Vol. 1, Iss. 4 (2024) 132-142, DOI: 10.61552/JMES.2024.04.002

JMES

Journal of Management and Engineering Sciences

www.jmes.aspur.rs

Characterization of Aluminium Metal Matrix Composites reinforced with Silicon Carbide and Nickel Particulates

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Keywords:

Aluminium matrix composite
Silicon carbide
Nickel
Stir casting
Microhardness
Mechanical properties

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Received: 22.04.2024.
Revised: 23.06.2024.
Accepted: 29.06.2024.

A B S T R A C T

This research article presents the procedure for the fabrication of Aluminium alloy (LM25) based metal matrix composites containing particulates of silicon carbide (10 wt. %) and nickel (0, 5 and 10 wt. %). Using the vortex casting technique, three composites were formulated and characterized as per ASTM standards. Microstructure analysis using "scanning electron microscopy" reveals the uniform distribution of reinforcing particulates within the base matrix without clustering. "Energy dispersive spectroscopy" illustrates the presence of ingredients within the composites. "X-ray diffraction" patterns indicate the formation of mesoporous NiSiAl compound within the composite resulting from internal reactions. The "optical microscopy" reveals the refinement of grain structure with the inclusion of nickel particulates within the composites. The influence of the composition of reinforcing particulates that is, silicon carbide and nickel on the properties of the base matrix was explored. An enhancement in the microhardness, tensile strength, wear resistance and traction force and a reduction in friction coefficient was observed together with a marginal reduction in elongation and the porosity level is also under the controlled limits (<5%).

1. INTRODUCTION

Industry 4.0 (also known as 4IR) demands novel materials that can fulfil modern industrial requirements and the existing monolithic metals/alloys are not best suitable for this. These demands can be accomplished using advanced composite materials that possess extraordinary properties which up swung the use of composite materials in industries. Metal Matrix Composites (MMCs) are new-generation materials that possess unique properties. In Metal matrix composites, hard and high-strength reinforcement particles are introduced in the high ductile and tough matrix and produced such sort of engineering materials. The newly developed materials possess marvellous characteristics (high weight/strength ratio, high wear resistance, high thermal etc.), which are the combination of both matrix and reinforcement. Due to these generated characteristics, composites are widely used in aerospace, automobile industries etc. and replace conventional monolithic materials [1,2].

The light metals like aluminium, lead, magnesium, copper, brass, Ni and their alloys etc. are used as a matrix in MMCs [3,4]. Aluminium is light in weight and exhibited high corrosion resistance; however, poor mechanical and tribological properties restricted its use in several applications [5]. Hard ceramic and metallic reinforcements like SiC, alumina, tungsten, graphite, B4C, flyash, aluminium borate, basalt, MoS_2 etc. are generally utilized to upgrade the matrix properties [6-8]. Silicon carbide, when used as reinforcement in aluminium and its alloys enhances their properties because it is very hard. However, Al-SiC composites possess difficulty during machining because the presence of SiC in the base matrix causes rapid wear of the cutting tool and reduces the tool life. Also, the addition of SiC decreases the toughness and stiffness of the base aluminium matrix. The materials like graphite, nickel and molybdenum improve the ductility of the base aluminium matrix when used as reinforcing materials in the base matrix [9,10]. The reinforcement grain size and its composition play an essential role in the density and characteristics variations of aluminium based MMCs [11,12]. The synergetic impact of two or more reinforcements influences the porosity that causes significant variations in the properties of the newly developed composites [13]. In the last 2-3 decades, hybrid aluminium matrix composites have engrossed the attention of the researchers and industrialists to understand the variation of properties that these materials have to offer [14,15].

