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Microstructure and Properties of Silicon Carbide and Yttrium Oxide Reinforced Copper Matrix Hybrid Composites (Cu-SiC-Y_2O_3)

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Hybrid metal matrix composites (MMCs) have a higher potential for widespread use in structural engineering and functional device applications because they show better overall mechanical and functional response than their conventional equivalents. Silicon Carbide (SiC) and Yttrium Oxide (Y_2O_3) reinforced Copper hybrid composites were produced by powder metallurgy (PM) process sequence. Both the reinforcements were included in the wt. % of 2.5, 5.0 and 7.5. The homogeneous presence of SiC and Y_2O_3 particles in copper MMC's was confirmed by morphology and characterization studies. The blended milled powders were produced in the form of cylindrical billets using a punch and die arrangement, by cold compaction method at 400 MPa pressure, in a hydraulic press. Sintering was carried out at 900°C for 5 hours in a Box furnace. The inclusion of SiC and Y_2O_3 in the copper matrix composites improved the density, hardness, compressive strength (CS), wear resistance and decreased the corrosion rate (CR).Pin on disc (POD) experiments was conducted to study the wear behavior of the composite samples. The minimum wear rate (WR) 3.31049 x 10^{-4} mm^3/m was obtained for the composite contain 7.5 wt. % of SiC and 7.5 wt. % of Y_2O_3.

Keywords: *Copper Hybrid Composites, Microstructure, Powder metallurgy, Silicon carbide, Yttrium Oxide.*

1. Introduction

In recent years, copper matrix composites (CMCs) have established a prominent place as an engineering material having great potential in view of their superior mechanical properties and wear resistance[1]. Inclusion of reinforcement particles and secondary processing enhances the wear properties of the copper composites[2]. Hybrid composites show the upgraded mechanical properties and lower electrical conductivity than its matrix also relatively lower density was found and reveals brittle nature[3]. Literatures conveyed that, accumulation of TiC in CMCs upgraded the properties of the composites[4]. Including graphene in CMCs had little adverse effect on thermal and electrical conductivity. But, remarkable improvement in tribological performance was noted leading to electrical applications[5].While increasing the high energy ball milling time without any loss of ductility, the tensile behavior of the composites improves and reducing the $MoSi_2$ particle size[6].

The thermal technique was used in monolithic Cu and Cu–Al_2O_3 nanocomposites. Rising alumina content up to 12.5% in Cu resulted in a marked enhancement in mechanical properties. The wear rate of the pure copper was found to be higher than that of the nanocomposites[7]. Copper composites with SiC-graphite reinforcement are used in heat exchangers. Adding copper decreases the density of hybrid composite while increasing the wear resistance[8]. MMCs are used widely in many industrial applications due to their better density of the composites[9]. Strength coefficient, hardness and strain hardening vary with graphite content in copper matrix composites. Addition of TiO_2 and higher graphite content were found to raise in the stress and strain axiallydue to graphite, enhances the densification, resulting in higher load transfer rate[10]. Raising SiC content beyond 25 wt.% (48 vol.%) in Copper MMC's, the hardness drops due to an severe reduction of the microstructural homogeneity and increased porosity of compact specimens was observed. SEM were used for microstructural study to confirm the availability and even distribution of reinforced materials[11].

Copper/graphite composites exhibit better wear properties and then an graphite reinforced copper composites displayed greater load bearing capacity[12]. Adding $TiO_2$and raise in weight percentage of graphite in aluminium MMC's, increased and

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the formability stress index (β) also increased[13]. The resistivity is decreased in the sintered composites while increasing the sintering temperature, also rising the percentage of W enhances the electrical resistivity of Cu composites[14]. Increasing SiC particles in Al–Cu–SiC composites, the mechanical properties go up, while thermal conductivity shows a decline[15]. Singh and Gautam[16] used HR-SEM to characterize the prepared CMCs to identify the phases availability of the materials and summarized that the properties were upgraded for composites.

Somani et al.[17] concluded that the presence of up to 20% of SiC particles in Cu matrix, the hardness, tensile strength were found increasing, but, the density was reducing owing to higher density of Cu as against SiC. The brake pads play a vital role in high-speed trains that demands a superior mechanical and tribological properties. Therefore, Xiao et al.[18] analyzed the brake pads made of Cu-MMC were produced using powder metallurgy technique. Singh et al.[19] described that CMCs possess better corrosion resistance while comparing pure copper. As regards to performance, The Cu-WC nano composite is ahead of Cu-WC micro composite and copper. A mixture of 80% Cu powder, 15% WC Powder and 5% of groundnut shell ash (GSA) were used having copper as matrix material. Tungsten carbide and groundnut shell ash were used as reinforcements. These reinforcements aids in improving hardness and lowering corrosion rate[20]. Comparing Al MMCs samples to pure Al, adding Y_2O_3 and raising the SiC percentage increases the samples' CS and hardness. SiC was essential in helping to strengthen the composite and record the greatest CS[21].

The hardness values, stress-strain relationships, and ultimate flexural and compression stresses are all impacted by the presence of nano particulates. The inclusion of strong ceramic nano particulates guarantees a 1.5–2.5 times reduction in the momentary coefficient of friction and helps composites runs up quickly. The composition of the nanoadditives has a considerable impact on the wear rate of the composites under study[22]. It has been noted that microwave sintering, as opposed to traditional sintering, removes significant flaws that deteriorate the qualities of composite materials with their special characteristics, such as internal heat generation, low sintering temperatures, and short sintering times[23]. In hybrid composites, the amount of Cu-CNT increases along with the heat conductivity[24]. A viable technique for MMCs with better mechanical performance is the hybrid reinforcement, which combines one-dimensional carbon nanotubes and zero-dimensional nanoparticles to produce a highly effective strengthening effect[25].

