

## ISOTHERMAL OXIDATION BEHAVIOR OF Ti40 ALLOY AT SUPER-HIGH TEMPERATURE

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### ABSTRACT

The isothermal oxidation behavior of Ti-25V-15Cr-0.2Si (Ti40) at the temperature from 500°C to 1500°C was investigated. The results indicated that when the oxidation temperature is below the melting point of V<sub>2</sub>O<sub>5</sub>, the surfaces of specimens show integrity and dense oxidation scale and which mainly consists of V<sub>2</sub>O<sub>5</sub> and TiO<sub>2</sub>. When the oxidation temperature exceeds the melting point of V<sub>2</sub>O<sub>5</sub>, the melting and evaporation of V<sub>2</sub>O<sub>5</sub> lead to the loose porous morphology of oxide scale, and there is an enrichment zone of element V and Cr at the interface between the oxide scale and the matrix alloy. When the oxidation temperature exceeds 1000°C, oxide scale start to peel off and the sub-surface will turn into the oxidation surface. Under this condition the oxidation scale consists of Cr<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>, which show better densification and barrier effect for diffusion of O form oxidation surface to matrix.

**Keywords:** Ti40 alloy, oxidation, super-high temperature.

### INTRODUCTION

Excellent mechanical properties combined with low density make titanium alloy attractive structural materials for aerospace applications. However, when titanium alloy combines with oxygen it creates a strong exothermic reaction. There have been numerous examples of titanium fires in jet engines over the past 20 years. Therefore, significant engine design changes need to be made to minimize the risk of titanium fire. Among these measures the identifying alloy compositions that are less susceptible to burning was thought a prospective method to avoid titanium fire. Over the past twenty years, several significant efforts have been devoted to development of so-called burn resistant titanium alloys. These alloys are all belong to Ti-V-Cr system burn resistant titanium alloy which include Alloy C (Ti-35V-15Cr) developed by Pratt and Whitney in USA (Hansen, 1996), BurTi (Ti-25V-15Cr-2Al-0.2C) developed by IRC in UK (Li, 1998) and Ti40(Ti-25V-15Cr-0.2Si) by Northwest Institute for Nonferrous Metal Research (NIN) in China (Zhao, 1999). These three alloys all show good burn resistance.

In principle, the ignition process of titanium alloy can be analyzed from the following steps. Firstly, the alloy undergoes the oxidation behavior at high and ultra-high temperature. During this process the heat accumulates at oxidation reactive foreland. When the aggregation of heat exceeds the ignition point of the titanium alloy, the alloy starts combustion (Borisova, 1993). Accordingly, the research on oxidation behavior of the titanium alloy is very important for the burn resistant character. However, the existing researchers on oxidation behavior of titanium alloy mainly focused on the influence of oxidation behavior on mechanical properties.

Oxidation behavior of titanium alloy is required to ensure safe and long-term operation of component under environmental temperatures. The experimental temperature was limited to the critical temperature level for different species titanium alloy in service. For this reason, there is little information on oxidation and corrosion behavior of the alloy at ultra-high temperature. Therefore, the investigations on oxidation behavior of titanium alloy at extreme high temperature are very significative for comprehension of burn-resistant titanium alloy.

## MATERIALS AND METHODS

Ti40 alloy used in this study was manufactured in Northwest Institute for Nonferrous Metal Research (NIN) with the nominal composition of Ti-25V-15Cr-0.2Si (wt%). Oxidation blank specimens were cut from the Ti40 bar with a size of 10 mm×10 mm×10 mm. The surface of the specimens was abraded to 1000 # SiC paper and following to polishing cloth. Then, all specimens were degreased in acetone using ultrasonic cleaned equipment for about 15 min. The specimens were put into the crucible. The isothermal oxidation experiment were carried out on muffle furnace at temperature range of 500 °C~1500 °C in static air for various times. The crucibles containing the specimens were regularly removed at a certain times, air cooled. The specific exposure temperature and exposure time of the crucibles were shown in Tab.1. The surface morphologies and cross-sectional microstructure of specimens were observed by an S-2700 scanning electron microscopy (SEM) equipped with energy dispersive spectrometry (EDS). The phases of oxidation surface for the specimens at different temperature for different times were tested by a D/Max-2400 X-ray diffractometer with Cu K $\alpha$  radiation.

