Original Article

Enhancement of tribological performance of centrifuge cast functionally graded Cu–10Sn–5Ni alloy with ceramic reinforcements

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Functional grade composites Cu–10Sn–5Ni reinforced with 10 wt% SiC and 10 wt% Al₂O₃, respectively, and their alloy was developed through horizontal centrifuge cast technique. Sample composites and alloy were cast at cylindrical dimensions of Φ[out] 100 × Φ[in] 70 × 100 mm. They were later subjected to tribology analysis during non-lubricated sliding. Anti-wear performance variations at inner (0–8 mm) and outer (8–15 mm) wall thicknesses of both composites and alloy were experimented using pin-on-disc tribotester. Experimentation with increasingly varied parameters like load and slid distance showed a rising trend of wear and friction. This was observed while comparing between the least (10 N, 500 m) and highest (60 N, 3000 m) varied parameter; for both alloy and composites. Also, a proportional decline in coefficient of friction with increase in slid velocity was exhibited for both composites; whereas alloy showed a linear rise. Worn specimen analysis using scanning electron microscopy on both composites revealed Mechanically Mixed Layer formation at both zones. This caused reduction in friction coefficient at high velocity (6 m/s).

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1. Introduction

High performance tribology engineering materials like Functionally Graded Metal Matrix Composites (FGMMCs) gained a high demand in recent decades, as it demonstrates its significant contribution over industrial fields of aerospace, architectural construction and automotive [1]. Advanced features like limited weight, improved specific strength and material stiffness, increased thermal conducting property etc. promoted its utility. Ceramic as reinforcements possess improved load bearing capacity. This thereby limits the plastic nature of the matrix thereby protecting the metal-matrix from wear [2]. Gradual transformation or gradation of microstructural orientation along a particular direction exhibiting a functional utility within a part [3]. Centrifugal casting
technique has gained wide popularity among the FGM fabrication techniques, as it provides specific properties like high temperature tribological performance, superior interfacial sliding friction, reduced interfacial stresses, improved metal–ceramic adhesion at the interface, crack retardation and fracture toughness [4]. This happens due to the gradient structure formation, where the relative locations as well as the extent up to which particle segregation occurs within a casting (deposits the enriching and depleting particles zones), are largely dependent on melting point, viscosity, solidification rate and direction, relative densities of the constituents, centrifugal acceleration and particle size [5,6]. The wall width of particle enrich zone, decreases with raise in pouring temperature of melt and die rotation speed [7]. A comparative study conducted between the centrifuge cast copper-graphite-10% (C90300) composite and a commonly used leaded (18–22% Pb) copper alloy showed improved results for composite by 88% at high loads of 118 N [8]. Copper is recognized as more effective in increasing the strength compared to silicon. But silicon showed more influence over improving the wear performance of eutectoid Zn–Al alloy [9]. Addition of tin has no effect over the coefficient of friction of spinodal–Cu–Ni–Sn alloys, but the rate of wear was found to decrease by 15% [10]. Copper nickel alloys due to its stable mechanical and wear resistive property at higher temperatures is highly preferred for heavy duty applications [11]. 45Ni–40Mo–15Si ternary metallic composite showed three times improvement in anti-wear, compared to conventional bearing steel. This was due to the presence of 15 wt%Si [12]. It was found that under non-lubricated conditions, increasingly varied weight percentage (up to 0.6%wt) enhanced anti-wear behaviour of Al2O3 reinforced CuMMCs which are produced by internal oxidation and mechanical alloying [13]. Even though alumina raises the friction coefficient of bronze composites, the anti-wearing of the same composite was observed to improve up to two fold with the addition of alumina, when produced by powder metallurgy [14]. Adhesive wear behaviour of Cu-11Ni-6Sn alloy was studied to determine that friction is not dependent on hard property of the material and dependent on the applied load and slide speed [15]. Pin-over-disc tribotest of Al-4Cu alloy, showed 14% rise in wear when load increased from 10 N to 40 N whereas, friction remained constant for all test condition [16]. The wear of the Cu–Ag–Cr alloy was found increasing rapidly initially up to 20 km followed by a subsequent rise with the increase of slide distance under different tribo-parameters [17]. Tribo-behaviour of sintered Cu MMC brake pads, reinforced with variable graphite content, compared against cast Al–Si/SiCp brake disc showed improved anti-wearing (40%) and a stable friction (0.2–0.45) at intermediate load (20 N) [18]. Electrolytic Cu mixed with Gr and BN (10 wt% each) using powder metallurgy showed 50% deduction in wear with a decline in slide speed (2.6 m/s–1.04 m/s), due to tribo-film layering [19].