Many authors published their valuable work related to aluminium based MMCs to enhance the characteristic properties of aluminium matrix composites using various sizes and types of reinforcements. Literatures revealed that hybrid AMMCs possessed higher tensile strength and hardness than single particulate reinforced AMMCs [16]. Kalra et al [17] observed that Al-20SiC+10Al_2O_3+7.5C composite shows maximum wear-rate, when tested at 14.72N normal load, 300 rpm disc speed on 60 mm track diameter using pin on disc apparatus. In another research, Pradhan et al. [18] reported that SiC inclusion in aluminium increased the wear resistance, and reduced the friction coefficient due to oxide layer formation. Also, the wear mechanisms of composites were "corrosive", "abrasive" and "adhesive" wear. Vencl et al. [19] observed superior wear resistance in SiC-reinforced composite than the composite reinforced with Al2O3. Furthermore, the addition of graphite with SiC shows a further reduction in friction coefficient and improvement in wear resistance. Donthamsetty and Babu [20] observed that 0.5 wt. % of SiC nanoparticles increased the wear resistance of the base matrix up to 54% and 47% at loads of 30N and 40N respectively. In another research, Sangeetha et al. [21] examined that the wear resistance can be improved by coating the SiC particles before their inclusion in the A356 alloy grain structure. Dwivedi and Pali [22] compared mechanically and electromagnetically stirred casting processes in terms of the wearing behaviour of A356-SiC composite. The experiments were performed using a "pin-on-disc" wear tester. Authors reported higher wear resistance and friction coefficient in an electromagnetically stirred composite than other ones. Also, the wear rate varied proportionally with the applied load and SiC. Kumar et al [23] reported that the inclusion of chromium particulates together with silicon carbide possesses significant improvements in the properties of hybrid aluminium metal matrix composites, which were formulated through stir casting. The authors also observed that chromium possesses a significant impact on the machining behaviour of the newly developed composites.

The stir casting method is one of the liquid-phase casting methods which involves the dispersed phase added to a melt of continuous phase and stirred. It is a cheap and simple route used to formulate mono and hybrid MMCs. liquefying temperature of the base matrix, stirring time, rate and preheating temperature of reinforcing agents, stirrer speed and its position in molten melt are the most influencing process parameters in this route [17]. Moreover, the drawbacks of this route include uneven distribution of reinforcement particles, deprived wettability resulting in higher porosity levels, internal reactions, particles agglomeration during solidification, cluster formation etc. [3]. Such limitations can be reduced using appropriate stirrer design, coating of wetting materials like CNT/Si/Cu/Mg on the reinforcement surface, appropriate stirrer speed and stirring time etc. [17,21].

Several studies have shown a significant improvement in the characteristics of base matrices with the incorporation of particulate reinforcements in them. To date, there has been a lack of studies on the use of nickel element as reinforcements in MMCs. This element is very hard and as an alloying element in steel, it significantly improves its properties. Therefore, in this research an attempt has been made to utilize nickel particulates together with silicon carbide particulates to fabricate aluminium metal matrix composites. The effect of the inclusion of reinforcement particulates in the aluminium alloy on its properties is investigated.

2. MATERIALS AND METHODS

LM25 (Al-Si alloy) was selected as the base matrix in this study. This alloy possesses excellent properties like "high corrosion resistance, high strength/weight ratio, a good conductor of heat and electricity and possesses applications in automobile industries to make automobile components like pistons, cylinder liners, brakes, discs, etc.", where high wear resistance and strength to weight ratio is required [24-26]. The composition of the base aluminium alloy is determined using a spark spectrometric analyzer as per ASTM: E 1251-11 standard [27]. Table 1 shows the composition of the aluminium alloy and Table 2 indicates its properties.

Table 1. Chemical Ranges of aluminium (LM25) 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

Table 2. Properties of base Aluminium Alloy.

