Effect of Yttria Content up to 15wt% on Mechanical Properties of Al-Y2O3 Composites Prepared Via Squeeze Casting and Powder Metallurgy Routes

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Abstract

In this study Al - (0-15 wt %) Y2O3 composites were prepared by both squeeze casting and powder metallurgy routes. It was found throughout this work that Vickers microhardness, compressive yield strength and wear resistance increase continuously with increasing Yttria content up to 15wt% despite the preparing method. Powder metallurgy composites showed higher hardness and compressive strength compared with those of squeeze casting. On the other hand, both squeeze casting, at squeeze pressure of 15 and 20 MPa, and powder metallurgy routes gave approximate wear rates except that of pure aluminum where squeeze casting specimens showed much lower wear rates than those of powder metallurgy. It was also found that squeeze pressure has great effect on grain refining and Chinese script microstructure evolution. XRD patterns reveal high level of harmful oxides and intermetallic compounds in squeeze casting composites as compared with those prepared by powder metallurgy technique.

Keywords : Al-Y2O3 composites, mechanical properties, squeeze casting, powder metallurgy.

1. Introduction

Composites are composed of two or more different materials. They combine the preferred properties of each constituent in the new material. In general they are composed of reinforcement phase in the form of particles, fibers, whiskers or plates, which is surrounded by the matrix phase. The matrix bonds between the reinforcing phase and protects it from the operating environment [1].

Composites are considered to be among the most important materials that are used in modern engineering applications due to their unique characteristic properties over the traditional materials and alloys, such as strength, toughness, wear resistance, corrosion resistance, heat and sound insulation, fatigue life and elevated temperature resistance [2,3].

Aluminum metal matrix composites (AMMC) occupy an important area between metal matrix composites (MMC) due to their high strength to weight ratio, high wear resistance and lower thermal expansion coefficient as compared with pure aluminum. AMMC found numerous important engineering applications such as internal combustion engines, airplanes structures and aerospace applications. Most of AMMC are produced by adding silicon carbide (SiC), alumina (Al2O3), zirconia (ZrO2) , magnesia (MgO), Yttria (Y2O3), and different types of fly ash to the aluminum and aluminum alloys matrix [2,4,5,6].

AMMC are produced by several processes including stir casting, squeeze casting, extrusion and powder metallurgy technique. Squeeze casting composites are characterized by their fine microstructure and low porosity due to rapid directional solidification and active inter-dendritic feeding, high dimensional accuracy and surface quality, good mechanical properties with the ability to add reinforcing particles as high as 40% [7-9]. On the other hand powder metallurgy techniques are widely used in producing MMC with the advantages of low material loss, the ability to control the degree of porosity, accurate control of chemical composition, the ability to produce alloys which cannot be produced by any other method, reduced gas pockets and segregation, good mechanical properties and the reinforcing material can be added to any desired content [10, 11].

W.B. Bounaeshi and D.Y.Li studied in 2007 the effect of Y2O3 particulates on microstructure, mechanical properties, electrochemical behavior, and corrosive wear of Al-Y2O3 composites prepared by powder metallurgy route. They found an increase in hardness, dry wear and corrosive wear resistance, an enhancement in polarization behavior, and grain refinement with increasing Y2O3 content [12].

In 2010, Ramu Yarra et al studied the densification effect of equal channel angular pressing (ECAP) on Al-Y2O3 composite prepared via powder metallurgy technique. They found that both density and hardness increase with increasing number of passes through ECAP [13].

Hafeez Ahamed and V. Senthilkumar (2010, 2011, and 2012) studied the compaction, sintering, microstructural and microhardness behavior of nanocomposite powders of Al6063-Al2O3, Al6063-Y2O3, and Al6063-Al2O3-Y2O3. They found that among the investigated nanocomposites, the one with combined Al2O3 and Y2O3 particulates was the most effective in increasing sinterability, microhardness, and homogeneity of reinforcement particles distribution. On the other hand they also found that the sinterability of Y2O3 particulates reinforced nanocomposites was more stable under varying sintering periods. It was observed that both Y2O3 and Al2O3 effectively sustain the crystallite size reduction and increase microhardness, 0.2% yield stress, and ultimate tensile stress [14-16].