The sliding wear characteristics under dry conditions, of Cu–Ni–Sn alloy and its composites fabricated using functionally graded concept has not been completely explored till the recent research findings. Hence a research attempt has been carried out to analyze the effect of ceramic reinforcements (SiC and Al2O3) in the tribological behaviour of Cu–Ni–Sn alloy, by comparing the wear and friction of composites with the alloy. Integration of FGM concept using centrifugal casting produces cylindrical casts. This enables research and investigations aiming its utility for applications like piston liners, bushes, bearings, cylinder liners etc. [20].

2. Material selection

Copper alloyed with 10 wt. % of tin, 5 wt. % of nickel having density of 8.76 g/cm3 was chosen as the matrix material. It was reinforced with 10 wt.% SiC and 10 wt.% Al2O3, respectively, resulting in two different composite samples whose tribological behaviour was studied in comparison with the unreinforced alloy. Tensile strength of matrix improved with nickel as an alloy composition not more than 6 wt.% during casting [21]. Even though, tin contributes ductile and anti-corrosion nature for copper (at an optimum 10–15 wt.%); nickel also have been added to improve the corrosion resistivity as well as the thermal stability. Al2O3 exhibits superior anti-wearing under non lubricating conditions. This is because cupro-nickel alloys imparts better wettability and bond strength with alumina. SiC being hard carbide ceramic, improves the wear resistance of the composite apart from its excellent corrosion resistance and low thermal expansion, when used as reinforcement. This makes SiC applicable in the fields of automotive manufacturing, mechanical seals, atomization nozzles, valves etc. where response in a corrosive environment and product life plays the major role.

3. Fabrication process

The copper alloy and both functional grade composites were developed through stir casting, and horizontal centrifugal casting as a follow process. Pure copper along with its alloy composition- nickel (5 wt.%) and Tin (10 wt.%) were melted in a ceramic (graphite) crucible in an inert condition, using an electric resistance furnace to prepare the alloy composition. In order to prepare the composites, preheated (250°C) reinforcement particles (SiC and Al2O3, respectively) of average size 10 μm were then added to this molten alloy compositions separately and stirred at 250 rpm for 5 min during both the casting processes. The thermal gradation was minimized by pre-heating the centrifuge mould (450°C).

The melt was later transferred to a centrifuge mould rotating at 900 rpm. The solidified cast attained a hollow cylindrical shape (Φout 100 × Φin 85 × 100 mm). This procedure was repeated during the casting of both composites and alloy.

4. Microstructure analysis

Microstructure of different wall zones of both the composites are observed in Fig. 1. This reveals the features like interfaces, grains, grain boundaries and second phase particles (reinforcements). The dark phase depicts the particles (reinforcements), dark thin line network shows the grain boundaries, whereas the light phase represents copper matrix. Microstructure of the inner wall zone of (1 mm) Alumina reinforced composite (Fig 1a) has least concentration of reinforcement particles than the outer (Fig 1b) which showed a highest concentration. Whereas, microstructure of
SiC reinforced composite also shows least concentration of reinforcement particles at the inner (Fig. 1c) rather than the outer wall zone (Fig. 1d) which shows a maximum of 25 vol.%. This was due to the variance in density between the reinforcement particle and the matrix. Also, the rotating mould generates centrifugal force which would cause movement of particles towards inner region (15 mm). In-addition, the low density gases produced during casting assisted in the gradation of reinforcement particles, more towards inner region; resulting in higher concentration of reinforcement particles at this zone. This also confirms supreme adhesion between matrix and reinforcement particles. In-spite of the density difference, the particle distribution undergoes gradation rather than accumulation at two extreme zones. This highlights the adhesive nature and effective bonding between the particle and matrix.