The consistent strain distribution found in the hybrid composites was primarily responsible for the increase in ductility. A very high dislocation density near the Al/SiC interface was detected in the distorted AMC-SiC composites, suggesting an early fracture risk[26]. As the weight % of SiC particles on Cu matrix grew, CTE, efficiency factor, and electrical conductivity values decreased, suggesting strong dimensional stability. Additionally, the values increase noticeably as the sintering temperature increases[27]. Hence, the present work aims to fabricate SiC, Y_2O_3 reinforced Copper matrix composite and study their microstructure and properties. The effect of SiC and Y_2O_3 in the copper matrix is studied in detail on the properties.

One of the greatest rare earth oxides for serving as a host material for rare earth ions like samarium, erbium, gadolinium, and europium is yttrium oxide (yttria). Because of their excellent corrosion resistance and great chemical stability, rare earth doped yttria nanoparticles are an excellent material for luminescence applications[28,29]. A layer of debris made of iron and its oxides that formed during sliding provided protection, and the addition of Y_2O_3 greatly increased the coating's resistance to wear. Oxidative wear was identified as the wear process of the Y_2O_3 layer. But during sliding, the coating lacking Y_2O_3 showed signs of brittle debonding and micro-cutting, which were brought on by crack propagation and channeling. As the sliding time for the substrate Ti_6Al_4V increased, the wear process shifted from microcutting alone to a combination of microcutting and adhesive wear[30].

Microstructural research revealed that the addition of yttria powder resulted in a finer microstructure for aluminum. Nevertheless, the metal's Al_3Y phase was present and no yttria particles were seen. During the arc melting process, the yttria particles may melt or break down. The metal was made harder by the Al_3Y phase, residual yttrium in the Al matrix, and a finer microstructure. The enhanced mechanical characteristics of the passive film and its adhesion to the substrate, which may also benefit from residual yttrium in the metal and the generated Al_3Y phase, could be the cause of the increased electrochemical properties of aluminum brought about by the addition of yttria[31]. When up to 2 vol.% of Y_2O_3 nanoparticles were added, the ductility remained largely unaltered, but the tensile tests showed an improvement in the yield and tensile strength of the Mg–Y_2O_3 nanocomposites[32]. MMCs are frequently used in the manufacture of tank armors because boron nitride is an excellent alternative to steel because of its great rigidity and resistance to dissolve in molten steel. For helicopters and other aircraft, lighter parts are necessary. Therefore, it is highly recommended to use strengthened MMC. Conventional spacecraft are strongly advised for usage in space applications since they encounter naturally occurring phenomena such as vacuum, heat radiation, and other radiation variables that are significantly impacted in near-earth orbit. Utilized widely in the automotive sector to produce a range of car parts, such as disc brakes, fasteners, and engine components[33].

2. Experimental Details

There are two most common methods for creating metal matrix nanocomposites are stir casting and powder metallurgy. The powder metallurgy method creates uniform composite goods[34]. When compared to stir casting, the P/M process requires a significantly smaller heat treatment schedule, making it one of the most cost-effective methods for creating high-quality MMNC products with superior mechanical and structural qualities[35]. The present investigation involves pure Copper powder atomized (Spherical) as the base metal of composite, having size 75μm and purity 99%. The reinforcement material used is Silicon carbide (SiC) powder of80 μm with 99% purity and Yttrium Oxide (Y_2O_3) powder.

Figure 1 shows the experimental plan. The mixing was done in a planetary ball milling (speed:350 rpm,2 hours, WC vials, 10 mm diameter WC balls, ball to charge ratio 20:1).

