Penerbit Akademia Baru

Journal of Advanced Research in Applied Mechanics

Journal homepage: http://www.akademiabaru.com/submit/index.php/aram/index
ISSN: 2289-7895

Investigation on oxide scale of low-cost Ti-6Al-4V substitution alloys composition

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ABSTRACT

Ti-6Al-4V has been a well-structural material in aerospace applications for both airframes and engine components. Considering corrosion resistance is an essential characteristic of Ti-6Al-4V, substituting the low-cost element may significantly influence the oxide scale because the oxide scale significantly impacts oxidation resistance. The oxidation behavior of oxide scale formation will be studied using Ti-6Al-4V as a reference alloy and the previous research article with a low-cost element substituted. When compared to the reference alloys, the development of various oxide scales and the properties of the formed oxide scale will be extensively examined and contrasted to provide a clearer image of whether the same oxide scale or a different oxide scale composition will be formed. When titanium alloys are exposed to oxygen, the most frequent oxide scale is TiO2, whereas Al2O3 is the most desirable oxide scale for titanium alloys due to its properties in strengthening oxidation resistance. Iron is the most popular low-cost element used among researchers to resolve this issue, whether it is added or substituted with a β-phase element such as vanadium in Ti-6Al-4V.

Keywords:
High-Temperature Oxidation; Oxide Scale; Ti-6Al-4V; Ti-6Al-Fe; Titanium Alloys

Received: 11 September 2021 Revised: 30 October 2021 Accepted: 15 November 2021 Published: 28 November 2021

1. Introduction

Ti-6Al-4V or Ti64 is well-known in aerospace applications as a structural material for both airframes and engine components due to its high strength to weight ratio, high tensile and fatigue strength, lightweight, biocompatible, and high corrosion resistance properties. This alloy consists of two phases (α+β) microstructures that can be readily and coherently altered by adding alloying elements [1][2]. This approach has demonstrated significant potential for enhancing the mechanical properties of substituting the costly ternary element vanadium (V) in Ti-6Al-4V with other inexpensive elements such as iron (Fe), chromium (Cr), manganese (Mn), Copper (Cu), Cobalt (Co), Nickel (Ni), Molybdenum (Mo) and aluminium (Al) [3][4][5]. Since corrosion resistance is an essential feature of Ti-6Al-4V, adding another low-cost element may substantially affect the oxide scale. Alloys can react violently with their environment usually at high temperatures causing the materials to fail by corrosion. As such, all high temperature alloys are designed to form a protective oxide scale This

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oxide scale forms a protective oxide scale on the alloy's surface by isolating the alloy from the gaseous environment has an apparent influence on oxidation resistance and is critical in preventing the metals from corroding [6][7][8].

The objective of development into a low-cost titanium alloy is to reduce costs rather than increase its properties. Therefore, the search for low-cost, continuous titanium beneficiation processes is still on. Furthermore, other current approaches in developing cost-effective titanium components include replacing expensive alloying elements with less expensive alloying elements, optimizing hot working processes for shaping and microstructural control, and determining optimal parameters for titanium alloy machining [9].

This study attempted to study previous research articles on the oxide scale formed from the titanium alloys substitution composition. The final properties of low-cost titanium alloys are not intended to improve or surpass the properties of Ti-6Al-4V but rather to be sufficient to evaluate the application in environments where the combination of cost and properties may offer an advantage [10].