Li Changqing a et al (2013) studied the solid state interaction between aluminum and Y2O3 mixture prepared via powder metallurgy route. Results of their study show that at low temperatures aluminum is isolated from Y2O3 by an air-formed aluminum oxide layer which prevents any direct reaction between Al and Y2O3. On Increasing temperature to 569 °C aluminum partly turned into transitional aluminas with which Y2O3 reacts to form yttrium aluminum monoclinic and yttrium aluminum perovkite phases [17].

S.F. Hassana et al (2011) studied the effect of Y2O3 on properties of Mg- Y2O3 composites prepared via powder metallurgy techniques through conventional and microwave sintering. They found that both sintering procedures give identical synthesize of the composite. However conventional slow sintering was more effective in microstructure refining, formability, and fracture strength while rapid microwave sintering was more effective in composite strengthening [18].

In 2007 Khin Sandar Tun, M. Gupta found that microwave sintering followed by hot extrusion gives near theoretical density of Mg- Y2O3 composites. Moreover, increasing Y2O3 was found to increase 0.2% yield stress, ultimate tensile stress, ductility, fracture strength, and reduce the coefficient of thermal expansion of the composite [19].

The present research represents a comparative study of the effect of up to 15wt% Yttria additions on microhardness, compression strength, and wear resistance of aluminum-Y2O3 composites prepared by both squeeze casting and powder metallurgy routes.

2. Experimental Procedure

2.1. Specimen Preparation

Al-Y2O3 composites were prepared by two techniques:-

1. Squeeze casting, where 99.7% Al wires, produced by Coreal Turkish Company, was melted in a graphite crucible and superheated to 800 °C using electric resistance furnace. Y2O3 powder 0,5,10 and 15 wt. % (< 25 µm particle size and 99.5% purity), produced by Fixanal Germany Company, was added to Al melt and mixed by mechanical stirrer. The mixture was then poured into steel mold that is preheated to 300 °C, as shown in figure (1). Squeeze pressure of 0, 5, 10, 15 and 20 MPa was applied when the mixture reaches the pasty state at 658 °C. The pressure was maintained until solidification process was completed.
2. Powder metallurgy route, where 99.7% Al powder with (< 53 µm particle size) produced by Merck Company, England was mixed with the same Y2O3 particulates at the same wt.% mentioned above. The mixture was then unidirectional compacted at 900 MPa for 30 seconds to prepare 10mm diameter specimens with 6mm thickness. The compacts were then sintered at 550 °C using silica – gray cast iron chip – fire clay configuration as shown in figure (2). The specimens were recompacted and resintered to obtain the final properties.

2.2. Mechanical Testing:

The following tests were conducted on the prepared specimens:-

1. Vickers hardness using, France (TG M) tester.
2. Compression test using universal testing machine, Shimadzu UH - 600KN to determine the compressive yield strength
3. Wear test using pin – on – disc method. The rotational speed was constant at 480 rpm.

The load was 20N and is applied for 30 min. Wear tests were conducted onto Wear and Friction Monitor ED – 201. Wear rate was determined using the following formula :

Wear rate = ΔW / SD (g / cm)

Where :

$\Delta W = W1 - W2$

W1 = specimen weight before testing (g)

W2 = specimen weight after testing (g)

SD = πD.N.t

SD = linear sliding speed (m/sec.)

D = sliding circle diameter (cm)

t = sliding time (min)

N = steel disc speed (rpm)

3. Results and Discussion

3.1.Effect of Y2O3 Content on Composite Microhardness

Figure (3) shows the relationship between Vickers microhardness and Y2O3 content for composites prepared by both squeeze casting and powder metallurgy routes. It is observed that increasing Y2O3 content increases hardness despite the preparing procedure.