Table 1 - Oxidation temperature and times

Temperature/	Oxidation exposure time				
500	10h	20h	40h	80h	120h
550	10h	20h	40h	80h	120h
600	10h	20h	40h	80h	120h
700	10h20h	40h	80h		
800	10h	20h	40h	80h	
900	1h	5h	10h	20h	60h
1000	0.5h	1h	2h	5h	10h
1050	10min	30in	1h	2h	5h
1100	10min	30in	1h	2h	5h
1150	5min	10min	30min	1h	2h
1200	5min	10min	30min	1h	2h
1300	1min	2min	5min	15min	
1400			5min		
1500			5min		

## RESULTS AND DISCUSSION

### OXIDATION BEHAVIOR FROM 500°C TO 700°C

Fig. 1(a) shows the XRD patterns for the specimen surface exposed below 700°C, which indicatesthe oxide surface mainly consists of V<sub>2</sub>O<sub>5</sub> and TiO<sub>2</sub>. Fig.1 (b) shows the surface morphology for the specimen exposed at 600°C for 120h, which represents the typical surface morphology for the specimen exposed below 700°C. From Fig.1 (b) it can be found that the large number of visible dendritic oxide can be found, which shows the morphology of outward-projecting growth. The combination analysis of EDS and XRD (as shown in Fig. 1 a) proved that the dendritic oxide is V<sub>2</sub>O<sub>5</sub>. The special growth morphology of oxide surface indicates that

$\text{V}_2\text{O}_5$  grow preferentially from the mixed oxide film of  $\text{V}_2\text{O}_5$  and  $\text{TiO}_2$  with the rise of oxidation temperature. It also suggests that element V diffuses from the matrix alloy to the oxide surface and the oxide layer of  $\text{V}_2\text{O}_5$  responds as the diffusion channel. The outward-diffusing element V reacts with oxygen at the surface of  $\text{V}_2\text{O}_5$ , which leads to the accumulation of new  $\text{V}_2\text{O}_5$  oxide on the original surface layers.

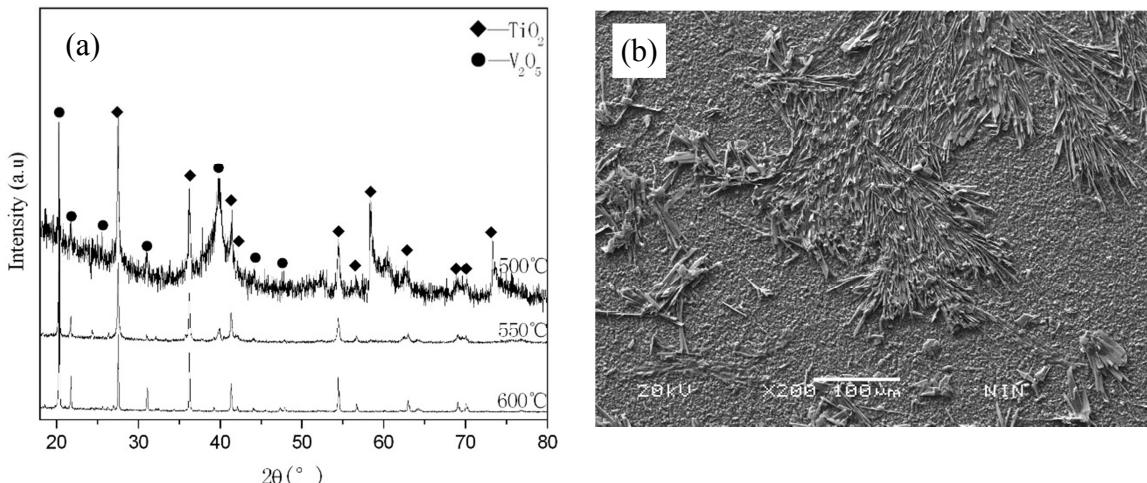


Fig. 1 - XRD patterns of oxidation surface for Ti40 alloy exposed at 500°C, 550°C, 600°C for 120h(a) and oxidation surface morphology for specimen exposed at 600°C for 120h (b)

