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Enhanced Tribological Performance of AA2024-Based Hybrid Metal Matrix Composite Reinforced with SiC and CNT: A Comprehensive Study

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Abstract:- Aluminum Metal Matrix Composites (AMMCs) are widely used engineering materials in a variety of fields, particularly in the aerospace and automotive industries due to certain specific properties such as high strength and stiffness, thermal stability, corrosion and wear resistance, and fatigue life. In the present study, the hybrid metal matrix composite with AA2024 as a matrix and SiC and CNT as reinforcements was fabricated with different wt% combinations of reinforcements using liquid stir casting method. The prepared specimens were then subjected to tribological and microstructural characterization to assess the suitability of the composite for the specific applications. The frictional force, coefficient of friction and wear rate were determined by using linear reciprocating wear analysis. The results reveals that the specimen AA2024-0.25%SiC-0.75%CNT composition exhibits lowest wear rate of 2.222 $x10^{-6}$g/Nm, 2.083 $x10^{-6}$g/Nm and 1.3168$x10^{-6}$g/Nm at three different loads 5N, 10N and 15N respectively when compared with the other composition. SEM analysis was done to study the microstructure of prepared specimens.

Keywords: *Reciprocating wear, Gravity die casting, Frictional force, Wear rate, coefficient of friction*

1. Introduction

In the past 50 years, metal matrix composites (MMCs) have emerged as a key category of advanced materials. These composites combine a pure metal or alloy matrix with ceramic or metal fibers for reinforcement. Studies have shown that MMCs reinforced with ceramic particles exhibit significant strength and wear resistance, albeit with moderate toughness [1]. Their importance spans various industries, including aerospace, automotive, and marine, owing to their augmented strength, stiffness, modulus of elasticity, low thermal expansion, and enhanced tribological behavior [2].

Aluminum alloys, renowned for their lightness, strength, and ductility even at low temperatures, are non-toxic and highly corrosion-resistant. Commonly utilized in composite manufacturing are aluminum alloys from the 2000, 5000, 6000, and 7000 series [3]. While these alloys find applications in tribology, their wear resistance is relatively low. This has spurred a demand for aluminum composites to enhance their tribological properties. Aluminum metal matrix composites (MMCs) are created by reinforcing an aluminum alloy [4]. Among these, aluminum alloy AA 2024 stands out for its remarkable fatigue resistance, high strength-to-weight ratio, low density, and superior mechanical attributes. This alloy is extensively employed in the aircraft industry due to its exceptional performance. In comparison to conventional metals and alloys, AA 2024 also offers superior wear and thermal expansion coefficients, high electrical and thermal conductivity, high reflectivity, ductility, and strength at a relatively low cost [5].

Common reinforcements in MMCs include flyash, molybdenum disulphide, WC (tungsten carbide), Al2O3 (alumina), graphite, and B4C (boron carbide) [6]. SiC particles, characterized by high hardness, excellent electrical conductivity, chemical durability, and outstanding temperature resistance made it suitable for MMC manufacturing. Additionally, Carbon Nanotube (CNT) materials, known for their superior physical and mechanical properties, are gaining prominence. MMCs made with CNT as a reinforcing material demonstrate higher thermal stability and superior wear resistance compared to other materials [7].

Ramezanali et al. [8] investigated the effect of stir casting parameters including stirring speed, stirring time, and temperature on the microstructure and mechanical properties of AA2024 aluminum alloy composites reinforced with Al-Ni intermetallic compounds. It was reported that stirring temperature has a dominant effect on raising Al_3NiCu intermetallic compounds. Similarly, studies by Vijaya et al. [4] focused on fabricating MMCs with AA2024 using SiC and Fly Ash, revealing a reduction in wear with increasing weight % of FA and SiC particles in the matrix. Muniyappan et al. [5] examined various characteristics of aluminum alloy AA 2024 in the presence of silicon (Si) and carbon nanotubes (CNTs), observing greater dry-sliding wear resistance in hybrid composites with higher reinforcements compared to unreinforced AA2024. Bhaskar et al. [9] analyzed the tribological features of hybrid aluminum metal matrix composites, reporting a decrease in wear as reinforcement (FA + SiC) is increased from 5% to 15%.

Shayan et al. [10] used stir casting to manufacture AA2024-TiO_2 hybrid nanocomposites. Their investigations showed that adding nanoparticles to the matrix alloy decreased the grain sizes of the hybrid nanocomposites. Senthil et al. [11] studied the fabrication and characterization of the AA2024/Al_2O_3/SiC metal matrix composite using squeeze casting, investigating the influence of particle size and Al_2O_3/SiC reinforcement weight % on the mechanical and tribological characteristics. Anil kumar et al. [12] focused on the fabrication and characterization of the AA2024/SiC/Gr/Fly Ash using stir casting, emphasizing the importance of process parameters for achieving homogeneous reinforcement distribution.

