newly developed AMCs were performed to

ensure the existence and distribution of the reinforcing constituents within the aluminium matrix. A scanning electron microscope attached to an energy dispersive spectroscope (JEOL-JSM 6510), was used. The samples were taken from the central part of the casting for analysis and mounted using epoxy resins according to the ASTM E3-11 standard. The samples were polished using different grade emery papers and alumina paste. The polished specimens were etched with Keller's reagent "(Hydrofluoric Acid-2 ml, Hydrochloric Acid-3 ml, Nitric Acid-5 ml, and Distilled Water-190 ml)" according to the ASTM 407-07 standard before scanning, and images were taken at different magnifications.

2.3.2 X-Ray Diffraction (XRD) Analysis

Aluminium matrix composites were developed using the liquid-state stir-casting technique. Because the base matrix was in a molten state during fabrication, there was a possibility of internal reactions among the constituents. These interfacial reactions may cause the formation of unwanted compounds, which can have a deleterious effect on composite properties. Therefore, a study of compound formation within the composite is required. Keeping in view of this, the XRD analysis was performed to predict the formation of unwanted compounds resulting from the internal reaction between the constituents during the fabrication. The XRD samples ($10 \times 10 \times 5$ mm) were removed from the defect-free region of each newly developed composite. The samples were cut using the wire-EDM process with aluminium wire electrodes having 0.25 mm diameter. The surfaces of selected sample were cleaned and analyzed using an "XPRT-PRO diffractometer system" in which the angle- 2θ was varied from 20 to 100°C .

2.3.3 Optical Microscopy (OM)

The microstructure is an important property of a material, which significantly affects its properties. Therefore, a study of the microstructural behaviour of a newly developed composite in terms of morphology and material properties is needed. The Optical Microscopy (OM) of the newly developed AMCs was performed to analyze their microstructural behaviour. An "image analyzer integrated optical microscope" was used for this purpose and images were taken at different magnifications.

2.3.4 Microhardness Test

Hardness is an important property of a material, which concerns its ability to resist scratching, penetration or indentation on its surface. It plays an important role in many sectors where the material wear is a predominant factor. For this purpose, a hardness test of all newly developed composite casting was performed. The procedure adopted for microhardness testing conforms with the ASTM E384 standards, which refer to static indentations made with a specific load.



Fig. 5. Image of the Square-base Pyramid Indenter, Vicker Hardness Tester, and indentation made on the specimen after testing.

Fig. 5 shows a square-based diamond pyramid having a cone angle of 136° is penetrated against the flat surface (and the length of diagonals of

square indentation made on the surface in mm is measured using a precision microscope. The testing is performed at an average load of 300 g applied for 15 sec with the help of the Knoop/Vicker hardness tester Model: 402MVD as shown in Fig. 5).

The microhardness in Vicker hardness is calculated according to Equation 1.

$$HV = \frac{2F \sin \frac{136^\circ}{2}}{D^2} = 1.854 \frac{F}{D^2} \text{ kgf/mm}^2 \quad (1)$$

Where 'F' represents the load in kgf, 'D' is the arithmetic mean of the length of two diagonals (d1 and d2) of the square formed on the specimen as shown in Figure 3.10.

2.3.5 Tensile Test

Tensile strength is the ability of a material to withstand high tensile loads without fracture. It is an essential property of the material that determines the suitability of the material for particular applications. In aluminium matrix composites, the variation in tensile strength and elongation depends on the type, size and composition of the reinforcement material and the fabrication technique used. Therefore, a study of the tensile strength and elongation of newly developed aluminium matrix composites is required.

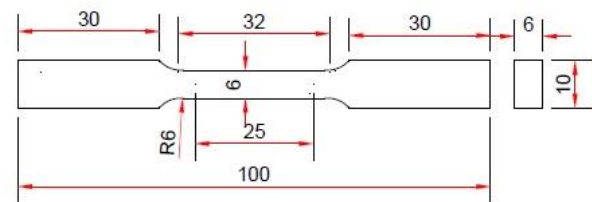


Fig. 6. Standard dimensions of a Tensile Test specimen.

For this purpose, tensile tests were conducted on samples with standard dimensions as per ASTM-E8-M09 standards, as shown in Figure 6. A twin-column tensile tester was used to perform the tensile tests. To evaluate the strength of each composite, the load applied by the specimen before fracture was noted, and the ultimate tensile strength was calculated using Equation 2.

$$UTS = \frac{\text{Tensile load applied before fracture}}{\text{Original cross-section area}} \quad (2)$$

The percentage elongation of the gauge length after each test was calculated using Equation 3.

$$\text{Elongation \%} = \frac{(L_f - L_i)}{L_i} * 100 \quad (3)$$

where 'Li' represents “the initial gauge length” before the loading and 'Lf' represents “the final gauge length” after a fracture. The strain rate was calculated using Equation 4.

$$\text{Strain rate} = \frac{(L_f - L_i)}{L_i * t} \quad (4)$$

where '(Lf-Li)' represents the change in the length of specimen after fracture at time t during tensile testing. The strain rate used for the tensile testing was 3.323x10⁻⁴/s.

2.3.6 Wear Test

Wear resistance is an important property of materials that ensures the suitability of the materials in many applications, where the wear of the materials is a predominant factor. Therefore, dry wear tests were conducted on all aluminium matrix composites using a pin-on-disc wear tester, and the wear behaviour was analyzed at room temperature.



