Effect of Yttrium Oxide Particles on the Mechanical Properties of Polymer Matrix Composite

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Abstract. Polymeric composite materials have emerged as one of the best composites used in modern and advanced applications due to the important and useful properties such as lightweight, excellent thermal and electrical insulation as well as relatively good resistance. In this paper, a composite material has been manufactured with polymer matrix which is reinforced with ceramic particles and the mechanical properties have been studied. Epoxy resin Quick mast 105 has been mixed with a hardener by a ratio 3:1, then reinforced with different volume fractions of Yttrium oxides Y₂O₃ (0, 1.5, 3, 4.5, 6%). The composites samples are manufactured with hand lay-up molding, then the mechanical properties such as hardness, compressive strength, flexural strength and the wear rates with different loads (5, 10, 15, 20) Newton are investigated. The results showed that both hardness and compressive strength were increased by increasing the content of the reinforcement as it increased by 62% and 12% respectively, in contrast to flexural strength which decreased by increasing the Y₂O₃ content by 45%, the wear results showed a decrease in the wear rate by increasing the Y₂O₃ content up to 3% and then the wear rate is proportional with the reinforcement content and 0% recorded the highest wear rate, on the other hand by increasing the load of the wear rate test, it was found that the wear rate increased at all the ratios of reinforcement.

Keywords: Polymer matrix composite, Y₂O₃ particles, Mechanical properties, Wear test.

1. Introduction
Polymer matrix composite (PMC) reinforced with ceramics particles are widely used for many engineering applications under hard working conditions due to unique mechanical properties of ceramics particles; ceramics outstrip polymers in their favorable melting point, strength and thermal expansion properties, ability with stand high temperature but due to their brittleness they are used to strengthen the polymer [1, 2]. Improvement of mechanical properties has been attributed to formation of conjugated biphasic materials due to addition of fillers. These fillers will then tolerate some of the applied tension to the polymer matrix leading to enhanced tensile properties of the end product. [3]

The properties and performance of polymers combined with ceramics materials helps to improve tribological characteristics, tensile and compressive strength, toughness (including abrasion), thermal stability, dimensional stability and cost reduction in terms of consumption of resin materials. The interfacial adhesion, the size of particles, the dispersed inorganic filler in polymer matrix, compatibility between matrix and filler phases are important effect on performance of composites [4, 5].
Emergence of stiff and strong reinforcement such as mineral oxides like Y2O3 along with advances in polymer research to produce high performance resins as matrix materials have helped meet challenges posed by the complex designs of modern applications such as aircraft structures, automobiles, space vehicles, marine tools, sporting goods, electronic packaging to medical equipment and many consumer products [2].

The Epoxy resin (Quick mast 105) has multipurpose uses like fabric reinforcement, bonding of wooden parts and variety of metals in addition of being used as adhesive for wide range of application. It is known to have no strong smell and high flash point making it safer than polyesters. It also can be shaped and sanded after being cured and hardened. However, its thermal and mechanical properties are limiting factor for new applications and uses [3].

In order to obtain perfect wear and friction properties many researchers modified polymers matrix using different fillers. Abdullah et al. [6] studied the effect of different types of ceramics fillers (granite, perlite, CaCO3) on wear characteristics of glass fiber epoxy composite, and reported that the wear loss of the reinforced epoxy increases by increasing the load, time and sliding distance, the adding of ceramics particles to glass epoxy composite increased the wear resistance more than glass epoxy composite without ceramics particles.

Al-Zubaidi et al. [3] studied the thermal, mechanical and wear characteristics of polymer composite reinforced with calcium carbonate (CaCO3) powder. Results showed that addition of CaCO3 powder to the epoxy resin produces a harder, less ductile and better heat insulator product, wear loss was found to increase with the increase of CaCO3 ratio.