Rahman et al. [13] conducted morphological characterization on Al infused with SiC as a reinforcement using stir casting. Their tests included microstructure, hardness, tensile, and wear testing, revealing clustering and non-homogeneous dispersion of SiC particles in the Al matrix, along with increased porosity with higher SiC reinforcing weight %. Harish et al. [7] summarized the effects of reinforcements like SiC and CNT in the aluminum matrix, highlighting better wear resistance and thermal stability of MMCs prepared with CNT as the reinforcing material. They also noted challenges in achieving uniform dispersion of SiC and CNT at high percentage concentrations during bulk manufacture of MMCs. Mohammed et al. [14] reviewed CNT as a reinforcement in Al matrix composites, emphasizing their positive impact on improving the mechanical characteristics of MMCs.

The ongoing need for lighter yet efficient products has driven a substantial demand for metal matrix composites (MMCs). This necessitates the continuous search for new materials to surpass current options. One such material is AA2024, an aluminum-copper alloy commonly used in rivets for the automotive and aerospace industries. Due to its exceptional strength and fatigue resistance, AA2024 finds extensive use in airplanes, particularly in stressed wing and fuselage components. Consequently, this alloy presents a significant area for research, with the potential for creating a composite with enhanced properties. This study focuses on fabricating an aluminum metal matrix composite with AA2024 as the matrix, reinforced with SiC and CNT, followed by an evaluation of its tribological properties and microstructure.

2. Materials and Methods

2.1.1 Matrix Material

The matrix material selected for this study is the AA2024 alloy, which is primarily composed of copper as the primary alloying component and magnesium as the secondary alloying element. The aerospace industry extensively utilizes AA2024 due to its excellent mechanical properties, which include its lightweight, high electrical conductivity, and corrosion resistance. The general chemical composition of AA2024 is presented in the table below1.

Table 1: Chemical composition of AA2024

Alloy	Cu	Mg	Mn	Si	Zn	Cr	Fe	Ti	Others	Al
AA2024	3.8–4.9%	1.2-1.8%	0.3-0.9%	<0.5%	<0.25%	<0.1%	<0.5%	<0.5%	<0.05%	Bal.

Figure 1. AA2024 alloy bars

2.1.2 Reinforcement Material

2.1.2.1 Silicon Carbide

Silicon carbide in the form of grey powder was used as a reinforcement for manufacturing of the composite. The SiC particles used in the casting was of F320. The grit size of SiC was in the range of 300-400 grit size. The silicon carbide reinforced composites tend to show enhanced mechanical properties like hardness.

Figure 2. Silicon Carbide powder

2.1.2.2 Carbon Nanotube

Multiwalled Carbon Nanotube was used as a second reinforcement for the manufacturing of the composite. CNT was bought from Adnano Technologies. From the literature survey, it was observed that CNT reinforced composites exhibited enhanced mechanical as well as wear properties.

Figure 3. Multiwalled CNT powder.

2.2 Die Design

The material used for the making of die was H13 which is a chromium hot work tool steel generally used in the industries. The die was made a spilt die shown in the Fig 4 reveals six slots of cavity in the metal die. The diameter for the cylindrical slots was set to 25mm. The length of the slots was made to 110mm.

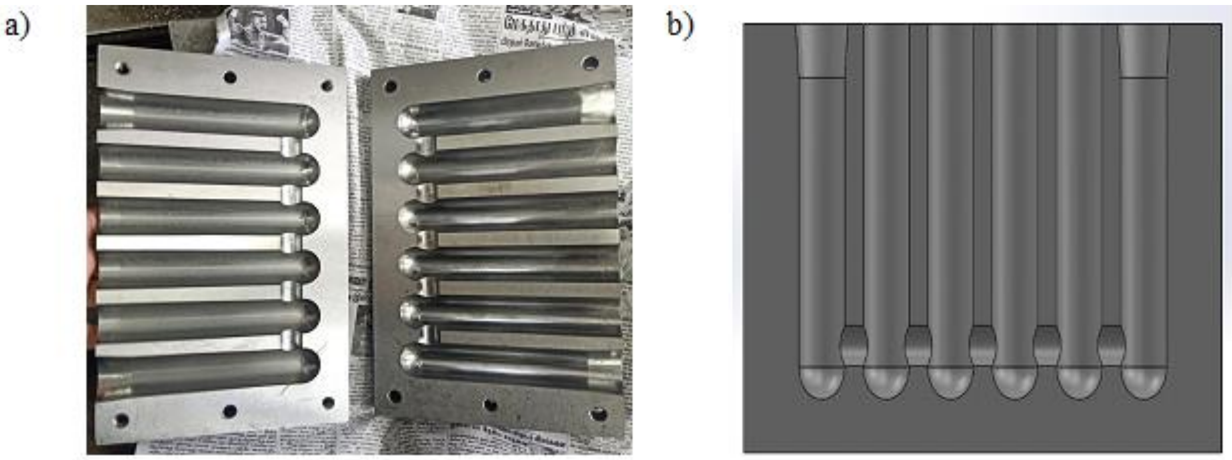

Figure 4. H13 metal die.