Fig. 7. Image of Pin-on-Disc Wear Tester.

Cylindrical samples with a diameter of 10 mm and a length of 30 mm were taken from each casting as per the ASTM-G99-95a standard.

Figure 7 shows the setup of the pin-on-disc wear tester used to analyze the wear behaviour of the newly developed aluminium matrix composites. A metallic disc (EN31) turned at 300 rpm was used as the counter surface. The test sample was made to slide on a disc with a track diameter of 70 mm, and velocity of 1.099 m/s for 2 min. The 1N load was applied during sliding for a distance sliding of 980 m. The reduction in specimen length was noted, and the volume of material removed in unit time was calculated, according to Equation 5.

$$\text{Wear rate} = \frac{\frac{\pi}{4} * d^2 * l_p}{t_w} \text{ mm}^3/\text{min} \quad (5)$$

Where 'd' represents the test pin diameter in millimeters, 'lp' represents a reduction in the linear length of the pin in millimeters and 'tw' represents the time of wear testing one sample in a minute. During testing, the friction force was also recorded, and the value of the friction coefficient (μ) was calculated using Equation 6.

$$\mu = \frac{\text{Friction Force}}{\text{Normal applied load}} \quad (6)$$

2.3.7 Scratch Test

A scratch test was used to determine the surface hardness of the material. To compare the newly developed AMCs, scratch adhesion tests were performed on all composites according to the “ASTM C-1624 standard,” and the tangential force required to make a track was recorded. The sample surface was cleaned, smoothened, and flattened before testing. Three scratch tests per sample were performed and their average was taken to maintain accuracy. The specifications of the scratch tests are listed in Table 4. The scratch adhesion tester setup used in this study is illustrated in Fig. 8. The ratio of the traction force to the normal load is known as “the apparent coefficient of abrasive friction (μ_a)”.

Table 4. Parameters for Scratch Adhesion Test.

No.	Parameter	Value
1	Starting load	20 N
2	Finishing load	20 N
3	Stroke length	10 mm
4	Scratching velocity	0.1 mm/sec
5	Scratch offset	1 mm
6	No of scratches/ sample	03



Fig. 8. Image of a Scratch Tester.

2.3.8 Density and Porosity Analysis

The porosity of the composite determines the effectiveness of the fabrication method. The increase in porosity level is due to the presence of air bubbles in aluminium melts, size and percentage contribution of reinforcements, gas entrapment during mixing particles, shrinkage during solidification, hydrogen evolution of water vapor on the particle surface, poor wettability, cluster formation, etc. [34,35,36]. The analysis aimed to determine the porosity levels of the newly developed composites. The actual density of the AMCs was determined based on Archimedes' principle using the Mettler Toledo apparatus and calculations were performed as per Equation 7.

$$\rho_a = \left(\frac{m_a}{m_a - m_w} \right) \cdot \rho_w \quad (7)$$

Where: m_a mass of the sample in air, m_w mass of a sample in water and ρ_w density of distilled water (0.998 g/cm^3 at 20°C).

The theoretical densities of the AMMCs were calculated according to the rule of mixtures. Equation 8 represents the details below.

$$\rho_t = \rho_{Al} \cdot W_{Al} + \rho_{SiC} \cdot W_{SiC} + \rho_{Ni} \cdot W_{Ni} + \rho_{Mo} \cdot W_{Mo} + \rho_{Cr} \cdot W_{Cr} \quad (8)$$

Where ρ represents the density and W represents the weight fraction of each constituent of AMCs.

Then after, the porosity level in each composite is estimated using Equation 9.

$$\text{Porosity Level (\%)} = \left(\frac{\rho_t - \rho_a}{\rho_t} \right) \cdot 100 \quad (9)$$

2.4 Multiple Objective Optimizations

Multiple objective optimizations simultaneously involve the optimization of more than one objective function. This is an important tool for solving problems with a number of solutions and choosing the best solution among all alternative solutions. The Taguchi approach is an important tool for reducing the number of trials with accuracy within acceptable limits. However, this technique is only suitable for a single objective function. Whenever there is more than one objective, multiple decision-making techniques are an excellent solution and grey relational analysis is one of them. The optimization techniques used for optimizing reinforcing materials in AMCs are mentioned as follows:

2.4.1 Taguchi Approach

Taguchi design or an orthogonal array is a fractional factorial-based powerful tool used to reduce the number of trials. This approach is used to determine that out of nickel, molybdenum and chromium materials, which material is the most predominating factor for individual properties of the newly developed AMCs. According to this approach, S/N ratio for each response can be calculated as shown in Equation 10 and Equation 11.

For the higher-is-the-better (maximize) type responses:

$$\frac{S}{N} = -10 \log \frac{1}{n} \sum_{i=1}^n \frac{1}{Y_i^2} \quad (10)$$

For the lower-is-the-better (minimize) type responses:

$$\frac{S}{N} = -10 \log \frac{1}{n} \sum_{i=1}^n Y_i^2 \quad (11)$$

Where Y_i individual response value and n number of trials.