5. Adhesive wear

Dry tribo-test was performed as per ASTM G99 standard using a Pin over disc tribometer. Rectangular specimens from inner and outer of both alloy and composites of dimension $10 \times 10 \times 15$ mm. Fixed track diameter of 80 mm selected as per ASTM G99 was followed throughout each experiment cycle. It was ensured that the disc was debris-free before each cycle to ensure proper interfacial contact. Proper contact ensures effective load transfer. Specimens were tested under varied loads (10–60 N) with steps of 10 N, varied slide distance (500–3000 m) with steps of 500 m and varied slide velocity (1–6 m/s) with steps of 1 m/s. Cleaned burr-free specimens were weighed with least count (LC) of 0.001 g before and after the experiment. Rate of wear and coefficient of friction (COF) of both the alloy and composite along with the effect of each of these variable parametric combinations were graphically studied.

6. Results and discussion

Influence of parameters like applied load (10–60 N), slide velocity (1–6 m/s) and slide distance (500–3000 m) over the wear and friction of both inner and outer zones of functional grade alloy and composites reinforced with SiC (composite A) and $\text{Al}_2\text{O}_3$ (composite B) has been discussed below using graphical trends.

6.1 Load on wear

Impact of load on the wear of both inner and outer wall thicknesses of functional grade composites A & B and its alloy has been explained using the trend lines of Fig. 2a. Both outer and inner wall zones of alloy showed a direct raise in the rate of wear. This was impacted by the hike in pressure that indirectly enhanced the surface contact during slide, also inducing gradual breaking of interstitial bond producing higher rate of wear. Inner region of the alloy showed higher wearing phenomenon than the outer region except at 40 N, this was due to ploughing action by the worn debris present at the interface. For composites, SiC in the inner zone gave better wear resistance for composite A, compared to composite B. SiC is a ceramic that shows better toughness, hardness and tensile strength [8]; this when used as a reinforcement, brings down the wear rate of composite A by 50% compared to its functionally graded alloy. Whereas, both inner and outer wall thicknesses of composite B shows a linear response in wear with respect to the
raise in load. Gradation of higher percentage of tough ceramic (Al2O3) towards the inner, contributed for the attainment of superior wear resistivity at this region, compared to the outer. Similar results were observed by another researcher, when cupro-nickel alloy was reinforced with 10 wt.% alumina to develop an FGM composite through stir casting for bearing application [15]. The load applied at the specimen surface was well received and distributed among the Al2O3 particles, least affecting the matrix.

The curves of plot (Fig. 2b) showed a linear response of COF with respect to the change in load. Functionally graded alloy at its inner zone, showed the maximum COF as the solidification and cooling starts from the inner zone. Slow cooling results in finer grain size which provides more toughness at the inner zone compared to the outer zone where the rate of cooling is faster due to delayed solidification; thereby increasing the friction at the inner wall. Whereas, the outer alloy showed minimum COF initially, followed by a periodic rise with the increase in load. This was due to the increasing load acting on the coarser grains, which improves the contact surface area and pressure at higher loads. Inner composite A showed the minimum COF, but still exhibiting a linear response with the load. Higher presence of SiC at the inner took up major percentage of load applied, preventing the direct contact of matrix with the sliding surface which results in lower COF. Both the inner and outer zones of composite B showed a linearly proportional rise in the COF. Crushed particle asperities at the interface causing third-body wear at the inner face was responsible for this; likewise at the outer zone, the plastic deformation due to temperature rise facilitated increase in COF [22].

SEM analysis (Figs. 3 and 4) on inner and outer wall thickness of the composite A, as it showed minimum wear. When the functional grade composite A specimen from inner periphery was slid against tribo-disc (hardened EN-31 steel) causing shallow scratches (Fig. 3a) and micro crack initiations when
observed at minimum load (10 N) maintaining the slide speed (1 m/s) and slide distance (500 m). These were features of minimum wear. As the load was raised (to 60 N) at similar constant conditions, the shallow scratches (Fig. 3b) were deepened and extended resulting in un-oriented surface peel offs and tearings under high pressures imposing heavy loads. The analysis performed on the worn specimens of outer periphery (Fig. 4a) of composite A at low applied load of 10 N, with constant parametric conditions showed the formation of small grooves and minor delamination. The minor wear features like deepened grooves, sheared dimples and micro-level layered cuttings were observed (Fig. 4b) on outer specimen at heavy loads, depicting superior wear. Even though both zones exhibited features of severe wear at high loads; the worn surface of the inner zone showed a comparatively mild wear.

