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Enhancing mechanical properties of 2024-Aluminium Alloy Matrix Composite strengthened by Y_2O_3 ceramic particles

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ABSTRACT

The development of high-strength, low-weight composite materials has been a high-priority demand in the structural, aerospace, automotive, renewable energy, and sports equipment sectors. Micro-particle size Yttrium oxide (Y_2O_3) has been utilized to enhance the microstructure and mechanical characteristics of the 2024-Al alloy. The stir-casting technique is employed to prepare 2024-Al alloy and aluminum matrix composites (AMCs) with different Y_2O_3 weight fractions (1 %, 2 %, and 3 %). Scanning electron microscope ESM with EDS analysis and optical microscope imaging have been used to assess the development in the microstructure of AMCs. Furthermore, optical microscope images have been analyzed by using image processing software, ImageJ to evaluate development in microstructure grain size. Vickers' micro-hardness, tensile strength, elongation, and wear-resistant tests were conducted to assess the mechanical properties of AMCs. AMC image analysis results demonstrated a significant reduction in microstructure grain size. The highest reduction in grain size was recorded when adding 2 wt. % of Y_2O_3, which was approximately 22.5 % smaller than that of the plain alloy. Other mechanical test results demonstrated an increase in the hardness and tensile strength of AMCs compared with the plain alloy by approximately 58 % and 116 %, respectively, upon the addition of 2 wt. % of Y_2O_3, also tensile test shows increasing of AMCs elongation at failure point with increasing Y_2O_3 content, 132 % upon adding 3 wt. %. Finally, wear tests show a decrease in the AMC wear rate with an increasing Y_2O_3 weight fraction compared to the plain alloy.

Keywords: *Yttrium oxide, Aluminum alloy, Composite materials, Aluminum matrix composites, Wear rate*

1. INTRODUCTION

High-technology applications, such as those in aerospace, underwater technology, bioengineering, and transportation industries, demand materials with unique and specialized properties. The expansion of material properties and their ranges has been achieved and continues to evolve through the advancement of composite materials. Composites refer to materials containing multiple phases that achieve improved property combinations by skillfully combining two or more distinct materials [1]. 2024-Al alloy is widely recognized and extensively employed alloy in various industries, because of its remarkable combination of mechanical properties, lightweight nature, and corrosion resistance. It demonstrates high tensile and yield strength, along with excellent fatigue resistance. Furthermore, this alloy can achieve additional enhancements in mechanical characteristics through heat treatment processes and cold working methods [2]. This makes it a commonly used material in numerous industries, including aerospace and aviation, automotive manufacturing, sports equipment production, marine applications, and structural engineering projects [3]. 2024-Al alloy is primarily consisting of aluminum (Al) as the base metal, with copper (Cu). It also contains smaller amounts of (Mn, Mg, Si), and composites (MMCs), so it is possible to create materials with desirable physical and mechanical properties that are not possible with conventional alloys [4]. Many parameters have an impact on the final properties of Metal Matrix Composites (MMCs), including the processing method, processing parameters, the selection of reinforcement types, sizes, orientations, and quantities. Additionally, it is essential to ensure a uniform distribution of reinforcement within the metal matrix and control the matrix-reinforcement interface [5]. The addition of ceramic particles could cause a significant downsizing of the grain microstructure of metals during the solidification process, as reported by many previous studies [6, 7]. Refining the grain structure is associated with an increase in total grain boundary area, which resists dislocation motion for two reasons. First, to transfer a dislocation from one grain to the next through the boundary, it must alter its direction to align with the orientation of the second grain. This adjustment becomes increasingly challenging as the mismatch between the two grains grows. In cases of a high angle between grains, dislocations accumulate, creating stress concentrations ahead of slip planes, which, in turn, result in the generation of new dislocations within the second grain. Second, the absence of atomic order in a grain boundary region disrupts the continuity of slip planes between neighboring grains.