2.4.2 Grey Relational Analysis

Grey relational analysis (GRA) is a multiple criteria decision-making technique that is used to optimize multi-objective optimization problems. Using this method the normalized values of the experimental results were initially calculated [37,38]. If the response is of maximization type, response data are normalized using Equation 12.

$$Y_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (12)$$

However, if the response is a minimization type, the normalization is performed using Equation 13.

$$Y_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min y_{ij}} \quad (13)$$

Where $\max x_{ij}$ is the maximum value, $\min x_{ij}$ is the minimum value and x_{ij} is the corresponding value of a particular response.

In current research work, the microhardness, tensile strength, percentage elongation, and scratch hardness were taken as the "large-is-better type" responses, while wear rate, friction coefficient, and percentage porosity were chosen as "the lower-is-better type responses".

After normalization, the deviation of the sequence is calculated using Equation 14.

$$\Delta_{ij} = | \max Y_{ij} - Y_{ij} | \quad (14)$$

Where $\max Y_{ij}$ is the maximum normalized value and Y_{ij} represents the corresponding normalized value. The grey relation coefficients (GRC) are then calculated according to Equation 15 as follows:

$$\xi_{ij} = \frac{\min \Delta_{ij} + \Psi \max \Delta_{ij}}{\Delta_{ij} + \Psi \max \Delta_{ij}} \quad (15)$$

Where $\min \Delta_{ij}$ represents the minimum deviated value, $\max \Delta_{ij}$ represents the maximum deviated value, Δ_{ij} corresponding value for a particular response and the ' Ψ ' is a constant function and its value is generally taken as 0.5. Finally, the grey relation grades are calculated using Equation 16, which are further optimized using suitable design of experiments [34].

$$\gamma = \frac{1}{n} \sum \xi_{ij} \quad (16)$$

where n is the number of trials and ξ_{ij} represents the GRC of the corresponding trial.

For the confirmatory experiments, the predicted value of GRG ($\gamma_{Predicted}$) was evaluated according to Equation 17.

$$\gamma_{Predicted} = \gamma_{mean} + \sum_{i=1}^q (\gamma_i - \gamma_{mean}) \quad (17)$$

Where γ_{mean} average GRG, γ_i average GRG at the optimal level and q no. of significant input parameters for GRG.

GRA was performed on the response characteristic parameters as described above and the optimization problems were solved and results are presented.

3. RESULTS AND DISCUSSION

3.1 Metallographic study

Metallographic studies of AMCs were performed to analyze the presence and distribution of reinforcement particulates within the base matrix. Various types of unwanted compounds formed within the composites, resulting from internal reactions among the constituents, were also identified in this study. The SEM images indicate the dispersion of respective reinforcement particulates (i.e., SiC, Ni, Mo, and Cr) within the aluminium alloy with small clusters at some locations. The SEM and EDS images are shown in Fig. 9 to Fig. 12. The peaks of Al, Si, carbon, Ni, Mo, and Cr in the EDS images confirm the presence of constituents within composites. The highest aluminium peak in all images indicates that aluminium is the main constituent in the highest composition and other gradients are presented accordingly.

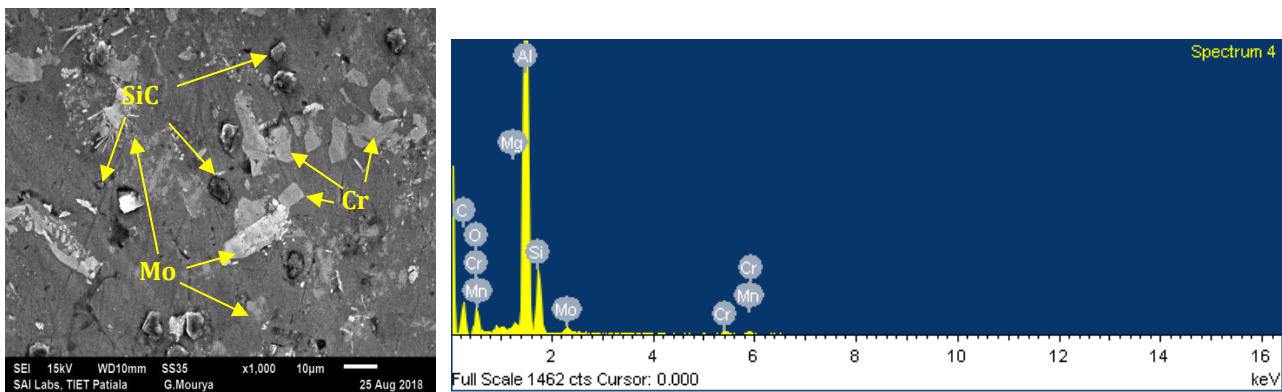


Fig. 9. The SEM and EDS image of the Al-SiC-Mo-Cr hybrid Composite.

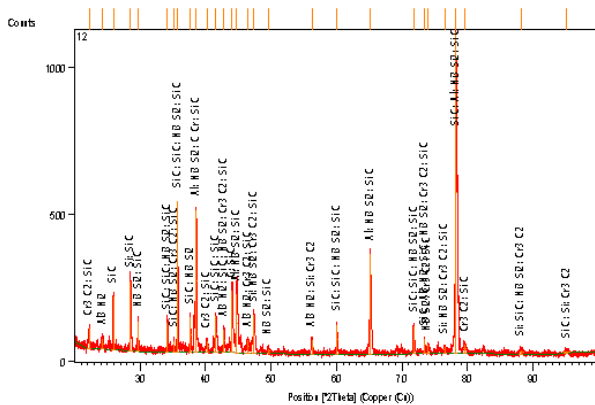


Fig. 14. The XRD pattern of the Al-SiC-Ni-Cr hybrid Composite.

