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# Effects of $Y_2O_3$ addition on microstructure, mechanical properties, electrochemical behavior, and resistance to corrosive wear of aluminum

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## Abstract

Aluminum has found many engineering applications due to its great formability, low density and high resistance to corrosion. Since aluminum is not very strong compared to other structural materials, it is usually strengthened by introducing second phases, reinforcing particles or fibers.

The objective of this work is to strengthen aluminum without decreasing its corrosion resistance. Yttria is selected as reinforcing particles. It is demonstrated that by adding yttria particles, aluminum can be strengthened with improved polarization behavior and higher resistance to corrosive wear in sulfuric acid and sodium chloride solutions. Microstructure of aluminum becomes finer with an increase in yttria content. However, the added yttria particles are not observed in the modified aluminum. Instead, a new phase,  $Al_3Y$ , is formed, which may result from possible decomposition or melting of the yttria particles during an arc melting process. The improved properties of aluminum by the yttria addition may thus be attributed to the formation of  $Al_3Y$  phase, possible residual yttrium in the Al matrix, and the resultant finer microstructure.

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*Keywords:*  $Y_2O_3$ ; Aluminum; Mechanical behaviour; Corrosion; Corrosive wear; Microstructure

## 1. Introduction

Aluminum is one of the most attractive materials widely used in industry, e.g., components and structures in vehicles, trains, aircrafts, boats and space shuttles, due to its great formability, low density and high corrosion resistance. Because of its low strength, aluminum has to be strengthened before being applied in industry, using various processes such as solution strengthening and precipitation strengthening. The treatments considerably increase hardness of aluminum, leading to a wide variety of aluminum alloys available for various engineering applications. Embedding ceramic particles in aluminum matrix is another effective way to strengthen the metal with enhanced resistance to mechanical failure and wear [1].

However, such strengthened aluminum (e.g., Al-matrix composites), more or less, loses its high corrosion resistance, which is one of the most attractive properties

of the metal for industrial application. This happens because of the difference in electrode potentials between aluminum and the reinforcing phase, which accelerates electrochemical reactions. Second phases or reinforcing particles may also influence the formation of a passive film on aluminum that protects the metal from continuous corrosion attack. The passive oxide surface film builds a barrier between the metal and the corrosive media to prevent further corrosion. Mechanical and electrochemical properties of the passive film as well as its adherence to the substrate are of importance to the performance of aluminum alloys in corrosive environments. If mechanical attack is involved, e.g., wear, during a corrosion process, the passive film may fail easily, thus resulting in larger material loss. Therefore, improving the passive film and associated passivation capability would largely help to prolong the service life of aluminum-based materials.

Previous studies have demonstrated that rare-earth elements (RE) or oxygen-active elements, e.g., yttrium and some of their compounds such as yttria can increase the oxidation resistance of high-temperature alloys through

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enhancing their oxide adherence to reduce the spallation of oxide scales [2–5]. The RE compounds may also reduce the growth rate of oxide [6–11], which may decrease the interfacial stress and thus the probability of oxide failure. In addition to oxidation, RE is also beneficial to corrosion resistance of passive alloys [12–17]. It was reported that cerium or yttrium significantly improved Al–Zn–Mg alloy against stress-corrosion [18].

The beneficial role of RE elements as corrosion inhibitors in aqueous solutions was also reported [19]. Various RE salts, such as  $\text{YCl}_3$ ,  $\text{LaCl}_3$  and  $\text{CeCl}_3$ , were found beneficial as corrosion inhibitors to alloys when added to aggressive media [20–26]. It has been demonstrated that corrosion of aluminum alloy [25,26], mild steel and stainless steel [22,27], and zinc [23] in aqueous chloride solution (0.1 N NaCl) is reduced when RE cations are added to the solutions, which help to develop a compact hydrated RE oxide film or adsorptive film on the metal surface that protect the substrate more effectively from the attack by aggressive electrolyte.

Recent studies [14–16,28,29] have shown that RE or oxygen-active elements can considerably enhance the corrosive wear resistance of passive materials. The situation is similar to the increase in high-temperature wear resistance of Stellite 6 alloyed with yttrium [30]. When oxidation is suppressed by RE, the synergism of wear and oxidation is diminished, thus leading to lower wear rate. Recent studies showed that not only the oxygen-active elements, but also their compounds were beneficial, e.g., yttria was found to enhance the resistance of aluminum to corrosion and corrosive wear [31]. Application of RE compounds rather than RE should be more feasible to industry, since there would be no problem with RE degradation during material processing.