Consequently, refining the grain structure could improve hardness and strength, the strengthening through grain refinement also known as grain boundary strengthening [1, 8], Orowan looping represents another significant strengthening mechanism that relies on limiting the movement of dislocations. Essentially, according to this mechanism when a particle engages with a dislocation, it experiences stress, and in case the particle can endure this force, the dislocation begins to curve, ultimately resulting in the formation of an Orowan loop encircling the particle so more stress is needed to make dislocation pass the particles. Furthermore, prismatic punching of dislocations at the interface might be caused by the notable difference in the coefficient of thermal expansion CTE of metal matrices and reinforcing particles leading to strengthening the MMCs [9]. Many earlier investigations works have focused on the development of the microstructure and mechanical properties of aluminum alloys using common ceramic particles such as Al_2O_3, SiC, B4C, etc [10]. However, there is a limited number of experimental studies dedicated to investigating the effects of rare earth materials on the microstructure and mechanical properties of 2024 Al-alloy and more efforts are needed in this area. This work addresses this need by assessing the effects of adding micro-sized Yttrium oxide (Y_2O_3) particles to 2024-Al alloy on its microstructure and mechanical properties.

2. MATERIAL AND METHODS

2.1. Materials

Y_2O_3 fine silt, with 99.95 % purity, produced by Riedel–De Haen AG, Germany, was used as a reinforcement phase. The stir casting method was used to prepare 2024-Al alloy. The weight percentages of the elements in the alloy ingredients are displayed in Table 1.

2.2. Specimens' Preparation

The pressure-less casting method for alloy elements was carried out in a ceramic crucible using a gas furnace. The alloy was cast into a metallic mold with rod cavities. The mold was preheated before receiving molten metal to prevent thermal residual stresses. The casting process was initiated by melting aluminum at 750 °C for 1 hour to achieve a homogeneous melt before adding other elements (Cu, Mn, Si). Meanwhile, the magnesium (Mg) element was wrapped in aluminum foils before insertion into the molten alloy to prevent oxidation. Subsequently, the molten mixture was stirred with a steel mixer to ensure homogeneity. To prepare aluminum matrix composite (AMC) specimens, the molten alloy was allowed to cool to 470 °C before adding Y_2O_3 particles. A degassing agent was only added to the plain alloy specimens to release trapped gases within the molten metal. The preparation of AMC specimens was completed without the use of a degassing agent, as it could potentially expel ceramic particles onto the molten surface. The chemical composition of the AMCs is shown in Table 2. Figure 1 shows the metallic mold, and the furnace used in the casting process, in addition to specimens of wear resistance, and tensile strength tests.

Table 1. Chemical composition of 2024 Al-alloy [8]

Elements	Weight fractions %
Al	93.1
Cu	4.4
Mg	1.5
Mn	0.6
Si	0.4

2.3. Testing Characterization

The Scanning Electron Microscope (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) were performed using equipment manufactured by Bruker, USA. For implementing optical microscope imaging, the EMZ-5TR stereo microscope made in Japan, was used. Specimens preparing processes included polishing by (180 - 200 - 400 - 600 - 800 - 1000) silicon carbide papers, followed by chemical solution treatment was executed before imaging. The average grain size structure of 2024 Al-alloy and AMCs was estimated by using image processing software, ImageJ.

Vickers' micro-hardness tests were performed by utilizing a digital precision hardness tester (HVS-1000), which used a diamond pyramid. The hardness tests of three points were tests for each specimen at least, and average values were dependent. Tensile tests were conducted in accordance with ASTM E8. The specimens had dimensions of 50 mm in

Table 2. Chemical composition of AMC specimens

Elements %	Sample 1	Sample 2	Sample 3
Al	92.1	91.1	90.1
Cu	4.4	4.4	4.4
Mg	1.5	1.5	1.5
Mn	0.6	0.6	0.6
Si	0.4	0.4	0.4
Y_2O_3	1	2	3

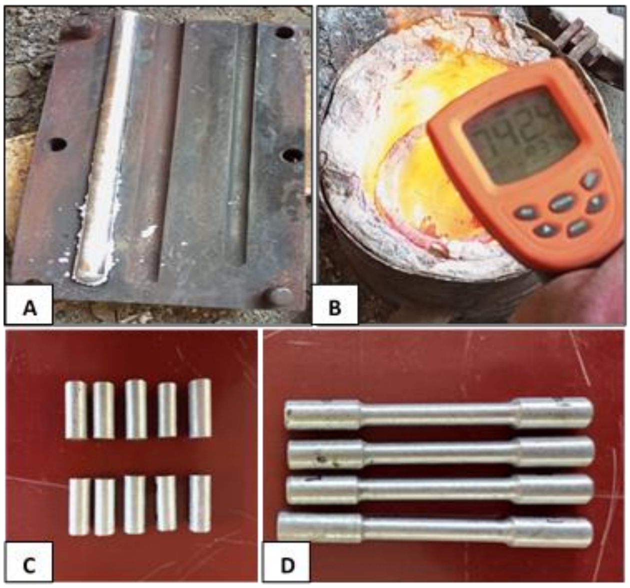

Figure 1. (A) Metallic mold, (B) a furnace used for the casting process, (C) wear resistance specimens, and (D) tensile strength specimens

