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Assessment of microstructure and property of a service exposed turbine blade made of K417 superalloy

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Abstract. In this paper, a turbine blade made of K417 nickel-based superalloy after service for 600 hours was investigated, the microstructural features were identified through metallographic observation, the size of γ' precipitates was adopted to quantitatively characterize the coarsening behavior, decomposition of primary carbides was also analyzed. In addition, micro-hardness tests were conducted on the turbine blade. The results indicated that size of γ' precipitates in the tip region of the blade had a small increase, the decomposition of primary carbides did not occur. Meanwhile, the little reduction in micro-hardness in the tip section was found, which was caused by the coarsening of γ' precipitates. To sum up, the service induced damage of the turbine blade after service for 600 hours was slight, the degeneration in the tip region was relatively obvious due to high temperature, the result is of great significance to evaluating the service safety of service exposed turbine blades.

1 Introduction

K417 cast nickel-based superalloy is extensively used in the manufacture of high-temperature engine components, due to its excellent high temperature strength, relatively low density and good casting property [1, 2]. Its microstructure mainly consists of γ matrix, strengthening phase γ', γ/γ' eutectic and different types of carbides. Cast nickel-based superalloy is strengthened by the γ' precipitates with a high volume fraction and massive distribution of blocky carbides, meanwhile, the distribution of fine carbides in the grain boundaries hampers grain boundary sliding, further enhancing its strength at elevated temperature.

As the engine blades are exposed to high temperature, complicated stress and hot corrosion during service, consequently leading to the degradation of microstructure, such as coarsening of γ' precipitates, decomposition of primary MC carbides, growth of the grain boundary fine carbides and formation of TCP phases [3, 4]. Qiang Feng assessed a turbine blade made of GH4033 nickel-based superalloy after service for 1600 hours [5], deduced the service temperature of the blade was lower than 700°C, its microstructure and mechanical properties did not degenerate significantly. AK Ray did a study on gas turbine blades made of Udimet-520 nickel-based superalloy after service [6], the results showed that the coarsening phenomenon of γ' precipitates occurred, coarsening behavior in the tip region was most serious. Meanwhile, in the middle region of blades, the primary carbides decomposed in the form: $MC + \gamma \rightarrow M_6C\ (M_{23}C_6) + \gamma'$, the continuous fine grain boundary carbides became discontinuous with a little increase in size. In addition, hardness and creep properties in the tip and middle region of the blades decreased sharply. Zheng Zhang investigated the turbine blades made

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of K002 superalloy after service for 400 and 650 flight hours [7], concluded that equivalent diameter of γ' precipitates increased with longer service time, but the volume fraction of γ' precipitates decreased. γ' precipitates in the middle region coarsened most severely and micro-hardness dropped greatly.

Although there are a few studies on the relationship between microstructure and property of turbine blade, compared with the importance of engine life prediction and safety management, they are far from enough. Therefore, this study is aimed at evaluating the service induced damage of turbine blade made of K417 superalloy after service for 600 hours, the result is not only helpful in exploring the degeneration of microstructure and property of turbine blades after service, but also provides an important reference for safety evaluation of turbine blades made of cast nickel-based superalloy.

2 Experiment

Table 1. Nominal Composition of K417 Cast Ni-base superalloy Turbine Blade (wt%)

Element	Co	Mo	Al	Cr	Ti	C	Fe	V	Ni
Content	14～16	2.5～3.5	4.8～5.7	8.5～9.5	4.5～5.0	0.1～0.2	1.0	0.6～0.9	Bal

The turbine blade made of K417 nickel-base superalloy was obtained from an aero-engine after service for 600 hours, the nominal chemical composition of K417 superalloy is given in Table 1.

Based on the known engine service temperature and load, the finite element analysis was carried out using ANSYS to calculate the distribution of temperature and stress in the turbine blade, the result is shown in Figure 1. According to the calculated results, the temperature increases from root to tip, up to 800°C at the leading edge in the tip region; Conversely, the stress decreases from tip to root , up to 500MPa at the suction surface in the root section. Taking the finite element results and relevant literature into consideration, six specimens were sectioned from the shank area and regions at different height of blade, as illustrated in Figure 2.

