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Experimental Investigation of Mechanical and Tribological Characteristics of Al 2024 Matrix Composite Reinforced by Yttrium Oxide Particles

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Abstract Composite materials offer distinct and unique properties that are not naturally inherited in the individual materials that make them. One of the most attractive composites to manufacture is the aluminum alloy matrix composite, because it usually combines easiness of availability, light weight, strength, and other favorable properties. In the current work, Powder Metallurgy Method (PMM) is used to prepare Al2024 matrix composites reinforced with different mixing ratios of yttrium oxide (Y_2O_3) particles. The tests performed on the composites include physical, mechanical, and tribological, as well as microstructure analysis via optical microscope. The results show that the experimental density slightly decreases while the porosity increases when the reinforcement ratio increases within the selected range of 0 ~ 20 wt%. Besides this, the yield strength, tensile strength, and Vickers hardness increase up to a 10 wt% Y_2O_3 ratio, after which they decline. Moreover, the wear results show that the composite follows the same paradigm for strength and hardness. It is concluded that this composite is ideal for application when higher strength is required from aluminum composites, as well as lighter weight up to certain values of Y_2O_3 ratio.

Key words Al2024 composite, microhardness, physical properties, wear test, Y_2O_3 particles.

1. Introduction:

Modern and advanced engineering applications need a mixture of unique materials with distinct and contemporary characterization. Composite materials have offered a combination of unique properties, such as lightweight, high strength, good corrosion resistance, and competitive wear resistance.[1,2] Aluminum Alloy Matrix Composites (AAMCs) are one of the commonly used composites that have served in numerous advanced applications within various industries. They can be found in applications of marines, aerospace, and automotive components, such as cylinder blocks, pistons, engines, and piston rings.[3] AAMCs maintain desirable performance for industrial applications, like high corrosion resistance, low electrical resistivity, high damping capacity, high specific strength, and good thermal conductivity.[3,4] In some cases, these composites are replaced with bronze alloys and cast iron due to their high wear resistance. Lately, more development of AAMCs is being achieved for automobile and aerospace applications because of the significance of lengthened lifetimes for the structural parts manufactured from these alloy composites.[3,5,6]

Along with the AAMCs, Ceramic Particles (CPs) are used widely as reinforcement materials since they possess excellent creep performance, higher hardness, fatigue resistance, and a high Young's modulus. Relatively, the addition of CPs in the AAMCs manufacturing process as a second phase improves the characteristics of the latter, including the wear resistance, strength-to-weight ratio, and even the cost-effectiveness.[7-10] Furthermore, CPs improve mechanical characteristics due to the fact that they are suitable to act as an obstacle to the movement of dislocations. Tribology-wise, CPs produce favorable performance by protecting the composites from immense wear through the sliding. These particles also play as load-bearing and can protect the surface of the matrix from the environment, thus making less delamination.[11,12]

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Numerous manufacturing techniques are employed in fabricating the AAMCs such as squeeze casting, stir casting, spray decomposition, mechanical alloying, and powder metallurgy. Powder Metallurgy Method (PMM) is classified as a highly effective technique to achieve well-distribution of particles in the matrix composite.[13,14) PMM offers several considerable advantages in manufacture composites such as easier matrix structure control and more suitable bonding of matrix with the particles. However, PMM possesses some disadvantages, such as large portions of porosity, high complexity, and high processing cost. A review in the present literature shows that although it is the most economical manufacturing method, little attention has been paid to the uniaxial pressing.[15,16] The other key reasons to choose uniaxial pressing in PM components' production are energy and material severity, the probability of pressing components with large geometric form, precision and repeatability tolerances in pressed component dimensions and high productivity levels (250 ~ 1250 part per hour).[17]