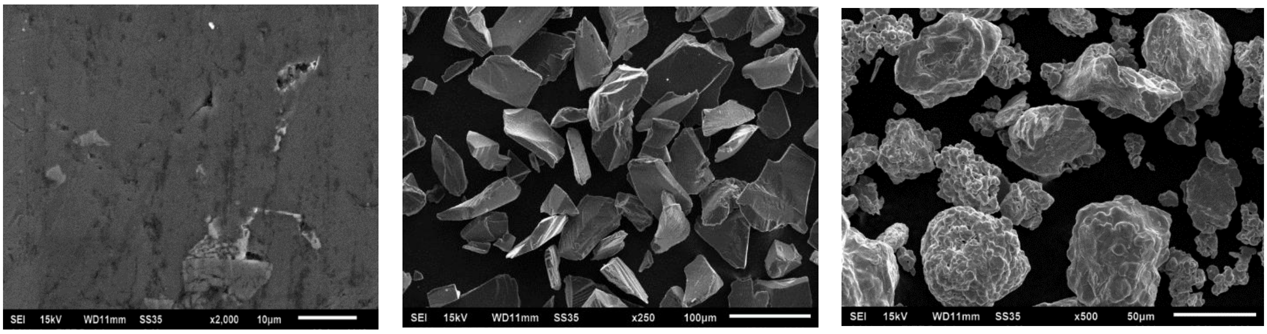
No.	Property	Value
1	Microhardness	99.08 HV
2	Ultimate Tensile Strength	174 MPa
3	Percentage Elongation	7.52 %
4	Wear Rate	2.032 mm^3/min
5	Friction Coefficient	0.148
6	Theoretical Density	2.685 g/cm^3
7	Actual Density	2.684 g/cm^3
8	Percentage Porosity	0.025
9	Traction force	8.46 N

Silicon carbide is one of the ceramic materials which are very hard. As a reinforcing material, it can improve the hardness and wear resistance of the base matrix in MMCs. Nickel material possesses excellent corrosion resistance even at high temperatures, good electrical and thermal conductivity [28], and high hardness and strength. Based on these characteristics, nickel is used to strengthen many alloys. Nickel, when added in the aluminium matrix, it retains its ductility together with improving its properties [29,30]. Therefore, greyish black silicon carbide powder containing a purity of 99.5% and nickel powder (purity level 99.9%) were chosen as reinforcing materials in AMCs. The SEM images of composite ingredients are shown in Fig. 1 and Table 3 indicates their properties.

Magnesium element has the ability to improve wettability and strengthen metallurgical bonding between the constituents of AMCs [31,32]. Therefore, 1% magnesium, in the form of silvery white powder (density 1.74g/cm^3) and purchased from the LOBA Chemie Pvt. Ltd. Mumbai, Maharashtra, India, was also added in all composites during fabrication.

2.1 Fabrication of AMCs

Silicon carbide (SiC) and nickel (Ni) particulates reinforced AMMCs were developed using stir casting route [23]. Required quantitative amounts of constituents are measured using high precision weight measuring machine having least count of 0.005 mg. Aluminium alloy melted at 630±20°C in ceramic crucible using an electric furnace. SiC and Ni particulates were preheated at 200oC for around 30 minutes to make them moisture free and oxidize their surfaces. A graphite stirrer was then introduced in the molten aluminium melt and revolved at 450-500 rpm. Preheated reinforcing particulates then poured in the melt and stirred continuously for 8-10 minutes at around 400 rpm under the argon gas environment. Finally, the mixture is poured to a preheated M.S. mould.



Al Si Ni

Fig. 1. SEM Images of composite ingredients.

Table 3. Properties of the Constituents used in AMCs.

Property	Al alloy	SiC	Ni
Average particle size	-	67 μm	64 μm
Density	2.685 g/cm³	3.21 g/cm³	8.9 g/cm³
Melting point	650 °C	2730 °C	1453 °C
Tensile strength	174 MPa	230 MPa	345 MPa
Hardness on mohs scale	2.75	9	4
Supplier	S.S. Moulding Industries, Jagadhari, Haryana, India	S.D. Fine-Chem Limited Mumbai, Maharashtra, India	LOBA Chemie Pvt. Ltd. Mumbai, Maharashtra, India

