Rare Metal Materials and Engineering
Volume 48, Issue 6, June 2019
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Rare Metal Materials and Engineering, 2019, 48(6): 1749-1755.

ARTICLE

Effect of Silicon on Mechanical Properties of Ti-6Al-2Zr-1Mo-1V Alloy

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Abstract: The influence of Si content on the mechanical properties of Ti-6Al-2Zr-1Mo-1V titanium alloy at room temperature and 500 °C was studied. The fracture morphologies and microstructures were analyzed by scanning electron microscope (SEM) and transmission electronic microscope (TEM). The nucleation and growth of silicide were related to the mechanical properties. The results show that the tensile strength and high-temperature strengthening performance are improved when 0.04 wt%~0.14 wt% Si is added to the Ti-6Al-2Zr-1Mo-1V alloy; the plasticity is less changed; the impact toughness and plane strain fracture toughness are decreased. An alternating tendency from ductile fracture to brittle fracture can be found with the addition of Si, the radial region is enlarged, and the area of fibrous region and shear lip is minified. When the content of Si is less than 0.09 wt%, the Si elements are dissolved in α and β phase, and solid solution strengthening mechanism dominates. The silicide precipitates along the phase boundary when the content of Si reaches 0.14 wt%, which leads to a combination of solution strengthening and precipitation strengthening.

Key words: titanium alloy; mechanical properties, fracture morphology, silicide precipitation, solution strengthening, precipitation strengthening

Attributed to its high specific strength, moderate high-temperature strength, good thermal stability, excellent weldability, creep resistance and corrosion resistance, Ti-6Al-2Zr-1Mo-1V near alpha titanium alloy has been applied in manufacturing aircraft structural components such as engine blades[1-6]. With the development of the aero engine, the blades need to work in the higher temperature environment. Improving the elevated mechanical properties of the materials is required.

Si element is one of eutectoid elements in titanium alloys, and the addition of Si can enhance the strength of titanium alloys by solid solution strengthening effect. However, due to the reduction of plasticity caused by the precipitation of silicide during long-term thermal exposure, Si is commonly considered to be the impurity element and is strictly controlled. Until the 1970s, Seagle et al [7] discovered that Si can greatly improve creep resistance and realized the effect of Si, so Si started to be introduced into the designing of high-temperature titanium alloys. Fentiman et al [8] indicated that the addition of 0.25% Si leads to the improvement of creep resistance and strength of Ti-679 alloy, with no reduction in plasticity by 400 °C creep tests. Up to now, Si element is added into the high-temperature titanium in order to enhance the creep resistance, like Ti-6242s[9,10]. However, different alloys with different elements, different processing methods and final mechanical properties result in different requirements for optimum Si content. The action of a small amount of Si in Ti-6Al-2Zr-1Mo-1V titanium alloy has been seldom studied.

In the present research, the effect of Si on the mechanical properties of Ti-6Al-2Zr-1Mo-1V titanium alloy was investigated, which will be useful for future works on optimizing chemical composition of Ti-6Al-2Zr-1Mo-1V and other titanium alloys.

1 Experiment

In order to study the effect of Si content on the mechanical properties of Ti-6Al-2Zr-1Mo-1V titanium alloy, three Si contents of 0.04 wt% (alloy A), 0.09 wt% (alloy B) and 0.14 wt% (alloy C) were added to the alloy. The three Si contained

Received date: June 25, 2018
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alloys were melted twice by VAR, and then forged into the billets with a diameter of 350 mm. The chemical composition of the three alloys is listed in Table 1 (tested by the ICP-AES), which shows that the contents of other elements in the three alloys are similar. The billets of the three alloys were then heat treated at 840 °C for 2.5 h, followed by air cooling (AC). The microstructures of the three alloys are shown in Fig.1. It exhibits a typical bi-model microstructure containing more than 80 vol% of the equiaxed primary α phase and a small amount of secondary α lamella. The diameter of primary α phase is between 10 and 20 µm.

The room temperature tensile properties, impact toughness, fracture toughness, 500 °C tensile and stress rupture properties of the three alloys were tested according to the corresponding Chinese standards. The stress rupture property was tested at 500 °C with creep rupture strength of 470 MPa.