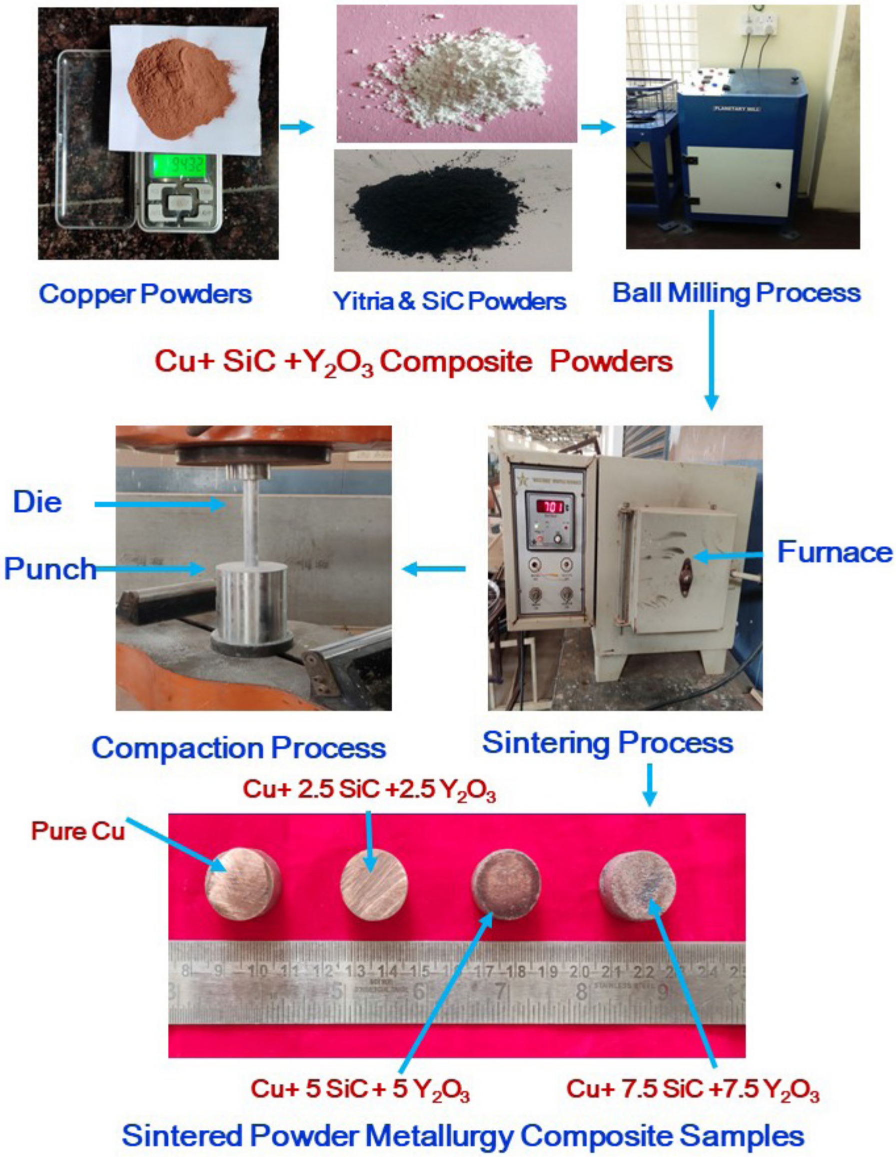

Figure 1. Preparation of composite material using PM technique.

Zinc stearate, a process control agent (PCA) used in ball milling, helps stop powder agglomeration by adhering to the powder particles surface and lowering surface energy and particle friction while the milling process is underway. When working with ductile materials, PCAs are introduced to the milling process to regulate the particle size distribution and avoid excessive agglomeration. The ultimate characteristics of the ground powder, including its size, shape, and reactivity, can be affected by the PCA selection. The composition detail is shown in Table 1. Subsequent to ball milling process, the blends were compacted into cylindrical billets by cold compaction method using a hydraulic press. The compaction setup has a punch and die and 400 KN pressure was applied for compaction. Zinc stearate powder was used as lubricant to prevent the powder getting stuck to punch, die and butt. Sintering of these specimens was done in an electric muffle furnace for 5 hours duration, at around 900°C. After completion of sintering, furnace cooling was done.

Table 1. Composition of composite sample.

Sample No	Cu (% by wt.)	SiC (Wt.%)	Y_2O_3(Wt.%)
1	100	0	0
2	95	2.5	2.5
3	90	5	5
4	85	7.5	7.5

Pin on Disc (POD) was employed to study the ‘WR’ of the CMCs. Standard ASTM G 99 was used to conduct the test. Figure 2 shows the wear test apparatus used for present study. The dimension of the sample 10 mm height

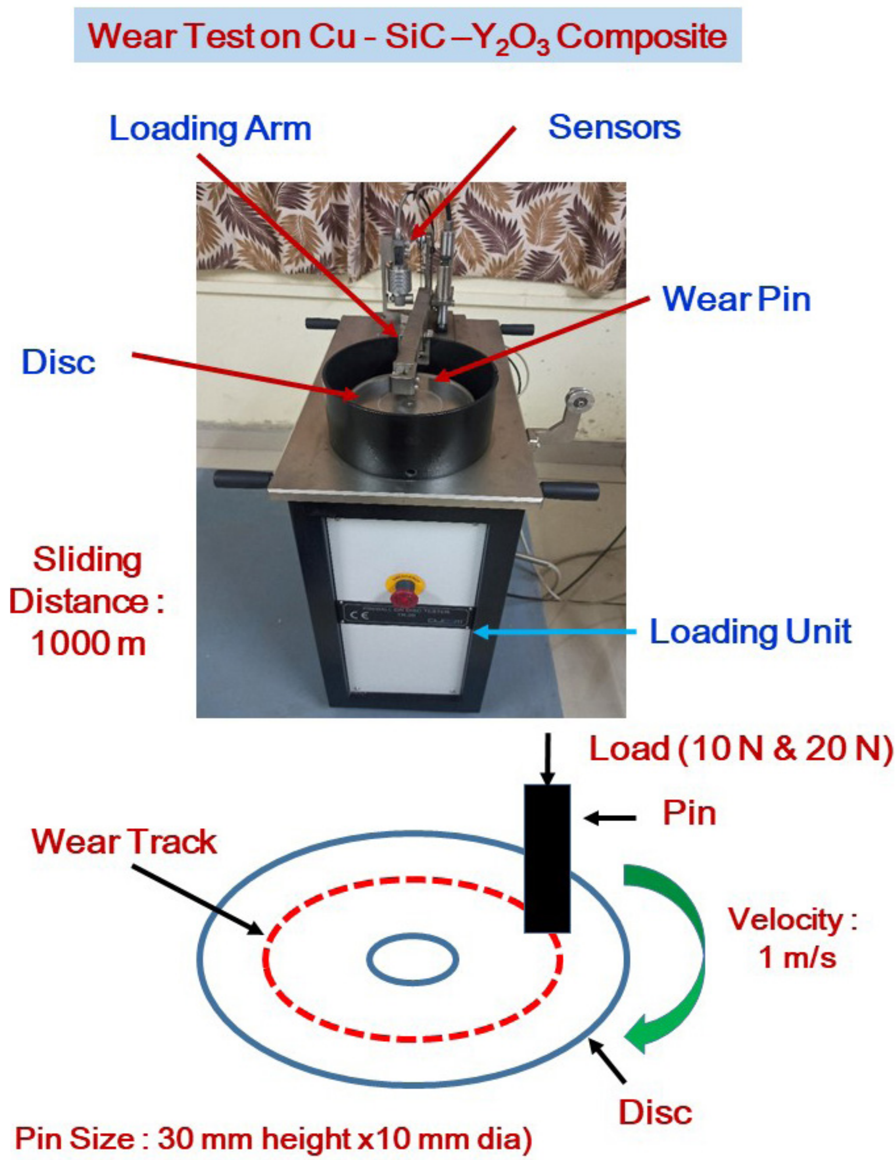

Figure 2. Wear testing apparatus and the parameters.

