ENGINEERING FAILURE MODES AND FRACTURE CHARACTERISTICS OF SINGLE CRYSTAL SUPERALLOY BLADES

He Yuhuai, Liu Changkui
Beijing Institute of Aeronautical Materials, Beijing 100095, China
heyuhuai@163.com; changkuiliu621@sohu.com

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Abstract

The common engineering failure modes of single crystal(SC) superalloy blades were analyzed and summarized, including fracture resulting from recrystallization, fatigue failure, creep fracture, fracture caused by overburning, and overload fracture. The fracture characteristics and failure mechanism of every failure mode were studied. In addition, the failure modes and fracture characteristics of SC superalloys in engineering and experiment environment were compared and discussed.

1 Introduction

Owing to the elimination of grain boundaries, single crystal (SC) superalloys have excellent mechanical properties, such as high heat resistance, fatigue strength, creep strength and vibration damping ability. With excellent high-temperature mechanical properties, SC superalloys have been widely used to make blades for the advanced military and civil aircraft engines[1, 2].

Because of the particular structure features, the fracture modes of SC superalloy blades are different from those of polycrystal superalloy blades. So it is necessary to investigate the failure modes and fracture characteristics of SC blades under different conditions to ensure their reliability. In the past several decades, SC superalloys have been paid extensive attention to. The failure modes and mechanisms of SC superalloys under different conditions have also been extensively studied. However, most of the studies were carried out in labs and little information concerning engineering failure modes and fracture characteristics of SC blades can be found in the open literature[3-5]. In the present work, the common engineering failure modes and fracture characteristics of SC blades were analyzed and summarized. In addition, the failure modes and fracture characteristics of SC superalloy blades in engineering and experiment environment were compared and discussed.

2 Failure resulting from recrystallization

The superior high-temperature mechanical properties of SC superalloys mainly result from the elimination of the grain boundaries perpendicular to the main stress axis. In SC superalloys, in order to enhance the incipient melting temperature, the addition of the elements that can strengthen the grain boundaries is generally omitted, such as C, B, Hf and Zr. If recrystallization takes place, the recrystallized grain boundaries will become the weakest regions and the mechanical properties will be dramatically reduced[6-8]. In engineering, recrystallization is one of the commonest failure causes for SC blades; the recrystallization of SC blades in engineering includes local surface recrystallization and complete recrystallizaiton, as shown in Fig.1. The fracture surfaces caused by recrystallization usually present intercrystalline cracking feature, shown in Fig.2. The recrystallization of SC blades usually forms during solution treatment because of the plastic deformation by grit blasting or other surface machining before solution treatment. In order to prevent recrystallization, it is necessary to pay more attention to the manufacturing processes. The main measures are proposed as follows: 1) anti-deformation design of the casting die; 2) adopting precision casting to reduce machining as much as possible; 3) strictly controlling deformation during surface treatment; 4) adopting reasonable procedures to make the cold deformation occur after solution treatment; 5) strictly controlling recrystallization depth according to relevant standards.

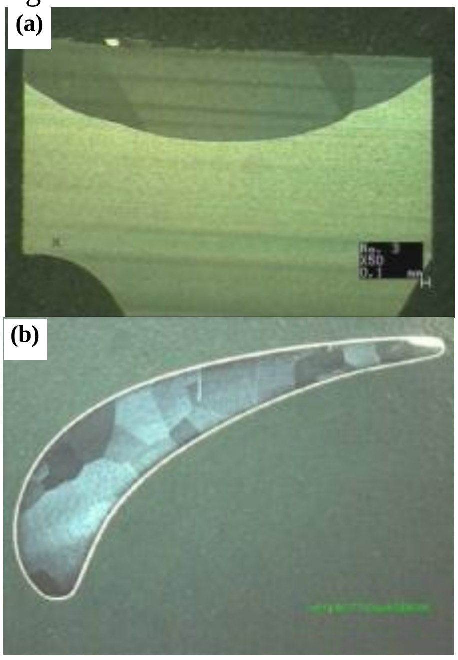

Fig.1 Recrystallization of SC blades
(a) Complete recrystallization of blade body
(b) Local recrystallization of blade rabbet