Bdaiwi [7] studies the effect of Nano (Y2O3) on the mechanical properties of the polymer blend composite and reported that the addition of Nano Y2O3 to the polymer composite the value of mechanical properties increases when increases ratio of Nano Y2O3 and the optimum value at 1.5 % Y2O3.

Therefore, the objective of this work is to investigate the mechanical and wear properties of polymer matrix composite at different volume fraction of Yttrium oxides (Y2O3) particles.

2. Experimental Part

2.1. The Materials Used

The following materials were used for preparing the polymer matrix composite specimens:

1. Matrix Material: the epoxy resin type Quick mast 105 (which is manufactured by (DCP) Jordan company) was used in this study as it is in the form a viscous liquid at room temperature, which is up to (19 – 30 °C). This epoxy resin could be converted to the solid state by adding a hardener (poly amine). The mixture rating of epoxy resin to the hardener was (3:1) any (3 gm) of epoxy was added to (1 gm) of hardener. The details of epoxy properties illustrated in table 1 [8, 9].

| Properties         | Values          |
|--------------------|-----------------|
| Density            | 1.1±0.05 g/cm³  |
| Compressive Strength| > 72 MPa       |
| Tensile Strength   | > 60 MPa        |
| Flexural Strength  | > 25 MPa        |
| Pot Life           | 50 – 85 min @ 25 °C |
| Boiling Point      | > 200 °C        |
| Viscosity          | 1.0 poise @ 35 °C |
| Min. Application Temperature | 5 °C          |

2. Reinforcement Materials: The reinforcement which was used in this work was Yttrium oxides (Y2O3) powder (particles size < 25µm, purity 99.5 %) and delivered from Fixanal company (Germany).

2.2. Composites Preparation
In order to investigate the effect of Yttrium oxides in the polymer matrix, pure epoxy resin, Y₂O₃–epoxy composites were fabricated separately with volume fraction of the Yttrium oxides ranged from (1.5, 3, 4.5 and 6 vol.%).

All samples were manufactured by hand layup technique. The mold that was used is made from glass with dimension of (75, 75, 10) mm. After cleaning the mold, it is covered the inside walls of the mold with fablon papers to prevent adhesion between the mold and polymeric material.

The epoxy resin (Quick mast 105) is prepared by mixing the epoxy with the hardener in (3:1) ratio at room temperature; the mixing was very slowly as possible to reduce the risk of introducing unwanted air and bubbles into the sample, using the glass rod for (20 min) until it becomes homogenous mixture.

After that, the reinforcement materials (Y₂O₃) was added to the epoxy resin with different volume fraction and also stirring with the epoxy resin very slowly for (15 min), then the mixture is poured in the mold from one side only gradually to eliminate the entrapment of bubbles and air into the sample. When the solidification process for all molds is completed within 24 hours, the samples are extracted from the mold, Figure 1 illustrates the samples of this study that proceed to heat treatment process by using electrical furnace at a temperature up to 60 °C for two hours. This process is necessary to obtain the best interlock and to remove the stresses generated by the manufacturing process. Then the samples are cut by CNC machine according to the dimensions of the international standard specifications and devices used for each test.

![Figure 1. Samples of this study with different volume fraction of Y₂O₃.](image)

2.3. Mechanical Properties Tests

2.3.1. Hardness Test. The hardness of the composites was measured using a micro Vickers hardness device and the average hardness data given in this study evaluated from five measurements over the surface of specimen.

2.3.2. Sliding Wear Test. Wear test was done according to ASTM G-99 [10] for cylindrical specimens with 10 mm for both diameter and height as shown in figure 2, and performed by using pin on disk tribometer type DUCOM (Wear and Friction Monitor ED-201) of Indian origin as shown in figure 3, in mechanical department laboratories in Tikrit University of Iraq. According to equation 1 [5, 6] the wear rate is calculated at different volume fractions of Y₂O₃ and different loadings such as 5, 10, 15 and 20 N. The device has a timer to measure the duration of the test accurately, which is stoped at the end of the pre-determined period of 20 min. The hardness of the disc installed in the machine is 62 HRC, 6 cm diameter and rotational speed 480 r.p.m, the disc and samples were ground with 1000 grid size emery paper. Then the amount of weight loss was measured during the test period using a sensitive electrical balance with accuracy (0.1 mg). All tests performed at temperature (25±2 °C).
Wear Rate = \frac{\text{Weight Loss}}{\text{Sliding Distance}} = \frac{W_1 - W_2}{2\pi RNT} \quad (1)