and 20mm diameter and the sliding distance was 1000 m and velocity was 1 m/s. The two different loads 10 N and 20 N were applied to study the wear rate and COF. For pure copper the adhesive wear mechanism was observed. While adding hard reinforcement like SiC and Yittria the abrasive wear is experienced during testing. Using the TESCAN VEGA3 Scanner Setup the Scanning Electron Microscopy (SEM) were taken for evaluation of the particle size and shape of the powder prior to and subsequent to ball milling process. Figure 3 demonstrates the scanning electron microscope (SEM) images of pure Copper, pure SiC and Y_2O_3 Powders. Using the blue star Universal Testing Machine (UTM) 1000 kN the compression test was done for the produced copper matrix composites. Hardness of the samples have been measured by Vickers hardness test. Densities of the samples have been measure by Archimedes principle. Salt spray test was employed to analyze the corrosion of the prepared CMCs and the details are displayed in Figure 4.

The wear rate in a pin-on-disk (POD) wear test is calculated using Archard's Law, which states that the amount of wear debris is proportional to the applied force and sliding distance (Equation 1).

$$K = W / (\rho FD) \quad (1)$$

Where;

K : Wear factor, in $mm^3/(N \cdot m)$

W : Wear rate of removed material, in mg

ρ : Material density, in mg/mm^3

F : Applied force, in N

D : Sliding distance, in m

While increasing the reinforcement's wt. % more 7.5the strong ceramic reinforcement in metal matrix composites

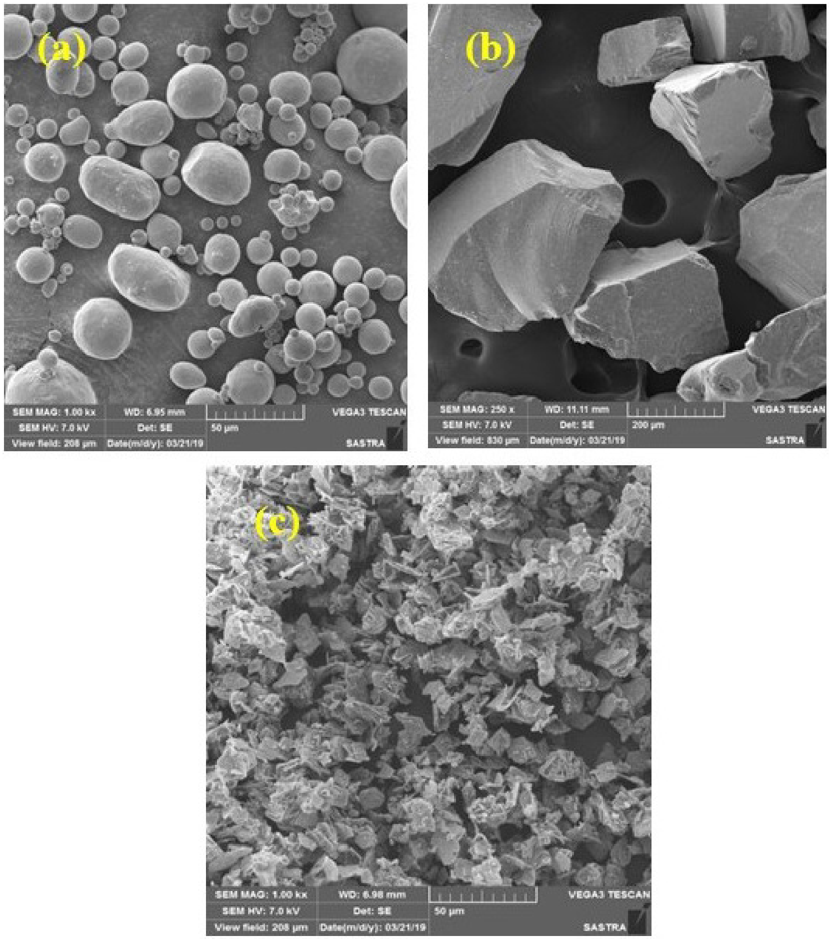

Figure 3. SEM images of (a) Cu, (b) SiC, (c) Y_2O_3 powders.