One of the Aluminum composite classifications that gained attention in recent years is the Al- Yttrium oxide (Y_2O_3) composite. A few interesting studies have shed light on the importance of this mixture and the power of using it to gain more favorable characteristics out of the constituents that make up the mixture. Mattli et al.[18] prepared Aluminum composite with different volumetric ratios of the Y_2O_3 by mechanical alloying with heating using the microwave energy during the sintering process. Their results revealed that the porosity keeps decreasing with the increase of the Y_2O_3, while the hardness is at its highest at a ratio of 1.5 %. The same rule applies to the yield and ultimate compressive strengths. The results showed that the influence of utilizing microwave sintering has some advantages over other methods. Moreover, Mahdi et al.[19] prepared an Aluminum composition with up to 15 % weight of the Y_2O_3 using squeeze casting and powder metallurgy methods. As expected, the increase in Y_2O_3 increases the hardness and the wear resistance. Also, the structure shows that the increase in squeeze pressure refined the grain size of the mixture, which had quantifiable impact on the strength of the composite. Similarly, Al khaqani et al.[20] prepared different composition for the Aluminum with up to 10 % weight of Y_2O_3 using powder metallurgy and tested the resulting mixture against erosion-corrosion behavior. Their results showed that the samples that went through sintering were less porous, denser and have larger hardness with the increase in Y_2O_3 content. The erosion-corrosion results showed that adding more Y_2O_3 to the mixture increases the resistance to this effect. To cross-study, the influence of other materials besides these two, Razooqi et al.[21] used mainly a three-combination composite. They mixed different ratios of the AL2024, Y_2O_3, and Gr; namely: (Al 2024-3wt% Gr - 0,2,4,6,8 wt% Y_2O_3), then the ratios were flipped between the Gr and Y_2O_3, then the mixtures were compacted and sintered. The results revealed that the bulk density increases when the Graphite ratio is held constant and the Y_2O_3 varied, the opposite happens when the Graphite ratio is varied. Moreover, the same trend can be seen when it comes to hardness and compressive strength. Interestingly, the wear rate study showed that changing the mixture ratios have the same effect on the behavior regardless of varying the ratio of the Y_2O_3 or Graphite.

In order to reduce fuel consumption, modern engineering applications, particularly in the aerospace and automotive industries, need priority vital and attractive characteristics such as lightweight with high strength. According to the literature survey of the existing study, it is therefore clear that mechanical properties and other dry sliding wear studies on the Al2024, reinforced with Yttrium oxide particles fabricated by PMM for the application of the automotive and aerospace industries, has not been achieved by other groups of research. The goal of the present study is to satisfy the knowledge gap necessary for the use of such hybrid composites in the aspects of those applications, and to offer a quantitative study of wear and mechanical properties at the specific scope of operating conditions.

2. Materials and Methods

2.1 Composite preparation

Aluminum alloy, type (2024), has been selected as a matrix material since it has commonly been used in many modern applications. Firstly, after weighting the samples, Al2024 powders, with various compositions shown in Table 1, were mixed together by a mechanical planetary miller with steel balls of 12 mm in diameter, for 1 hour. The rotational speed and the ratio of steel balls to powders were 300 RPM and 10:1, respectively. Secondly, Yttrium oxide (Y_2O_3) particles were utilized as the reinforcement material with a purity of 99.5 %, and particles size < 25 μm.

A universal uniaxial loading machine was utilized to compact the mixture with 500 MPa for 1 min to obtain a cylindrical specimen with dimensions of 10 mm in diameters and 6 mm in height. Then, the samples were sintered in an oven for 2 hours and 600 ^{o}C in an environment filled with Aragon gas. Finally, the samples

Table 1. Chemical Composition of Al2024 powder.

Composition (wt%)								
Element	Cu	Mg	Mn	Zn	Ti	Fe	Si	Al
%	4.35	1.5	0.6	0.25	0.15	0.5	0.5	Bal.

were cleared out of the furnace and left to cool down in room temperature.

2.2 Characterization and testing

The examination of the surface microstructure was performed and characterized via the optical microscope to investigate the structural features of the micro-level of the composites. The tests revealed the nature of the fabric, the dispersion of the reinforced material into the matrix, and the type and distribution of the phases in the manufactured composites. Using Archimedes' rule, the experimental density was measured for the mixtures, in accordance with the ASTM B 962-13.[3,15,22] On the other hand, the mixture rule was considered for the calculation of the theoretical density. With the two densities in hand, the porosity of the prepared mixtures was determined from the difference between the theoretical and actual densities. The first mechanical test was the Vickers hardness test, which was performed on the polished surfaces after cleaning them and applying 10 N of load for 15 seconds on five locations, the average of which was taken after that. Based on the results of the Vickers hardness, both the tensile and yield strengths were calculated using Cahoon equations 1 and 2 which suggested and recommended by Cahoon et al.,[23] and accepted by Annaz et al.,[13] Adebiyi et al.[24] and Ujah et al.:[25,26]

$$Ts = (VH/2.9) \times (k/0.217)^k \quad (1)$$

$$Ys = (VH/3) \times (0.1)^k \quad (2)$$

where Ts, Ys, VH, and k are the tensile strength (MPa), the yield strength (MPa), Vickers hardness (MPa), and the coefficient of strain-hardening, respectively. For this research, k was taken and registered from Callister and William reference.[27]