2.2 Testing

The metallographic study of the aluminium matrix composite is needed to observe the existence and dispersion of the reinforcing materials in the aluminium matrix and to explore the development of unwanted compounds within the composite resulting from internal reactions. Composite properties were evaluated to analyze the impact of nickel particulates addition in the base Al-SiC composite. For this, casting was pulled out from the mould and testing samples were cut as per ASTM standards using wire-EDM. Test specimens were mounted as per "ASTM E3 standard" and etched with "Keller's reagent (HF-2ml, HCL-3ml, HNO_3-5ml and Distilled water-190ml)". SEM and EDS analysis were performed using "JEOL/JSM-6510 EDS integrated apparatus" to ensure the presence and particulates distribution within the base alloy. The microstructure of newly developed composites was analyzed using optical microscopy. XRD is carried out on the "XPERT-PRO diffractometer system in which angle 2θ was varied from 20° to 100°. The procedure adopted for the microhardness test conforms to ASTM E384 standards. The microhardness test is conducted under 300g load applied for 15 seconds with the help of a Vicker hardness tester. Tensile test was performed as per ASTM-E8-M09 using "twin column universal testing machine". Ultimate tensile strength and elongation for each specimen is calculated and compared with the base alloy. Wear behaviour of newly developed composites was analyzed according to ASTM-G99-95a standard. Wear tests were conducted on cylindrical specimens (diameter 10mm and length 30mm) under dry condition using a "pin-on-disc wear test apparatus". A metallic disc (EN31) turning around at 300 rpm is used as a counter surface. The pin is made to slide on the disc with a 70 mm track diameter, and 1.099 m/s velocities for the period of 2 minutes. The 1N load is employed during sliding for a 980m sliding distance. The variations of wear rate (μm/min) and friction force are recorded and the friction coefficient is calculated.

The porosity levels in each cast composite are determined using the density analysis. Equation 1 uses the "Archimedes' principle" to compute the real density, where ma stands for the mass of the sample in the air and mw for the mass of the sample in the water. The density of distilled water is represented by ρ_w (0.998 g/cm^3 at 20°C). Equation 2 uses the "Rule of mixtures" to compute the theoretical density, where W is the weight fraction and is the density (g/cm^3) of the constituent particles. Equation 3 is used to determine each composite's porosity level.

$$\rho_A = m_a/(m_a - m_w) \times \rho_w \quad (1)$$

$$\rho_T = \rho_{Matrix} \times W_{Matrix} + \rho_{SiC} \times W_{SiC} + \rho_{Ni} \times W_{Ni} \quad (2)$$

$$\%Porosity = 1 - (\rho_A / \rho_T) \times 100 \quad (3)$$

3. RESULTS AND DISCUSSION

3.1 SEM and EDS analysis

SEM and EDS image of the newly developed Al-SiC composite ensures the presence and dispersion of SiC within the base matrix without clustering (Fig. 2), which possesses a positive effect on the composite properties.

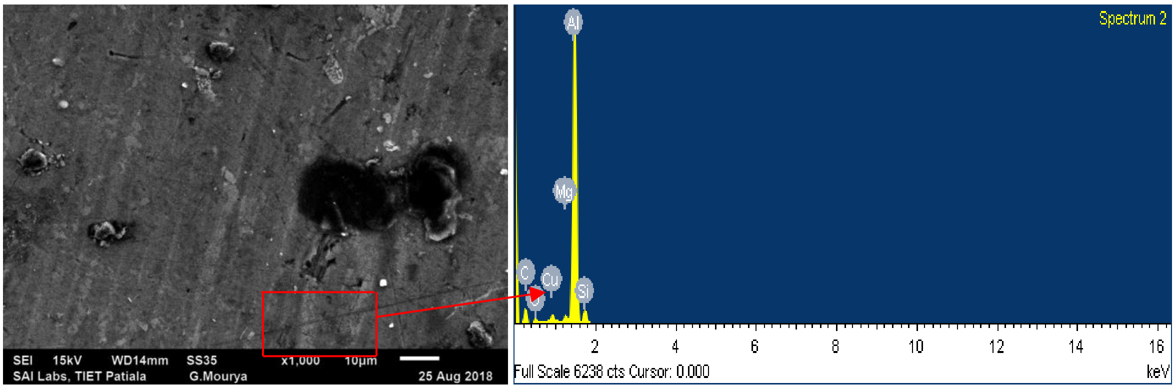


Fig. 2. SEM and EDS image of the Al-10%SiC Composite.