The formation of these unwanted compounds, resulting from internal reactions among the constituents deteriorated the composite properties. Fig. 15 shows the X-ray diffraction pattern of Al-SiC-Ni-Mo hybrid composite. The pattern shows that Al_4Si_3 , $NiSi_3$ and Ni_2Si_2 compound were formed by the reactions of nickel with aluminium and silicon. In addition, molybdenum reacts with aluminium to form $Al_{12}Mo$ and Al_5Mo compounds; however, the intensities of $NiSi_3$ and $Al_{12}Mo$ are minimal.

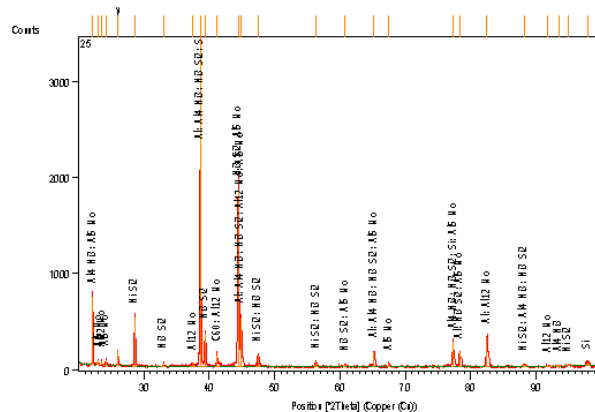


Fig. 15. The XRD pattern of the Al-SiC-Ni-Mo hybrid Composite.

The XRD pattern of the Al-SiC-Ni-Mo-Cr composite shown in Fig. 16 indicates that nickel reacts with other ingredients to form highly intense $NiSi_2$, Al_3Ni_2 , Ni_3Mo_3C , and $Cr_{13}Ni_5Si_2$.

From the XRD analysis, it was observed that a number of unwanted compound are formed in the hybrid aluminium matrix composites and their intensity is increased by increasing the composition of the reinforcement particulates.

These compounds produce a harmful effect on the composite properties like a reduction in strength and elongation, and an increase in the porosity level.

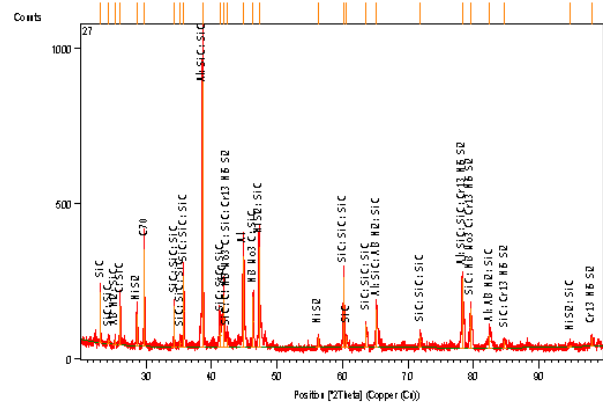


Fig. 16. The XRD pattern of the Al-SiC-Ni-Mo-Cr hybrid Composite.

3.2 Properties Evaluation

The properties of the novel composites in the form of microhardness, tensile strength, wear rate, elongation, friction coefficient, traction force and porosity were determined according to ASTM standards and compared with those of the base Al-SiC composite [39-44]. Table 5 shows the detail of the evaluated properties of the hybrid aluminium matrix composites.

It was observed that the hardness and wear resistance were increased by increasing the Ni and Mo contents. This improvement was attributed to the hard Ni and Mo particles. Instantaneously, the addition of these particles caused a reduction in strength and ductility and increased porosity level. This is due to the internal reactions of Ni and Mo with other ingredients, which result in the formation of unwanted compounds such as Al_2Ni_3 , Ni_3Si_3 , $NiSi_3$, Ni_2Si_2 , Al_3Ni_2 , Ni_3Mo_3C , Al_4Si_4 , $Cr_{13}Ni_5Si_2$, $Al_{12}Mo$, and $CrMo$ in various composites. The addition of Cr showed no significant effect in improving the composite properties as it reacted with other constituents resulting in the formation of $CrMo$, Al_8Cr_5 , CCr , Cr_2C_2 , $Cr_{13}Ni_5Si_2$, etc. The hardness and wear resistance initially decreased and then increased with increasing Cr content. This is due to the formation of the chromium carbide compound, which has a hardness value five times greater than that of the un-plated mild steel.

Table 5. Evaluated Properties of the Composite Castings.