Moreover, the microstructures and fracture morphologies of the three alloys were observed by scanning electron microscope (SEM) and transmission electron microscope (TEM).

2 Results

2.1 Tensile properties at room temperature

The tensile properties of the three alloys with different Si contents are shown in Fig.2. The relationship between tensile properties and Si content is shown in Fig.3. Both yield strength and tensile strength increase significantly when Si content increases from 0.04 wt% to 0.14 wt%, whereas, elongation (A) and reduction (Z) of the area are almost unchanged.

2.2 Impact toughness and plane strain fracture toughness

The impact energy (A_{ku}) and plane strain fracture toughness (K_{IC}) of the three alloys are shown in Fig.4. The results demonstrate that the impact toughness decreases by almost half as the content of Si increases from 0.04 wt% to 0.14 wt%. And the results of plane strain fracture toughness (K_{IC}) show a similar tendency.

Table 1 Chemical composition of each alloy (wt%)

Alloy	Al	Mo	V	Zr	Si	Fe	C	N	O	H	Ti
A	6.52	1.68	2.21	2.11	0.04	0.02	0.01	0.003	0.105	<0.001	Bal.
B	6.57	1.71	2.21	2.05	0.09	0.03	0.007	0.004	0.112	<0.001	Bal.
C	6.58	1.71	2.24	2.12	0.14	0.02	0.008	0.003	0.111	<0.001	Bal.

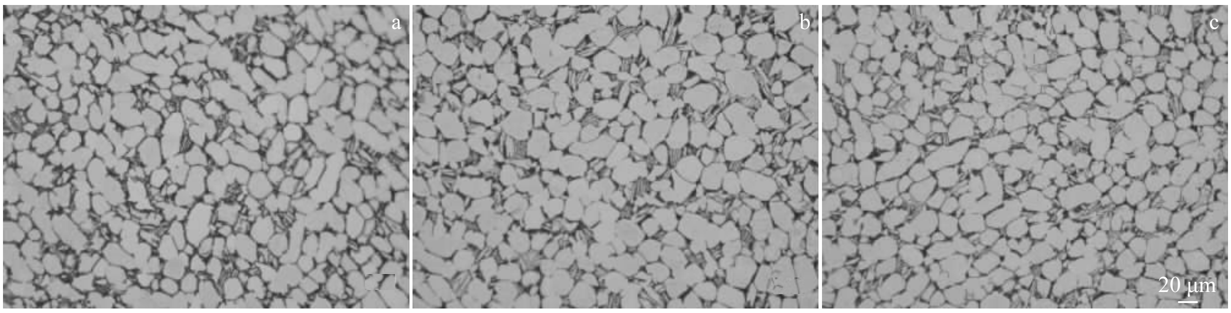

Fig.1 Metallographic microscope microstructures of samples: (a) alloy A, (b) alloy B, and (c) alloy C