In squeeze casting specimens, it is observed that the hardness increases with increasing squeeze pressure at any Y2O3 content. The effect of Y2O3 content and squeeze pressure on composite hardness can be attributed primary to the high hardness of Y2O3 and its action as a barrier to dislocation motion and local plastic deformation [20]. Moreover, the low coefficient of thermal expansion of Y2O3 as compared to that of Al matrix contributes in the production of large number of dislocations at the interface between reinforcement particles and matrix. This effect increases with increasing Y2O3 content causing further increase in hardness [12]. At the same time Y2O3 particles acts as heterogeneous nuclei on solidification which refine the microstructure, this effect is reinforced by squeeze pressure, which reduces or eliminates the gap between the ingot and internal surface of the steel die causing fast cooling rate which further refines the microstructure as shown in figure (4) which reveals the evolution of Chinese script morphology of the composite microstructure with significant refinement on increasing the squeeze pressure from 0 to 20MPa (figure 4- A to E). On grain refinement, the grain boundary area increases causing an increase in the microhardness of the composite due to its effects as barriers to dislocation motion and resistance the plastic deformation. Moreover squeeze pressure activates the interdendritic feeding mechanism which reduces the shrinkage porosity and enhances the bonding between Al matrix and Y2O3 particles.

Referring to figure (3) it is observed that Al-Y2O3 composites prepared by powder metallurgy route is harder than those prepared by squeeze casting for all Y2O3 contents and all squeeze pressure. This can be attributed to the casting conditions which provide a chance for interaction between Y2O3 and Al matrix and its constituents, forming a harmful intermetallic compounds and oxides as observed in the XRD patterns shown in figures (5) and (6). These figures reveal the high level of oxides and intermetallic compounds in squeeze casting composites as compared with powder metallurgy composites. Moreover, some Y2O3 particulates may be lost with slag and some can be settled down in the crucible on stir mixing and on transporting period between mixing and pouring. On the other hand not any Y2O3 particulates were lost on preparing by powder metallurgy route.

XRD patterns of Al- Y2O3 powders prepared by both squeeze casting and powder metallurgy techniques are shown in figures (5) and (6) respectively. In figure (5) it can be observed that considerable reactions were occurred between aluminum matrix, it's accompanied impurities (Fe and Si), with Y2O3 and dissolved oxygen due to stirring effect during mixing process and vortex formation. These reactions lead to the formation of oxides and intermetallic compounds. These reaction phases have harmful effects on the interface bonding and on mechanical properties of squeeze casting composites as compared with those of powder metallurgy composites in which not any oxidation was observed and only small quantities of intermetallic compounds were found due to some interactions between aluminum matrix, Y2O3 and impurities as shown in figure (6).

3.2. Effect of Y2O3 Content on Compressive Yield Strength

Figure (7) represents the relationship between compressive yield strength ($\sigma 0.2$) and Y2O3 content. It is observed that increasing Y2O3 content increases ($\sigma 0.2$) despite the applied squeeze pressure and even the preparing method. This is due to the effect of Y2O3 particulates in producing high density of dislocations and hindering their motion i.e. reduces the capability of composites to plastic deformation and increases the compressive yield strength. This effect is

enhanced by grain refining by both heterogeneous nucleation and rapid cooling in squeeze casting.
Figure (7) also reveals that (σ0.2) values for powder metallurgy composites were higher than those for squeeze casting. The same causes that reduced the hardness of squeeze casting composites reduced their compressive yield strength as compared with those of powder metallurgy composites.

3.3. Effect of Y2O3 Content on Wear Rate

Figure (8) represents the relationship between Y2O3 content and wear rate of Al-Y2O3 composites. It is observed that increasing the reinforcement content up to 5% has a drastic effect in decreasing wear rate for both squeeze casting and powder metallurgy composites, after which almost little effect is observed on increasing Y2O3 between 5 and 15%. This can be attributed basically to the hard Y2O3 particulates themselves, where sintered bulk Y2O3 hardness was found to be 700HV [21], and partly the Chinese script microstructure, shown in Figure (4C – 4E), which contributes in decreasing the wear rate. Comparing wear rates of squeeze casting composites with those prepared by powder metallurgy route, it can be seen that powder metallurgy composites show wear rates approximate to those of squeeze casting at pressures of 15 and 20 MPa with Y2O3 content of 5-15wt% while squeeze casting gave much more wear resistance for pure aluminum (0% Y2O3) than powder metallurgy route.

