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# Underlying burning resistant mechanisms for titanium alloy

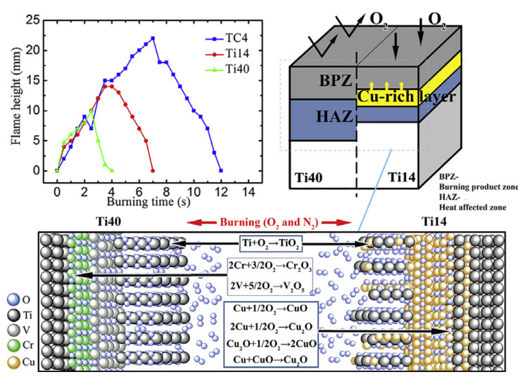
Yongnan Chen [a,b,*], Wenqing Yang [a], Arixin Bo [b], Haifei Zhan [b,c,**], Fengying Zhang [a], Yongqing Zhao [d], Qinyang Zhao [e], Mingpan Wan [f], Yuantong Gu [b]

[a] School of materials science and engineering, Chang'an University, Xi'an 710064, China
[b] School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology (QUT), Brisbane, QLD 4001, Australia
[c] School of Computing, Engineering and Mathematics, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia
[d] Northwest Institute for Nonferrous Metal Research, Xi'an 710016, China
[e] Waikato Centre for Advanced Materials, School of Engineering, The University of Waikato, Hamilton 3204, New Zealand
[f] College of Materials and Metallurgy, Guizhou University, Guiyang 550025, China

## HIGHLIGHTS

- The formation of $V_2O_5$ and $Cr_2O_3$ oxides during burning of Ti40 alloy enhances the density of oxide layer to block burning.
- A Cu-rich layer is formed in Ti14 alloy by the diffusion of Cu to reduce exposure of Ti to oxygen.
- A portion of Ti were replaced by Cu in Ti14 alloy to react with oxygen to consume a certain amount of oxygen.
- The burn resistance of Cu could offer a much lower materials cost to design burn resistant titanium alloys.

## GRAPHICAL ABSTRACT

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## ABSTRACT

The "titanium fire" as produced during high pressure and friction is the major failure scenario for aero-engines. To alleviate this issue, Ti-V-Cr and Ti-Cu-Al series burn resistant titanium alloys have been developed. However, which burn resistant alloys exhibit better property with reasonable cost needs to be evaluated. This work unveils the burning mechanisms of these alloys and discusses whether burn resistance of Cr and V can be replaced by Cu, on which thorough exploration is lacking. Two representative burn resistant alloys are considered, including Ti14 (Ti-13Cu-1Al-0.2Si) and Ti40(Ti-25V-15Cr-0.2Si) alloys. Compared with the commercial non-burn resistant titanium alloy, i.e., TC4 (Ti-6Al-4V) alloy, it has been found that both Ti14 and Ti40 alloys form "protective" shields during the burning process. Specifically, for Ti14 alloy, a clear Cu-rich layer is formed at the interface between burning product zone and heat affected zone, which consumes oxygen by producing Cu-O compounds and impedes the reaction with Ti-matrix. This work has established a fundamental understanding of burning resistant mechanisms for titanium alloys. Importantly, it is found that Cu could endow titanium alloys with similar burn resistant capability as that of V or Cr, which opens a cost-effective avenue to design burn resistant titanium alloys.


* Correspondence to: Y. Chen, School of materials science and engineering, Chang'an University, Xi'an 710064, China.
** Correspondence to: H. Zhan, School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology (QUT), Brisbane, QLD 4001, Australia.
*E-mail addresses:* frank_cyn@163.com (Y. Chen), zhan.haifei@qut.edu.au (H. Zhan).

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## 1. Introduction

Titanium and its alloys are broadly applied in advanced aero-engines owing to their high thrust-weight ratio and excellent corrosion resistance. However, the so-called "titanium fire" occurs under high pressure and friction ignites unfavorable and rapid burning, which is hard to control and leads to catastrophic accidents [1–3]. To address this critical issue, tremendous attempts have been made to reduce friction, or develop burn resistant coating and burn resistant alloys in advanced aero-engine, gas industry and automobile transportation [4–6]. Since early 1970s, researchers in America and Russia had evaluated burning characteristics of titanium alloys such as Ti3515, Ti64 and Alloy C by using laser ignition, and revealed the functional relations between combustion products and gas flow conditions. In last decade, there were some researches on burn resistant property of Ti40 alloy by friction ignition method, and established the relationship between ignition temperature and pressure of Ti40 alloy.

Although several studies already reported the burn resistant performance of Ti40 alloy [7–10], wide engineering applications are very limited due to its low formability, instability at high temperature, high cost, with its burn resistant mechanisms still under study [11–13]. Recent years, researchers have turned to alternative Ti-Cu-Al series burn resistant titanium alloys, such as BTT-1(Ti-13Cu-4Al-4Mo-2Zr), BTT-3(Ti-18Cu-2Al-2Mo) [2, 3] and Ti14(Ti-13Cu-1Al-0.2Si) [9]. Specifically, Ti14 alloy belongs to a new $\alpha + Ti_2Cu$ type burn resistant titanium alloy, which has the burn resistant functionality [14] and comprises the low-cost alloying element Cu. Through the direct current simulation burning (DCSB) method [15] and metal droplet method (MDM) [16], researchers have studied the burning characteristics of Ti-Cu-Al series burn resistant titanium alloys during stable burning stage, e.g., the burning velocity and duration. However, the effect of Cu element on impeding the burning of the alloy needs to be further explained, due to the fact that the existing test methods cannot fully represent burning characteristics and more parameters needed to be considered while investigating the burn resistant mechanism of the alloys in various gas conditions.