6.2. Slide velocity on wear

Impact of slide velocity on wear of both inner and outer wall thicknesses of functional grade composites A & B along with its alloy were graphically (Fig. 5a) studied. Outer wall thickness of the alloy showed better anti-wearing than inner. This is because of the fine grain structure observed along the outer zone, formed due to delayed solidification. The inner zones of both composites A & B showed an initial decrease in wear rate up to 3 m/s and 4 m/s respectively followed by a further increase. This was due to contributions from the relatively sliding surfaces that formed of an oxide layer, which cyclically transforms as a tribolayer at the slide interface reducing the interfacial friction. This tribolayer is called as Mechanically Mixed Layer (MML) [23]. Among the outer zones of both the composites, zone which is reinforced with SiC showed 17% increment in wear resistance in comparison with that reinforced with Al2O3. But the wear rate observed at these outer zones were 28% and 30% higher than the inner zones of composites A & B, respectively. This was due to gradually increasing gradient of particle distribution observed towards the inner due to the centrifuge force. A researcher states that SiC is sharper and harder compared to alumina, providing better wear resistance. But also found that SiC particles are less durable as they are more brittle in nature [24]. Coefficient of friction (Fig. 5b) was found rising with increase in slide velocity for alloy. Raise of slide velocity at unchanged load imposed strain of elastic nature, which led to the disruption of the oxide layer which protects the bulk of the material and enables the occurrence of adhesive tribo-effect. This contributed for superior COF at high slide speeds for alloy. But, a decline in friction was observed for composites A & B at its both zones, with a constant rise in slide velocity. This was in effect of tribo-debris interfacial accumulation at optimal temperature and pressure conditions. This facilitated formation of low friction tribolayer over the tribo-specimen. This causes a slippery action at the sliding interface minimizing the COF.

Fig. 5 – Impact of slide velocity on (a) wear rate (b) coefficient of friction.

Fig. 6 – X-ray diffraction (XRD) peaks of (a) Composite A (b) Composite B.
XRD results shown in Fig. 6, depict the presence of oxides like SiO$_2$ and O$_2$Si for the analysis (Fig. 6a) carried out for composite A. Phases like Cu and Ni3Sn were identified other than the oxides. Ni3Sn was identified (Fig. 6b) for composite B along with Cu3Sn and Fe1.4Ni1.4O4Sn0.3. These phase formations reduced wear and improved strength at intermediate and high velocity test cycles.

SEM observations (Fig. 7a) over the tribo test surfaces of inner wall specimens of composite A (at slide velocity—1 m/s, slide distance—1000 m, load—10 N) revealed features of high wear. Major delamination and non-uniform debris formation was observed on the worn surface due to random pullout of surface particles by the sliding action of protruded counterface particles at low velocity. Whereas, agglomeration and clustering of the oxidized debris were seen (Fig. 7b) on surface of the same composite worn at high velocity (4 m/s) and unchanged other parameters. Similar phenomenon of increase in friction with accumulation of debris was also reported by another researcher who studied the load-bearing ability of wear debris particles during dry sliding [25]. As the slide velocity increases (beyond 4 m/s) more surface oxidation is facilitated forming an oxide layer over the slide specimen surface. This includes contributions from both the relatively sliding surfaces, forming a tribolayer (MML). The height of tribolayering raises with promotion in the rate of oxide formation. Similar transformation of oxides to tribo-layering phenomenon reported 59% deduction of wear with 10 wt% rise in SiC content for Al–10Si/SiC composite [8]. SEM detailing over the tribo-surface of composite A (outer) at variable slide speed and unchanged parameters showed similar results (Fig. 7). At minimum velocity (1 m/s), formation of deeper grooves were observed (Fig. 8a) over the worn surface. This was due to the comparatively weaker high reinforced matrix observed at the outer zone, unlike the coarse structure of the particle rich inner zone. At higher velocity (4 m/s), similar formation of MML was observed (Fig. 8b) which reduced the friction and resulted in minimum tribo-effect. But the thickness of MML formed at the outer is lesser than the inner, this is due to the lesser contribution of particles (reinforcements) as wear debris from the specimen surface, as the particle concentration at the outer zone is lesser than the inner zone. Contribution of particles from the specimen surface has more effect in the MML formation than the counterface.