4. Conclusions

1. Vickers microhardness and compressive yield strength increase with increasing Y2O3 despite the preparing procedure.
2. Increasing Y2O3 content up to 5% decreases drastically the wear rate for both squeeze casting and powder metallurgy composites, after which almost little effect was found on increasing its content up to 15%.
3. Powder metallurgy composites show higher hardness and compressive yield strength as compared with those prepared by squeeze casting.
4. Powder metallurgy composites show wear rates approximate to those of squeeze casting at pressures of 15 and 20 MPa with Y2O3 content of 5-15 wt%.
5. Squeeze pressure has great effect on grain refining and Chinese script microstructure evolution.

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تأثير محتوى اليتيريا لغاية wt15% على الخواص الميكانيكية لمتراكبات Al-Y2O3 المحضرة عن طريق السباكة بالعصر وتقانة ميتالورجيا المساحيق

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الخلاصة :

تم في هذا البحث تحضير متراكب ألمنيوم – (0 – 15 wt%) يتيريا عن طريق السباكة بالعصر وتقانة ميتالورجيا المساحيق . وجد في هذا البحث أن كل من صلادة فيكرز المايكروية ومقاومة الخضوع الانضغاطية ومقاومة البلى تزداد باستمرار مع زيادة محتوى اليتيريا حتى wt15% بغض النظر عن طريقة التحضير . أبدت متراكبات ميتالورجيا المساحيق صلادة ومقاومة خضوع أعلى مقارنة بمتراكبات السباكة بالعصر . على الجانب الآخر فقد أعطت كل من تقانة ميتالورجيا المساحيق والسباكة بالعصر ، عند ضغط عصر MPa15 و MPa20 ، معدلات بلى متقاربة ولجميع المتراكبات باستثناء الالمنيوم النقي المحضر بطريقة السباكة بالعصر إذ تميز بمعدل بلى منخفض جدا مقارنة بنظيره المحضر بتقانة ميتالورجيا المساحيق . وجد في هذا البحث كذلك أن ضغط العصر له تأثير كبير في تنعيم البنية المجهرية وتكوين البنية المجهرية الشبيهة بالخط الصيني . أظهرت نماذج فحوصات حيود الأشعة السينية XRD وجود مستوى عالي من الأكاسيد والمركبات المعدنية البينية الضارة في متراكبات السباكة بالعصر مقارنة بنظيراتها المحضرة بطريقة ميتالورجيا المساحيق .

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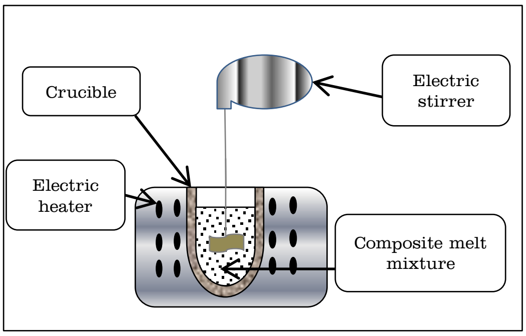


Figure (1) : stir mixer components.

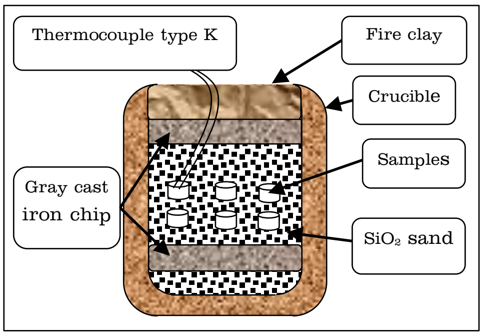


Figure (2) : sintering configuration.