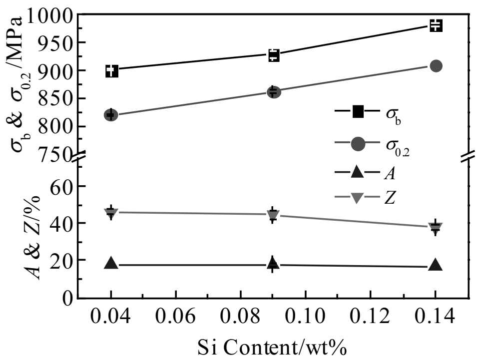

Fig.2 Tensile properties of each alloy

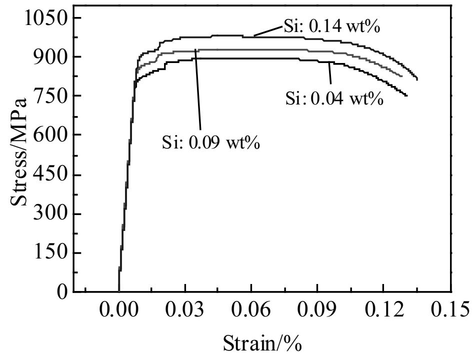

Fig.3 Effect of Si content on tensile properties at room temperature

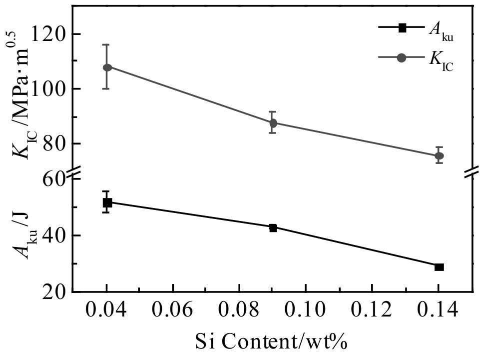

Fig.4 Effect of Si content on impact energy and K_{IC}

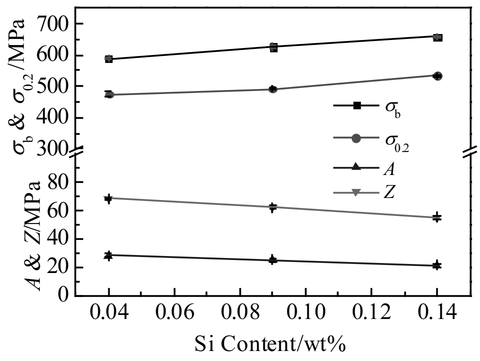

Fig.5 High temperature tensile properties of each alloy at 500 °C

2.3 Tensile and stress rupture properties at 500 °C

Fig.5 shows the elevated temperature tensile and stress rupture properties at 500 °C of the three alloys. At 500 °C, the yield strength and tensile strength also increase obviously with increasing the Si content, similar to RT tensile strength. However, A and Z declines slightly when the Si content increases. Furthermore, the long-term rupture time (τ) of the alloy also improves with increasing the Si content. After adding 0.14 wt% silicon, the τ of the alloy C can reach to 133.01±3.543 h, which is 70% higher than 76.76±3.896 h of alloy A, and τ of alloy B is 105.92±3.408 h.

2.4 Fracture analysis of tensile tests

Fig.6 shows the macro and micro fracture morphologies of the three alloys. From Fig.6, it can be found that all samples show the characteristics of ductile fracture. Furthermore, with increasing the silicon content, the fracture morphology becomes smoother and flatter, implying a lower plasticity. And alloys with higher content of Si show larger radial region, smaller fibrous region and shear lip. The same conclusion can be drawn from the elevated temperature tensile fracture morphology at 500 °C of the three alloys, as shown in Fig.7.

2.5 Fracture analysis of impact toughness tests

Fig.8 shows the macro-fracture and micro-fracture morphologies of the three alloys. It can be found that the samples of impact toughness tests show characteristics of ductile fracture like tensile samples. Moreover, larger shear lips are found in the samples with higher content of Si.

3 Discussion

3.1 Influencing mechanism of Si on tensile properties and stress rupture properties

The room temperature strength, high-temperature strength and long-term rupture time increase with increasing the Si content. The performance of stress rupture and creep is similar. The typical microstructure of the fracture of Ti-6Al-2Zr-1Mo-1V is shown in Fig.9.