In this work, yttria particles were added to aluminum for improved performance of aluminum during corrosive wear. The objective of the research is to investigate changes in microstructure, mechanical, electrochemical and tribological properties of aluminum when yttria powder was added to the metal using an arc melting process.

## 2. Experimental procedures

Commercial aluminum powder (99.8%, –40 to +325 Mesh) was used to make samples, respectively, containing 0, 5, 10, and 20 wt%  $\text{Y}_2\text{O}_3$  powder with particle size smaller than 10  $\mu\text{m}$ . Al and  $\text{Y}_2\text{O}_3$  powders were mixed in a rotating plastic bottle with alumina milling balls for 10 h. The mixed powder was then pressed in a tool steel die having its diameter equal to 25.4 mm using a Carver press machine to make samples, followed by melting in an arc-melting furnace. Before melting, the furnace was evacuated to  $5 \times 10^{-2}$  Torr and then filled with argon gas to a pressure of 1 atm. An argon flow was maintained at a rate of 2 L/min during melting and solidification processes. All samples were turned over, remelted and cooled for four times in order to reduce the microstructural inhomogeneity.

The produced samples had dimensions of  $5 \times 10 \times 10$  mm and were examined using X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). Before the examination, samples were mounted with epoxy resin, polished to 0.05  $\mu\text{m}$  and etched using a *Keller's reagent* (2 mL HF (48%), 3 mL HCl (con), 5 mL  $\text{HNO}_3$  (con) and 190 mL water). Mechanical properties, polarization behavior, electrochemical scratch resistance and corrosive wear performance of the samples were evaluated. A Rockwell B hardness tester (Wilson) was used to determine hardness of the samples; each reported hardness value is an average of 10 measurements. Local mechanical properties of the samples were evaluated using a micro-mechanical probe (Fischer Technology Inc.). A Gamry PC4/750 electrochemical measuring system was employed for polarization and electrochemical scratch test at a scanning rate of 0.33 mV/s under an applied potential of 0.5 V. The electrochemical scratch test was performed using a universal micro-tribometer (UMT, Center for Tribology, California, USA) under a constant load at a speed of 1 mm/s<sup>-1</sup>. The scratching tip was made of diamond. In all electrochemical measurements, a saturated calomel electrode (SCE) was employed as a reference electrode, and a platinum wire as an auxiliary electrode. The electrochemical scratch has been widely used to study dynamics of repassivation process [32,33]. The electrochemical scratch test is useful not only to investigate passive film but also to investigate wear of a material in a corrosive medium [34]. In this study, electrochemical scratch tests were performed to determine current–time curves of  $\text{Y}_2\text{O}_3$ -free and  $\text{Y}_2\text{O}_3$ -added samples in a 0.1 M  $\text{H}_2\text{SO}_4$  solution. Before the test, the samples were prepared by connecting them with conductive copper wires, mounting them in epoxy/hardener followed by polishing to a roughness value of 0.05  $\mu\text{m}$ .

Mechanical properties of passive films and their resistance to scratch were evaluated. The former were evaluated using a Triboscope (Hysitron)—a combination of nanoindenter and atomic force microscope. The indenter tip was a four-sided pyramidal diamond. The force and displacement resolutions of the instrument were 0.1  $\mu\text{N}$  and 0.2 nm, respectively. Before nanoindentation test,  $\text{Y}_2\text{O}_3$ -free and  $\text{Y}_2\text{O}_3$ -added aluminum samples were polished (roughness: 0.05  $\mu\text{m}$ ) and etched using *Keller's reagent* for 10–15 s in order to remove the deformed layer caused by polishing.

Micro-scratch tests were performed on passive films formed on the  $\text{Y}_2\text{O}_3$ -free and  $\text{Y}_2\text{O}_3$ -added Al samples using the UMT. The scratch tip was made of tungsten carbide having a pyramidal shape. The scratch tests were performed at a scratch speed of 0.02 mm/s<sup>-1</sup>. During the scratch test, the normal load continuously increased until the passive film failed, which was determined by the drop of the electrical contact resistance (ECR).

Compositions of surface layers of  $\text{Y}_2\text{O}_3$ -free and  $\text{Y}_2\text{O}_3$ -added Al samples were analyzed using KARTOS AXIS X-ray photoelectron spectroscopy (XPS). Since XPS signals come from a very thin surface layer (20–100 Å), the