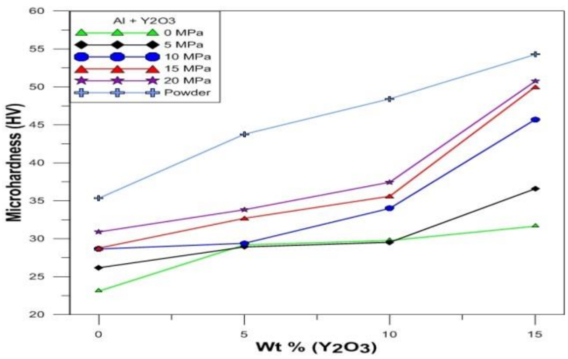
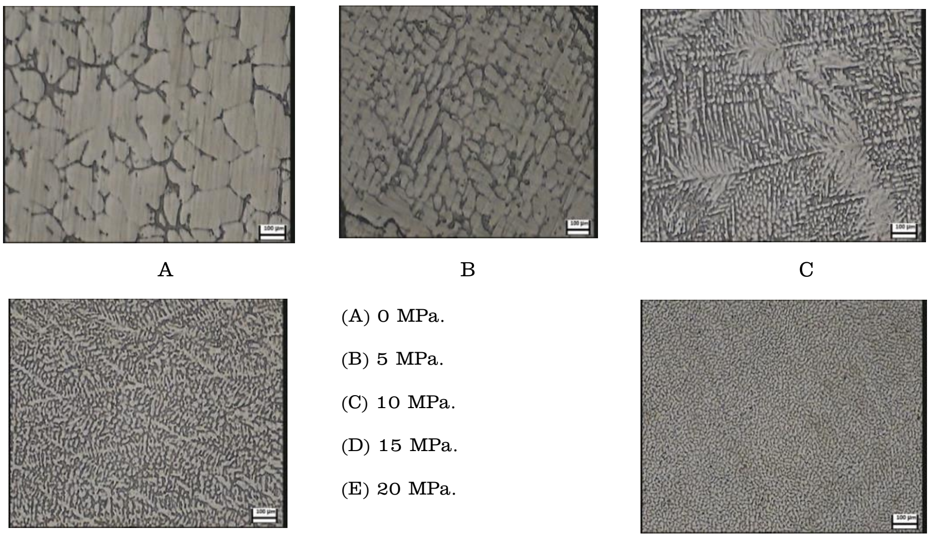


Figure (3) : effect of Y_2O_3 on Vickers microhardness of Al- Y_2O_3 composites



A

B

C

D

E

(A) 0 MPa.

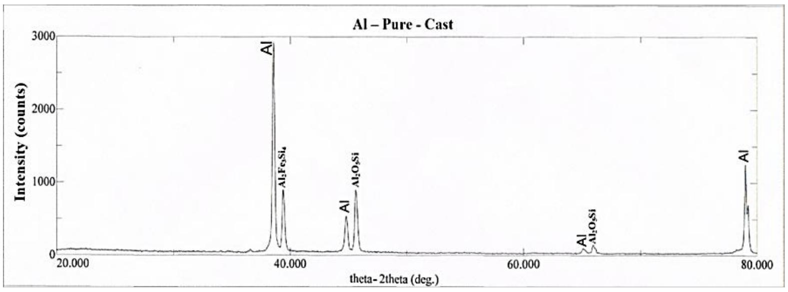
(B) 5 MPa.

(C) 10 MPa.

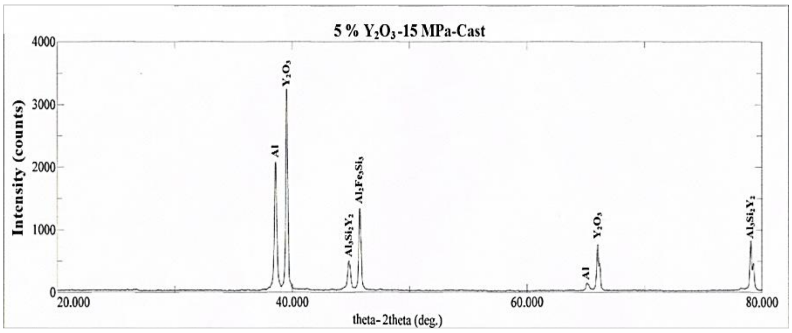
(D) 15 MPa.

