Tribo-mechanical properties of graphite/talc modified polymer composite bearing balls

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Abstract
In this study, epoxy resin blended with graphite/talc micro fillers are used to fabricate the composite bearing balls of uniform diameter of 12.7 mm. These bearing balls were tested in four ball test rig for investigation of friction and wear. The fabricated composite bearing ball of composition graphite (10 wt%) /talc (10 wt%)/epoxy demonstrated a significant reduction by ~63% in coefficient of friction and a moderate increment by ~34% in wear resistance as compared to pure epoxy bearing ball under dry condition. Further, the compressive strength and hardness test were carried out on the composite bearing balls which revealed a reduction in compressive strength after adding the fillers but approximately similar compressive strength and a marginal improvement in hardness by ~5% was exhibited by graphite (10 wt%)/talc (10 wt%)/epoxy composite bearing ball with respect to pure epoxy bearing ball. Hence, the fabricated polymer composite bearing balls can be implemented for low to moderate load bearing application with enough capability to eliminate the bulk lubrication requirements as in case of conventional metallic bearing balls.

Introduction
Steel is most commonly used material in bearing industries. The various kinds of bearings such as ball bearing, roller bearing and thrust bearing etc has been used in different applications of automobile; power driven machine etc [1, 2]. The friction coefficient of steel on steel interaction has been reported of a very high coefficient of friction (~0.7–1.0) [3]. Because of high coefficient of friction, a significant damage on the surfaces of bearing balls occurs by crack propagation, cavity formation etc which affects the life of bearing negatively. Therefore, the reduction in coefficient of friction is highly needed. To achieve low friction coefficient, the companies are using extravagant quantity of lubricant which affects the environment and creates the health hazard. Hence, the researchers have shifted their attention towards some alternate methods so that consumption of lubricant can be reduced. The researchers fabricated a polymer composite coating using solid friction modifier or additives which possessed lower friction coefficient because of self-lubricating property of coating [4]. Now a days various polymers are available in market such as epoxy, PMMA, PTFE etc; out of them, the epoxy resin is selected for present investigation because of its better mechanical, thermal and tribological property over other polymers [5–7]. The researchers added different nano/micro friction modifiers in epoxy resin so that they could achieve self-lubrication property. In this series, Samad et al [8] blended UHMWPE/CNT nano fillers in epoxy resin for fabrication of composite coating on steel at elevated temperature. They observed the drastic improvement in mechanical properties such as load bearing capacity and hardness as well as tribological properties such as friction and wear of composite coating. Further, the effect of graphene oxide (GO) with the thermo tropic liquid crystalline epoxy (TLCP) was observed by Qi et al [9]. They observed the increment in glass transition temperature by 15 °C, with 46% more tensile strength and 48% more flexural strength from the pure epoxy. Moreover, Dong et al [10] studied the effect of MWCNT in epoxy resin and observed that an optimum
concentration of MWCNT nano powder in epoxy has given higher wear resistance and lower friction coefficient. Kumar et al.[11] investigated the influence of graphite and graphene nano fillers in epoxy resin and observed that the graphene with epoxy resin has shown lower coefficient of friction and high wear resistance property in comparison to pure epoxy. Katiyar et al.[12] developed the polymer composite coating for MEMS application using graphite and talc powder. They reported that the graphite has enabled lower coefficient of friction and talc has added higher wear resistance. To utilize both properties at same time, they mixed graphite and talc in equal weight percentage in epoxy resin. Further, they also added the liquid lubricant with solid nano friction modifier in epoxy resin and observed that the friction coefficient has drastically reduced by 9 times and wear resistance has improved by more than three-fold [13–15]. Moreover, researchers has developed the soft coating as well as hard coating to prevent the wear and to achieve lower friction coefficient. For hard coating, they used titanium nitride, titanium carbide and DLC nano coating on bearing surface but these coating shows higher friction coefficient, higher wear resistance property in comparison to softer coating such as MoS2, lead, copper, graphene, graphite, CNT etc. Therefore, to achieve lower friction coefficient and higher wear resistance property, researchers decided to fabricate a sandwich layer of hard and soft coating. They reported the application of such types of coatings in automobile and bearing industry [16, 17].