Where:
W_1: Weight of sample before testing (g).
W_2: Weight of sample after testing (g).
R: Radius of disc = (3 cm).
N: Rotational speed = (480 r.p.m).
T: Time of test = (20 min).

2.3.3. Compressive Strength test. This test was carried out using the universal testing machine type (HOYTOM) with chines origin according to ASTM D695 [11] for cylindrical samples by a diameter (12.7 mm) and high (25.4 mm). The test was carried out at room temperature with a constant load according to the strength of the sample load for the purpose of calculating the maximum compressive strength of the sample at the break point according to equation (2) [11]:

\text{Compressive Strength} = \frac{P}{A} \quad (2)
Where:
P: Maximum compressive load (N).
A: cross sectional area of the sample (mm²).

2.3.4. **Flexural Strength test.** This test was carried out according to ASTM D 790 [12] for samples with standard dimensions by length (127 mm), width (12.7 mm) and height (3.2 mm). The three-point flexural test was performed using the universal testing machine by applied the load gradually using the pointed head at the center of the sample which installed from both ends until the failure occurs. From the flexural test we can found the flexural strength which is defined as the material resistance of the external bending stresses when exposed to different central loads until the fracture is achieved. The flexural resistance is measured by the following equation [12]:

\[
\text{Flexural Strength} = \frac{3PL}{2bd^2}
\]

Where:
P: Maximum flexural load (N).
L: Support span (mm).
b: width of beam tested (mm).
d: depth of beam tested (mm).

3. **Results and Discussion**

3.1. **Hardness Test**
The hardness test is depending on the resistance of the material to penetrate its surface. Figure 4 shows relationship between the Micro – Vickers hardness and the volume fraction of the Yttrium oxide content. We It illustrated that the hardness increased (62%) by increasing the reinforcement content. This increasing is due to the high hardness of the oxide particles compared to the matrix material, this is due to the fact that hardness is a measure of plastic deformation, so the presence of reinforcing materials, which are Yttrium oxide particles with high hardness, act as obstructions to deformation of the matrix material, which increases the value of the material hardness due to the increased resistance of the material to plastic deformation. A similar effect of different ceramic particles on hardness has been observed by suror et al. and Khansaa et al. [13, 14].

Low particles size of the reinforcement particles (< 25 µm) is also working to improve the hardness values, because small particles are of high ability in penetration into the material matrix and into the voids and pores interfaces, which leads to increase contact area between the components of composites, thereby increasing interdependence among them [13].

![Figure 4](attachment:image.png)
3.2. Compressive Strength Test

Figure 5 shows the relationship between compressive strength and the Yttrium oxide content. We observe that the ratio of compressive strength is increased (12%) by increasing the reinforcement content. This increase can be attributed to the high resistance to compressive load of Yttrium oxide particles, which by increases its content to withstand a large part of the compressive load instead of the matrix material. These particles also impede the movement of the cracks and reduce the strains values and then increase the compressive resistance. Similar results were found previously by W. Bdaiwi [7] and K. Karthik et al. [15].

![Figure 5. Relationship between the compressive strength and Yttrium oxide content.](image)

3.3. Flexural Strength Test

This test is considered as a complex test because the sample is subjected to several stresses at the same time which are: the tensile stresses obtained at the outside of the sample, the compressive stresses obtained to the inside surface of the sample and the shear stress that occurs at its interface surface, So the composite material fails under the influence of one of these three stresses depend on the type of reinforcement material and the bonding strength between them and the matrix material [16].