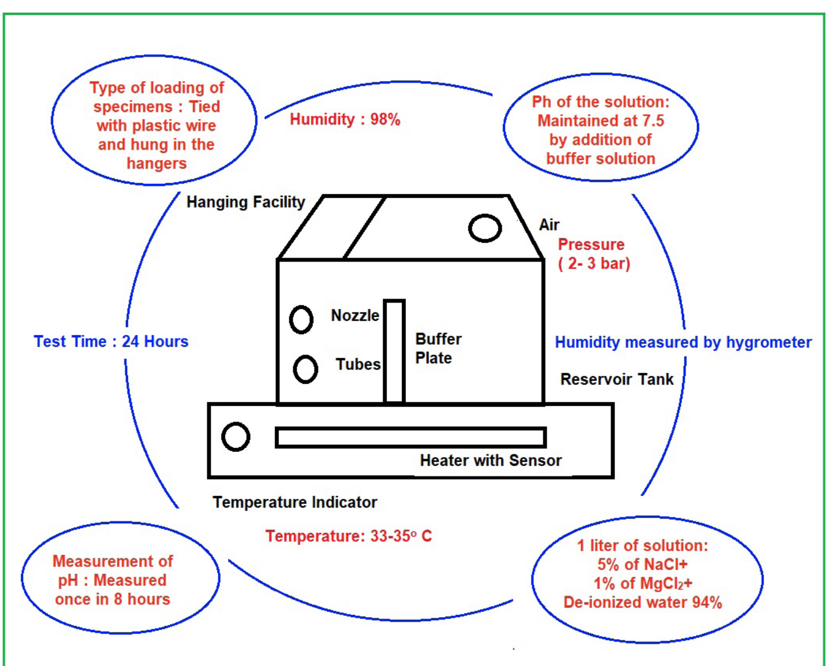

Figure 4. Corrosion test and its parameters**.**

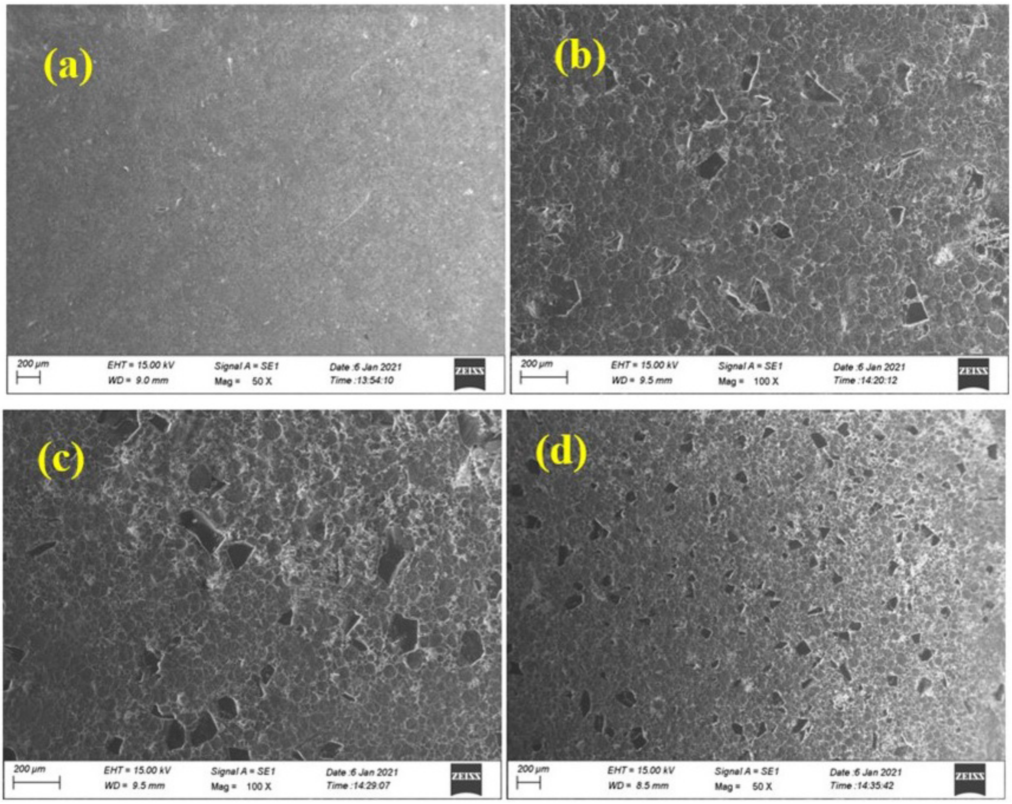

Figure 5. SEM images of (a) Cu(b) Cu-2.5wt.%SiC-2.5wt%Y_2O_3, (c) Cu-5wt.%SiC-5wt.%Y_2O_3, and (d) Cu-7.5 wt.% SiC-7.5wt.%Y_2O_3composites. (c) Cu-7.5 wt. % SiC-7.5wt. %Y_2O_3.

(MMCs) can make MMCs more abrasive, which can wear out other components of the component assembly. This is just one of the drawbacks of increasing reinforcement in MMCs. The hard ceramic reinforcement may complicate other production processes, such as machining. The reinforcing phase may fracture during cooling as a result of the metallic matrix's and the ceramic reinforcement's different thermal expansions. Inadequate wettability between the matrix and reinforcement might cause unintended reactions and slow down the production process and MMC can develop porosity. Ceramic reinforcement is susceptible to breaking.

3. Results and Discussion

3.1. Characterization studies

The SEM images of sintered Copper Matrix Composites of various compositions are shown in Figure 5. It shows that (a) Cu-0wt. %SiC-0%Y_2O_3, (b) Cu-2.5wt%SiC-2.5wt%Y_2O_3, (c) Cu-5wt%SiC-5wt% Y_2O_3 and (d) Cu-7.5 wt% SiC-7.5wt% Y_2O_3.The structure also depicts better attachment between the Cu and SiC and Y_2O_3 particles.

The X-ray diffraction (XRD) spectra ofCu-2.5wt. %SiC-2.5wt. %Y_2O_3, Cu-5wt. %SiC-5wt.% Y_2O_3 andCu-7.5 wt. % SiC-7.5wt. % Y_2O_3 powders is furnished in Figure 6. The XRD results corroborate the existence of SiC and Y_2O_3 in Copper Matrix. The base material Copper and reinforcement material SiC and Y_2O_3 peaks were seen. From the XRD it is also evident that the high peak indicates the presence of Cu and lower peak indicates the SiC and another lower peak indicates the reinforced material Y_2O_3.The diffraction patterns validate absence of any reaction between the base material Cu and reinforcements SiC and Y_2O_3.