To assess the wear resistance of the produced composites, the Pin-on-Disk (PoD) standard method was used according to ASTM G99.[13,28,29] Prior to testing, the rotating disk and the holding fixtures were cleaned using a solvent. The loading of the sample was 5, 10, 15, and 20 N under a sliding velocity of 1.5 m/s at the centerline of the sample's contact face. The tests were performed for 20 min, which means 1810 m of sliding distance to allow for enough averaging of the wearability of the prepared composites. The wear of the samples was, then, determined via the mass difference between pre-and pro-wear measurements. An average of 5 successive readings for each test was reported. The collection of the data was completed for four specimens for each test, then the statistical analysis, including the averages and the standard error, was conducted.

3. Results and Discussion

3.1 Microstructure analysis

Fig. 1 shows the optical images of the microstructure to the composites reinforced versus various Yttrium Oxide content. At a first note, the high contrast of the micrographs between the matrix material and the reinforcement can be observed, which is due to the high-density difference between them. The microstructure can be classified into three regions; the white region refers to the matrix material (Al2024), the grey one refers to the reinforcement material (Y_2O_3 particles). Finally, the black region refers to the porosity content. On top of that, the good distribution of the reinforcement particles can be observed clearly in the matrix material, especially up to the 10 % Y_2O_3 ratio. After that, some clustering and agglomeration in the particles with a high content of Yttrium Oxide particles can be observed. Hence, we may infer that increasing the porosity content is directly linked with the reinforcement particles content. Moreover, well-bonded are observed between the materials of the composite.

3.2 Physical properties

The impact of Yttrium Oxide content on both the density and porosity of aluminum alloy composite is shown in Fig. 2. As can be noticed, increasing the content of reinforcement particles slightly drops the experimental density and significantly increases the porosity occupied percentage, which may be noticed as early as adding a 5 % content of Yttrium Oxide. This behavior can be attributed to several reasons. Firstly, ceramic particles possess high melting point as compared to the matrix material of Aluminum alloy, which serves as an impediment for the densification and consolidation with the matrix particles during the heating stage of the preparation. Furthermore, the Yttrium Oxide increased content means stronger lattice that can withstand more oversized loads, which reflects on the compaction of the samples during the pressing stage.

3.3 Mechanical properties

The two groups of mechanical testing results, strength and wear, are shown in Figs. 3 and 4. Starting with the mechanical strength, the graph shows, in general, the yield strength, tensile strength, and hardness having the same pattern. The yield and tensile strengths are showing that with the increase of the Y_2O_3 ratio increases the strength up to around the 10 % mark after which the composite seems to lose strength noticeably. The initial gain in strength can be explained by the fact that the Y_2O_3 particles cause the composite to become less prone to the deformation and dislocation movement. Those ratios of less than 10 % limit the elastic and plastic

