Study on Micro Cracks of K424 Alloy Power Turbine Impeller Hub of an Air Starter

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Abstract: The fault piece K424 nickel base equiaxed superalloy power turbine impeller has a micro crack after 1000 times of high-power starting. After comparing the fault parts with the stereotype, the fracture surface, the chemical composition, the mechanical properties and the metallographic structure, the changes of the microstructure and mechanical properties of the turbine impeller and the mechanical properties of the turbine impeller are analyzed in five aspects. The results show that the micro crack of the fault part belongs to the low cycle fatigue fracture which occurs under the alternating stress. The crack source is located near the surface of the wheel hub and extends along the carbide boundary, and the grain boundary strengthening element B, Zr is low, and the microstructure exists a certain amount of skeleton carbide phase defects. These factors lead to the K424 turbine. The formation of micro cracks on impeller blades and hub joints.

1. Introduction

Turbine impeller plays an important role in aero engine. The production of turbine impeller depends not only on its functional and structural factors, but also on the demanding characteristics such as safety and reliability. In the whole turbine impeller, due to the change of the thickness of the section from 0.4mm to the hub of 70mm, the obvious difference of heat flow will cause a great change in the solidification structure of the whole castings. The difference of solidification structure results in the difference of mechanical properties, which is not conducive to the safe use of the whole turbine impeller. K424 alloy is a high strength, low density nickel based casting superalloy. It has high temperature specific strength, good plasticity and technological properties. It is suitable for working in the range of 850 to 1000°C and working at a higher temperature for a short time. It is widely used in engine and starter blades and the whole casting turbine rotor and so on. Eight alloying elements were added to the alloy, with Co, Cr, Al, Ti, Mo, W and other elements[3]. These components, while improving the comprehensive properties of the materials, have a direct impact on the precipitates in the solidification process of the alloys, and the complicated solid phase transition in the process of subsequent processing and use, thus forming a more complex structure.

In this paper, after 1000 times of high power starting of the K424 power worm wheel, microcracks were examined by fluorescence, and the mechanism of micro crack formation was carried out through five aspects of crack and fracture morphology, chemical composition, mechanical properties,
metallographic structure and so on, which realized the optimization of tissue and the improvement of mechanical properties, thus guiding the high quality aero engine.

Figure 1 Power turbine impeller diagram

2. Test materials and methods

A power turbine impeller of a certain engine has a micro crack in the hub after 1000 times of high-power starting. The turbine material is K424 nickel base cast superalloy, and its standard components (mass fraction %)\(^5\) and the measured components of the fault parts are shown in Table 1.

| Metal grade | The element | C | Cr | Ni | Co | Mo | W | Al | Ti | Nb | V |
|-------------|-------------|---|----|----|----|----|---|----|----|----|---|
| K424 alloy  | The scope of allowance | 0.1 | 8.50 | 12.0 | 2.7 | 1.0 | 5.0 | 4.2 | 0.5 | 0.5 |
|             | 0.2 | 10.5 | 15.0 | 3.4 | 1.8 | 5.7 | 4.7 | 1.0 | 1.0 |
| Failure parts | 0.1 | 9.19 | base | 13.6 | 3.0 | 1.41 | 5.34 | 4.57 | 0.76 | 0.85 |

The specimens were inspected for structural and mechanical properties at the junction between the blade and the hub (near the crack). The specimens were polished, polished, and corroded with high corrosion agent (HCl (=1.19) + (1~15) H\(_2\)O\(_2\)) for 2-5 minutes. The metallographic microstructure was observed by LEicaDM1500OM metallographic microscope after corrosion of the metallographic structure. The microstructure and element composition of high power were analyzed by SEM and EDS, and the characteristics of microstructures were quantitatively characterized. In order to analyze the depth of the crack, one of the coarser cracks in the sample fault part is cut open, and it is compared with the original casting, the prototype and the finalized parts produced by the original process, as shown in the cross section (as shown in Figure 2).