Elemental level analysis (EDX) detected (Fig. 9) the presence of each element used in the particular composition. C (0.15 keV) and Fe (0.26 keV) peaks pointed towards the counter body particle formation during experiment cycles. Whereas
the detection of oxide (0.28 keV), affirms the accumulation of MML at conditions of high velocity slide.

### 6.3. Slide distance on wear

Impact of slide distance on wear of both inner and outer wall thicknesses of functional graded composites A & B and its alloy were (Fig. 10a) studied. Inner alloy showed better anti-wearing than outer. This is because of the fine grain structure observed along the outer zone, which showed better bonding even at extreme interfacial temperature raise observed due to longer slide distances (beyond 1500 m) of test cycles. Whereas for the inner alloy, coarser grains formed at a faster cooling rate provided better wear resistance. At the inner composite, rich particle accumulation promoted effective load transferring even at higher temperature preventing plastic deformation.

As a result, in case of both composites a firm hold of reinforcement particles on matrix were observed, even at longer cycles without rupture. For outer, lesser particle distribution induced increased plastic deformation at the matrix, as it is directly exposed to higher interfacial temperature with less particle concentration.

Friction always had a direct influence over the wear. Composite A revealed (Fig. 10b) minimum COF compared to composite B. On statistical analysis, the inner wall exhibited 55% and 33% lower friction than the outer of both composites A and B, respectively. Accumulation of maximum percentile of SiC towards the inner improved anti-wearing at this region, compared to outer. Whereas, the inner composite A showed 46% lower friction than the inner of composite B; likewise 16% at the outer. On comparison to all, the inner alloy showed the highest friction (COF) due to the absence of reinforcement.

**Fig. 10** – Impact of slide distance on (a) wear rate (b) coefficient of friction.

**Fig. 11** – Impact of slide velocity on inner wall samples of composite A (a) for 500 m (b) 3000 m.

**Fig. 12** – Impact of slide velocity on outer wall samples of composite A (a) 500 m (b) 3000 m.
particles that resist plastic deformation induced due to cyclic stresses.

SEM observations (Fig. 11a) over the tribo-surfaces of inner composite A (at least slide distance—500 m, slide velocity—2 m/s and applied load—10 N); revealed thin flake peel outs pointing towards minor wear. As the slide distance raised (up to 3000 m) at unchanged other slide parameters, shear dimples and larger flakes (Fig. 11b) were torn from the exterior skin. Flake formations are observed at the particle rich zone where the crack propagation occurs surrounding the grain where the bond strength is high [26]. The analysis performed at the outer composite A (at minimum slide distance—500 m, and other unchanged slide parameters) revealed (Fig. 12a) formation of regular surficial delamination and scrapped debris. Low percentile of reinforcements at the outer, which directly transferred the applied load towards the matrix caused these features; indicating least wear at least slide distance. As the slide distance raised (to 3000 m) without changing the other slide parameters, repeated cycles dug (Fig. 12b) the grooves more and introduced local deformations over the wear track, along the slid direction. Tribo-debris popped-out during the shorter cycles act as free motile particles under vibration. They are observed to be stiffer than their parent material [27,28]. This induced features of high wear during longer cycles.

7. Conclusion

Fabrication and tribo-analysis of functional grade alloy and copper composites reinforced with silicon carbide and alumina, observes as:

1) Tribo-analysis of composites showed minimum wear compared to alloy, due to the high structure based rigidity provided by tough ceramics (SiC/Al2O3). Wear and friction increased proportionally with applied load (for both alloy and composites), as friction heat introduced plasticity at raised pressure.

2) At higher slide velocities, alloy showed a proportionally increasing rate of wear and friction coefficient at both wall zones. Whereas composites showed a decline in wear and friction at high velocities due to the low friction oxides in layers. This formation was confirmed by the XRD results.

3) Raising of slide distance resulted in a proportional increment of wear and friction, for both alloy and its composites. This was influenced by the direct contact of asperities of disc with the test composite sample, during periodic cycles. Comparative study on the tribology experimental results of functionally graded copper composite reinforced with SiC and Al2O3 and their alloy, suggests SiC reinforced composite as the best suitable among all. Especially for slide applications in various engineering applications like engine liners, motile bearings, slid-able guide bars, brake shoes etc., as its inner wall thickness provides the maximum wear resisting property.

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Conflicts of interest

The authors declare no conflicts of interest.