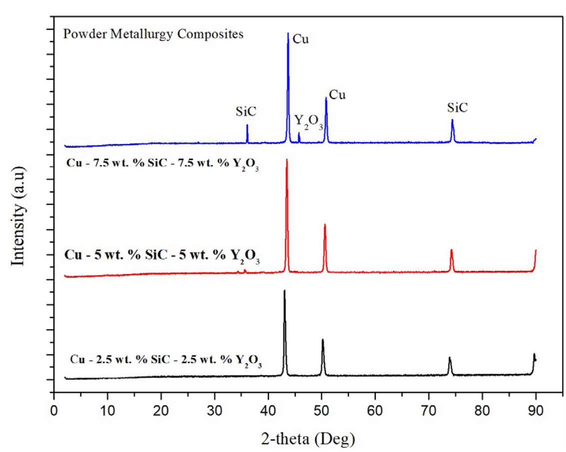

Figure 6. XRD patterns of (a) Cu-2.5wt. %SiC-2.5wt. %Y_2O_3, (b) Cu-5wt.%SiC-5wt.%Y_2O_3

The EDX spectra of different sintered composites, Cu-0wt%SiC-0wt%Y_2O_3,Cu-2.5wt. %SiC-2.5wt.%Y_2O_3, Cu-5wt. %SiC-5wt% Y_2O_3 andCu-7.5 wt% SiC-7.5wt%

Y_2O_3 show the uniform distribution of the elements as seen in the Figure 7 and also observed that copper possessed the strongest peak. The presence of SiC peaks and Y_2O_3 peaks substantiates the occurrence of SiC and Y_2O_3 in the CMC. The SiC and Y_2O_3 peaks rise with the rising SiC and Y_2O_3 weight percentage. The EDX spectrum shows the peak for the elements Cu and Si and Y in the surface of Cu-SiC- Y_2O_3sample. It is observed that SiC and Y_2O_3 are consistently spread in copper matrix.

3.2. Mechanical properties

Composite density and porosity for various reinforcement contents is depicted in Figure 8. It is evident that composite density decreases with increasing SiC and Y_2O_3 content in the Cu MMC. It is also seen that density of the CMCs comprising SiC and Y_2O_3 exhibit lower density than the pure copper. When SiC and Yttrium Oxide are added to composites, their density decreases because of an increase in porosity and the density of Y_2O_3 and SiC is lower that Cu.The ceramic materialsare hard by nature, and exhibit non-deformation characteristic under pressure. However, soft materials such as copper and Y_2O_3 undergo deformation easily and behave like viscous plastic. The density of the composite materials is a factor of shape, fraction and size of the particles and nature of the matrix. Observations show that the composite density decreases with the finer SiC particles and Y_2O_3 addition. The porosity is increased for the increase in wt. % of Yttria and SiC particles in Cu matrix. The density of the SiC-graphite hybrid metal matrix composite reinforced by copper is decreased by the inclusion of graphite. As the graphite volume percentage rises, the density falls. The density of the composite decreases with the addition of graphite to the Cu matrix, which is beneficial for applications that call for low weight. Additionally, the size and shape of the reinforcing particles are found to affect the composite materials density[36].

Hardness and ‘CS’ is shown in Figure 9 with respect to SiC and Y_2O_3 additions. As anticipated, the hardness increased significantly with increased SiC and Y_2O_3 reinforcement ratio in the copper MMC. The increase in hardness is owing to SiC being the hardest material. The hardness of the CMCs was found higher than the pure Cu. The addition of SiC fine particles facilitate in achieving optimum hardness value[20]. The pure copper specimen was found having minimum hardness and

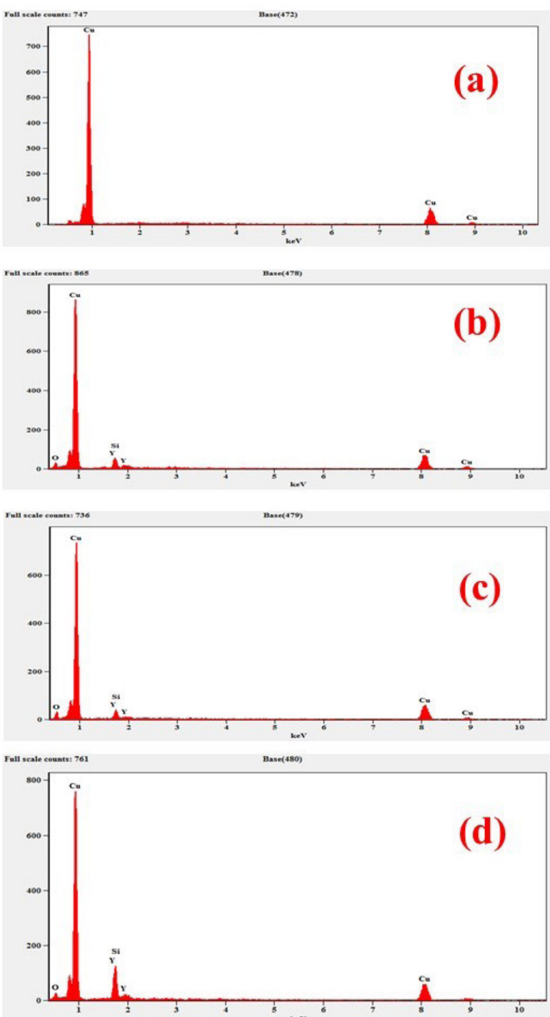

Figure 7. EDX analysis of blended composite powders(a) Cu-0wt%SiC-0%Y_2O_3(b) Cu-2.5wt%SiC-2.5wt%Y_2O_3, (c) Cu-5wt%SiC-5wt%Y_2O_3, and (d) Cu-7.5 wt% SiC-7.5wt%Y_2O_3.

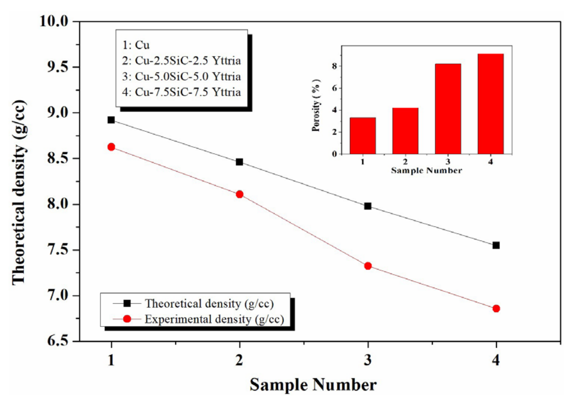

Figure 8. Effect of SiC and Y_2O_3 on density and porosity.

