# Optimization of Microstructure and Fracture Toughness of Nb<sub>4</sub>FeSi-Containing Nb-Si Based Alloy Using V, Zr and C Elements

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Abstract: Nb-Si alloy is considered an ideal material to replace Ni-based alloys, but toughness is the key limiting factor for its application. In this work, the microstructure and room temperature fracture toughness of the alloy by adding V, Zr and C elements were investigated. After doping with 3 at.% V, the microstructure is similar to the base alloy, consisting of Nbss and  $\beta$ -Nb5Si3. After doping with 3 at.% Zr, partial  $\beta$ -Nb5Si3 phase evolves into hexagonal  $\gamma$ -Nb5Si3 blocks, while obtaining fine eutectic structures. After doping with 3 at.% C, dispersed TiC particles appear, and the silicides are refined and spheroidized. The toughness of the alloy has been improved after alloying, and the toughness of the S4% higher than the base alloy.

Keywords: Nb-Si, alloying, microstructure, toughness

# **1** Introduction

With the development of aerospace, the demand for temperature bearing capacity of the hot-section components of engine has been increased [1-3]. Nb-Si in-situ composites can withstand service temperatures above 1200 °C and are considered as alternative materials for Ni-based alloys [2]. The main constituent phases of this alloy are niobium solid solution (Nbss) and silicides [3]. However, the insufficient room temperature toughness limits the industrial application of the alloys.

Extensive attempts have been made to improve the properties of the Nb-Si based alloy via suitable alloying using Ti, Hf and B, etc. [4, 5]. By adjusting the morphology and proportion of the constituent phases, the optimized properties maybe meet the requirements of industrial applications [5]. Up to now, the effect of V, Zr, and C elements on microstructure and fracture toughness of Nb<sub>4</sub>FeSi-containing Nb-Si based alloy is still unclear.

In this work, the constituent phase and structural evolution of the alloy after adding V, Zr, and C were investigated. In addition, the room temperature fracture toughness of the optimized alloy was tested.

# 2 Experimental procedure

The investigated alloys with the nominal compositions of Nb-24Ti-16Si-2Al-4Fe-X (X=3V, 3Zr and 3C, at.%) were

prepared by vacuum non-consumable arc melting in a water-cooled copper crucible.

The microstructure of the alloy was analyzed using the BSE-SEM (Merlin Compact). The single-sided notch bending test was conducted on the Instron 5569 universal electric testing machine to obtain the fracture toughness. The size of the test sample is  $20 \times 4 \times 2$  mm<sup>3</sup>, with a notch depth of 2 mm. The fracture toughness K<sub>Q</sub> value is calculated using the formula mentioned in reference [6]. The fracture toughness test of each alloy shall be conducted at least 3 times at a loading rate of 0.2 mm/min.

#### **3 Result and discussion Microstructure**

Fig. 1 shows the microstructure characteristic of the alloy after adding alloying elements. As shown in Fig. 1(a), the constituent phase of the matrix alloy is Nbss,  $\beta$ -Nb<sub>5</sub>Si<sub>3</sub> and Nb<sub>4</sub>FeSi. Nbss is the light gray contrast,  $\beta$ -Nb<sub>5</sub>Si<sub>3</sub> is the dark grav, and Nb<sub>4</sub>FeSi is the darker contrast in BSE-SEM mode. Nbss and β-Nb<sub>5</sub>Si<sub>3</sub> exist in a eutectic structure, while Nb<sub>4</sub>FeSi appears near β-Nb<sub>5</sub>Si<sub>3</sub> block. The microstructure of 3V alloy (Fig. 1(b)) is mainly composed of three phases: Nbss, β-Nb<sub>5</sub>Si<sub>3</sub> and Nb<sub>4</sub>FeSi phases. Element V is mainly enriched in the Nbss phase. Thus, the addition of V element has little effect on the microstructure and the constituent phase. The microstructure of 3Zr alloy (Fig. 1(c)) is composed of Nbss,  $\beta$ -Nb<sub>5</sub>Si<sub>3</sub>,  $\gamma$ -Nb<sub>5</sub>Si<sub>3</sub> and Nb<sub>4</sub>FeSi phases. The addition of Zr element causes the formation of hypereutectic structure and the appearance of primary hexagonal y-Nb<sub>5</sub>Si<sub>3</sub> blocks. During the solidification process, the leading precipitation of primary  $\gamma$ -Nb<sub>5</sub>Si<sub>3</sub> causes a decrease in the surrounding Si content, thereby forming a fine eutectic structure around it. The microstructure of 3C alloy (Fig. 1(d)) is composed of Nbss, β- Nb<sub>5</sub>Si<sub>3</sub>, Nb<sub>4</sub>FeSi, and TiC phases. The addition of C element is mainly enriched in fine TiC particles, leading to their formation. In addition, compared to the initial microstructure, the silicides are refined and spheroidized after adding 3 at.% C.





Fig. 1 The microstructure of Nb-16Si-24Ti-2AI-4Fe-X alloy after alloying: (a) base alloy; (b) 3V; (c) 3Zr; (d) 3C.

### 4 Room temperature fracture toughness

The room temperature fracture toughness of the alloys by the notched three-point bending tests is shown in Fig. 2. The fracture toughness  $K_Q$  value of the base alloy is 8.29 MPa·m<sup>1/2</sup>. After adding 3 at.% V and 3 at.% Zr, the fracture toughness  $K_Q$  value increased to 10.46 MPa·m<sup>1/2</sup> and 12.78 MPa·m<sup>1/2</sup>, respectively. The fracture toughness  $K_Q$  value of the C-doped alloy is the best, reaching 13.61 MPa·m<sup>1/2</sup>, which is 64% higher than the base alloy. The increase of  $K_Q$ value after V doping is mainly due to the solid solution of V in phase Nbss, which promotes the toughening of the alloy. The fine eutectic structure obtained by doping Zr is beneficial for hindering crack propagation and improving toughness. After adding C element, it is attributed to the refinement of the silicides and the presence of small TiC particles, which played a role in toughening the alloy.



#### Fig. 2 The room temperature fracture toughness of the alloys.

#### **5** Conclusion

(1)The microstructure doped with 3 at.% V is composed of Nbss,  $\beta$ -Nb<sub>5</sub>Si<sub>3</sub> and Nb<sub>4</sub>FeSi. The  $\gamma$ -Nb<sub>5</sub>Si<sub>3</sub> appears and fine eutectic is obtained by doping 3 at.% Zr. Dispersed TiC particles appear and the silicides are refined and spheroidized by doping 3 at.% C.

(2)After adding 3 at.% V and 3 at.% Zr, the K<sub>Q</sub> value increases to 10.46 and 12.78 MPa  $\cdot$ m<sup>1/2</sup>, respectively. The K<sub>Q</sub> value of the C-doped alloy reaches 13.61 MPa  $\cdot$ m<sup>1/2</sup>, which is 64% higher than the base alloy.

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