From the literature, it has been clearly observed that the researchers used different nano/micro solid friction modifiers in epoxy resin matrix to achieve lower friction coefficient and enhanced the wear resistance property. However, to the best of author’s knowledge, the use of solid additives inside the epoxy has not been reported for fabrication of bearing balls in open literature. The early researchers have only fabricated the polymer protective composite coatings for serving the various applications as per the demands of industries. Moreover, the properties of graphite and talc mixture in epoxy resin had shown more interesting result. Therefore, the graphite, talc and mixture of graphite/talc micro fillers have been blended in epoxy resin for the fabrication of polymer composite bearing balls. The tribological testing on fabricated bearing balls have been performed on four ball test rig tribometer. This investigation has shown the influence of fillers/additives on friction coefficient and wear resistant properties of fabricated bearing balls. These polymer composite bearing balls can be envisaged to eliminate the bulk lubrication requirement as needed in conventional steel bearing balls.

### Experiment and methodology

**Materials**

Epoxy polymer resin (AW 106) with hardener (HV 953) (supplied by nano research lab Bengaluru, India) was used to fabricate the bearing balls. The composite bearing balls were fabricated by blending of graphite (size \(\sim 10 \mu m\)) and talc (size \(\sim < 1 \mu m\)) in epoxy resin using stirring process. The micro fillers were added in different weight percentages in epoxy resin such as 5 wt%, 10 wt% and 20 wt%, respectively. The abbreviations used in further investigation of polymer composite bearing balls are shown in table 1.

**Fabrication of bearing balls**

In order to prepare multiple polymer bearing balls of uniform shape and size, it is necessary to have a standard preparation method for each of the ball. Hence, the acrylic mould was prepared in two halves, each half contains precisely cut hemi spheres using conventional machining. The two halves were kept together and fixed by using dowel pins which provides a complete sphere of diameter 12.7 mm. The mould is shown is figure 1. The prepared epoxy resin mixture was further transferred into mould cavity using spatula in a very short duration.

### Table 1. Abbreviations of polymer bearing balls.

| Composite sample | Symbol |
|------------------|--------|
| Steel            | S      |
| Pure Epoxy       | E      |
| Epoxy + 5 wt% talc | 5T    |
| Epoxy + 5 wt% graphite | 5G    |
| Epoxy + 2.5 wt% talc + 2.5 wt% graphite | 5GT |
| Epoxy + 10 wt% talc | 10T   |
| Epoxy + 10 wt% graphite | 10G   |
| Epoxy + 5 wt% talc + 5 wt% graphite | 10GT  |
| Epoxy + 20 wt% talc | 20T   |
| Epoxy + 20 wt% graphite | 20G   |
| Epoxy + 10 wt% talc + 10 wt% graphite | 20GT  |
| Polymer composite bearing ball | PBB    |
because of the hardening characteristics of epoxy resin. As soon as the mixture transferred, the moulds were closed and applied a 1 kg weight over it to insure that no gap between two halves. Further, Filled mould was allowed to rest for a day for curing. A grease layer was applied on the surface of the mould before pouring of mixture, for ease removal of bearing balls from the mould after curing. The prepared samples were removed and cleaned using acetone. The purpose of acetone is to remove any traces of grease from the surface as well as any unnecessary dust particles. Each ball was then smoothened manually using emery papers with soft hand for achieve a good surface finish. After that finished balls were kept in desiccator for further test and characterization.

**Tribology test**

The friction and wear test were performed on four ball test rig (Ducom Instruments, Bangalore, India) as per the standard of bearing industry. Each test was carried out for a duration of 15 min at constant speed 1200 rpm and 100 N applied load as per the ASTM D4172 under dry condition. For each test, three balls were taken from fabricated bearing balls and placed in a ball holder while as fourth ball was always taken a standard bearing steel ball of high chrome steel. All fabricated bearing balls were kept stationary while as the steel ball was rotated (schematic is shown in figure 1(b)). The machine was automatically calculated the instantaneous frictional torque and also shown the coefficient of friction at the end of the test using Lab View software. The test for each fabricated bearing balls were repeated at least three times and their average data has reported here. For each test, a new bearing steel ball was used. The standard procedure was maintained for all the tests and final comparison was done to analyse the best combination of fillers. After that the obtained best composition alone was further run for higher duration of time to understand a tribological behaviour of the polymer composite bearing ball.

**Mechanical properties**

**Compressive strength test**

The test was carried out on universal Testing Machine (UTM) as per as per ASTM D3410 standard. The PBB was kept at an appropriate location on the machine followed by progressively applied load on PBB. At certain applied load, the PBB has broken into pieces. That critical load was noted down through UTM. Each test has repeated at least three times and average data of compressive strength has reported.