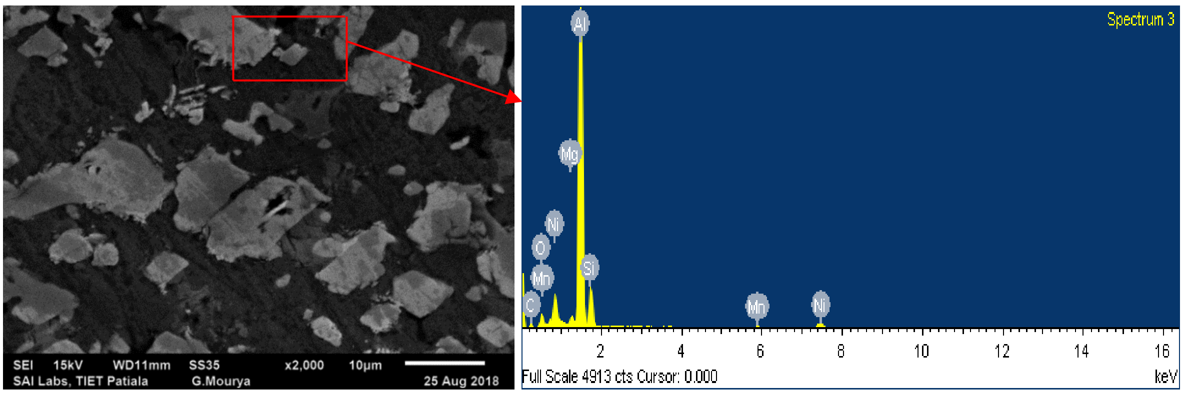


Fig. 3. SEM and EDS image of Al-SiC-Ni hybrid Composite.

Fig. 3 revealed that the SEM image of Al-SiC-Ni hybrid MMC ensures regular distribution of reinforcement particulates within the aluminium alloy without clusters and peaks of Al, Si, C, and Ni in EDS photographs validate the results. Also, the small oxygen peaks confirms the composite protection from oxidation during the fabrication process.

3.2 XRD analysis

The XRD pattern of the Al-SiC composite indicates that a harmful aluminium carbide (Al_4C_3) compound was not formed within the composite (Fig. 4) resulting in improved composite properties than unreinforced alloy [33]. The XRD patterns for Al-SiC-Ni hybrid

AMMCs are shown in Fig. 5 and Fig. 6 indicate the formation of mesoporous nickel silicon aluminium (NiSiAl) mixed oxide compound resulting from the internal reactions of Ni particulates with Si, C, O_2 and Al ingredients. Generally, these mesoporous compound comprises pores with a diameter ranging from 2 to 50 nm [34,35]. The increasing peak length of this compound by increasing the Ni contents indicates the rising intensity of this compound, which in turn increases the porosity level. This increase in porosity levels produces a negative effect on composite properties. Different constituents, like Al, SiC and Ni, are identified in these patterns.

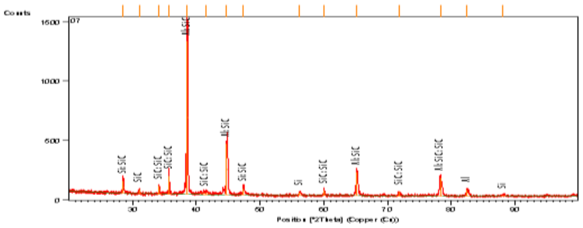


Fig. 4. X-Ray Diffraction pattern of the Al-10%SiC Composite.

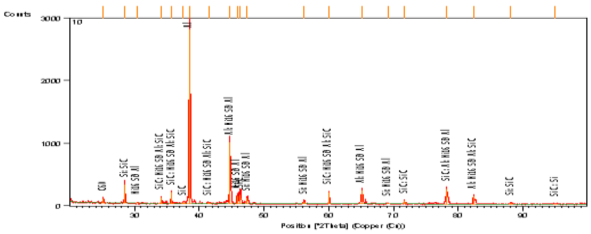


Fig. 5. X-Ray Diffraction pattern of Al-10%SiC-5%Ni hybrid Composite.

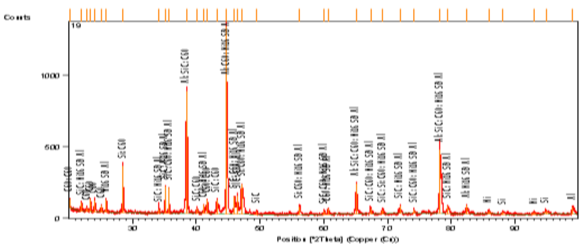


Fig. 6. X-Ray Diffraction pattern of Al-10%SiC-10%Ni hybrid Composite.