length, 12.5 mm in diameter, and 25 mm in length for gripping on both sides. The geometry and dimensions of the specimens are illustrated in Figure 2.

The tests were executed by a computer-controlled universal testing machine, produced by Laryee Technology CO. LTD, at room temperature and under 100 k.N force. Two specimens have been tested for each kind of composite.

For evaluating the wear rate of 2024-Al alloy and AMCs, a dry sliding wear test, pin on desk device, shown in Figure 3. has been used. Specimens with 10 mm diameter and 20 mm length were in contact with a steel rotating disc under 10 Newton force. The loss in weights of specimens after 10 minutes of running has been measured by 4-digital sensitive balance, and the wear rate of each specimen has been calculated according to Equation (1):

$$W = \frac{V}{F_n d} \tag{1}$$

where W is the wear rate, F_n is the applied normal force, and V is the worn volume, which can be calculated from Equation (2):

$$V = \frac{\Delta w}{\rho} \tag{2}$$

where Δw is losing weight during running, ρ is the density, and d is the total sliding distance, which can be calculated from Equation (3)

$$d = 2\pi RNt \tag{3}$$

Where R is disc radius, N is angular speed (number of revolutions per minute), and t is running time [11, 12].

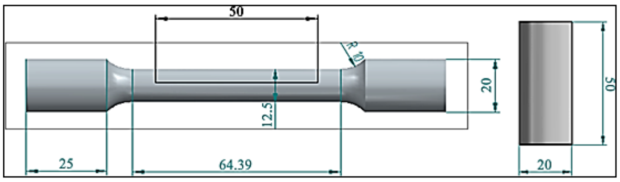

Figure 2. Geometric schematic of tensile test specimen

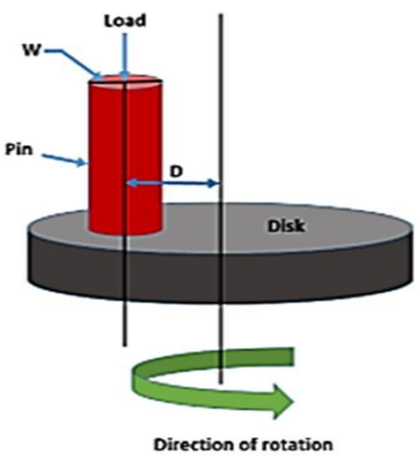

Figure 3. Pin on desk device [13]

3. RESULTS AND DISCUSSION

3.1. Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) Analysis

The secondary electrons SEM images of AMCs with 3 wt.% Y_2O_3 and EDS analysis at the selected area is shown in Figure 4.

According to chemical analysis of the EDS chart, it can be observed the presence of peaks corresponding to Yttrium elements, derived from the addition of Y_2O_3 and other introduced elements. Furthermore, it can be noticed the presence of Y_2O_3 particle agglomerations, appearing as large white blocks due to high reflectivity to the incident SEM rays, due to the higher atomic number of yttrium compared to the aluminum matrix which represents the darker background.

3.2. Microscope Images

The optical microscopic images of specimens after the preparation processes are shown in Figure 5. Average grain size estimation by using image processing software, ImageJ, is shown in Table 3.