2. Formation of Oxide Scale

The formation of an oxide scale on the surface of a metal involves four steps: oxygen adsorption at the surface, formation of oxide nucleation, lateral growth of the nuclei, and formation of a compact oxide scale [7]. When exposed to any oxygen-containing environment at high temperatures, titanium and its alloys usually an oxide scale of TiO_2 forms on the surface while at relatively lower temperatures an amorphous Ti_2O_3 scale was formed, or a mixture of both were formed. The most frequent variations of the TiO_2 oxide scale create are rutile and anatase [11][12]. As for titanium alloys, the most common component is titanium and aluminium. At high temperatures, when the aluminium content in titanium alloys increases, the proportion of Al_2O_3 in the oxide scale increases, considerably improving the oxidation resistance of the titanium alloys due to outstanding compactness, moderate growth velocity and strong adhesion. The ductility and deformation capability of titanium alloys will deteriorate as the aluminium concentration in the composition increases. The proportion of Al_2O3 in the oxide scale increases with an increasing aluminium concentration in titanium alloys at high temperatures. High-concentration aluminium may be selectively oxidized into a single alumina scale at a specific point, substantially inhibiting titanium and oxygen transport and significantly improving high-temperature oxidation resistance of titanium alloys [13]. However, aluminium concentration in titanium alloys should be limited to no more than six wt.% [14].

It can be anticipated that iron will continue to play a role in developing low-cost titanium alloys. Iron exhibits a remarkable ability to stabilize the β-phase and has a high strengthening effect in titanium alloys. In addition, titanium's rapid diffusivity aids in sinterability. The main drawback of utilizing iron in titanium alloys is segregation, resulting in the formation of intermetallic compounds such TiFe or beta flecks in the alloys [9][15]. According to one study, when exposed to a temperature of 400℃, TiFe begins to form on the surface of titanium alloys. As a result, the tensile strength and ductility of titanium alloys are reduced [16]. Iron also has the capabilities to produce iron oxides product namely Wustite (FeO), Hematite (Fe_2O_3), and Magnetite (Fe_3O_4), which these oxides scales are known to be porous and non-protective. Oxide scale such as V_2O_5 had been discovered by Garbacz *et al*. on oxidation studied of Ti-6Al-4V with the addition of 0.2Fe wt.% resulting in a change in density which creates localized stress regions which showed cracks and delamination [17][18]. According to Ti-6Al-4Fe by Yoon et al., increasing the iron in the composition resulting on degradation of Al_2O_3 formed on the surface of the alloy [19].

3. Oxide Scale

3.1 Ti-6Al-4V

In Du *et. al* research, oxidation of Ti-6AI-4V alloy followed a parabolic rate law at 650°C and 700°C after a logarithmic period. Then oxidised according to linear-parabolic kinetics above 700°C. After 50 hours of linear parabolic oxidation at 850°C, the alloy's oxidation followed a parabolic rate law once more. The oxide scale that formed was composed of alternating layers of Al_2O_3 and TiO_2, and the number of layers increased with time and temperature exposure [20]. As for Guleryuz and Cimenoglu researched, Thermal oxidation of the Ti–6Al–4V alloy at 600°C and 650°C produced oxide scale layers. With increasing oxidation temperature and time, the thickness of the oxide layer and the depth of the oxygen diffusion zone grew progressively. TiO_2 anatase and rutile structures made up the oxide layers. After oxidation at 650ºC, the roughening of oxidised surfaces was more severe. The creation of a hard oxide layer and an oxygen diffusion zone beneath it resulted in a considerable increase in surface hardness [21].