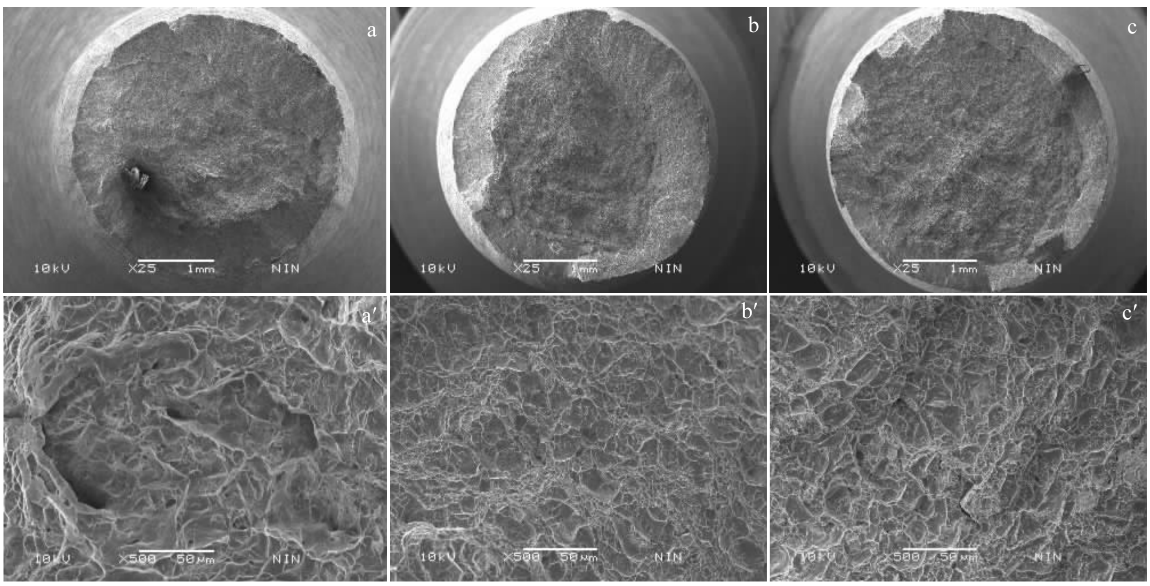

Fig.6 Tensile fracture morphologies of three alloys at RT: (a, a') alloy A, (b, b') alloy B, and (c, c') alloy C

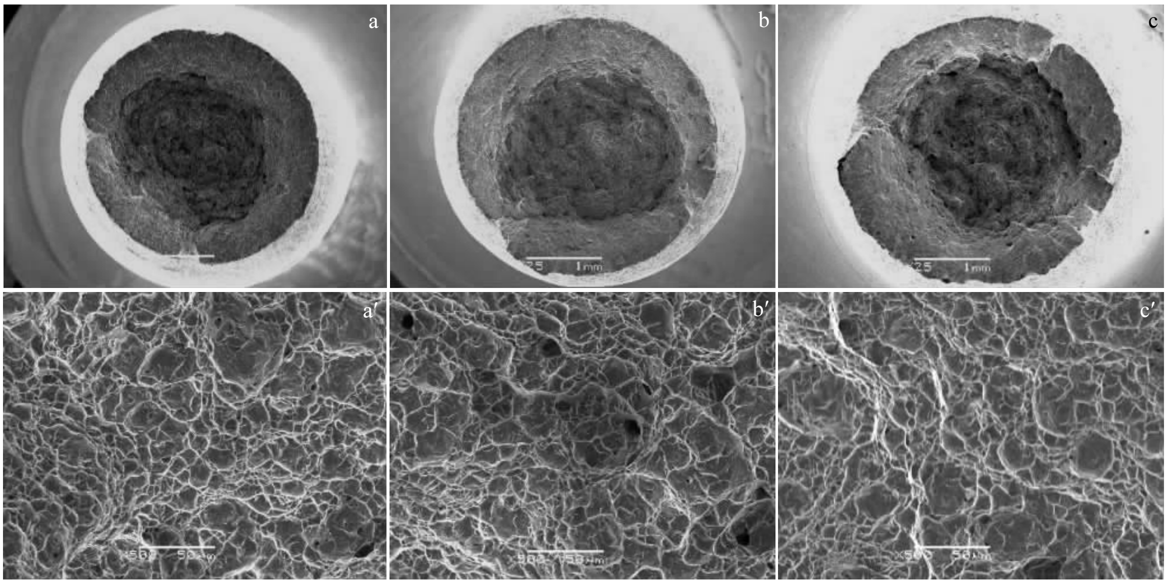

Fig.7 Tensile fracture morphologies of three alloys at 500 °C: (a, a') alloy A, (b, b') alloy B, and (c, c') alloy C