Figure 6 shows the relationship between flexural strength and the Yttrium oxide content. We notice that the flexural strength values decreased (45 %) by increasing the reinforcement content. The reason of the decrease in flexural strength values is that increasing the volume fraction of the Yttrium oxide particles reduces the wettability within the matrix material, making it a concentration center for stresses, cracks and imperfections will increase, thereby weakening the bond between the matrix and the reinforcing material, or the presence of a large agglomerate of Yttrium oxide in the epoxy resin, may have occurred to cause the lower flexural strength and causing the sample to fail suddenly. Similar effect of different ceramic particles were found previously by Sihama [16] and Osman [17].
Figure 6. Relationship between the flexural strength and Yttrium oxide content.

3.4. Wear Test

3.4.1. Effect of Yttrium Oxide Volume Fraction on Wear Rate. Figure 7 shows the relationship between the wear rate and the Yttrium oxide content. We notice that the wear rate decreased by increasing the reinforcement content up to 3% and then increased for all loads. Pure epoxy resin (0% Yttrium Oxides content) recorded highest wear rate of the composites.

It is possible to explain the reason for the decrease in the wear rate by increasing the reinforcement content up to (3%) to the higher values of the composite hardness by increasing the reinforcement content as shown in Figure 4, Where the reinforcement particles give the composites high resistance to wear due to its high hardness and the bonding force between them and the matrix material. Similar effect of different reinforcement materials were found previously by Mahmood et al. [5], Wear of a composite was inversely proportional to the hardness of the wearing sample H, as indicating in the following equation [18]:

\[ W = K \frac{NS}{CH} \]  

(4)

Where:

W: Wear volume loss.
K: The wear constant.
N: The applied normal load.
S: The sliding distance.
C: Geometrical factor depends on the microstructure.
H: Hardness of the sample.

The reason for the increase wear rate after the reinforcement content (3%) is due to the presence of Yttrium oxide particles, where the increase in content within the composite and emergence during the wear process the formation known as the wear debris on the surface between the sample and the metal disc, which change the wear type between the surfaces from adhesive to abrasive cause increasing the machining in sample surface and increasing the wear rate by increasing in reinforcement content and the increase in the wear debris which rich in Yttrium oxide particles work to increase the plastic deformation occurring at the protrusions and areas near the surface of the sample and thus increase the density of the dislocations by increasing deformation, minimum cracks will be on the surface of the composite and then meeting of these cracks with each other and with wear lines and parallel direction to the separator surface, causing removal of pieces of composite when micro-surface layers and these pieces still easily towards the slide direction and the formation wear debris, leading to increase in wear rate, Similar effect of different reinforcement materials were found previously by Al-Zubaidi [3].
3.4.2. Effect of Applied Load on Wear Rate. Figure (8) shows the relationship between the wear rate and the applied loads. We observe that the wear rate for all the reinforcement content increased by increasing the applied load. From equation (4) the wear rate must be increased by increasing the applied load because the effect of friction and contact between the sample and metal disc (two surface) will be increased by increasing the load and leading to rapid deformation of the composite due to frictional and compressive forces dominate in dry sliding conditions as was found by previous works [3, 5].

4. Conclusions
Throughout this work the following conclusions were made:
1. Epoxy resin (Quick mast 105) reinforced with Yttrium oxide particles has been achieved successfully to produce polymer matrix composite.
2. The hardness and compressive strength were increased (62 %) and (12 %) respectively by increasing the Yttrium oxide content.
3. Flexural strength which decreased (45 %) by increasing the Yttrium oxide content.
4. The addition of Yttrium oxide particles as a reinforcement material leads to decreased the wear rate up to (3 %) and then increased for all the applied loads.
5. The highest wear rate is that of the pure epoxy resin (0 % Y₂O₃).
6. The wear rate for all reinforcement content increased by increasing the applied load.

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