3.2 Ti-Fe

Ti-5Al-2.5Fe in Kuphasuk et. al showed lowest corrosion rate than Ti-6Al-4V. Oxide films formed were identified as rutile-type tetragonal structure TiO_2 and also had a trace amount of Ti_9O_{17} [22]. Fujii, H. and Takahashi developed the compositions of Ti-5.5Al-1Fe alloys to substitute the Ti-6Al-4V. The composition properties was further raised by solution treatment and aging at annealing temperature of 300ºC and 450ºC for 2048h. Early 100h shown that short-range ordering of Ti_3Al occur and FeTi formation was slowly observed above 100h starting at temperature 400ºC [16]; Ti-6Al-4Fe and Ti-6Al-1Fe composition by Yoon *et. al* follow the parabolic rate law with superior oxidation resistance compare to Ti-6Al-4V. However, Ti-6Al-4Fe at 800ºC discovered the degradation of Al_2O_3 formation [19]; Ti-6Al-4Fe, Ti-6Al-4Fe-0.1Si and Ti-6Al-4Fe-0.25Si by Kim *et. al* shown a grain boundary sliding during deformation process at temperature 700ºC [23]; Ti-6Al, Ti-6Al-1Fe, Ti-6Al-2Fe and Ti-6Al-4Fe by Lu et. al shown that rapid formation of TiO, Ti2O and Ti2O3 on the surface of composition due to Fe addition once immerse in the electrolyte [24]; Ti-6Al-3V-1Fe, Ti-6Al-2V-2Fe, Ti-6Al-1V-3Fe and Ti-6Al-4Fe experiment in 3.5 wt% NaCl and 3.5 M H_2SO_4 by Bondunrin *et. al* yielded lower corrosion rates. In all of the alloys, the main phases were α-Ti (hcp), β-Ti (bcc), and TiO2. $FeTiO_3$ and V_2O_5 were discovered as minor phases in the experimental Ti–6Al–4Fe and commercial Ti–6Al–4V, respectively. The presence of $FeTiO_3$ shows that intermetallic TiFe developed and oxidised in the Ti–6Al–4Fe alloy, in which vanadium was totally replaced by iron [25]; Ti-5Al-2.5Fe by Simsek and Ozyurek developed a lot more pores, and the pores at grain boundaries are rich in Fe [26].

3.3 Ti-Mo

In Kuphasuk et. al researched, there was no significant difference in corrosion resistance among Ti-6Al-4V, Ti-5Al-3Mo-4Zr and Ti-4.5Al-3V-2Mo-2Fe. Oxide films formed were identified as rutile-type tetragonal structure TiO_2 [22]. Ti-8Al-1Mo-1V by Atapour et. Al (2011) shown the surface was more corroded in comparison to Ti-6Al-4V. Weight loss tests in 5% HCl solution indicated that Ti-8Al-1Mo-1V exhibited inferior corrosion resistance compared to Ti-6Al0-4V [27].

3.4 Ti-Cu

Ti-6Al-4V ± 0.9 mass % Cu and Ti-6Al-4V ± 3.5 mass % Cu were cast by Koike et. al. Rutile TiO2 were formed but not as a homogeneous oxidized film. Author relate the event on the concentration of copper in the composition did not slowed down the corrosion. Author also conclude that addition of the copper give similar corrosion characteristic with Ti-6Al-4V [28].

4. Conclusion

For Ti-6Al-4V, the oxide scale of TiO_2 will mainly be formed on the surface of the alloy. By increasing the aluminium element into the composition, oxide scale Al_2O_3 will form on the alloy surface and cover completely, thus separating the alloy from the gaseous environment, which gives the corrosion resistance properties to the Ti-6A-4V. In order to achieve the low-cost Ti-6Al-4V, iron commonly plays its role. Substituting or adding it to the Ti-6Al-4V will give multiple results depending on the composition and environment setting of the alloys. As for future studies, different compositions of various low-cost elements should be study and not intended to improve or surpass the current properties of Ti-6Al-4V but rather to be sufficient to evaluate the application in environments where the combination of cost and properties may offer an advantage. For a low cost, substitution is mainly been done using Iron instead of other element and modification on Ti-6Al-4V with other low cost element rarely focus on oxidation properties rather than harness and wear resistance of the research composition alloy.

Acknowledgement
The authors would like to express their greatest appreciation and utmost gratitude to the Ministry of Higher Education for awarding the Fundamental Research Grant Scheme with FRGS UTM Vote No.: R.K130000.7856.5F205, Razak Faculty of Technology and Informatics, Universiti Teknologi Malaysia (UTM), and Malaysia Japan International Institute Technology for the facilities provided.

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