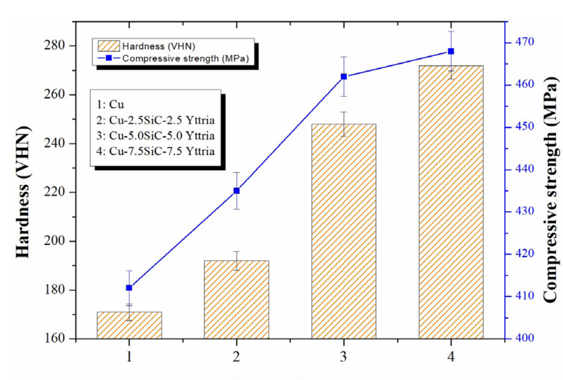

Figure 9. Hardness and CS of composites.

7.5 weight percentage of reinforcement addition leads to higher hardness among the composites spectrum. The Stress Vs Strain is plotted for the sintered Copper Matrix Composites for different compositions, (a) Cu-0wt%SiC-0%Y_2O_3 (b) Cu-2.5wt%SiC-2.5wt%Y_2O_3, (c) Cu-5wt%SiC-5wt% Y_2O_3, and (d) Cu-7.5 wt% SiC-7.5wt% Y_2O_3 as shown in Figure 10. The figure results clearly indicate that during the compression, as the stress increases and the strain percentage also increases. After reaching the breaking point, the stress was reduced.The ball milling process reduces the grain size to micrometric stage. While increasing the ball milling time, the sizes of base metal and reinforcement materials were found to be not the same. Increasing the milling time improves the bonding between the base metal and reinforced particle and also enriches the properties of the composites without compromising ductility. The accumulation of secondary particles improved the strength of the composites due to grain refinement in the grain boundaries[17].

3.3. Corrosion behavior

The salt spray corrosion test is the preferred method for evaluating the corrosion resistance of materials and coatings because it is quick, easy to compare samples, standardized, and repeatable. It also gives a good indication of how a material will perform in a moderately corrosive environment. Figure 11 shows the weight loss and Figure 12 shows the 'CR' of the sintered Cu-SiC-Y_2O_3 composites samples. The corrosion test data are provided in Table 2. The weight loss and the 'CR' is decreased due to the inclusion of SiC and Yttria in the Cu matrix. The high 'CR' is observed for the plain Cu samples as 0.001586142 mm / year and for composite sample contain 7.5% SiC and 7.5% Yttria is low as 0.001135699 mm / year. The reason for the decrease in 'CR' is the barriers provided by the particles in the matrix.

Many researchers reported that, ceramic particles decreases the 'CR' of the CMCs. Zakaria reported that accumulation of SiC in Al matrix lessened the corrosion[37]. Sennur Candan reported that the decrease in SiC particle size also decreases the 'CR' of the Al composite in NaCl solution[38]. Feng et al.[39] also reported the same results for the pitting corrosion of the SiC/Al composites. The enhancement in the resistance for corrosion of hybrid composite is due to a respectable joining of the matrix with the SiC-Y_2O_3 particles. Another important reason for the poor corrosion of composite sample is that the poor conductivity of SiC-Y_2O_3 particles these could not perform as a cathode for reaction to induce corrosion[40].

Reinforcement content may have a beneficial impact on hybrid composites' corrosion mechanism and the connection between the reinforcement and the composite. By functioning as a barrier to corrosive media, enhancing resistance to charge transfer, acting as a partial coating, and preventing ions from corrosive media from entering the composite matrix, the reinforcements can increase corrosion resistance.

3.4. Wear analysis

Figure 13 displays the 'WR' of the CMCs and Figure 14 shows the COF of the CMCs tested in POD wear testing machine. From the Figure 13, it clearly shows that the CMC has high wear resistance than the unreinforced alloy. From the Figure 14, it is noted that, the increase in load decreases the COF for all the samples tested. The addition of reinforcement particles also decreases the COF for both the loads tested. Among the samples tested composite with the addition of 7.5% reinforcement provides better wear resistance. The increase in load increases the materials loss of the CMCs irrespective of the composition. The higher load yield high materials loss for the composite as well as unreinforced copper matrix. The less wear observed for the hybrid composite samples even though the load is raised from 10 N to 20 N. The reason for the low WR is that, the hard particles in the matrix resist deformation[14].

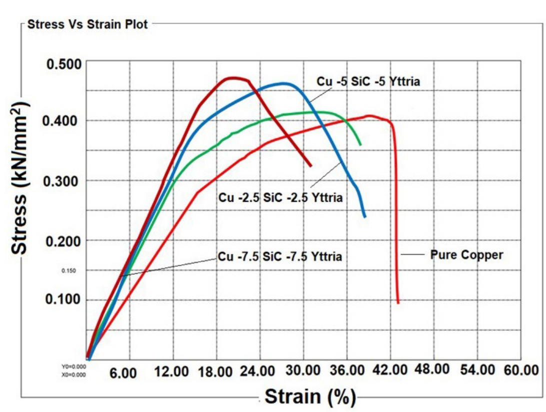

Figure 10. Stress vs strain graph of sintered samples.

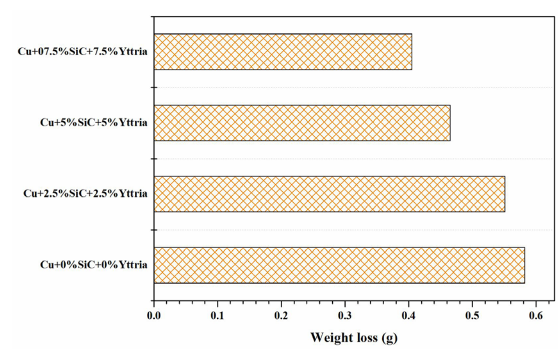

Figure 11. Corrosion of composite samples (weight loss).