(E) 20 MPa.

Figure (4) : microstructure of Al-5%Y_2O_3 prepared by squeeze casting.



A



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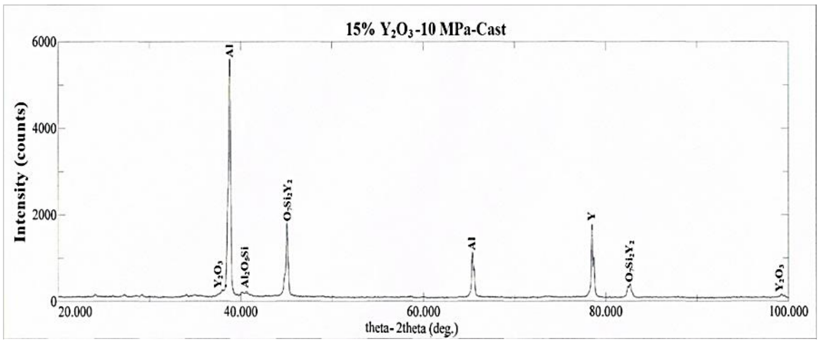
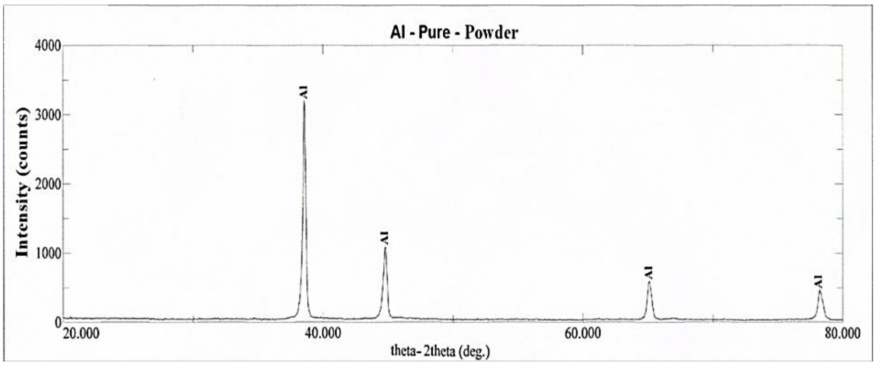
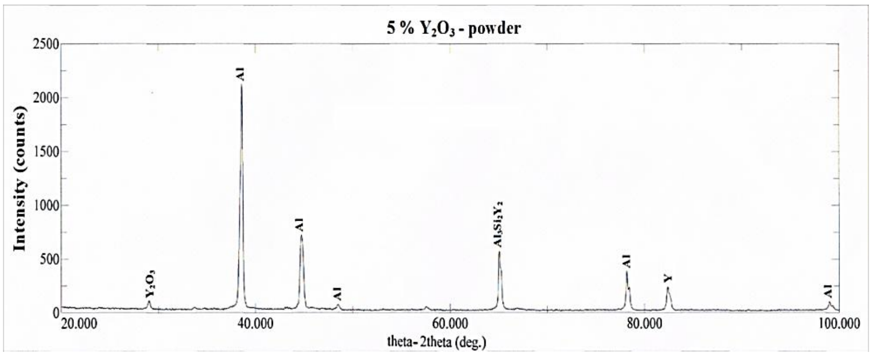


C

Figure (5) : XRD pattern of squeeze casting specimens (A) pure Al 0MPa (B) Al-5%Y_2O_3-15MPa (C) Al-15%Y_2O_3-10MPa