It can be observed that the microscope images of AMC specimens exhibit a finer average grain size structure compared to that of the 2024-Al alloy. Furthermore, the average grain size decreases with an increase in the content of Y_2O_3 particles and minimum average grain size was reported for the AMC with 2 wt. % Y_2O_3. One possible reason behind the downsizing of the grain structure is the availability of more nucleation sites within the molten matrix of AMCs during the solidification process, due to the

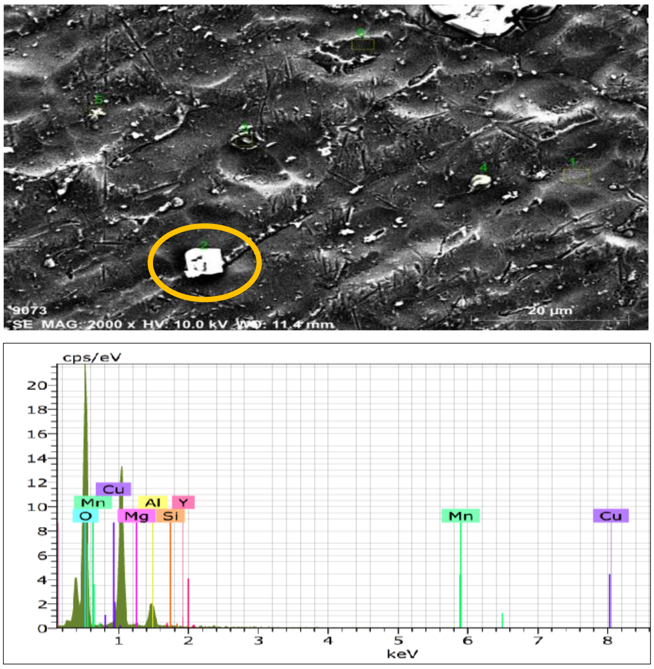

Figure 4. SEM image of AMC with 3 wt. % Y_2O_3 and EDS analysis at the circular specified area

Table 3. Average grain size measured by image processing software "image J"

Specimen	Average grain size (μm)
Plain 2024-Al alloy	19.20
2024-Al alloy + 1 wt. % Y_2O_3	15.62
2024-Al alloy + 2 wt. % Y_2O_3	11.72
2024-Al alloy + 3 wt. % Y_2O_3	14.87

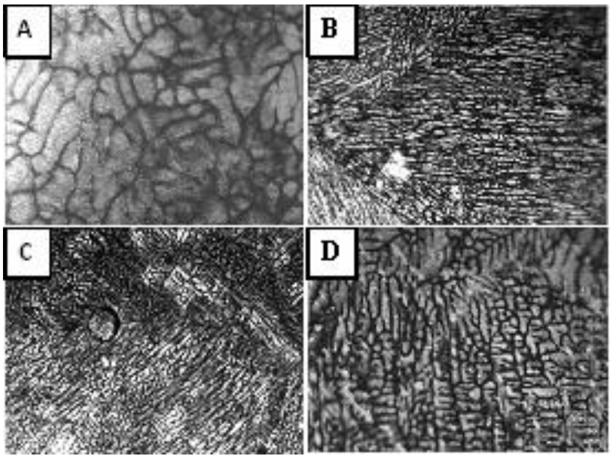

Figure 5. Microscope images of (A) 2024 Al-alloy, (B) 1 wt. % Y_2O_3 AMCs, (C) 2wt. % Y_2O_3 AMC, and (D) 3wt. % Y_2O_3 AMCs specimens

existence of ceramic particles, which act as additional nucleation sites according to metals' heterogeneous solidification mechanism, so the numbers of grains increase in cost of grains growths. Furthermore, the presence of ceramic particles could hinder the grain's growth mechanism during the solidification stage [1, 6, 8]. However, AMC with high Y_2O_3 content, 3 wt. %, show less grain refinement efficiency, and that may be because development of Y_2O_3 agglomeration sites as shown in the SEM image, due to difficulties associated with distributing high ceramic content uniformly within metal by the traditional stir casting method. However, the role of Y_2O_3 in the refinement of the Al-alloy matrix is similar to that of many other additive ceramics in metal matrices such as AlN and Al2O3, as reported in previous studies [6, 14].

3.3. Hardness

The results of 2024-Al alloy and AMC specimens' hardness tests are shown in Figure 6.