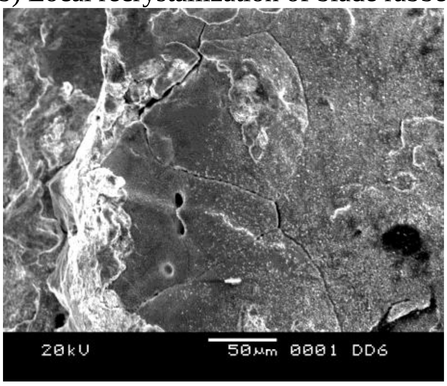

Fig.2 Intergranular cracking feature caused by recrystallization

3 Creep failure

During service, the main stress on SC turbine blades is centrifugal load, so creep damage is one of the commonest failure modes for SC turbine blades. In engineering, the creep failure cases of SC blades usually present the following two phenomena: the tips of the blades scratching with the outer ring, and fracture of the blades because of creep elongation. The first phenomenon is more common than the second. The fracture surfaces of the blades caused by creep elongation can often be divided into two parts: creep cracking section and fast fracture section, shown in Fig.3. The creep cracking section was more seriously oxidized, and was nearly perpendicular to the main axis of the blades. In addition, it was covered with many small square-shaped facets, shown in Fig.4. The fast fracture section was flat, and extended in the 45° direction from the main axis. Local shear dimples can be found at the fast fracture section. The microstructure near fracture surface presented rafting feature, shown in Fig.5.

The creep fracture mechanism and features of SC superalloys have been extensively studied in labs. Hopgood et al.[9] found that the fracture surfaces by high-temperature creep were usually covered with a large amount of square-shaped facets, and nearly every facet had a micro-pore in the center. They thought that these micro-pores were pre-existing casting pores; these square-shaped facets were caused by microcrack growth around the pre-existing casting pores in the materials.

Fig.3 Macro feature of fracture surface of SC blade by creep

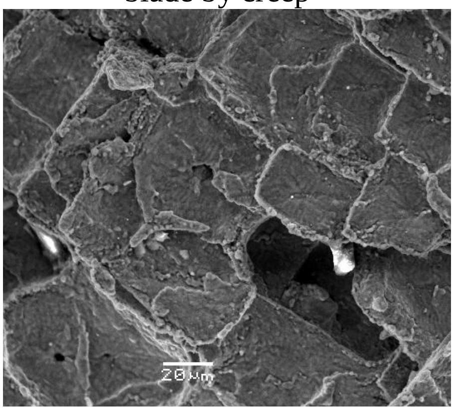

Fig.4 Square-shaped facets at creep cracking section

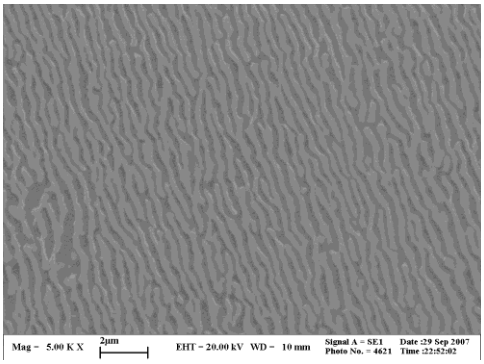

Fig.5 Rafting microstructure near the fracture surface

4 Fatigue failure

During service, other than centrifugal load, SC turbine blades are also under the effect of vibration stress and impact load of gas flow, so fatigue failure is also a common failure mode. Fatigue cracks may occur in rabbets, blade roots, blade bodies or blade tips. The fatigue fracture surfaces of SC blades present three patterns. The first pattern is that the fracture surfaces consist of intersecting smooth facets(Fig.6) and the fatigue cracks present zigzag appearance, as shown in Fig.7. The second pattern is that the fracture surfaces consist of rough surfaces caused by crack intracrystalline propagation(Fig.8). The third pattern is that the fracture surface is made up of smooth facets and rough faces and the fatigue source region is rough surface (Fig.9). In microscopic view, at the smooth facets of fatigue fracture surfaces, river pattern initiating from source region and beach mark can be seen(Fig.10), but fatigue striations can rarely be seen. At the end of smooth facets, fatigue striations can sometimes be seen. The rough surfaces presented typical fatigue fracture features; beach mark and fatigue striations can be seen easily, shown in Fig.11.

According to the studies on fatigue fracture characteristics of SC superalloys in labs[10], fatigue fracture characteristics of SC superalloys are affected by stress or strain. Under high strain amplitude, the fracture surfaces of low-cycle fatigue specimen present more than one fatigue sources. The fracture section forming in the initial stage is perpendicular to stress axis, and then the fatigue crack propagates along the special crystallographic plane. Under low strain amplitude, the fracture surfaces of low-cycle fatigue specimen present one fatigue source. The crack initiated and propagated along the special crystallographic plane. The fracture surfaces of high-cycle fatigue specimen present a fatigue source. Under large stress, the fractures are composed of several special intersecting crystallographic planes. Under low stress, the fractures are composed of a large crystallographic plane and a fast fracture region.

In engineering, the fatigue fracture characteristics of SC blades are also affected by stress. The fatigue fractures surface under large stress present the pattern of rough surface, including a linear source or multi-sources. At the source regions, fatigue steps can be seen, as shown in Fig.8 and Fig.9. Fine dimples can be seen at some fracture surfaces, as shown in Fig. 12. This type of cracks usually initiates from rabbet teeth or such stress concentration regions as cooling windows. If the stress is lower, the fracture surfaces present the pattern of smooth facets.