2.3 Composition

The composition of reinforcements used to cast the hybrid metal matrix composites are as follows:

Table 3: Different composition reinforcements for composites preparation

Sl No.	**Wt% of SiC**	**Wt% of CNT**
1	0	0.25
		0.5
		0.75
		1
2	0.25	0.25
		0.5

		0.75
		1
3	0.5	0.25
		0.5
		0.75
		1

2.4 Liquid Metal Stir Casting Method

The hybrid metal matrix composite was fabricated considering AA2024 as a matrix alloy and SiC and CNT as reinforcements of the composite. The process includes the melting of base alloy AA2024 with the help of muffle furnace was kept at 850°C. The die was prepared for the pouring of the liquid metal by applying chalk powder into the cavity of the die. As the base alloy melts, reinforcements SiC and CNT were added to the melt according to wt% of the composition. Degassing tablets of cleansing hexachloroethane were used. The mechanical stirrer was introduced into the melt to ensure uniform dispersion of the reinforcements. The stirrer was kept at 500rpm for 5min of time. The liquid melt was then poured into the prepared die. The liquid hybrid metal matrix composite was then allowed to solidify for approximately 3-4 hrs.

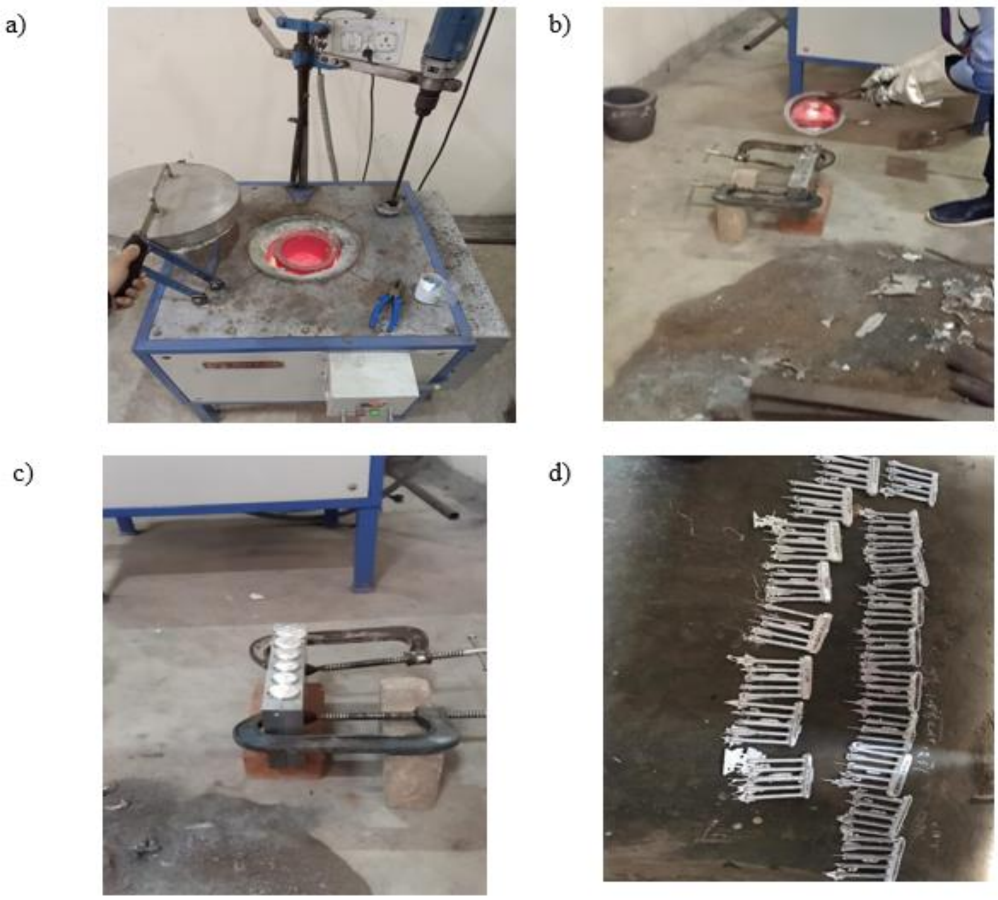

Fig 5. Die casting

2.5 Wear Analysis

In this study, linear reciprocating wear analysis was used by considering three independent variables sliding velocity, load and time. Coefficient of friction, frictional force and wear rate were interpreted from the wear test. The sample size for test equipment is 6mm diameter and 15mm length. The parameters chosen for performing the wear test are as follows:

Table 4: Process parameters for wear analysis:

Load (N)	**Velocity (m/s)**	**Time (min)**
5	0.02	15
10	0.04	30
15	0.06	45

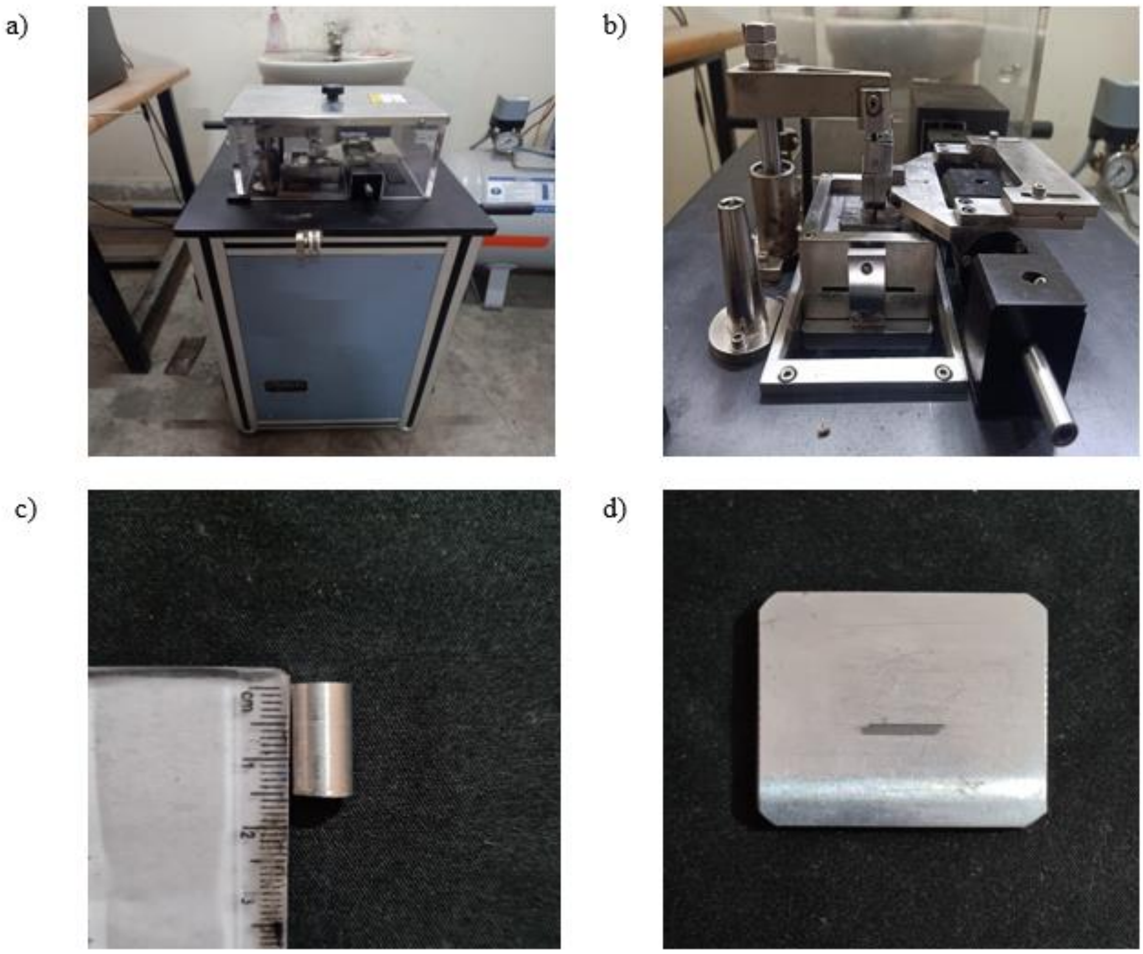

Figure 6 Sample for Reciprocating wear test. a) Linear Reciprocating test rig b) closeup look of wear test equipment c) Test specimen d) Base plate EN32

The weight of the test specimen was noted before starting of the experiment. The test specimen was fixed firmly into the pin holding place. With the help of computer software WINDUCOM 2010, the parameters of the experiment were set. The experiment rig was set on and it automatically the experiment starts with the set input parameters. As the experimentation cycle gets over, the result graphs for the coefficient of friction and frictional force were captured in the computer. The weight of the test specimen was also recorded after the completion of experiment. With the help of noted weight loss, the wear rate was calculated for the tested specimen.

2.6 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is an advanced and powerful analytical tool that outperforms traditional light microscopy. A compound microscope's standard array of magnifying lenses makes it possible for sample magnification of up to 1000x using visible wavelengths of light in the 400 - 700 nanometer (nm) range. This allows investigators to optically resolve points in a specimen that are no more than 200nm apart. Topographical features in close proximity to this lower detection range cannot be reliably distinguished. SEM was carried out to study the microstructure of the casted base alloy AA2024. SEM was carried out to study the morphology of the wear out specimen. The samples which were undergone SEM analysis are:

Sample 1: AA2024.

Sample 2: AA2024-0.25%SiC-0.75%CNT

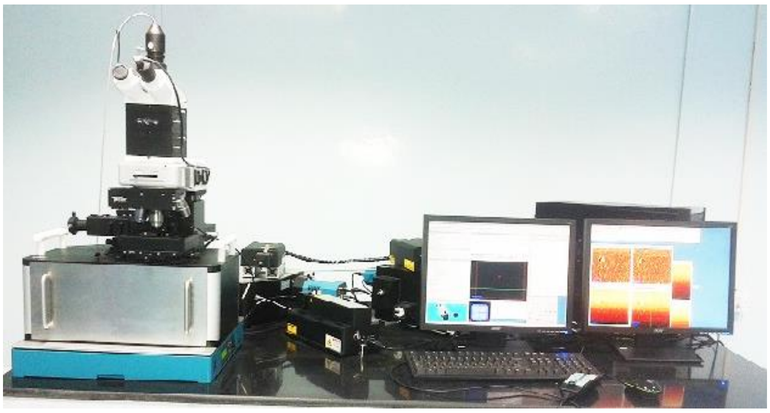

Figure 7. SEM Equipment.