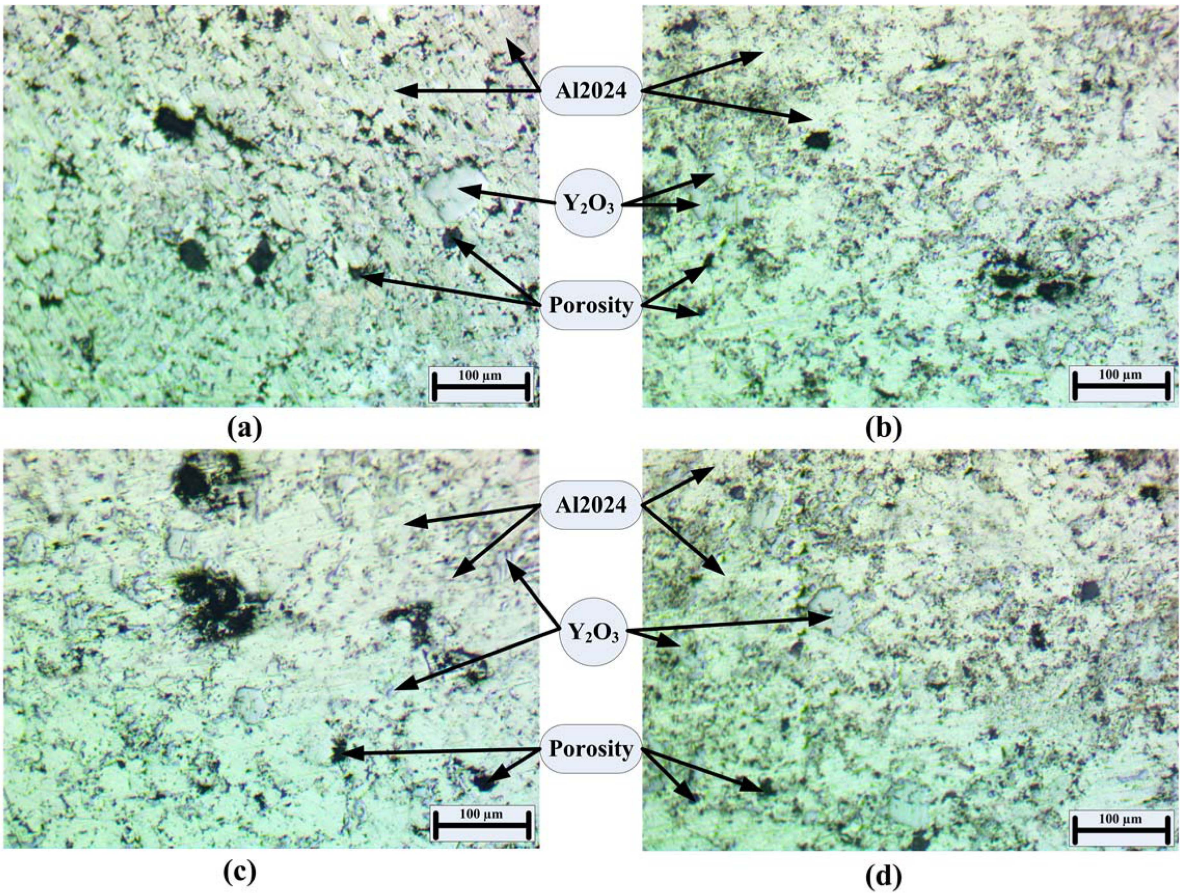

Fig. 1. Optical microstructure micrographs of Al2024 - Y_2O_3 composite produced with (a) 5 % Y_2O_3 (b) 10 % Y_2O_3 (c) 15 % Y_2O_3 (d) 20 % Y_2O_3

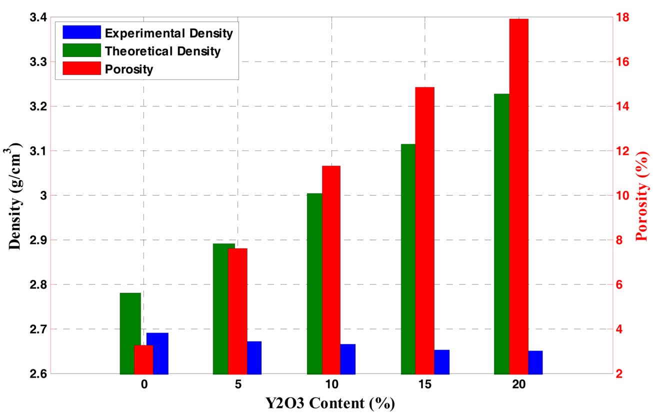

Fig. 2. The correlation between the yttrium oxide content with both porosity and density.

deformations of the matrix and create internal resistance to the formation and build of new boundaries and grains from the collapsed ones. Beyond this ratio, the strength drops, which can be interpreted by the fact that the excessive amount of the Y_2O_3 generated higher porosity, which weakens the internal structure by providing more means to the dislocations and internal deformation to happen in a softer way. An essential observation of Fig. 3 is that at the 20 % ratio mark, the composite's strength acts as if there is no Y_2O_3 presence in the matrix, which means that although the Y_2O_3 occupies 20 % of the weight, the gain mechanical properties is mitigated by the deficiencies caused by the porosity. This can help in deciding whether to use the composite in density reduction application if no mechanical strength gain is required or to maximize the strength at 10 % Y_2O_3 and moderately reduce the density. Fig. 3 also shows the Vickers hardness results, which, in general, follow the same discussed behavior for the yield and tensile strengths. The pattern of the HV plot shows the consistency of the behavior with the other strength measures, which means that the preparation procedure made them consistent, less diverted when it comes to the internal structure, and evenly distributed Y_2O_3 over the composite matrix.