3.3 Optical Microscopy

The optical micrographs of mono and hybrid AMCs are shown in Fig. 7 which depicts a tree-like dendritic structure formed in the composite casting and reinforcing materials distributed evenly throughout the matrix grain structure. It has also been observed that more refinement in grain structure is observed in Al-SiC-Ni hybrid composites than in Al-SiC mono composites. This refining microstructure possesses a beneficial effect on the wear resistance of the AMMCs [36].

3.4 Microhardness Test

It has been observed that the microhardness of newly developed composites enhance significantly with the addition of hard reinforced particulates the aluminium alloy and increases with increasing their percent composition. The improvement is attributed to hard Ni and SiC particles, which restrict the dislocations and increases the hardness [37]. The variation of hardness with Ni contents is shown in Figure 8.

3.5 Tensile Test

The tensile test shows a marginal improvement in the tensile strength and elongation in the Al-10%SiC-5%Ni hybrid composite. This enhancement may be due to better bonding among the constituent particles along with a small increase in the porosity level. However, increase in the nickel composition beyond 5% resulting in a negative effect on the strength and elongation as shown in Fig. 9. This reduction in strength and elongation is due to the formation of mesoporous NiSiAl compounds, which produces negative impact on the material strength by increasing the porosity level [34,35].

3.6 Wear Test

The outcomes of the pin-on-disc wear test indicate a slight reduction in the wear rate composite (or increase in wear resistance) of the base with the inclusion of 5% hard nickel together with 10% SiC particulates in the base matrix and the credit goes to the hardness of the reinforced particulates [38] and their even distribution. The effect of nickel composition in AMCs is shown in Fig. 10. An increase in wear was also observed when nickel composition increases upto 10%. This is due to the increasing intensity of the unwanted mesoporous compound formed within the composite, which possessed a harmful effect on the wear resistance property. A small increment in the friction coefficient of the base composite is also observed. This is due to increasing in the "resistance to plastic deformation" by the nickel particulates in the base composite.