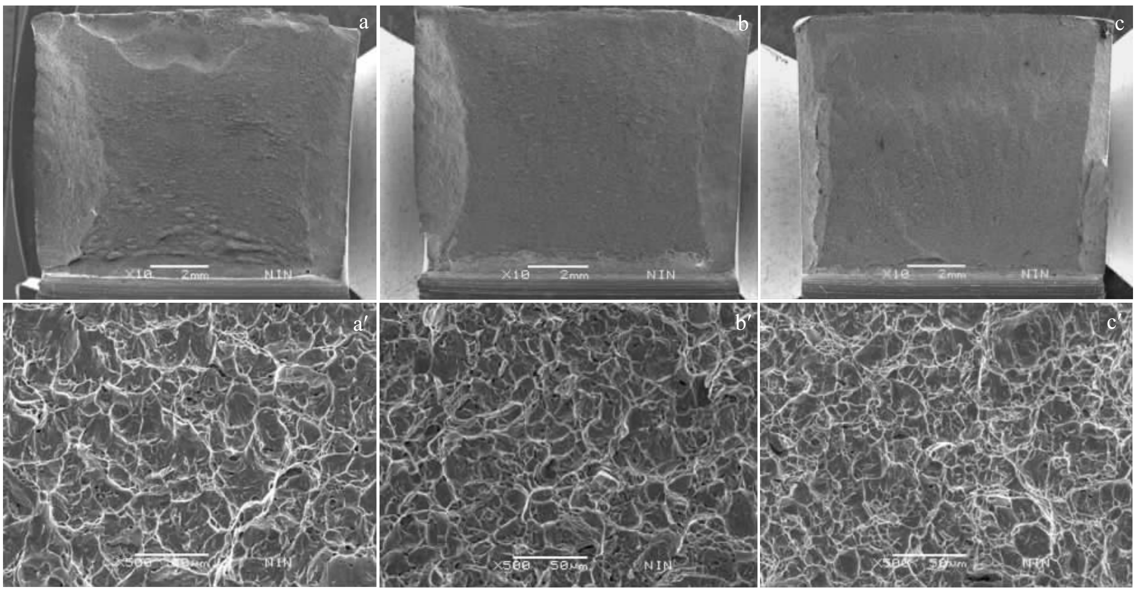

Fig.8 Impact toughness fracture morphologies of three alloys at RT: (a, a') alloy A, (b, b') alloy B, and (c, c') alloy C

It can be seen from Fig.9 that the fracture passes through the α and β phases, which mainly determines the strength of the α and β phases themselves. There are two states of silicon in titanium alloys: solute and precipitate. For the case of a solid solution, silicon is usually dissolved in the matrix by replacing titanium atoms to enhance strength and creep resistance. The maximum solid solubility of Si in pure titanium is about 3.0 wt% in β phase, which is much higher than 0.45 wt% in α titanium[9]. This significant difference in the solid solubility of Si in α and β phase is the major factor that leads to the precipitation of Si in the subsequent heat treatment, which is also one of the determinants to final mechanical properties.

The content of Si is commonly controlled under 0.25 wt% in the commercial titanium alloy, which is much lower than the maximum solid solubility of Si in titanium alloys. However, the silicon elements are actually uniformly distributed, which is caused by characteristics of vacuum arc remelting (VAR) and redistribution of Si elements when phase transformation repeatedly happens during forging and heat treatment. This kind of uniform distribution of Si might contribute to a certain amount of silicide. After aging, in particular, Si dissolved in preceding silicide would precipitate, thus reducing the Si

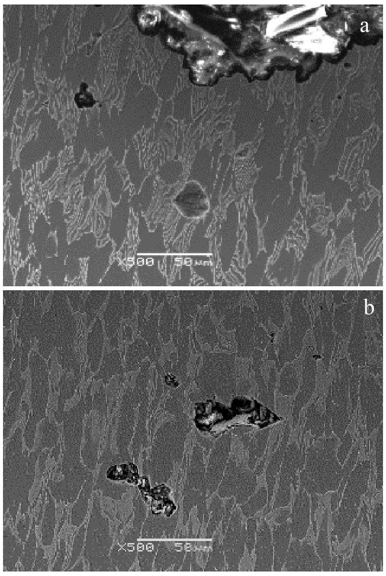

Fig.9 Typical microstructure of the fracture of alloy A (a) and alloy B (b)

content in α phase and influencing the mechanical properties. The strength at room temperature and high temperature of 500 °C can be improved significantly when adding Si as solution strengthening elements. This means that the solid solution Si element has an effect of solid solution strengthening, and the precipitated silicide has an effect of precipitation strengthening[10,11].