It is generally observed that the hardness of the AMC increases with the ceramic particle content. It is generally observed that the hardness of the AMC increases with the ceramic particle content. This development in hardness is a reflection of microstructure changing as previously shown by microscope images. The reduction in particle size with increasing ceramic content can explain the improvement in hardness and strength of AMCs, as suggested by the strengthening mechanisms discussed earlier: grain boundary strengthening, Orowan looping, and thermal expansion coefficient mismatch. These mechanisms hinder and restrict dislocation movement. Furthermore, according

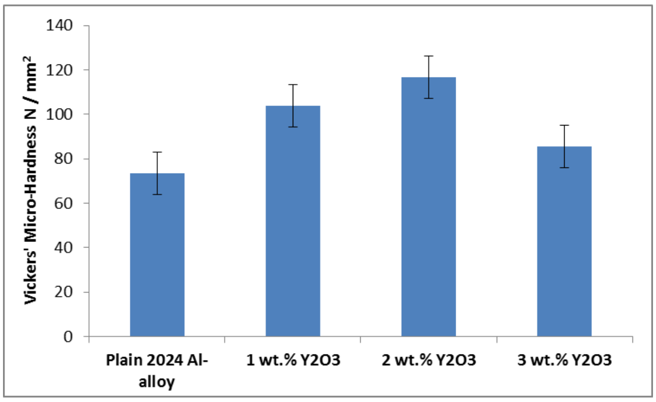

Figure 6. Vickers micro-hardness of 2024 Al-alloy and AMCs specimens

to the rule of mixture, an increase in the ceramic particle content leads to a higher composite hardness. However, similar behavior has been documented by many previous works that used Y_2O_3 and other different ceramic kinds like Al_2O_3, SiC, and TiO_2 [6, 7, 15, 16]. The relatively decreased AMC hardness of high ceramic content, 3 wt. % Y_2O_3, may justified by non-uniform ceramic particle distribution and relatively high average grain size structure of AMCs.

3.4. Wear Rate

The wear test is an essential procedure for evaluating the resistance of materials to degradation when they come into contact with other surfaces under external force. Wear rate test results of 2024-Al alloy and AMCs specimens are shown in Figure 7.

It can be noticed that the wear rates, the amounts of material loss under frictional action, of AMCs are less than that of pure 2024-Al alloy. Essentially wear rate is highly dependent on the microstructure, surface conditions practically hardness. Therefore, the enhancement in AMC hardness, and strength as the reduction into grain microstructure achieved by reinforcing the metal matrix with dispersed ceramic particles, could explain the decrease in the wear rate of AMCs. These findings are consistent with many similar earlier studies that reported a decrease in the wear rate of AMCs with increasing ceramic content in composite [19, 20].

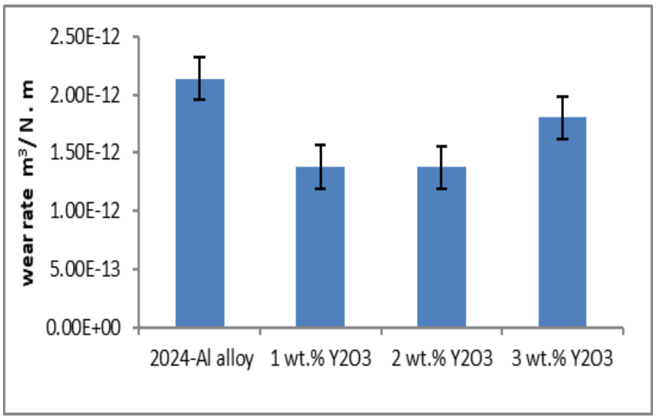

Figure 7. The dry sliding wear rate of 2024 Al-alloy and AMC specimens

3.5. Tensile Strength

The strain-stress behavior of 2024-Al alloy and AMCs specimens, with their respective maximum tensile strength and elongation percentages, is illustrated in Figure 8.

It can be noticed that that AMCs demonstrate higher tensile strength, modulus of elasticity, elongation percentages at the points of failure, and consequently higher toughness than plain 2024 Al alloy. The highest strength is recorded for AMCs content 2 wt. % Y_2O_3. The increase in AMC specimens' strength agrees with the changes in microstructure, particularly the reduction in grain size, as earlier shown. Ceramic particles could strengthen the metal matrix by hindering and restriction dislocation motion, as mentioned previously, by several proposal mechanisms including grain boundary strengthening, Orowan looping, and mismatch thermal expansion coefficient.