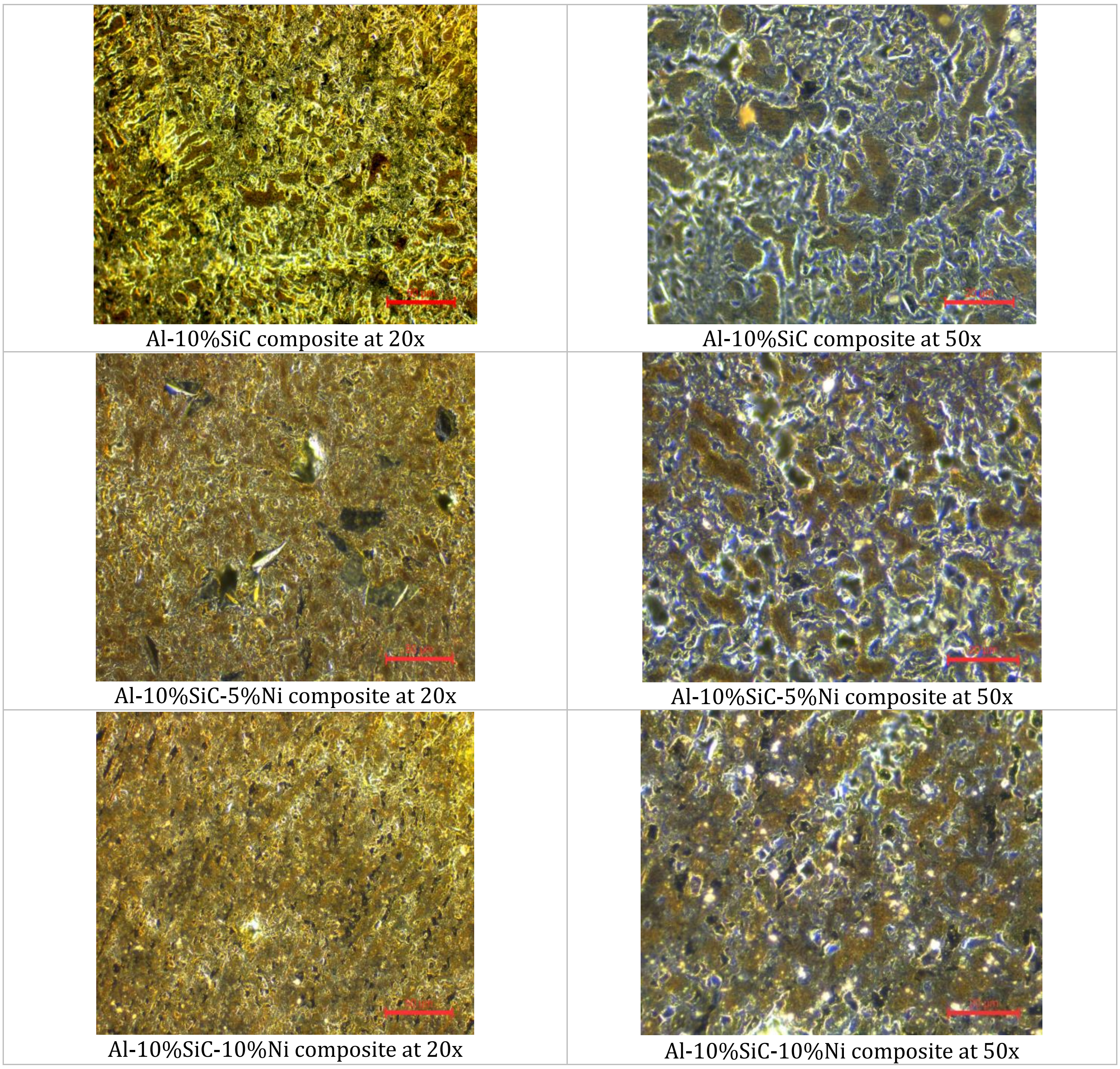


Fig. 7. Optical Micrographs of the AMMCs at different magnifications.

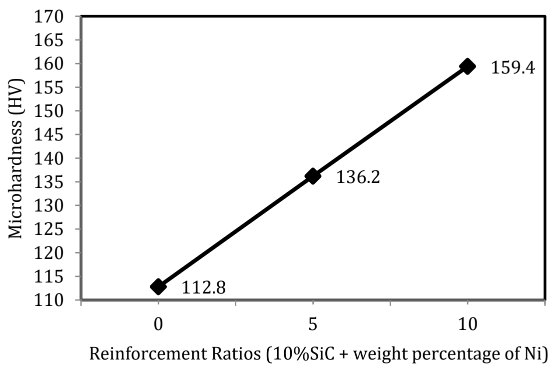


Fig. 8. Impact of nickel particulates on the microhardness.

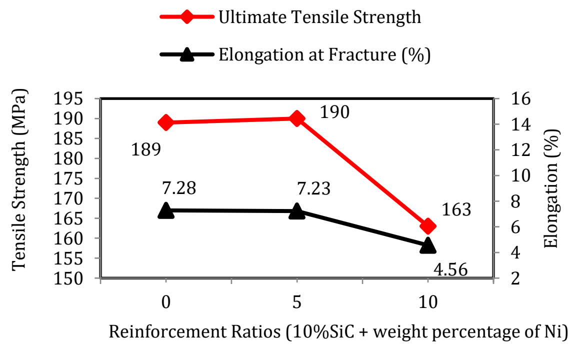


Fig. 9. Impact of the nickel particulates on the tensile strength and elongation.

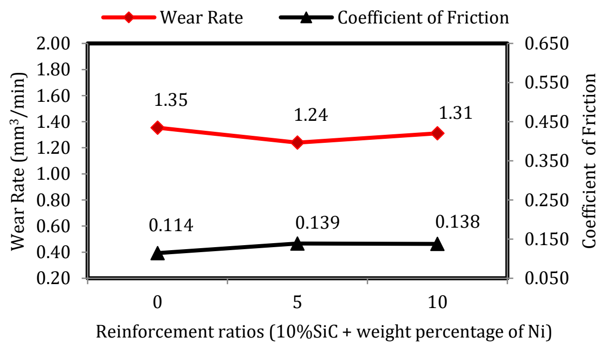


Fig. 10. Impact of nickel particulates on the wear rate and friction coefficient.