**Hardness test**

The hardness of fabricated PBBs were measured by using shore hardness Durometer. The test was conducted according to ASTM D2240. In this test method, a hardened steel indenter was used to make a small indentation on the sample, and the resistance of the material to that indentation was noted down by the machine. The hardness value is given in ‘shore d hardness’.

**Surface morphology**

Surface morphology of tested PBB was observed by image analyser (Olympus Optical Microscope) at 50X magnification. Further, the more magnified images of wear scar was captured by using machine vision camera. That has been only used for those samples which has shown lower coefficient of friction. An approximate value of the scar diameter was determined for each scar and average value has reported.
Result and discussion

Fabrication of bearing balls
The polymer composite bearing balls of 12.7 mm uniform diameter were fabricated by mixing fillers in epoxy resin. An acrylic mould was used to cast the composite mixture into a ball shape. After 24 h curing, the casted bearing balls were removed from the mould followed by cleaning using acetone. The figure 2 shows the images of the few fabricated polymer composite bearing balls. Others balls are also look similar. The uniformity is assured in fabrication to check the diameter from Vernier callipers.

Mechanical testing
The fabricated bearing balls were tested for investigation of their mechanical properties such as compressive strength and hardness. These results are essential because load bearing capacity is very important for any bearing ball.

Compressive strength
The figure 3(a) shows the compressive strength of each bearing ball. It has been observed that the pure epoxy possesses the highest compressive strength whereas addition of fillers show a decrement trend of compressive strength. The trend of reducing compressive strength with increased concentration of fillers is attributed because of weakening of bonds. The fillers tend to occupy the position in between the epoxy bonds which generates epoxy-filler-epoxy bond in addition to epoxy-epoxy bond. In combination of both fillers, T–G bond is also formed in addition to T–E, G–E and E–E bonds. At 20 wt% concentration of both fillers, the compressive strength has shown comparable to that of pure epoxy. The same phenomenon was explained by researcher in which they had shown the bond strength and determined their glass transition temperature [12]. They used graphite and talc mixture in SU-8 based epoxy resin.

Hardness
Hardness was determined for the composite samples using Shore D hardness test. This test is widely used to check the hardness of bearing balls. The test reveals that the marginal change in hardness by ~5% due to blending of micro fillers in epoxy resin. Figure 3(b) shows the hardness data of composite samples using shore D hardness. The graphite and talc with epoxy resin shows more shore D hardness as comparison to others because
of the better bonding between epoxy-talc and graphite. Talc consist –OH group which made better bond with epoxy and graphite by polymerization phenomenon [18].

**Tribology test**

The friction test was carried out on four ball test rig as per bearing industry standard under dry condition for a duration of 15 min. Figure 4 presents the data of coefficient of friction of each and every bearing ball with standard error. From figure 4, it is observed that the coefficient of friction is very high (∼0.75) in case of steel on steel interaction which is already reported by most of the researchers [19, 20]. In case of steel on epoxy interaction, the friction coefficient was drastically reduced by ∼3 times. This reduction occurred due to the self-lubricating properties of polymers [21]. Furthermore, it has been observed a further decrement in friction coefficient with an increase in the micro filler concentration. Moreover, it has also been observed that in each set of concentration the combination of graphite and talc shows lower coefficient of friction. The reason is because of the better bond between epoxy-talc-graphite. The better bonding is observed because of the –OH group present in talc. Also, the graphite gives the lower coefficient of friction and talc increases the wear resistance property which was already reported by researcher [11]. The 20GT bearing ball shows a drastic reduction in coefficient of friction as compared to pure epoxy bearing ball. This reduction is approximately ∼3 times from pure epoxy. Apart from better bonding, another reason of this drastic reduction in friction coefficient is higher hardness of composites among all composites which is observed in figure 3(b).

After friction test, the wear scar was observed using machine vision system. Figure 5 shows the wear scar data of each and every bearing ball with standard error. It is observed that the pure epoxy bearing ball shows the largest wear scar while as 20GT bearing ball shows lowest wear scar. After addition of micro fillers in epoxy resin, the wear resistance property improve as comparison to pure epoxy PBB. The ∼34% increment in wear resistance property has been observed for 20GT bearing ball from others bearing balls. This increment is because of the better bonding, higher hardness and optimum concentration of talc and graphite.