## OXIDATION BEHAVIOR FROM 700°C TO 1000°C

When the oxidation temperature is above 700°C, the XRD patterns of oxidation surface was shown in Fig.2 (a). With the increasing oxidation temperature, the diffraction peaks of  $\text{V}_2\text{O}_5$  are gradually disappearing and the diffraction peaks of  $\text{V}_2\text{O}_5$  completely vanish for the alloy oxidation exposure above 800°C. The oxidation surface film only mainly consists of  $\text{TiO}_2$ . Fig.2 (b) shows the morphology of the specimen oxidation exposure at 800°C for 80h, which represent the typical surface morphology for the specimen exposed above 700°. The vanishment of  $\text{V}_2\text{O}_5$  form the mixture oxidation film of  $\text{TiO}_2$  and  $\text{V}_2\text{O}_5$  is mainly resulting from the low-melting oxide of  $\text{V}_2\text{O}_5$ . The melting point of  $\text{V}_2\text{O}_5$  is about 680° C. When the oxidation temperature exceeds 700° C, the  $\text{V}_2\text{O}_5$  in mixed oxide layer melts and evaporates which leads to the loose porous morphology of oxide surface as shown in Fig. 2 (b).

Fig.3 (a) shows cross-section morphologies and oxide layer thickness of alloy after oxidation exposure at 900°C for 20h. Because of loose porous morphology, oxide film lost its barrier effect on diffusion of O element from surface to matrix. Therefore, Ti40 alloy shows very big thickness of oxidation scale. However, in comparison to other titanium alloys, the oxide scale of Ti40 alloy keeps integrity and no desquamation when the oxidation temperature is below 1000°C, which is mainly resulting from the weakness internal stress of oxide scale for loose porous oxide scale structure. Fig.6 (b) shows the composition profiles of Ti, V, Cr, O at the both sides of the interface between oxidation layer and matrix for the specimen exposed at 800°C for 80h. With the extension of distance from oxide surface to matrix, the content of Ti, V, Cr gradually increases and the O content gradually decreases. However, a very important phenomenon should be pointed out that there is a mixed enrichment zone of elements V and Cr at the interface between oxide scale and matrix. When the extension distance exceeds the position of interface from the oxide surface, the content of O element sharply decreases to the same level of matrix, which indicates that the mixed enrichment zone has the barrier effect on the diffusion of O element.

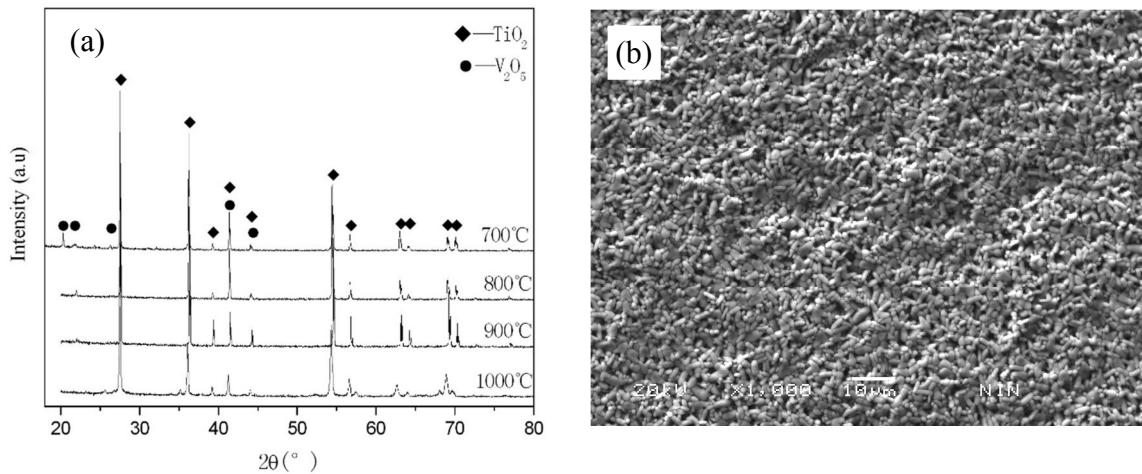


Fig. 3 - XRD patterns of oxidation surface for the alloy exposed at 700°C/ 80 h, 800°C/80 h, 900°C/60 h, 1000°C/10 h(a) and oxidation surface morphology for specimen exposed at 800°C for 80h (b)