Casting No.	Characteristic Properties						
	Microhardness (HV)	Tensile strength (N/mm ²)	Elongation (%)	Wear rate (mm ³ /min)	Friction coefficient	Porosity (%)	Traction Force (N)
1	112.8	189	7.28	1.354	0.1143	3.4521	9.10
2	100	131	4.32	0.673	0.2755	2.433	11.96
3	126.6	98	4.36	0.674	0.1704	3.4975	11.42
4	120	173	7.12	1.565	0.1480	1.884	11.16
5	140	104	3.18	1.169	0.1245	2.743	12.62
6	146.2	103	4.08	1.197	0.1194	3.637	22.4
7	159	99.1	3.46	1.058	0.2745	3.861	9.16
8	140	114	4.76	1.148	0.1061	3.993	12.68
9	164	96.9	3.43	0.541	0.1194	3.748	16.48

3.3 Optimization of the Composition of Reinforcements

From Table 6, it is evident that the composition of reinforcement has a significant effect on the properties of the newly developed composites. By changing the reinforcement compositions in the composites, significant variations in the composite properties, that is, an improvement in the hardness, wear resistance and traction force and a reduction in the strength and elongation, have been observed. Therefore, optimization of the reinforcement composition is required to obtain optimal properties. In view of this, the research is further extended to optimize the composition of nickel, molybdenum and chromium particulates. Taguchi's approach was used to identify the most effective secondary reinforcement for each composite property. Multiple response optimizations were carried out with the help of the Taguchi coupled Grey Relational Analysis (TGRA), as it is simple and one of the most used multiple attribute decision-making techniques. In this approach, the multi-objective optimization problem was converted into the optimization of GRGs. An ANOVA for grey relational grades was also carried out and the significant parameters for response properties were investigated. The results were then validated by comparing the experimental grey relational grade with its predicted value.

3.3.1 Taguchi Analysis

The Taguchi analysis was applied for each response and the most influential parameters for

each response were determined. The detail is given as follows.

The main effects plots for composite properties are shown in Fig. 17(a-g). The study of the main effects plots revealed that nickel is the most predominant factor affecting the hardness of AMCs, followed by molybdenum and chromium. In addition, the composite containing 10% nickel 4% molybdenum, together and 10% SiC exhibited the highest microhardness. However, the maximum traction force was obtained in the composite containing 10% SiC, 5% nickel, and 1.5% chromium. For tensile strength and elongation, the addition of secondary reinforcements had a negative effect owing to the formation of unwanted compounds within the composites. In addition, a composite containing 4% molybdenum, 1.5% chromium and 10% SiC yielded the minimum wear rate. However, the minimum value of the friction coefficient was obtained for a composite containing 10% nickel, 4% molybdenum, and 10% SiC. The minimum level of porosity was observed in the composite reinforced with 10% SiC, 5% nickel and 1.5% chromium.

The results of the ANOVA for the responses are mentioned in Table 6. It has been observed that nickel is the most significant factor for composite hardness contributing 70%, whereas molybdenum and chromium have a small effect on it.