A



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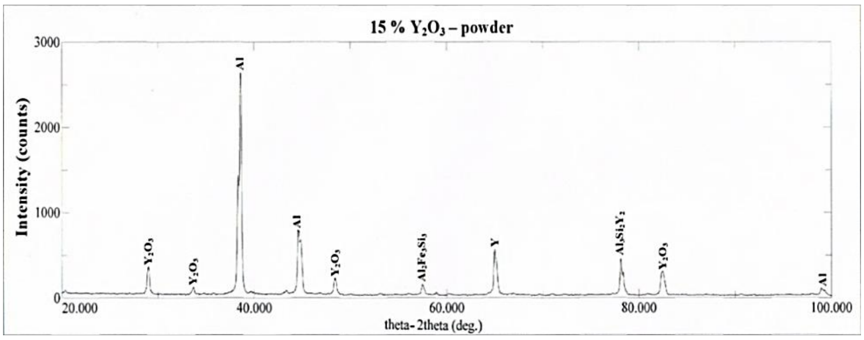

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Figure (6): XRD pattern of powder metallurgy specimens (A) pure Al (B) Al-5%Y_2O_3 (C) Al-15%Y_2O_3

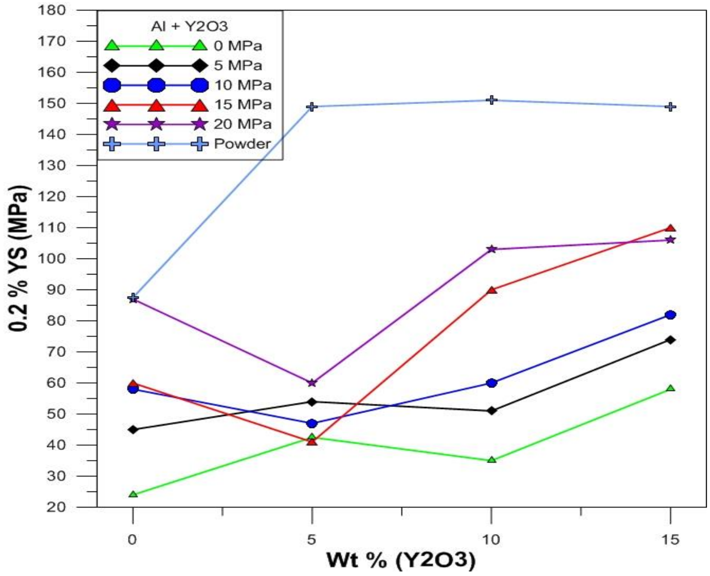

Figure (7) : effect of Y_2O_3 on compressive yield strength of Al-Y2O3 composites.

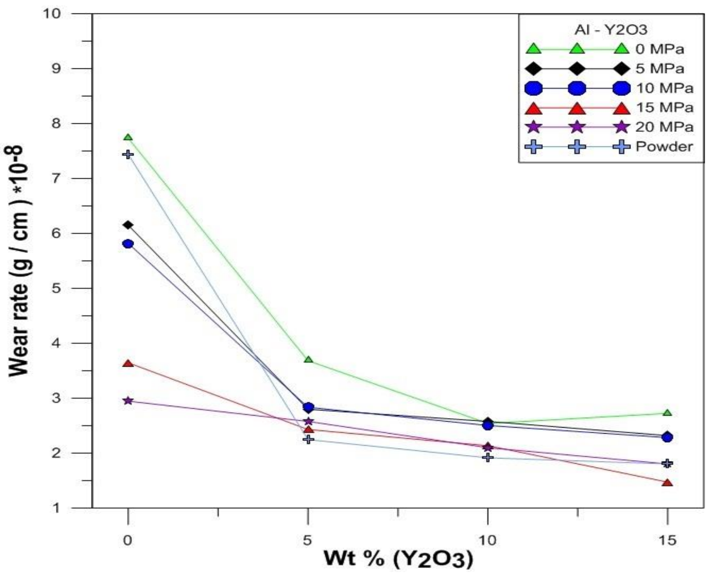

Figure (8) : effect of Y_2O_3 on wear rate of Al-Y_2O_3 composites.