3 Results and Discussion:

3.1 Tribological Analysis

The tribological analysis was performed on linear reciprocating wear testing rig. It was done on all the samples with different compositions. The wear test was undergone to get the output of coefficient of friction, frictional force and wear rate of each sample which will determine the tribological properties.

The independent parameters used for performing the test are sliding velocity, time and load. Three levels of each parameter were chosen for the test. The three sets of experiments with different level of values were performed.

As the per the result data obtained by performing the test, it can be said that as the percentage weight composition of the SiC and CNT increases the wear rate of the sample decreases and then again it increases further. The lowest wear rate among all the samples noted was of $1.3168x10^{-6}$g/Nm AA2024-0.25%SiC-0.75%CNT.

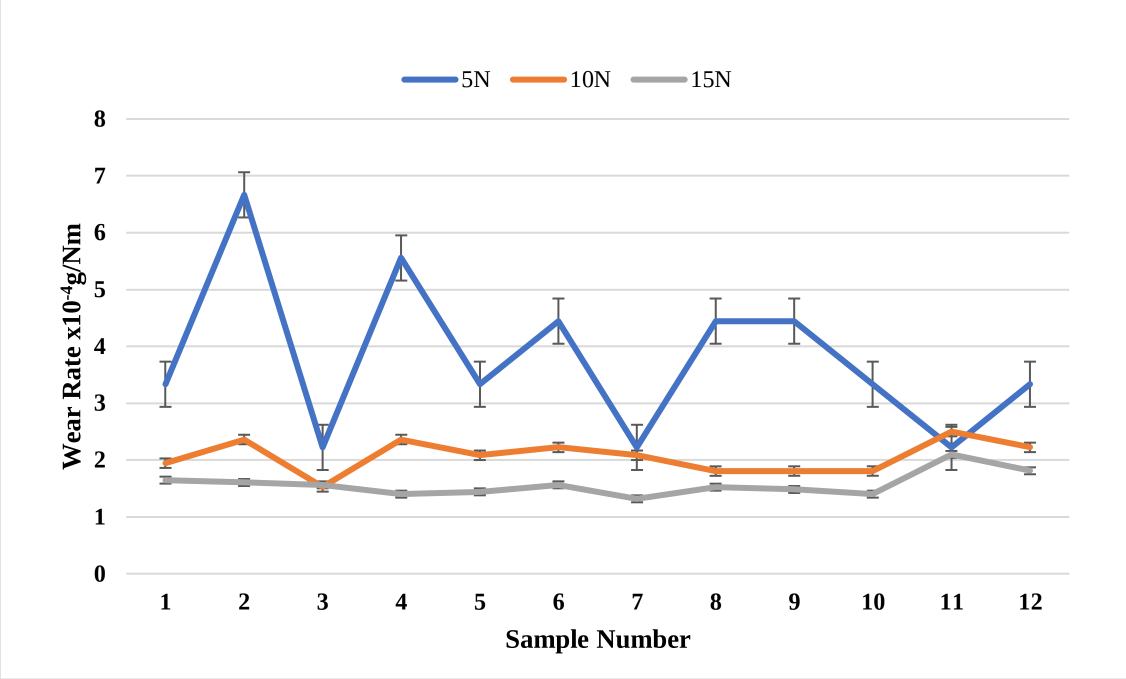

Figure 8. Graphs of wear analysis for Wear Rate vs Load.