When analyzing and evaluating the mechanical properties of the fault parts, the wheel hub of the power turbine impeller is cut open along the diameter direction, the cast sample is taken from the 1/2 hub, and the mechanical performance bar is processed according to figure 2. The tensile test machine is used for tensile test at room temperature and the endurance test of 975 degrees centigrade, and the comparison analysis is made with the prototype to determine the suitable heat treatment regime (as shown in Figure 3).
3. Test results and analysis

3.1 Macroscopic examination

The micro crack is located near the hub of the hub and cracks on the hub. Fig. 4 shows the appearance of the junction between the blade and the hub (near the crack) at a lower multiple. The problem of micro cracks existed in the K424 and the hub connection of the whole power turbine impeller of the K424 nickel based equiaxed grain superalloy after high power starting. In the design of the hot end parts of the engine, there are complex parts of different sizes and uneven thickness. In the manufacturing of the integral impeller, the blade is required to have good high temperature endurance and creep strength, and the hub should have excellent low cycle fatigue and tensile strength. Under the conventional casting conditions, thin parts of the blade are easy to form fine grain, while thick grain is formed at the thick hub, which cannot meet the requirements of yield strength and low cycle fatigue performance, which seriously restricts the production of high performance aeronautical structures.

3.2 Analysis of crack and fracture morphology

Under Zeiss scanning electron microscope, magnification 160 times, the micro cracks on the hub surface were observed as shown in Figure 5. It can be seen from the diagram that the crack is a multi source micro crack, and the length and width of each micro crack are very small. The length and width
of the crack are about 2mm. Fig. 6 shows the morphology of another micro crack nearby. It can be seen that the crack is relatively small and the number of cracks is less.

![Figure 7 Microcrack profile structure](image)

The crack in the middle of 7a is cut off from the middle, and the depth of the crack is analyzed from its cross section. The samples were polished, polished and corroded with high magnification, and then observed by Zeiss scanning electron microscope. The results are shown in Figure 7a. By measurement, the depth of the main crack is about 0.15mm. In addition, there are two other thinner and thinner microcracks in the section, corresponding depths of 0.05mm and 0.03mm respectively, as shown in Figure 7b.

![Figure 8 The fracture morphology of fatigue crack](image)

As shown in figures 7a and b, the crack is transgranular fracture without branching, and there is no obvious "poor" region around the crack. The crack extends to carbides, and the carbide boundary is extended due to the weak bonding force between the carbide phase and the base metal. The overall crack is very shallow, the deepest seen is only 0.15mm.

Break the above section cracks and analyze the fracture surface. The results are shown in Figure 8. On the micro fracture of 0.15mm, obvious fatigue stripe can be observed, the stripe is uniform arc, and the arc line is not very fine, the fatigue stripe region is discontinuous, which is the characteristic of the typical low cycle fatigue fracture of casting superalloy. Based on the above analysis, the dynamic turbine crack is a microcrack caused by low cycle fatigue.

### 3.3 Chemical composition analysis

The chemical composition analysis was taken from the hub of the fault parts and compared with the sample parts and the stereotyping parts. Table 2 to 4 shows the specific changes of the main elements, trace elements and gas content respectively.

| Table 2 | Comparison of composition of the main elements (wt%) |
|---|---|
| | C | Cr | Co | W | Mo | Al | Ti | Nb |
| Technical conditions | 0.1~0.20 | 8.5~10.5 | 12~15 | 1.0~1.8 | 2.7~3.4 | 5.0~5.7 | 4.2~4.7 | 0.5~1.0 |
| Fault parts | 0.16 | 9.19 | 13.62 | 1.41 | 3.07 | 5.34 | 4.57 | 0.76 |
| Prototyping | 0.19 | 9.4 | 14 | 1.5 | 3.2 | 5.3 | 4.5 | 0.8 |
| Stereotype | 0.17 | 9.7 | 14.85 | 1.34 | 3.04 | 5.55 | 4.42 | 0.79 |
Table 3  Comparison of composition of the trace elements (wt%)

|                | B   | Zr  | Ce  | Fe  | Si  | Mn  | P    | S    | Pb   | Bi   |
|----------------|-----|-----|-----|-----|-----|-----|------|------|------|------|
| Technical conditions | 0.015 | 0.02 | 0.02 | 2.0 | 0.4 | 0.4 | 0.015 | 0.015 | 0.001 | 0.0005 |
| Fault parts     | 0.0056 | <0.01 | 0.0066 | 0.06 | 0.03 | <0.005 | <0.005 | 0.0014 | <   | <      |
| Prototyping     | 0.008 | 0.02 | 0.02 | <2  | <0.4 | <0.4 | <0.015 | <0.001 | <0.001 | <      |
| Stereotype     | 0.016 | 0.021 | <0.005 | <2  | <0.4 | <0.4 | <0.015 | <0.015 | <   | 0.0005 |

Table 4  Comparison of the composition of main gas

|                | O   | N   | H   |
|----------------|-----|-----|-----|
| Technical conditions |     |     |     |
| Fault parts     | 19  | 9   | 0.7 |
| Prototyping     | 40  | 10  | —   |
| Stereotype     | 14  | <10 | —   |

The results of composition test show that the main elements and impurities in the technical conditions of the main element chemical components are all qualified, the content of Cr and Co of the solid solution strengthening elements is slightly lower, and the W and Mo elements are lower than those of the samples, but not lower than the finalized parts. The content of oxygen, nitrogen and hydrogen in fault parts is well controlled in comparison with the main gas content.