Fig.6 Fatigue fracture surface consisting of smooth facets

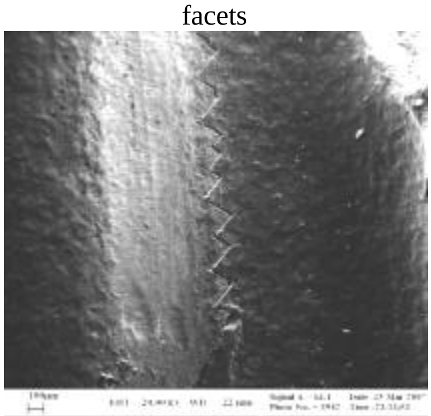

Fig.7 Zigzag fatigue crack

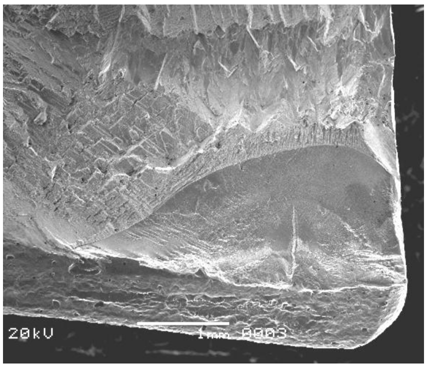

Fig.8 Low-power appearance of rough surface

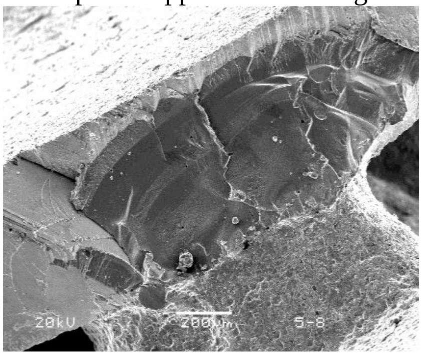

Fig.9 Fatigue fracture consisting of smooth facets and rough faces

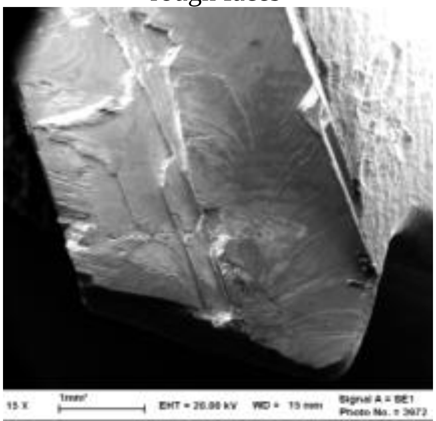

Fig.10 River pattern and beach mark at smooth facet

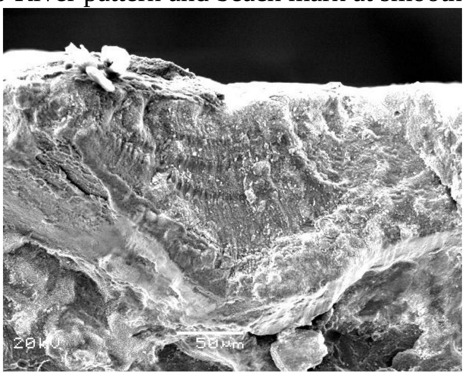

Fig.11 Fatigue fracture feature of rough surface

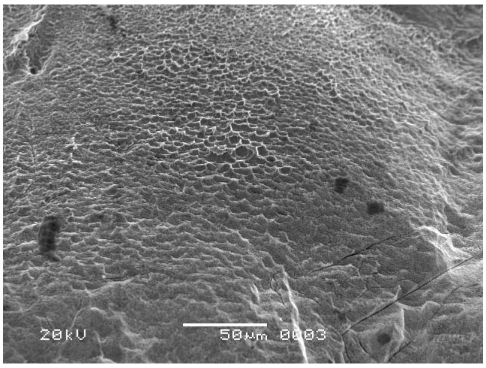

Fig.12 Fine dimples at the fracture surface after low-cycle fatigue testing

5 Failure resulting from overburning

SC turbine blades work at high temperature. If the temperature is too high, the microstructure of the blades will change, and the strength will decrease dramatically. In engineering, the fracture of SC blades caused by overburnng was commonly caused by other failure factors, such as friction of blade tips or collision of blade bodies. The fracture surfaces caused by overburning are usually dark colored. Metal globules and oxide can be clearly seen on the fracture surfaces, shown in Fig.13. Holes by overburning and smaller γ' particles deriving from the melting of original γ' particles can be seen in the microstructure of the overburned blades(Fig.14).