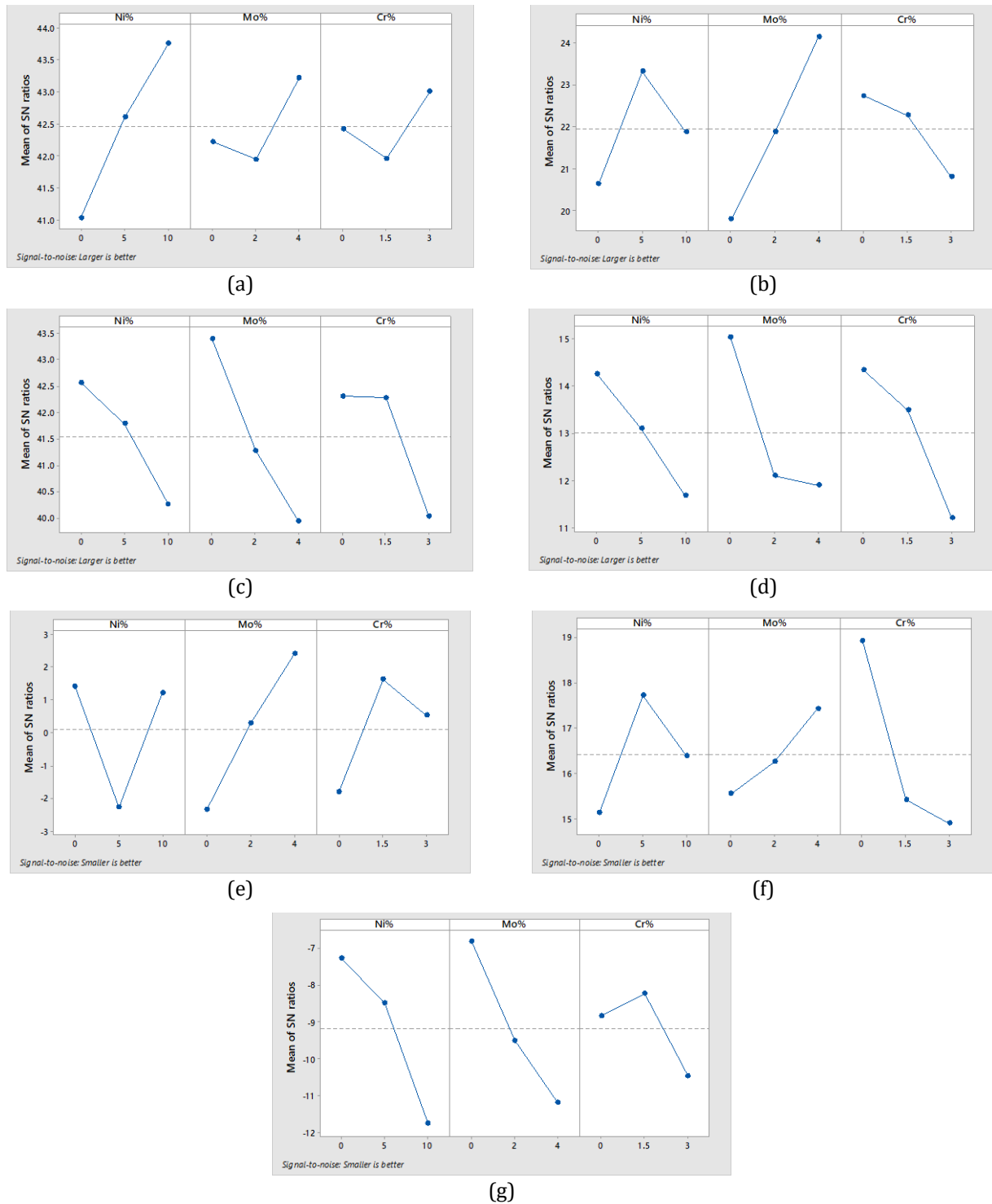


Fig. 17. Main Effects Plot for (a) Microhardness; (b) Traction force; (c) Tensile Strength; (d) Elongation; (e) Wear rate; (f) Friction coefficient; (g) Porosity Level.

However, molybdenum is the most influential factor for traction force, that contributing 59.75% to achieve maximum traction force, while the composition of nickel and chromium was also showed a small effect on it. Molybdenum is the most prominent factor influencing the tensile strength, wear rate, and porosity level. Molybdenum contributed 47.01%, while the

nickel and chromium contributed 21.11% and 26.26% to obtain maximum tensile strength. For elongation, molybdenum contributes 33.71%, while the composition of nickel and chromium are also influencing the elongation and contributing 18.27% and 28.92 %, respectively. For minimum wear rate, molybdenum showed a 42.29% contribution, while the composition of

nickel and chromium indicated 32.19% and 22.36%, respectively. However, composition of chromium was the most important parameter for friction coefficient followed by the composition of nickel and molybdenum. ANOVA for porosity

indicates that the composition of nickel and molybdenum are the most influential factors for porosity in AMCs, followed by the composition of chromium.

Table 6. ANOVA for the Composites Properties.

Microhardness							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contributions
Ni%	2	11.1666	11.1666	5.5833	22.82	0.042	70.00%
Mo%	2	2.6685	2.6685	1.3342	5.45	0.155	16.73%
Cr%	2	1.6276	1.6276	0.8138	3.33	0.231	10.20%
Residual Error	2	0.4893	0.4893	0.2447			3.07%
Total	8	15.952					
Traction Force							
Ni%	2	10.929	10.929	5.465	4.88	0.170	22.73%
Mo%	2	28.732	28.732	14.366	12.84	0.072	59.75%
Cr%	2	6.187	6.187	3.094	2.76	0.266	12.87%
Residual Error	2	2.238	2.238	1.119			4.65%
Total	8	48.086					
Tensile Strength							
Ni%	2	8.242	8.242	4.121	3.77	0.210	21.11%
Mo%	2	18.352	18.352	9.176	8.39	0.107	47.01%
Cr%	2	10.252	10.252	5.126	4.68	0.176	26.26%
Residual Error	2	2.189	2.189	1.094			5.61%
Total	8	39.035					
Percent Elongation							
Ni%	2	11.927	9.927	4.964	0.96	0.511	21.95%
Mo%	2	18.318	18.318	9.159	1.76	0.362	33.71%
Cr%	2	15.718	15.718	7.859	1.51	0.398	28.92%
Residual Error	2	8.383	10.383	5.192			15.43%
Total	8	54.346					
Wear Rate							
Ni%	2	25.734	25.734	12.867	12.61	0.073	32.19%
Mo%	2	33.809	33.809	16.904	16.57	0.057	42.29%
Cr%	2	18.356	18.356	9.178	9	0.100	22.96%
Residual Error	2	2.041	2.041	1.02			2.55%
Total	8	79.94					
Coefficient of Friction							
Ni%	2	19.997	9.997	4.999	0.27	0.790	24.47%
Mo%	2	15.386	5.386	2.693	0.14	0.874	18.82%
Cr%	2	38.831	28.831	14.416	0.77	0.565	47.51%
Residual Error	2	7.52	37.52	18.76			9.20%
Total	8	81.734					
Porosity Level							
Ni%	2	31.993	31.993	15.997	3.55	0.220	41.01%
Mo%	2	29.055	29.055	14.528	3.22	0.237	37.24%
Cr%	2	9.96	7.96	3.98	0.88	0.531	12.77%
Residual Error	2	7.01	9.01	4.505			8.98%
Total	8	78.019					

The Taguchi approach was applied individually to each evaluated composite property to

determine the best composition of the secondary reinforcements, which provided the best value.

Then, the composites were fabricated and their properties were evaluated, and the results are shown in Table 7.

From the confirmatory tests, it was observed that that each property of the composite significantly improved when the composition of the secondary reinforcements was chosen according to the

settings suggested by the Taguchi approach. However, during the testing, other properties were also evaluated for each composite and it was observed that these properties were also affected in different ways. Owing to this, multi-response optimization is needed to determine the single combination of input parameters to obtain optimal composite properties.