Fig. 4 shows the wear test results of the composite with the 5 N load increment. For the first three loads, the increase in the Y_2O_3 ratio resulted in more wear-resistive composite up to the 10 % ratio mark. This means that the generated matrix can sustain more frictional load without losing too much material and have stronger tribological

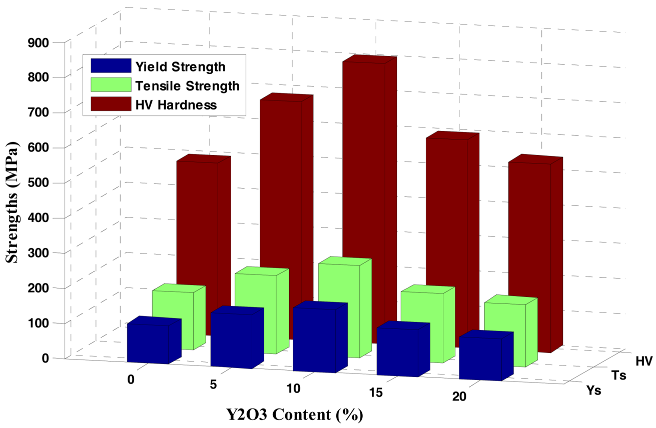

Fig. 3. The correlation between the yttrium oxide content with hardness, tensile strength and yield strength.

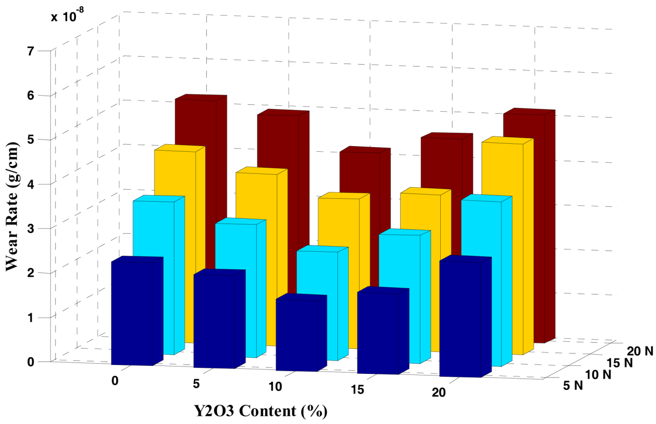

Fig. 4. The correlation between the yttrium oxide content with wear rate at various applied loads.

features. Knowing the nature of the dry sliding dynamical conditions (load and thermal-wise), Fig. 4 shows that the increase of the Y_2O_3 ratio makes the composite's surface more resistant as the plastic deformation is obstructed with the increase of the Y_2O_3 presence. Moreover, the dry wear behavior shows the resulting matrix is better at dissipating heat with the increase of the Y_2O_3 ratios since the higher the temperature during the sliding, the higher the wear rate, having all other parameters constant. Quantitively, the first three loads (5, 10, and 15 N) behave similarly when it comes to the pre-and post-10% Y2O3 behavior, in which the wear rate increases after the minimum at the same rate for the three loads, and the maximum wear rate being at the 20 % Y_2O_3. However, for the 20 N load, the wear rate at 20 % Y_2O_3 is the same as if there is no Y_2O_3 at all.

Furthermore, comparing Fig. 4 with Fig. 3 is beneficial in such cases in order to understand the inherited behavior of the composites. From these two figures, we can notice that the wear rate correlates with the Vickers hardness; therefore, the dry-sliding behavior of this composite follows the Archard's law, in which the wear rate is inversely proportional to the hardness.

4. Conclusions

Based on the findings of the current study, we may conclude the following:

1) The used method of PMM gives homogenous and well-distributed Y_2O_3 content in the matrix of the Al2024-Y_2O_3 composite.

2) The experimental density slightly decreased with the increase of the Y_2O_3, ratio, unlike the theoretical density and porosity, which showed a dramatic increase over the same ratio span.

3) The Vickers hardness, as well as the yield and tensile strengths, increased as the Y_2O_3 ratio increases up to 10 % point, after which they declined.

4) Following the same pattern as the hardness, the wear-resistance showed that the composite is at its most vital point at 10 % Y_2O_3 ratio; whereas, any increase leads to lower wear resistance. Besides, the wear resistance reduced evidently with the increase in the applied loads.

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