Further investigation is needed on whether the burn resistivity provided by Cu are the same as V and Cr. Alternatively, whether Cu can totally replace V or Cr to achieve cost-effective burn resistant titanium alloy. This work aims to address these questions by studying the burning behaviors of two representative alloys through a serial of modified direct current simulation burning tests, including Ti14 and Ti40 alloys. The burning characteristics, e.g., flame height, burning duration, burning velocity, burned sample structure is performed to discuss the effect of element composition during burning process and derive the burn resistant property of the alloys. This can be an effective way to achieve competitive burn resistant function while using titanium alloys with lower cost.

## 2. Experimental methods

### 2.1. Materials

Two typical burn resistant titanium alloys used in this study are Ti14 [17] and Ti40 [18] alloys. Raw materials of Ti40 (Ti, 25wt%V, 15wt%Cr and 0.2wt%Si), Ti14 (Ti, 13wt%Cu, 1wt%Al and 0.2wt%Si) are mixed to form electrode, respectively, and 25 kg ingots of Ti40 and Ti14 alloy are fabricated by triple consumable vacuum arc melting, Ti40 and Ti14 alloys are conventional forged at 950 °C followed by water cooling and air cooling into a bar shape with a diameter of 40 mm to be tested, respectively [9]. The forging rate is 500 mm/min and heating rate is 25 °C/s. In order to determine the difference in burning behavior and burn resistant mechanism caused by V, Cr and Cu, commercial TC4 alloy (in Fig. S1) were also tested for comparison under the same testing standard. Microstructural characterization of the alloys before burning was analyzed by optical microscopy (Axio Scope-A1 equipped with a Carl Zeiss digital camera). The forged Ti14 alloy mainly consist of α-Ti matrix and $Ti_2Cu$ precipitates (Fig. 1a) which are indicated by the

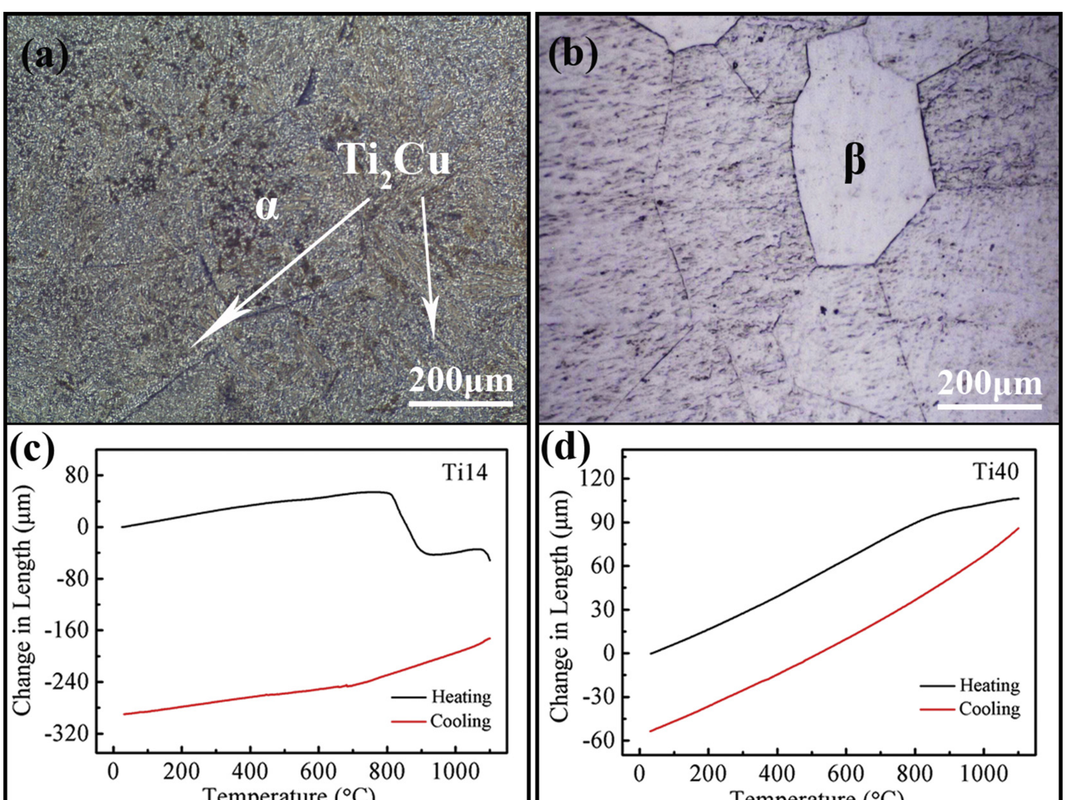


**Fig. 1.** Microstructure of Ti alloys. (a) Ti14 alloy. The $Ti_2Cu$ phase in Ti14 alloy is highlighted by white arrows; (b) Ti40 alloy. Clear grain boundaries in Ti40 alloy are shown. Phase change during heating and cooling process for: (c) Ti14 alloy, and (d) Ti40 alloy.