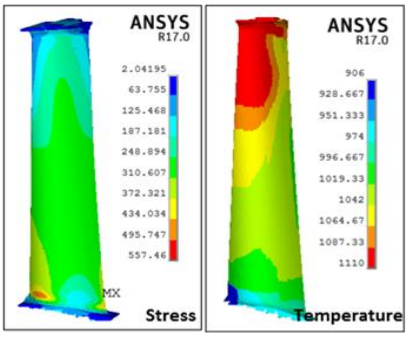

Figure 1. Distribution of temperature and stress in K417 turbine blade

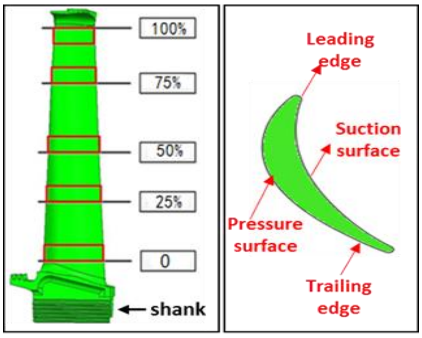

Figure 2. Location of metallographic specimens in K417 turbine blade

The metallographic specimens were mechanically polished, then etched with solution of 2g CuSO4, 10ml HCl and 10ml H_2O. The microstructural observation was performed using LEICA DM4000 optical microscope and JSM 6010 scanning electron microscope (SEM). The EDS analysis of phases were conducted by JSM7500 field emission SEM. To quantitatively characterize the coarsening behavior of γ' precipitates, the Image-pro Plus software was used to get the mean equivalent diameter of γ' precipitates. In addition, with the purpose of evaluating mechanical property of the turbine blade, an F800 Vickers indentor with a load of 100g was adopted to measure the micro-hardness at 4 locations for each specimen, leading edge, trailing edge, pressure surface and suction surface, respectively.

3 Results and discussion

3.1 *Microstructural observation*

The results show that the microstructure of K417 superalloy is composed of equiaxial grains with different size, and presents a typical dendritic morphology, there are a number of γ'/γ eutectics and blocky MC carbides spreading in the interdendritic region, as shown in Figure 3a, b. Figure 3c shows that blocky carbides, continuous fine carbides and γ'/γ eutectics distribute along the grain boundary. Moreover, the main strengthening phases in the K417 superalloy, γ' precipitates, present a cuboidal and regular shape, the size of γ' precipitates is uniform, as shown in Figure 3d.

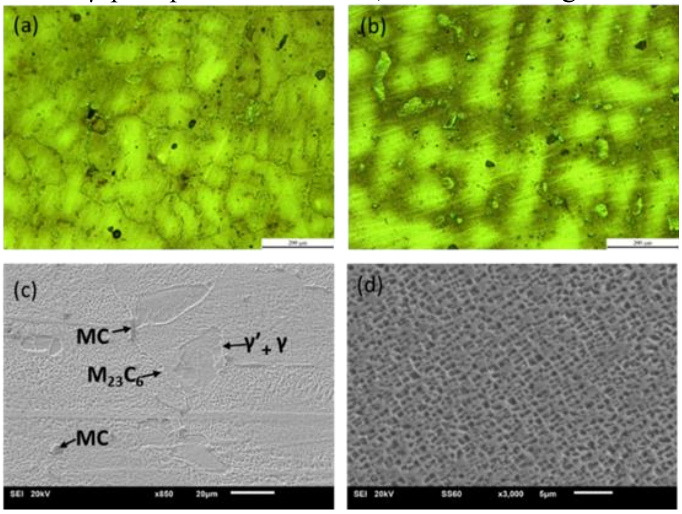

Figure 3. Microstructure of K417 turbine blade (a) equiaxial grains; (b) dendritic morphology; (c) phase distribution; (d) cuboidal γ' precipitates

3.2 *Coarsening of γ' precipitates*

Since the cast nickel-based superalloy is primarily strengthened by γ' precipitates, the shape and size of γ' precipitates have a significant influence on the property of the nickel-based alloy. After service for 600 hours, the shank region of the turbine blade can be taken as the original section because of the low stress and temperature, the distribution of γ' precipitates in the shank region is ordered with a cuboidal shape. In comparison with the original microstructure, the shape of γ' precipitates in the airfoil became irregular and the size of γ' precipitates increased slightly, as shown in Figure 4.