Fig.10 shows the TEM microstructures of alloy A and alloy B. For the sample of alloy A, it can be seen that the secondary α phases precipitate along the phase boundaries, and most of the precipitated phases are parallel to each other. For the sample of alloy B, the secondary α phase has little difference in precipitation morphology. There is a slight increase in the precipitation in local area, and the secondary acicular α phase precipitates at a certain angle to each other. Additionally, a great number of dislocations can be seen at the phase boundary, which means that the secondary precipitation has a significant hindrance effect on the dislocation movement[12]. When the Si content is 0.09 wt%, the β phase and EDS distribution of Si in the α phase are shown in Fig.11 and Table 2, respectively. The distribution of Si is uniform. However, no silicide precipitation was found, which indicates that Si plays a role of solution strengthening when its content in the alloy is less than 0.09 wt%. Since Si is relatively uniformly distributed in α and β phases and the α and β phases are strengthened at the same time, the deformation coordination is relatively good. A small amount of Si has little effect on the plasticity at room temperature.

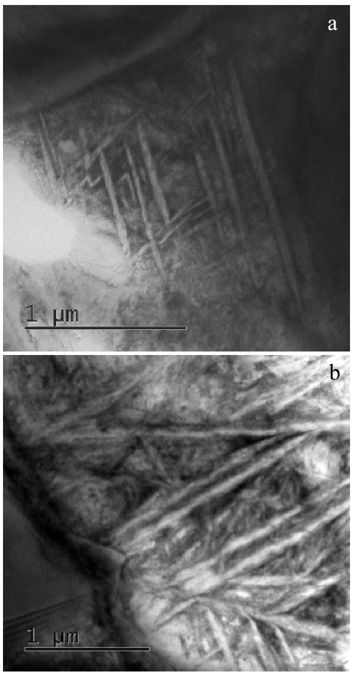

Fig.10 TEM images of alloy A (a) and alloy B (b)

Fig.12 shows the microstructure of alloy C as the Si content reaches 0.14 wt%. A lot of dislocations were found in the matrix, and some nano-sized precipitates appeared at the grain boundaries and phase boundaries. The precipitate was defined as a silicide of (Ti, Zr)$_x$Si$_y$ through diffraction analysis[13].

When Si is completely dissolved in the α matrix, the difference in size between the Si and Ti atoms causes an elastic interaction between the solute atoms and the dislocations, and the Cottrell gas mass is easily formed. When Si exceeds the solid solubility limit, silicide will precipitate, which will strongly pin the dislocation motion, prevent the slip and climb of dislocations, and significantly improve the high temperature creep performance[14]. At high temperatures, the relative retardation of the sediment is more pronounced, and the IMI550 is a model that has been successfully developed using this effect[15]. The addition of Zr to the

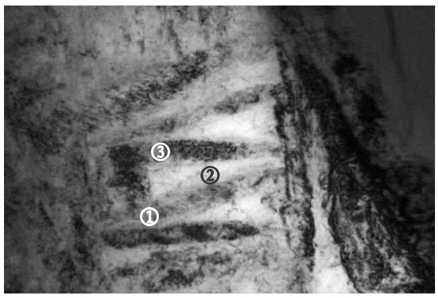

Fig.11 TEM image of alloy B

Table 2 Chemical composition of selected zones in Fig.11 (wt%)

Zone	Al	Si	Ti	V	Zr	Mo
①	4.95	0.10	88.55	2.26	3.53	0.71
②	4.73	0.08	88.11	2.05	4.01	1.02
③	3.10	0.09	73.36	8.09	4.47	10.89