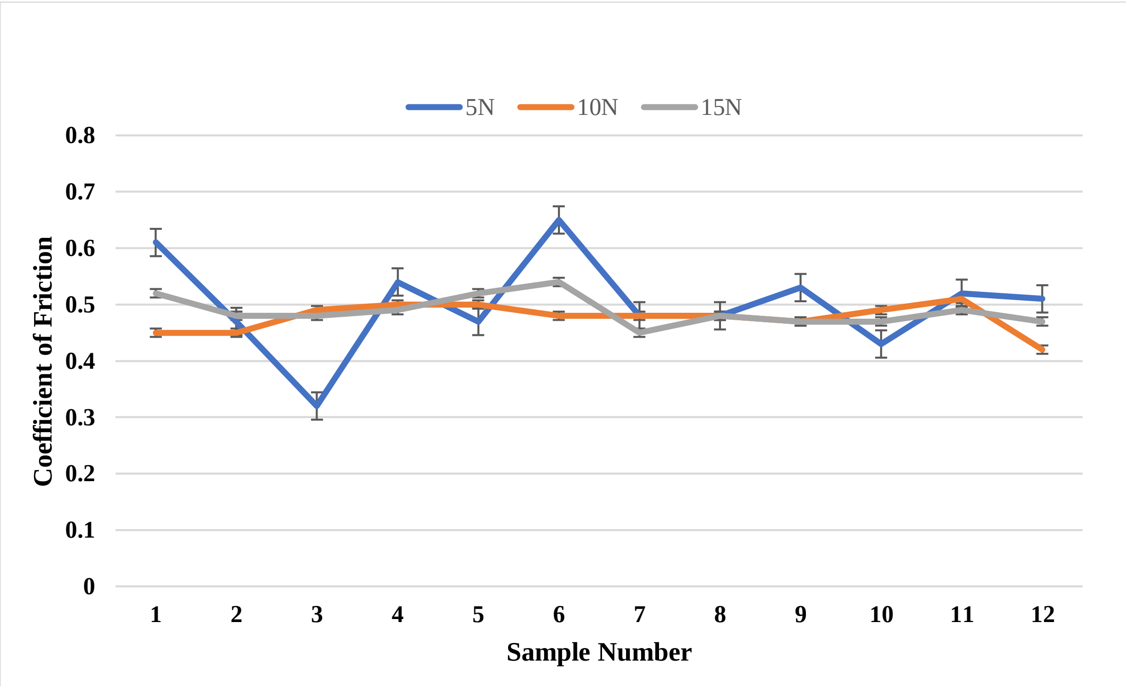

Figure 9. Graphs of wear analysis for Coefficient of Friction vs Load

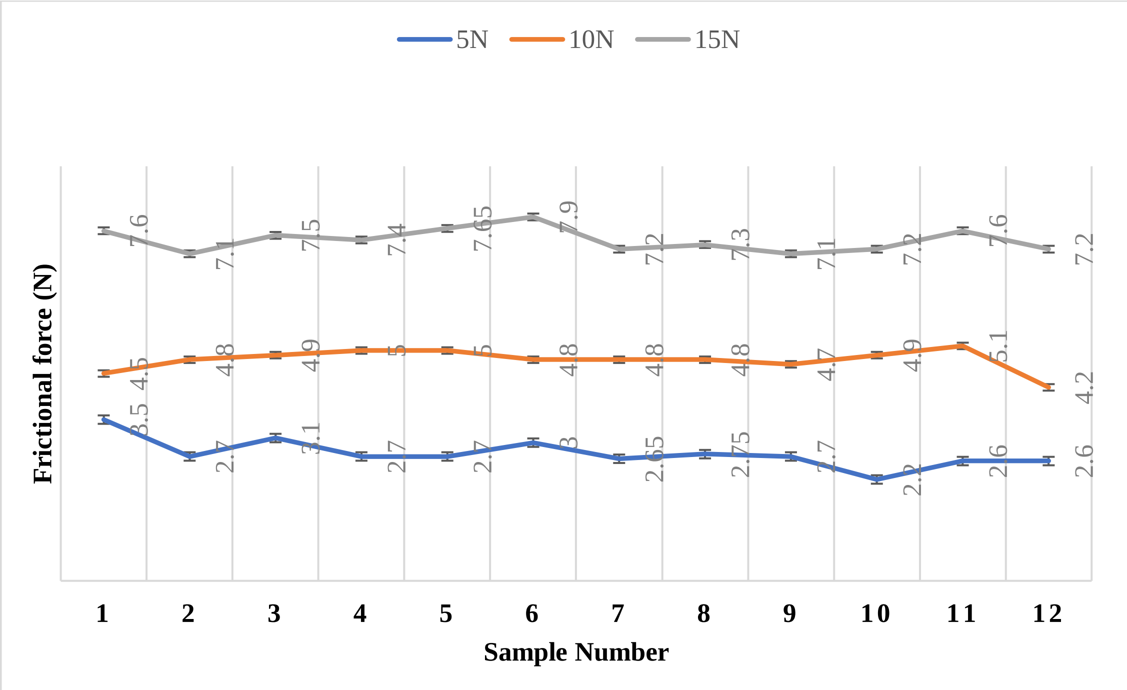

Figure 10. Wear analysis for Frictional Force vs Load

Figure 8, 9 and 10 shows the graphical representation of the coefficient of friction, wear rate and frictional force vs load respectively. The wear rate line graph for 5N shows deviation of values of wear rate among all the samples. The lowest recorded wear rate for the 5N load is of $2.222x10^{-6}$g/Nm for the sample seven with composition of AA2024-0.25%SiC-0.75%CNT. Similarly, for the 10N and 15N load line graphs the lowest recorded wear rate is also for the sample seven with composition of AA2024-0.25%SiC-0.75%CNT. The wear rate values recorded for 10N and 15N load are $2.083x10^{-6}$g/Nm and $1.3168x10^{-6}$g/Nm respectively.

The coefficient of friction line graph is given above in Figure 9. The coefficient of friction line graphs for all the load shows a general trend that as the load increases the coefficient of friction decreases. The corresponding value of coefficient of friction for the sample seven which had least wear rate for 5N, 10N and 15N load are 0.48, 0.47 and 0.45 respectively.

The frictional force line graph is given in Figure 10. The general trend for frictional force line graph vs load shows that when the load is increased the frictional force also increases with it. The values of frictional force for sample seven for 5N, 10N and 15N loads which recorded the least wear rate are 2.65N, 4.8N and 7.2N respectively.