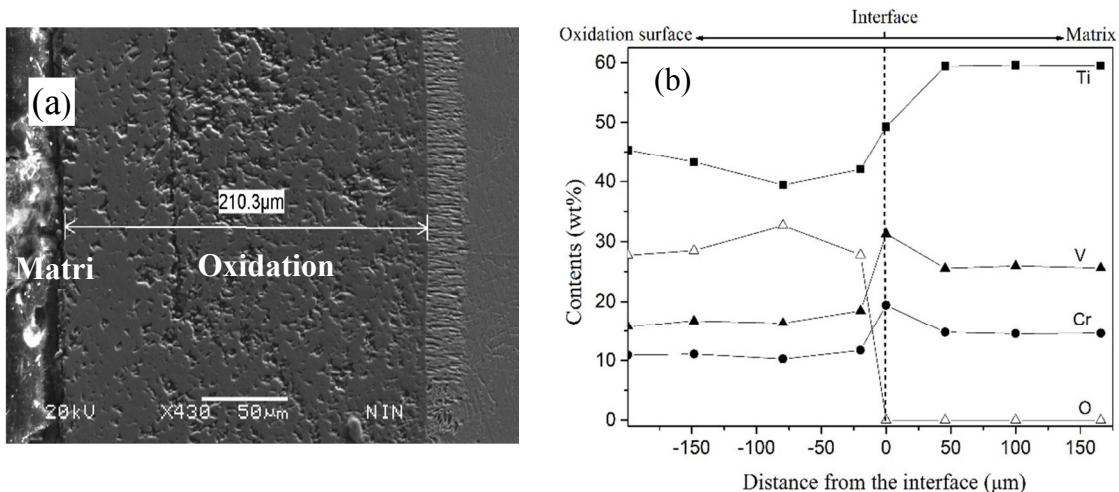


Fig. 4 - Cross-section morphologies (a) and composition profiles of Ti, V, Cr, O at the both sides of interface on the cross-section (b) for the alloy oxidized at 800°C for 80h

## OXIDATION BEHAVIOR FROM 1000°C TO 1500°C

When the oxidation temperature is above 1000°C, with the increasing exposure time, oxide scale is gradually peeling off. Fig.5 shows specimen surface morphology for no desquamation (1200°C/30min) (a) and desquamation (1200°C/2h) (b) of oxide scale. After totally desquamation of oxide scale, the surface of specimen shows compact morphology and no holes and loose as shown in Fig.5(b). Fig.6 shows the XRD patterns of the surface before (Fig.6 a) and after (Fig.6 b) desquamation of oxide scale at different temperature. It can be found that the oxide scale mainly consists of TiO<sub>2</sub> before desquamation and TiO<sub>2</sub> and Cr<sub>2</sub>O<sub>3</sub> mixture after desquamation of oxidation surface. The correlated researches have indicated that the precondition for forming protection Cr<sub>2</sub>O<sub>3</sub> oxide scale requires a critical value of Cr content (Samimi, 2015). Ti-Cr binary alloy with 19wt.% Cr content still cannot form the protection Cr<sub>2</sub>O<sub>3</sub> oxide scale (Chaze, 1982). Thus Ti40 alloy has not formed the oxide scale of Cr<sub>2</sub>O<sub>3</sub> at oxidation surface during oxidation process. However, the mixed enrichment zone of elements V

and Cr at the interface between oxide scale and matrix provide the formation requirement of  $\text{Cr}_2\text{O}_3$ . Therefore, when the surface oxide scale peel off, the enrichment zone of elements V and Cr will transform to oxide surface and form the mixture of  $\text{TiO}_2$  and  $\text{Cr}_2\text{O}_3$ . The  $\text{Cr}_2\text{O}_3$  is a stable oxide film with good protect effect as same as  $\text{Al}_2\text{O}_3$ , thus the new mixed oxide film of  $\text{TiO}_2$  and  $\text{Cr}_2\text{O}_3$  shows a better sticky ability with matrix and prevent further oxidization as shown Fig.5 (b).