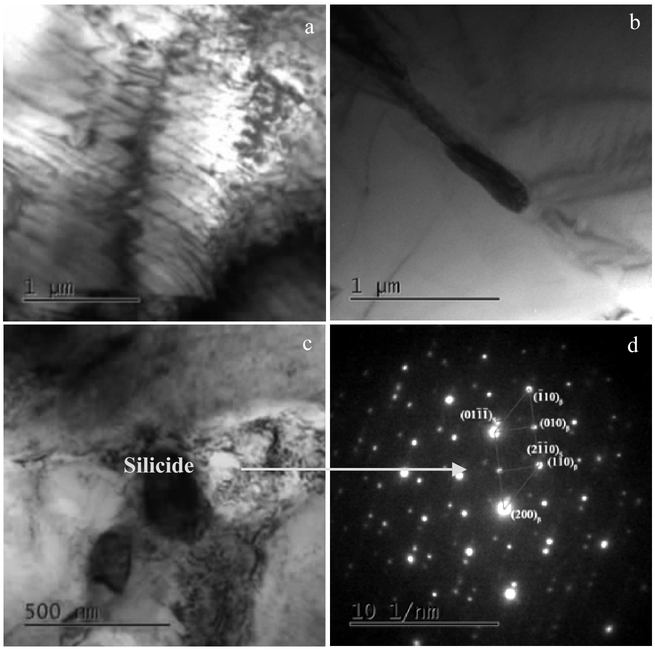

Fig.12 TEM images of alloy C: (a, b) dislocations, (c) grain boundaries and phase boundaries, and (d) SAED pattern of silicide of (Ti, Zr)$_x$Si$_y$

titanium alloy can also reduce the nucleation activation energy of the silicide, and contribute to the uniform fine dispersion of the silicide, which is advantageous for improving the creep performance and strength[16]. In the Ti-6Al-2Zr-1Mo-1V titanium alloy, the Zr element content is about 2.10%, which facilitates the formation of silicide. The precipitation of silicide would cause an obvious strengthening and improve long-lasting performance, but it also led to a little reduction in plasticity.

From the results above, the strengthening mechanisms of Si element in Ti-6Al-2Zr-1Mo-1V alloy are solution strengthening and precipitation strengthening, and the plasticity changes less.

3.2 Influencing mechanism of Si on impact toughness and plane strain fracture toughness

In general, the impurity phases will be segregated along grain boundaries for reaching lower system energy, which is proved by the silicide of (Ti, Zr)$_x$Si$_y$ along grain boundaries and phase boundaries found in TEM images (shown in Fig.11). This kind of intergranular brittle phase was the cause of a drastic drop in impact toughness. In addition, adding Si elements enlarges the strength gap between the α phase and the β phase. It would be prone to cause deformation of softer β phases, especially the larger ones near grain boundaries, which accelerates the formation and expansion of voids in some β phases, thus reducing the ductility and toughness[17,18].

4 Conclusions

1) The addition of element Si significantly improves the tensile strength and long-term rapture time as the content of Si increases from 0.04 wt% to 0.14 wt%. The plasticity is less changed, while the impact toughness and plane strain fracture toughness show an opposite tendency.

2) Fracture analysis of tensile and impact toughness tests shows a characteristic of ductile fracture. A higher content of Si results in larger radial region, smaller fibrous region and shear lip, which implies lower plasticity.

3) When the content of Si is less than 0.09 wt%, the Si elements are dissolved in α and β phases and increase strength, i.e. solid solution strengthening. On the other hand, when the content of Si reaches 0.14 wt%, the silicide precipitates along phase boundary, leading to a combination of solution strengthening and precipitation strengthening.

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Si 元素对 Ti-6Al-2Zr-1Mo-1V 钛合金力学性能的影响

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摘 要：研究了 Si 元素含量对 Ti-6Al-2Zr-1Mo-1V 钛合金在室温和 500 ℃下力学性能的影响。采用扫描电镜（SEM）和透射电镜（TEM）对断口形貌和微观结构进行了分析，硅化物的形核和生长与力学性能关系密切。结果表明：在 Ti-6Al-2Zr-1Mo-1V 合金中加入 0.04%~0.14%（质量分数，下同）的 Si 可以提高合金的抗拉强度和高温持久性能，塑性变化较小，冲击韧性和平面应变断裂韧度显著降低。Si 的加入使合金呈现由韧性向脆性断裂转变的趋势，放射区增大，纤维区和剪切唇区减小。当 Si 含量小于 0.09%时，Si 元素完全溶解于 α 和 β 相中，以固溶强化机制为主。当 Si 元素含量达到 0.14%时，相界处析出硅化物，强化机制为固溶强化和析出强化的结合。

关键词：TA15 钛合金；力学性能；断口形貌；硅化物析出；固溶强化；析出强化

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