Table 7. Taguchi's optimized Input Parameters for the Best Composite Properties.

No	Best Setting of input parameters	Composite Properties	Optimized Values
1	Ni% 3 Mo% 3 Cr% 3	Microhardness	175 HV
2	Ni% 1 Mo% 1 Cr% 1	Tensile strength	189 N/mm ²
3	Ni% 1 Mo% 1 Cr% 1	Percentage elongation	7.12%
4	Ni% 1 Mo% 3 Cr% 2	Wear rate	0.52124 mm ³ /min
5	Ni% 2 Mo% 3 Cr% 1	Friction coefficient	0.1061
6	Ni% 1 Mo% 1 Cr% 2	Percentage porosity	1.4527 %
7	Ni% 2 Mo% 3 Cr% 1	Traction force	23.2 N

Table 8. Normalized experimental results for Response Characteristic Properties.

Casting No.	Normalization (Y)						
	MH	UTS	% E	WR	FC	%P	TF
1	0.213	1.000	1.000	0.206	0.952	1.000	0.000
2	0.000	0.370	0.278	0.871	0.000	0.614	0.215
3	0.443	0.012	0.288	0.870	0.620	0.195	0.174
4	0.333	0.826	0.961	0.000	0.753	0.830	0.155
5	0.667	0.077	0.000	0.387	0.891	0.492	0.265
6	0.770	0.066	0.220	0.359	0.921	0.140	1.000
7	0.983	0.024	0.068	0.495	0.006	0.052	0.005
8	0.667	0.186	0.385	0.407	1.000	0.000	0.269
9	1.000	0.000	0.061	1.000	0.921	0.096	0.555

3.3.2 Grey Relational Analysis

The Taguchi approach was used to optimize the composition of the secondary reinforcements and characterization was performed. From these findings, it was noticed that by changing the type and composition of nickel/molybdenum/chromium, each property was varied in its way. Each AMC, when cast according to the Taguchi approach, provides the best corresponding property; however, but the alteration in other properties is not considered. Therefore, multi-objective optimization of the composite properties is required to obtain the common optimum composition of the secondary reinforcements. In view of this, the research is further extended to perform multi-objective optimization of the reinforcement contents to

obtain optimal composite properties using TGRA. The first step involved the normalizing the obtained composite properties, and the results are listed in Table 8. During normalization, the microhardness, tensile strength, percentage elongation, and scratch hardness were taken as "higher-is-the-better" type responses, while wear rate, friction coefficient, and percentage porosity were taken as "lower-is-the-better" type responses.

After the normalization of responses, the deviation of sequences, grey relation coefficients (GRC) and grey relational grades (GRGs) were calculated using standard equations. Based on the obtained values of GRGs, the cast composites were ranked, as shown in Table 9.

Table 9. Calculated GRC and GRG.

Casting No.	Grey Relation coefficients (ξ)							Grey Relation Grades (γ)	Rank
	MH	UTS	% E	WR	FC	%P	TF		
1	0.389	1.000	1.000	0.386	0.456	1.000	0.333	0.65203	1
2	0.333	0.443	0.409	0.795	0.333	0.564	0.389	0.46670	8
3	0.473	0.336	0.412	0.794	0.568	0.383	0.377	0.47775	7
4	0.429	0.742	0.928	0.333	0.669	0.746	0.372	0.60267	3
5	0.600	0.351	0.333	0.449	0.822	0.496	0.405	0.49373	6
6	0.685	0.349	0.390	0.438	0.864	0.368	1.000	0.58492	4
7	0.968	0.339	0.349	0.498	0.335	0.345	0.334	0.45251	9
8	0.600	0.380	0.449	0.458	1.000	0.333	0.406	0.51802	5
9	1.000	0.333	0.347	1.000	0.864	0.356	0.529	0.63291	2
Mean GRG (γ_m) = 0.54236									

Table 10. Analysis of Variance for the Grey Relational Grades.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Ni%	2	3.4887	0.4887	0.2444	0.15	0.868	29.59%
Mo%	2	2.628	2.628	1.314	0.82	0.55	22.29%
Cr%	2	5.4619	5.4619	2.731	1.7	0.37	46.32%
Residual Error	2	0.2129	3.2129	1.6064			1.81%
Total	8	11.7915					

Taguchi's approach is the most suitable technique for single objective optimization problems. Keeping in view of this, the optimization is further extended by applying this approach considering GRG as the maximization type response. ANOVA was also performed to identify the significant input factors for the GRG mean material properties. The results were validated by comparing predicted GRG value with the experimental value. The purpose of this study is to maximize the hardness, tensile strength, elongation and traction force, and minimize the wear rate, friction coefficient and porosity.

The ANOVA results for the GRG were shown in Table 10. It has been observed that the composition of chromium and nickel are the most significant factors affecting GRGs that is, composite properties, followed by the composition of molybdenum. Figure 18 indicates that the composition of the secondary reinforcement (i.e. Ni, Mo, and Cr particulates) is a predominant factor influencing the composite properties. The purpose of this study is to obtain a large value for the GRG, that is, optimal values of the composite properties. According to TGRA, a composite containing 10% silicon carbide and

5% nickel particulates possesses optimal composite properties.