The wear rate line graph results show an unusual trend of decreasing the value of wear rate and then again increasing. The reason due to which this unusual trend is observed can be explained as the percentage weight of SiC and CNT increased to a certain percentage, the value of wear rate kept on decreasing. As the percentage weight of the SiC and CNT increased more than a certain percentage, the value of wear rate kept on increasing.

The material properties like hardness, toughness, etc are imparted on using SiC and CNT as reinforcement in a metal matrix composite, but when excess amount of SiC and CNT is added, the composite acts as a brittle material. Thus, the value of wear rate kept on increasing after certain percentage weight of SiC and CNT [4].

3.2 Microstructural Characterization

The scanning electron microscopy was carried out to study the close view of the interior structures of aluminum samples. The SEM was performed on the two of the samples out of all the samples fabricated. The samples which were undergone for the SEM imaging were:

Sample 1: AA2024

Sample 2: AA2024-0.25%SiC-0.75%CNT.

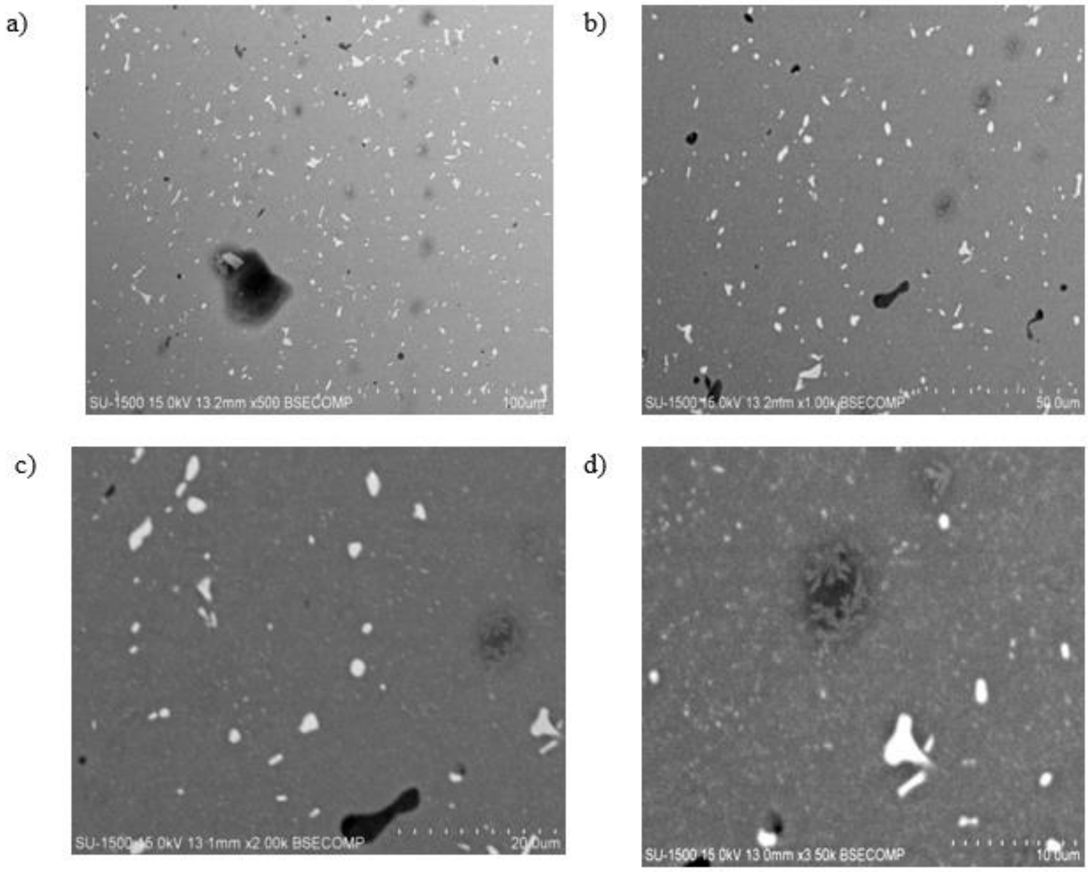

Figure 11. SEM images of AA2024 at a) 500X b)1000X c) 2000X d) 3500X

From the Figure 11, it was observed from the microstructure of the AA2024 that microporosities were present in the casting. The development of Al Cu intermetallic particles, which strengthen the alloy, is the reason of the rise in strength. The bright area in the figure indicates the existence of an Al-Cu intermetallic complex at the grain boundaries.