Furthermore, the image of wear scar on each and every bearing ball is shown in figure 6(a) and the figure 6(b) shows the zoomed images of worn out surface of pure epoxy and their composites after test. The images were
captured using machine vision system at 50 × magnification and 100 × magnification, respectively. From figures 6(a) and (b), it is clearly observed a fracture and re-solidified surface over pure epoxy bearing ball after test. This is because of the lower hardness of the composites and brittleness nature of the pure epoxy. Hence, the responsible wear mechanism in case of pure epoxy is the combination of abrasive wear and surface fatigue causing catastrophic failure which is clearly observed from the figures 6(a) and (b). The similar phenomenon was reported by Saravanan et al [22] and Fusaro [21] in case of pure epoxy composite. But the surface of bearing ball has improved after addition of the micro fillers. This is because of the improvement of hardness of the composites which is observed from figure 3(b). Moreover, in lower concentration of graphite and talc combination such as 5GT, the deformation of surface has only been observed with no mass transfer observed on steel ball. The responsible mechanism in this combination is the adhesive wear. Furthermore, the deformation is
eliminated in higher concentration such as 20GT because of the high hardness of the composite balls. In case of pure talc in epoxy resin, at lower concentration, the cracks were developed on the surface but these small propagated cracks were reduced at higher concentration of talc. The development of these cracks on the surface was developed because of the surface fatigue. But as concentration of talc increases the friction coefficient is decreased and hardness increased. Therefore, the wear phenomenon changes from surface fatigue to the adhesive wear which can be observed clearly in figure 6(b) in worn out surface of 20 T. Due to which talc/epoxy bearing ball shows lower friction coefficient and wear scar form pure epoxy bearing ball but more from 20GT bearing ball. Hence, the 20GT bearing ball shows more wear resistance under 100 N applied load for a duration of 15 min. Also, the responsible wear mechanisms are adhesive wear, abrasive wear and surface fatigues in bearing ball composites.

From above it has been observed that 20GT composite bearing ball shows lower wear scar, lower coefficient of friction, and higher hardness among all other composite bearing balls. Therefore, 20GT bearing balls alone was again allowed to run in the four ball tester for more time duration (up to 1 h) under the same conditions of speed 1200 rpm and load 100 N. The duration was varied in 15 min segment. This was carried out to check the durability of these bearing balls in real-life applications. Each test run was repeated three times for each duration. In friction coefficient, the increment has been observed from ∼0.1 to 0.15 after test duration of 45 min and 60 min, respectively but it has been observed same after test duration of 30 min while as the wear scar diameter increases with the increase in time duration. The wear scar diameter has observed 5.41 mm, 6.03 mm and 6.10 mm after test duration of 30 min, 45 min and 60 min, respectively. This increment in wear scar is because of the impression by steel ball on composite bearing ball. For long duration test, the interface temperature has also increased which causes the localize melting and solidification. Due to which the enlargement of scar diameter occurs without damage of bearing ball which can be clearly observed from figure 7.

**Conclusions**

The polymer composite bearing ball of uniform diameter 12.7 mm was fabricated using epoxy resin by addition of graphite, talc and a mixture of graphite and talc micro fillers. The mechanical and tribological characterizations were carried out using UTM, Shore D Hardness test and four ball tester. The friction test was carried out as per bearing industry standard at 1200 rpm rotational speed and 100 N applied load under dry condition. The wear scar was observed using machine vision system after friction test. The following conclusions are drawn from this investigation.

1. Mechanical property like hardness has increased with addition of micro fillers. But it has shown more in the case of mixture of graphite and talc in epoxy resin. The increment in hardness by ∼5% has observed in 20GT bearing ball as comparison to pure epoxy bearing ball. This increment is because of the better bonding between epoxy-talc-graphite-epoxy. Furthermore, compressive strength has decreased after addition of micro fillers but for 20GT bearing ball, it is same as of pure epoxy bearing ball.

2. The coefficient of friction has reduced after addition of micro fillers in epoxy resin. The 20GT sample has shown lower coefficient of friction (∼0.103) as comparison to pure epoxy (∼0.276) and others bearing balls. The same composite sample also has shown lower wear scar diameter (3.464 mm) as comparison to others bearing balls. The responsible wear mechanisms are adhesive wear, abrasive wear and surface fatigues in bearing ball composite.

3. The time duration has further increased in the spam of 15 min for 20GT bearing balls and it has observed that for the 60 min duration, the wear scar has raised by ∼75% and friction coefficient has increased by ∼49%. This is because of the increase in area of contact but after certain time duration, the resistance offered by the balls have stabilized which result in constant scar diameter.
Therefore, it has been observed that 20GT composite bearing balls have shown superior properties from pure epoxy resin bearing balls in terms of friction coefficient, wear resistance, compressive strength and hardness. Hence, it can be useful for the low load bearing application without using any external lubricant inside bearing because of its self-lubrication property.

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