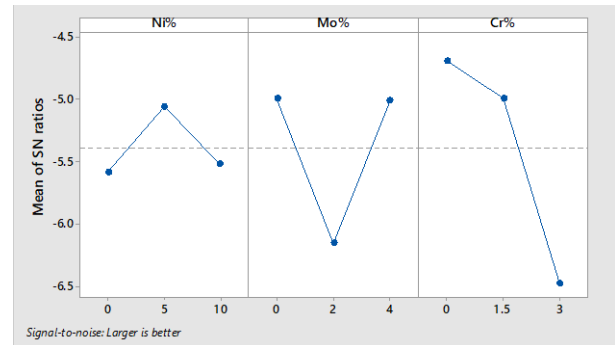


Fig. 18. Main effects plot for grey relation grades.

The significance level for the composition of each secondary reinforcement material is calculated to obtain the optimal value of GRG, and the results are listed in Table 11. In addition, according to the delta value, the secondary reinforcing elements are ranked.

Confirmatory tests were also conducted as per the setting suggested by Taguchi-Grey Relational Analysis. The predicted GRG was calculated according to Equation 17.

$$\gamma_{Predicted} = 0.54236 + (0.560442 - 0.54236) + (0.589069 - 0.54236) + (0.584989 - 0.54236) = 0.64978 \quad (17)$$

Table 11. Response Table for GRGs.

Level	Ni%	Mo%	Cr%
1	0.53216	0.5890697*	0.5849899*
2	0.560442*	0.49281565	0.56742468
3	0.5344769	0.56519386	0.47466467
Diff	0.0282823	0.0962541	0.11032523
Rank	3	2	1

*Significant Levels

Based on best settings, a new aluminium matrix composite was fabricated and properties were evaluated. The experimental GRG was then calculated, and the results are listed in Table 12. The properties were then compared with those of the composite cast according to the initial composition of the secondary reinforcements. The experimental GRG was compared with the GRG obtained from the initial levels of the input parameters that is, Ni 1 Mo1 Cr 1. From the results, it was observed that an 18.08% improvement in the hardness, 9.23% improvement in the wear resistance (a reduction in wear rate), and 64.94% improvement in the traction force were obtained and the composite retained its tensile strength and elongation.

Table 12. Results of Responses using Initial and Optimum Input Parameters.

	Initial Input Parameters	Optimum Input Parameters	
		Predicted	Experimental
Setting Level	Ni% 1 Mo% 1 Cr% 1	Ni% 2 Mo% 1 Cr% 1	Ni% 2 Mo% 1 Cr% 1
Microhardness	112.8 HV		133.2 HV
Tensile strength	189 N/mm ²		190 N/mm ²
Percentage elongation	7.28%		7.23%
Wear rate	1.35 mm ³ /min		1.24 mm ³ /min
Friction coefficient	0.114		0.139
Percentage porosity	1.45%		2.66%
Traction Force	9.10 N		15.01 N
Grey Relation Grade	0.65352	0.64978	0.66643
Improvement in GRG = 0.10906			

The experimental GRG of the optimized composite was 1.97% higher than the GRG value obtained from reference, which shows significant improvements in the composite properties. In addition, the predicted GRG value differed from the experimental value by 2.56%, which validates the experimental results.

From the Taguchi analysis, it was also observed that the composite properties were greatly influenced by the composition of the secondary reinforcements. Nickel is the predominant factor affecting the hardness and porosity of aluminium matrix composites. The tensile strength, elongation and wear rate of aluminium matrix composites are highly influenced by the composition of molybdenum, whereas the friction coefficient is affected by the chromium content. According to the Taguchi coupled grey relational analysis, an aluminium matrix composite, which contains 5% nickel and 10%

SiC possesses optimal characteristic properties, and the results are validated by comparing the predicted value of GRG with the experimental value of GRG.

4. CONCLUSIONS

In this study, silicon carbide, nickel, molybdenum, and chromium-reinforced aluminium matrix composites were developed using stir casting with the aim of optimizing the composition of nickel, molybdenum, and chromium in AMCs. The results of the research revealed that liquid vortex casting (stir casting) is the best suitable route to develop Al-SiC-Ni/Mo/Cr hybrid AMMCs. In the Al-SiC composite, SiC particulates are distributed uniformly within the aluminium matrix without clusters. The optical micrograph shows that a dendritic microstructure was formed within the composite. The XRD pattern showed the absence

of unwanted secondary phases (such as Al₄C₃) in the AMC. The highest peak of Al in the EDS image confirms that Al is the main constituent of the composite and other elements are also present. The hardness, tensile strength, wear resistance and traction force are increased together with a minor decrease in the elongation and friction coefficients. The percent porosity in the newly developed composite was less than the prescribed limit and in composites containing a mixture of secondary reinforcement elements, a number of secondary phases were observed. These compounds have a harmful effect on the composite properties. In addition, the reinforcements were scattered throughout the aluminium matrix. The Taguchi Analysis revealed that the compositions of Ni, Mo, and Cr were the predominant factors influencing the material properties. The results of grey relational analysis shows that a nickel composition of 5% together with 10% SiC, without using molybdenum and chromium is an optimum composition for secondary reinforcements to develop hybrid aluminium matrix composites. The grey relational grade was improved by 2.56% using a globally optimized solution. The predicted GRG value differed from the experimental value by 2.56%, which validates the experimental results.

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