In the analysis of the chemical composition of trace elements, it is found that the content of the element B and Zr of the fault parts is obviously lower than that of the prototype and the prototype, so the percentage of the eutectic phase volume is less. The B and Zr elements in K424 alloys are important intergranular strengthening elements, which play a role in reducing grain boundary diffusion, improving grain boundary and interdendritic structure and improving the bonding strength. Although the content is not high, there is no limit in the technical conditions, but the effect cannot be ignored. At the same time, Zr element helps to improve the morphology of carbides and eutectic phases, making carbides change from skeleton to stripe, and eutectic transformation is small and dispersed.

3.4 Analysis of mechanical properties

From the position of the wheel hub of the engine power turbine rotor near the blade root, a small sample of 3mm is taken to test the tensile and high temperature endurance performance at room temperature. The test results are shown in Table 5. The results show that the tensile property at room temperature is the same as that of the stereotype, lower than that of the prototype 200MPa, and the endurance property is higher than that of the stereotype, which is similar to that of the prototype.

Table 5  Mechanical properties test results

| state         | 975℃/196 MPa Persistent performance | Room temperature tension |
|---------------|--------------------------------------|--------------------------|
|               | ≥40h   | ≥835 | ≥5  | ≥7   |
| Fault parts   | 31.4   | 735  | 8.0 | 12.3 |
| Prototyping   | 32.2   | 755  | 4.0 | 7.2  |
| Stereotype    | 21     | 755  | 12  | 14.5 |
|               | 23.9   | 765  | 3   | 5.5  |
| Stereotype    | 34.5   | 940  | 5.0 | 16.0 |
|               | 35     | 980  | 8.0 | 9.0  |
3.5 Metallographic examination and analysis

In view of the hub of the wheel, the blade, the set and the sample parts of the fault parts, the high microstructures of the samples were observed, and the quantitative metallographic study of the dendrite arm distance and the number of eutectic phase was carried out. As shown in Figure 9, the experimental results show that the arm spacing of the hub parts of the prototype, the set and the fault parts is equal to 90~100μm, indicating that the cooling rate of the solidification is equal. In addition, the dendrites are more dense than the dendrites at the hub.

![Fig.9 Dendritic structure of different samples.](image)

a wheel hub prototype; b wheel hub stereotype; c failure hub; d fault blade

Table 6 shows the two dendrite arm distance and the volume percentage of the eutectic phase of different samples. It can be seen that the cooling speed is faster and the dendrite arm distance is obviously lower than the hub position because of the thin wall of the blade. Due to the refinement of dendrite structure, the number of eutectic phase in the blade position is significantly reduced and the particle size is smaller than that at the hub. It is found that the eutectic phase content of the domestic parts varies from 1.61% to 2.76%, and the number of the eutectic phase is the least, and the finalized parts are the most. The size of eutectic phase of the domestic parts is basically the same, but slightly larger than that of the prototype. The prototype has a considerable number of eutectic phases (2%) and is relatively small and dispersed. This is because the B and Zr elements have a significant effect on the number of eutectic phases. The higher B and Zr contents will lead to higher eutectic volume fraction. According to table 3, the content of B and Zr in fault parts is low, so the volume fraction of eutectic phase is less.

### Table 6 Comparison of two dendrite arm spacing and volume fraction of eutectic phase

|                      | Wheel hub | Stereotyped hub | Fault hub | Failure blade |
|----------------------|-----------|-----------------|-----------|---------------|
| **Second dendritic arm distance, (μm)** | 96.8      | 94.7            | 99.3      | 55.3          |
| **Total crystal phase volume percentage %** | 2.0       | 2.76            | 1.61      | 0.69          |
Figure 10 shows the high microstructures of different samples. The results show that the carbide in the hub of the defective parts shows a significant skeleton shape, and so does the blades. Carbide in the hub of the molding piece is well punctuated, and there are very small amounts of near skeleton carbides in the prototype, most of which are distributed in dots or short strips. The binding force between the carbide and the alloy matrix is low, and the skeleton or strip carbide boundary is easy to provide the channel for crack propagation, while the spot carbide at the grain boundary may block the channel of crack propagation, so the sample and the mold have better carbide morphology, and the carbide morphology of the fault parts prevents the crack growth. It is unfavourable. The higher Zr content and faster cooling rate are beneficial to the formation of point carbide phase. Therefore, the low content of Zr in failure parts is a main reason for the skeleton appearance of carbide phase.