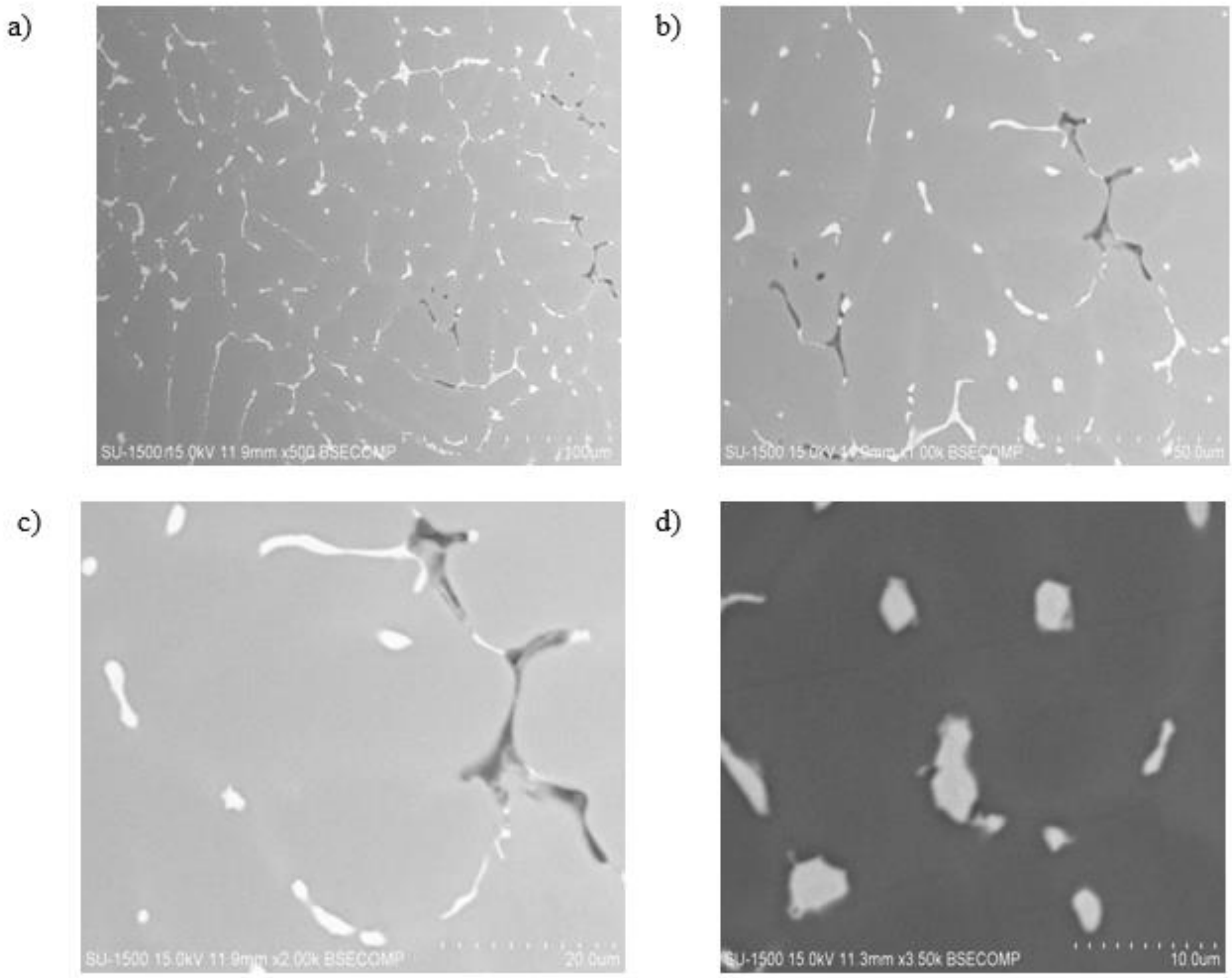

Figure 12 :SEM images of AA2024-0.25%SiC-0.75%CNT at a) 500X b) 1000X c) 2000X d) 3500X

Figure12 shows the microstructure at various magnification of the fabricated composite with reinforcements in it. From the image, it is observed that uniform distribution of the reinforcements is seen because there was no segregation of SiC particles and CNT particle. Thus, uniform distribution of the reinforcements was observed. The bright line in the Figure indicates the intermetallic complex of Al-Cu at the grain boundaries. The SiC and CNT reinforcements can be represented by the black colored line on the grain boundaries. There was no porosity found from SEM images of the fabricated composite, which suggests that to cast a product with minimum defect, bottom gating system or anti-gravity gating system is more suitable.

4 Conclusion

In the present study, the fabrication of the hybrid metal matrix composite with AA2024 as matrix material and SiC and CNT as reinforcement materials was done using liquid stir casting method. Further, the fabricated samples were subjected to tribological analysis as well as microstructural characterization and the results were interpreted. The following conclusions were interpreted:

- The fabrication of the hybrid metal matrix composite was performed successfully with the help of liquid stir casting method.
- As the %wt of reinforcements and wear rate are inversely proportional, with the increase in %wt of reinforcements in the sample the wear rate decreases. The lowest wear rate was observed for the sample with composition of AA2024-0.25%SiC-0.75%CNT, i.e. for 5N, 10N and 15N load, the wear rates recorded were $2.222x10^{-6}$g/Nm, $2.083x10^{-6}$g/Nm and $1.3168x10^{-6}$g/Nm respectively.

- From the SEM images, no porosity was observed in the fabricated hybrid metal matrix composite.
- Uniform distribution of reinforcements was observed in the fabricated hybrid metal matrix composite.

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