In order to quantitatively characterize the coarsening behavior of γ' precipitates, mean equivalent diameter was adopted as the characterization parameter. According to the calculation results, the average equivalent diameter of the γ 'phase in shank area was 0.72μm, the average equivalent diameter in the airfoil ranged from 0.71 to 0.85μm, the maximum γ' precipitates appeared at the leading edge in the tip section, as shown in Figure 5. As the coarsening of γ' precipitates is controlled by diffusion of alloying elements [8, 9], the higher temperature contributes to the larger size of γ' precipitates in the tip region.

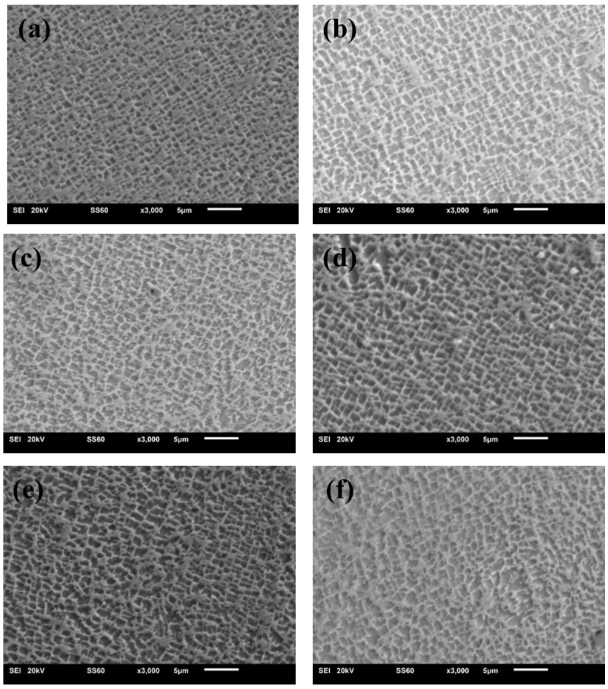

Figure 4. γ' precipitates of specimens at different heights
(a) shank; (b) root regio; (c) 25% height; (d)50% height; (e)75% height; (f) tip region

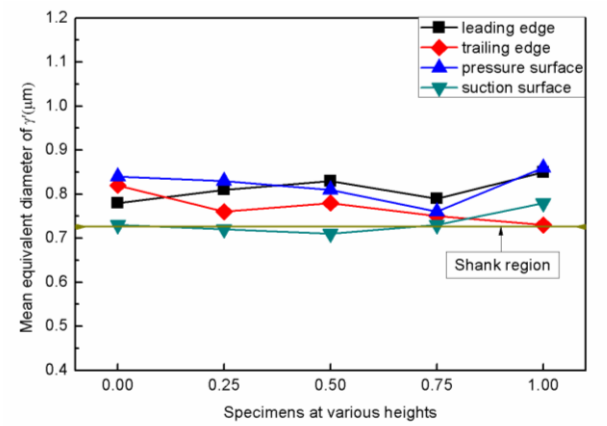

Figure 5. Mean equivalent diameter of γ' precipitate

3.3 *Decomposition of primary carbides*

In order to identify the type and composition of carbides in K417 superalloy, EDS analysis was performed on different carbides, including the intragranular carbides, blocky carbides and continuous fine carbides along the grain boundary. By referring to the ratio of elements of different carbides in the literature [10], combined with element content obtained by EDS analysis, it can be determined that the blocky carbide in the K417 alloy is MC, rich in Ti, continuous fine grain boundary carbide is $M_{23}C_6$, M is mainly Cr, as shown in Figure 6.

According to the relevant studies, primary MC carbides decompose during service with a reaction: MC + γ→ M_6C ($M_{23}C_6$) + γ′, MC is rich in Ti and Ta, $M_{23}C_6$ rich in Cr. Transformation of primary carbides is rare at 800 ℃, but the primary carbides decomposes severely above 1000 ℃. Sun held an idea that the decomposition of primary carbides is actually an interdiffusion behavior between primary MC and γ matrix, the C elements in the decomposition product were mainly from primary MC, Ni, Al and Cr were from γ matrix [11]. The edge of blocky MC carbides

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was observed and decomposition behaviour was not discovered. However, it was found that the Ti content at the edge of MC carbide was extremely low, but the amount of Cr increased, implying that a serious element diffusion occurred and a by-product of primary carbide degeneration was formed. This result is in accordance with the conclusion Jahangiri MR made on IN919 turbine blades [12].