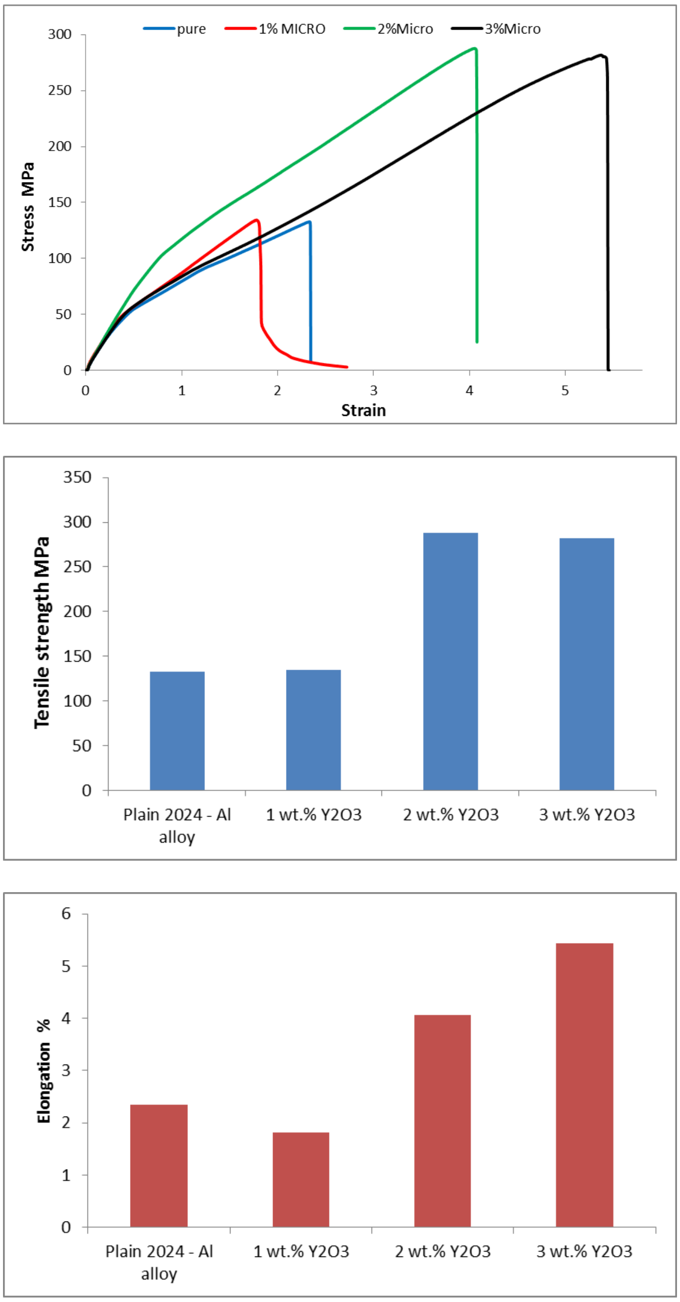

Figure 8. (A) stress-strain diagram, (B) tensile strength, and (C) elongation percentage of as-cast 2024 Al-alloy and AMCs specimens

Essentially, larger grain structures typically exhibit lower strength because dislocations can move more freely within them, encountering fewer grain boundaries that could impede dislocation motion and disperse their energy. On the other hand, the presence of uniform dispersion ceramic particles can reduce the micro-yielding stress due to an increasing number of stress concentration sites, consequently, dispersion applied stress. The tensile strength results are consistent with similar previous studies related to reinforcing the aluminum matrix with common ceramic particles like SiC, Al_2O_3, and TiO_2 [16, 17, 18, 21]. The increase in elongation percentage or ductility with the rise in Y_2O_3 content can also be attributed to the reduction in average grain size. A finer-grain structure is known to exhibit more plastic deformation before fracture compared to a coarse-grain structure [22].

4. CONCLUSION

The main conclusions based on implemented mechanical tests are the following:

- Y_2O_3 with micro-sized particles can be effectively used as a practical reinforcing phase to prepare Al-alloy matrix composites (AMCs) by the stir casting method.
- Adding Y_2O_3 particles to the 2024-Al alloy can refine metal grain size microstructure and improve mechanical properties such as hardness, tensile strength, modulus of elasticity, and wear resistance.
- The best results are achieved with the addition of 2 wt. % Y_2O_3, while higher Y_2O_3 additions exhibit less improvement efficiency to the AMCs mechanical properties.

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