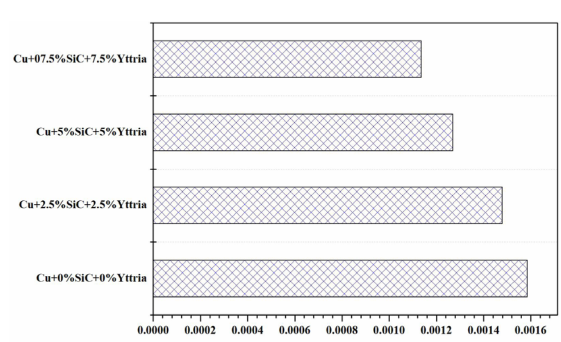

Figure 12. Corrosion of composite samples (mm/ year).

Table 2. Corrosion parameters calculated for Cu–(SiC-Y_2O_3) composites.

Sample	Initial Wt. (g)	Final Wt. (g)	Loss in (g)	R (cm)	H (cm)	V (cm^3)	ρ (g/cm^3)	Area in (cm^2)	Corrosion (mm/year)
Sample 1	17.623	17.041	0.582	1.01	0.617	1.9763	8.9170	150.1936	0.001586
Sample 2	17.655	17.104	0.551	1.01	0.617	1.9763	8.9332	152.1936	0.001479
Sample 3	17.483	17.018	0.465	1.01	0.617	1.9763	8.8462	151.1936	0.001268
Sample 4	17.596	17.191	0.405	1.01	0.617	1.9763	8.9034	146.1936	0.001135

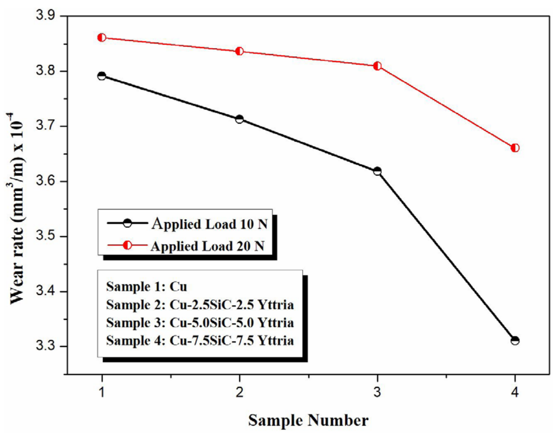

Figure 13. Wear rate of the composite samples.

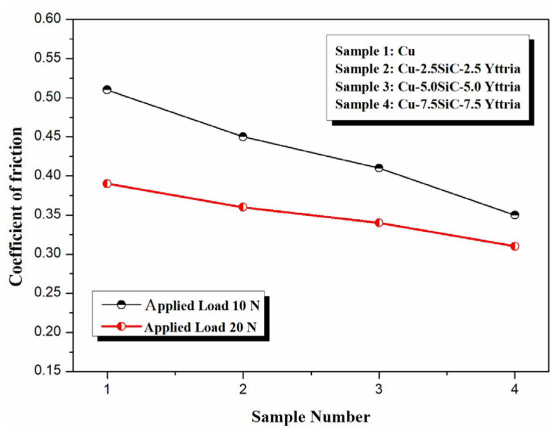

Figure 14. COF of the composite samples.

The increase hardness decreases the wear loss of the composite samples. Another important reason is that, the bonding between the particle and constant spreading of the SiC and Y_2O_3 in the matrix. These are achieved by the proper milling, compaction and sintering process during the fabrication of the composite samples. Abd El Aal and Kim[2] conveyed that, the wear property depends on the nature of fabrication route. They described that, accumulation of SiC in the Cu matrix improved the wear resistance and the abrasive wear was seen for CMCs. Fathy et al.[7] reported the similar findings for the composite with alumina particle and found that alumina particle improved the wear resistance of CMCs and the reason is that presence hard reinforcement particle. The wear rate of the composite increases with the amount of stress. Under larger loads, composites deteriorated more quickly due to their higher coefficient of friction. Wear rates are decreased with higher reinforcement concentrations because ceramic particles provide a lubricating coating on the counter surface, reducing the coefficient of friction. Thereby lowers the wear rate of the composite[41].

4. Conclusions

- Cu-SiC-Y_2O_3 composites was produced through powder metallurgy route and the following conclusions are drawn. The PM specimen's SEM photos verify the SiC and Yttrium Cu matrix's consistent distribution.
- XRD spectra results indicated that there is no reaction between Cu with SiC and Y_2O_3 reinforcements. EDX spectra test was carried out for the PM specimen in order to confirm the reinforcement in the CMC.
- 'CS' of composite was observed to increase with the addition of reinforcement materials SiC and Y_2O_3, that tends to affect the ductile property of the Copper matrix while increasing the hardness.
- CR is lower for the CMCs samples as compared to pure copper because of SiC and Yttria in the matrix.
- Density of SiC-Y_2O_3 reinforced CMCs decreases with the Y_2O_3 content. Pure copper leads to higher density. Particle shape and size of reinforcement was found to influence the density of the composite.
- SiC and Y_2O_3 reinforced hybrid composite possess higher hardness than pure Cu matrix. Hard nature of the SiC and Y_2O_3 is attributed to higher hardness with increasing weight % of reinforcement.
- From the pin on disc experiments it was found that the minimum 'WR' 3.31049 x 10^{-4} mm^3/m was obtained for the composite contain 7.5 wt. % of SiC and 7.5 wt. % of Y_2O_3 and higher 'WR' was observed for plain Copper matrix.

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