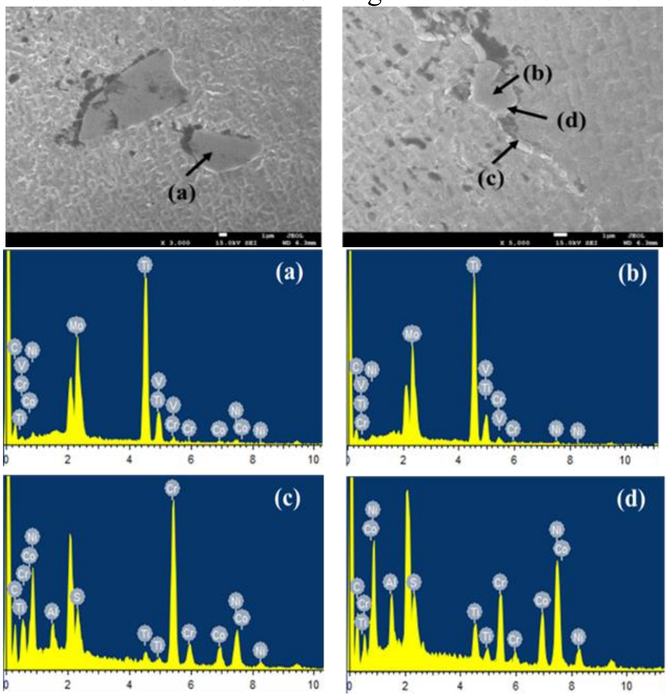

Figure 6. EDS analysis of carbides in turbine blade (a) intragranular primary carbide; (b) GB primary carbide; (c) GB continuous carbide; (d) edge of GB primary carbide

3.4 *Micro-hardness*

According to the micro-hardness test results, the Vickers hardness in shank region was 404.79HV, the hardness in airfoil was in the range of 375~440 HV. The minimum hardness, 375.35HV, appeared at leading edge in the tip area of blade. The variation of micro-hardness of different specimens is shown in Figure 7. The chart shows that hardness at the trailing edge is slightly greater than that at leading edge, the tip region has the lowest hardness longitudinally. Since K417 is a γ'-strengthened superalloy, the microstructural features of γ' phase affect its property greatly. Therefore, it is apparent that the coarsening of γ' phase results in the degradation of mechanical property.

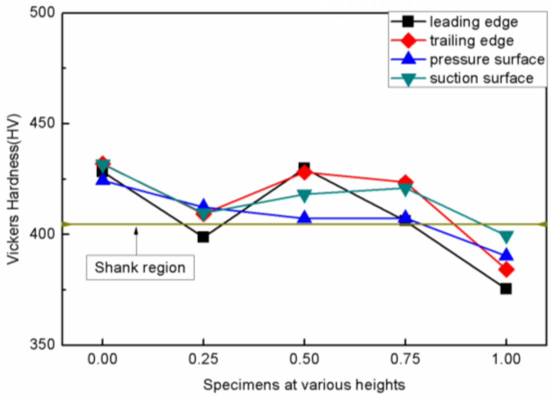

Figure 7. Vickers hardness of various specimens

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4 Conclusions

Through the microstructural observation and micro-hardness test of the turbine blade, the conclusions can be summarized as follows:

(1) After service for 600 hours, the γ' precipitates in the turbine blade made of K417 superalloy no longer maintained the regular cubic shape, and slight coarsening occurred. Relatively, the coarsening of the γ' precipitates in the tip region was more serious, the size of γ' precipitates at leading edge with the same height was larger, because of the higher temperature;

(2) According to EDS analysis results, it can be seen that the grain boundary primary carbides did not decompose, but the by-product of the decomposition reaction appeared around the blocky carbides, which may be caused by the relatively low working temperature and short service time;

(3) By measuring the micro-hardness of specimens from the turbine blade, the results showed that micro-hardness in the airfoil had a slight decrease, the micro-hardness in the tip region was the lowest. Combined with the changes of microstructure, it can be inferred that the degradation of γ' precipitates led to the decrease in micro-hardness.

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