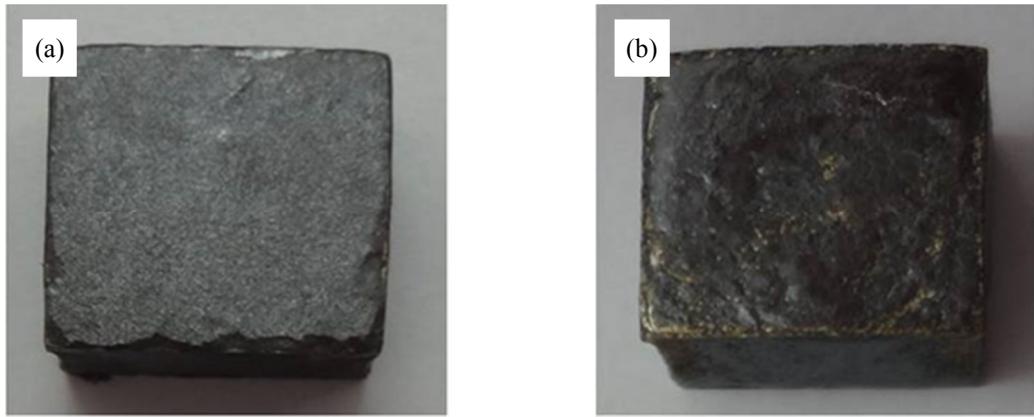


Fig. 5 - Surface morphology for no desquamation ( $1200^\circ\text{C}/30\text{min}$ ) (a) and desquamation ( $1200^\circ\text{C}/2\text{h}$ ) (b) of oxide scale

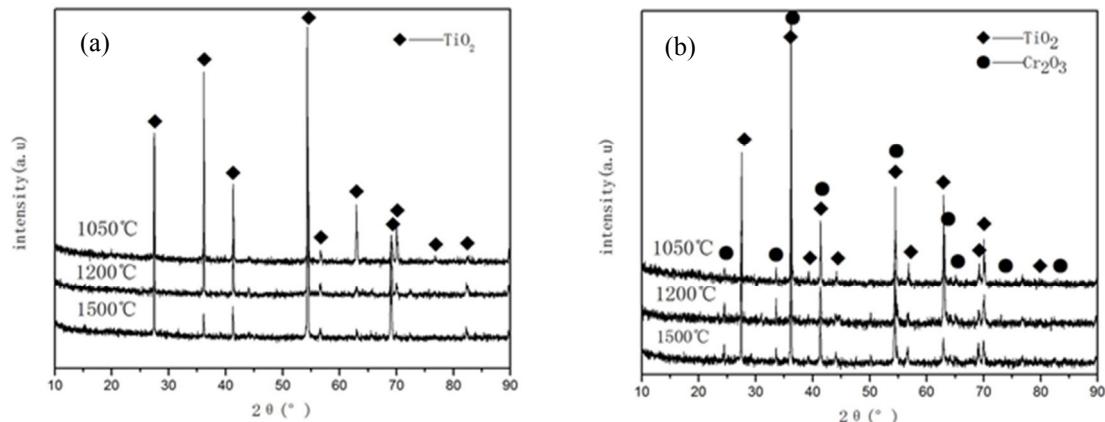


Fig. 6 - XRD patterns of the surface before (a) and after (b) desquamation of oxide scale

## CONCLUSIONS

For Ti40 alloy, when the oxidation temperature is from  $500^\circ\text{C}$  to  $700^\circ\text{C}$ , the oxidation scale mainly consists of  $\text{V}_2\text{O}_5$  and  $\text{TiO}_2$ , the  $\text{V}_2\text{O}_5$  of mixed oxide scale preferentially grows and shows dendritic morphology. The special morphology of  $\text{V}_2\text{O}_5$  at the surface of specimens is mainly resulting from the orientation diffusion of element V along  $\text{V}_2\text{O}_5$ . When the oxidation temperature exceeds  $700^\circ\text{C}$ , the melting and evaporation of  $\text{V}_2\text{O}_5$  lead to the loose porous morphology of oxide scale. There is an enrichment zone of elements V and Cr at the interface between oxide scale and matrix. When oxidation temperature is above  $1000^\circ\text{C}$ , because of the desquamation of oxide scale, the enrichment zone of elements V and Cr transformed to oxide surface and form the mixture of  $\text{TiO}_2$  and  $\text{Cr}_2\text{O}_3$ . The new oxide surface shows better sticky ability with matrix.

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