3.7 Density and porosity analysis

From density analysis an increase in density of the base composite and matrix is observed due to the addition of dense silicon carbide and nickel particulates in them together with increase in the porosity level as shown in Fig. 11. This is due to the formation of unwanted mesoporous NiSiAl compound within the hybrid composites, whose intensity is increased with increasing the composition of nickel particulates [34,35]. However, newly developed composites are free from casting defects as the porosity level < 5% [38-45].

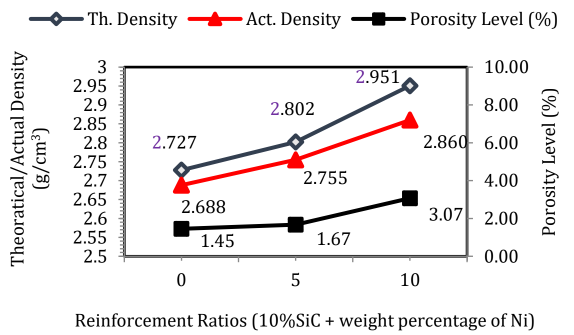


Fig. 11. Impact of nickel particulates on the density and porosity level.

3.8 Scratch Test

From Fig. 12, it is evident that the traction force (which is required to make scratches on the material surface) is increased with the addition of nickel particulates. It is due to the presence of hard reinforcements in the composite resulting in enhance scratch resistance. Similar results were also observed in the hardness test. Moreover, an increase in the apparent coefficient of friction is also observed in the composite which increases with increasing the nickel particulates.

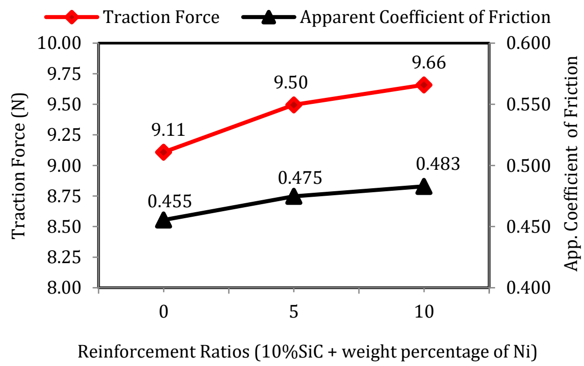


Fig. 12. Impact of nickel particulates on the traction force and abrasive friction.

4. CONCLUSIONS

In this research work, silicon carbide and nickel reinforced AMMCs were fabricated using the liquid vortex casting with an aim to determine the effect of silicon carbide and nickel particulates addition on the base aluminium alloy. The consequences drawn from this study are as under:

- Stir casting is suitable to fabricate SiC and Ni particulates reinforced hybrid AMMCs.
- In an Al-SiC composite, silicon carbide particulates are evenly distributed within the aluminium matrix without clusters. The formation of dendritic-type microstructure is also observed in the AMMCs. Moreover, the unwanted secondary phases (like Al4C3) were not formed in the composite resulting in a positive impact on the matrix properties. An increment in the microhardness, tensile strength, wear resistance and traction force was also observed along with a small decrement in the elongation and CoF. The porosity level in the newly developed composite is less than the predetermined limit.
- In Al-SiC-Ni hybrid composites, silicon carbide and nickel particulates were dispersed evenly within the base aluminium matrix without clusters. Also, mesoporous nickel silicon aluminium (NiSiAl) mixed oxide compounds were formed within the composite and the intensity of this compound is increased with the increase in the composition of nickel particulates. A more refined grain structure in hybrid composites

is obtained when compared with the base Al-SiC composite. The addition of 5 % nickel together with 10 % silicon carbide in aluminium shows a significant improvement in the hardness, wear resistance, and traction force along with marginal gain in strength and negligible loss of elongation and gain in friction coefficient value, when compared with Al-SiC composite. However, all these obtained values are much better than unreinforced alloy.

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