The excellent mechanical properties of the superalloy are derived from the $\gamma'$ phase, which is close to the lattice constant of the matrix $\gamma$ phase, which is the main strengthening phase in the nickel base superalloy. It is an orderly arrangement of the face centered cubic structure and is a metastable phase. The size and distribution of the amount and distribution of the number of $\gamma'$ phase are important factors affecting the strengthening of the alloy. Under different solidification conditions, the shape of the ball, the regular cubic and the field character can be presented in the cast structure. The high volume fraction and the fine $\gamma'$ precipitation phase are ideal structures for the alloy to obtain the best high temperature properties. The large $\gamma'$ ray in the cast microstructure is unfavorable to the mechanical properties of the superalloy. By means of proper solution treatment, a small cubic $\gamma'$ phase can be obtained.

The higher multiple microstructure analysis shows that the domestic parts are typical of K424 alloy cast structure, and the particles are distributed on the matrix, and the grain boundary is relatively large and irregular in shape. The carbides and eutectic phases are mainly distributed in grain boundaries. As the formation of eutectic phase consumes more of the phase formation elements, the surrounding precipitation is smaller. In addition, the dendritic stem has a more regular cube granule, and there is no obvious difference in the morphology of different domestic parts.

Further comparison prototype parts and domestic, 200 times and 500 times the microstructure changed obviously showed the $\gamma'$ phase solubility and precipitation phenomenon, undissolved interdendritic $\gamma'$ than as-cast interdendritic $\gamma'$ phase is more bulky, suggest that the interdendritic relatively bulky $\gamma'$ happened in a certain degree of integration. Observed under higher multiples (as-cast) prototype and local parts of dendrite dry $\gamma'$ phase (figure 11), visible prototype pieces of $\gamma'$ phase rule of cube grains, but more small particles, more neatly arranged. Prototype pieces of this prototype according to tissue morphology of the solid solution treatment, dendrite stem of $\gamma'$ phase.
after solid solution, precipitation in the subsequent cooling process more tiny rules cube γ' phase particles, and interdendritic γ' phase itself, the particles are relatively bulky, cannot completely solid solution, but a degree of mutual confluence, to form more massive γ' phase.

![Fig 11. γ′ phase between dendrites, ×2000. a prototype; b stereotype](image)

The solution treatment can improve the segregation effectively, improve the grain boundary and interdendritic state of the cast alloy, promote the homogenization of the microstructure, thus effectively improve the strength and the plasticity of the alloy. The power turbine of the starter is rotating at high speed and starting frequently. It requires high strength, plasticity, mechanical fatigue and thermal fatigue properties of the alloy. It is appropriate and necessary to take solid solution treatment to make the material performance and uniformity best. The size and shape of the γ' phase after solution treatment of cast superalloy are affected by the cooling rate after solid solution. The γ' phase particle size of the prototype is larger than that of the mechanical test bar, which is treated by ‘1210°C × 4 hours, air cooling’. Therefore, the possible heat treatment of the prototype is as follows: solid solution and control cooling rate.

4. Conclusions

By comparing the microstructure of the microcracks and the microstructure of the failure parts with the stereotypes and prototypes, the main conclusions are as follows:

(1) The crack at the junction between the blade and the hub is caused by excessive residual stress. Its micro crack belongs to the low cycle fatigue fracture which occurs under the alternating stress. The crack source is located near the hub surface, and the carbide boundary provides the channel for the crack propagation.

(2) The chemical composition of the fault parts meets the technical requirements, and the gas and five harmful elements are well controlled. However, the grain boundary strengthening elements B and Zr are lower than the stereotypes and prototype parts, which are not conducive to grain boundary strengthening, and make the carbide phase form skeleton shape.

(3) The tensile property at room temperature is lower than that of the sample, and the durability is higher than that of the finalized part, which is equal to the prototype.

(4) The microstructure of the failure parts and the stereotypes is basically the same as that of the K424 alloy as cast structure. However, there is a certain amount of skeleton-shape carbide phase in the defective parts, which is unfavorable to prevent crack propagation.

(5) The microstructure of the prototype showed solid solution treatment, and the regular cube γ' phase was precipitated in the subsequent cooling process.

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