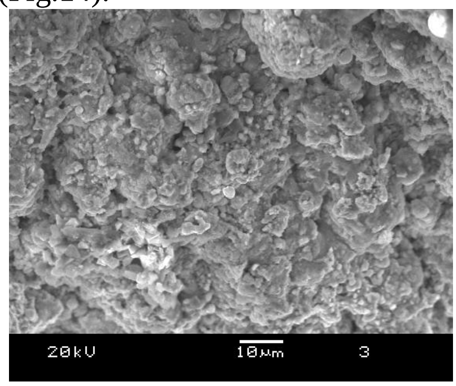

Fig. 13 Fracture surface caused by overburning

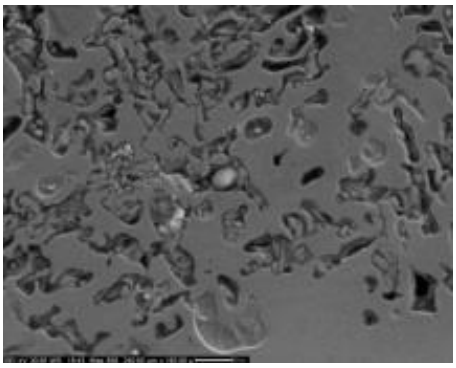

Fig. 14 Microstructure near fracture surface of the failed blade by overburning

6 Failure resulting from overload

In engineering, the overload fracture of SC blades was commonly caused by other failure factors. The blades were struck and thus fractured. The failed blades caused by overload can be found to have plastic deformation and wear trace. The fracture surfaces often present slipping and facet feature, as shown in Fig.15.

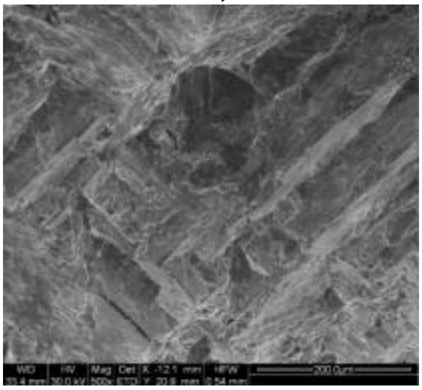

Fig.15 Slipping and facet feature

7 Conclusion

The common engineering failure modes of SC superalloy blades include fracture resulting from recrystallization, fatigue cracking or fracture, creep fracture, fracture caused by overburning and overload fracture. Among them, fracture caused by overburning and overload fracture are two secondary damage forms caused by other failure factors. In engineering, more attention should be paid to recrystallization, fatigue failure, and creep fracture, as well as their influencing factors.

References

[1] Gell A D, Duhl D N, Giamei A F. The development of single crystal superalloy turbine blades[C]. Superalloys 1980. Warrendale:TMS,1980:205-214.

[2] Cheng R Z. Development of Cast Superalloys and Processes in BIAM for 40 Years[J]. Journal of Materials Engineering, 1998, (10):3 (in Chinese).

[3] MacLachlan D W, Wright L W, Gunturi S S K, et al. Modeling the anisotropic and biaxial creep behavior of Ni-base single crystal superalloys CMSX-4 and SRR99 at 1223 K[C]. Superalloys 2000. Warrendale:TMS,2000:357-366.

[4] Yu J J, Sun X F, Jin T, et al. High temperature creep and low cycle fatigue of a nickel-base superalloy[J]. Materials Science and Engineering A, 2010, 527(9): 2379-2389.

[5] Kiyak Y, Fedelich B, May T, et al. Simulation of crack growth under low cycle fatigue at high temperature in a single crystal superalloy[J]. Engineering Fracture Mechanics, 2008,75(8): 2418-2443.

[6] D.Goldschmidt, U.Paul, P.R. Sahm. Porosity Clusters and Recrystallization in Single-crystal Components[A]. S.D. Antolovich, R.W. Stusrud, R.A. MacKay, et al. eds. Superalloys 1992[C]. Warrendale:TMS, 1992. 155.

[7] Zhang B，Liu C K，Lu X，et al．Effect of surface recrystallization on the creep rupture property of a single-crystal superalloy[J]．Rare Metals，2010，29(4)：413．

[8] Zhang B，Tao C H，Lu X，et al．Recrystallization of single crystal nickel-base superalloy[J]．Journal of Iron and Steel Research，International，2009，16(6)：75．

[9] Hopgood A A, Martin J W. The creep behavior of a nickel-based single-crystal superalloy[J]. Materials Science and Engineering,1986,82:27-36.

[10] Liu C K, Yang S, He Y H, et al. Fracture features of Single Crystal Superalloys[J]．Failure Analysis and Prevention, 2010, 5(4): 16-19(in Chinese)．

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