

Postprint: Crack Initiation and Propagation Behavior Around Circular Holes in Nickel-Based Single Crystal Superalloys During Thermal Cycling

Authors: Wang Li, Zhou Zhongjiao, Zhang Shaohua, Jiang Xiangdong, Lou Langhong, Zhang Jian

Date: 2023-03-19T00:00:00+00:00

Abstract

A second-generation nickel-based single-crystal superalloy was selected to prepare two groups of plate-type specimens oriented parallel to the directional solidification direction and along the (100) and (110) planes, respectively. Circular holes with a diameter of 0.5 mm were machined perpendicular to the plate surface at the specimen center using the electrical discharge machining (EDM) method. Thermal fatigue experiments from room temperature to 1100 °C were conducted to investigate the crack initiation and propagation behavior around the circular holes in plate-type specimens with different crystallographic planes during thermal cycling. The results show that in plate-type specimens located on different crystallographic planes, a thin recast layer was produced around the circular holes machined by the EDM method, with a maximum thickness of approximately 15 μm. The crystallographic plane of the plate-type specimens has a significant influence on the crack initiation and propagation behavior around the circular holes. After 80 cycles, cracks in the (110) plane specimens initiated at the hole edge perpendicular to the dendrite growth direction, and then propagated rapidly at a 45° angle to the dendrite growth direction. In contrast, for the (100) plane specimens, no cracks were observed at the hole edge even after 200 cycles. The essential cause of this difference is the combined effect of thermal stress differences resulting from the anisotropy of the single-crystal superalloy crystal structure and microstructural characteristics.

Full Text

Crack Initiation and Propagation Around Holes in Ni-Based Single Crystal Superalloy During Thermal Fatigue Cycling

WANG Li¹), ZHOU Zhongjiao¹), ZHANG Shaohua¹), JIANG Xiangdong²), LOU Langhong¹), ZHANG Jian¹)

¹) Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

²) Beijing Beiye Functional Materials Corporation, Beijing 100192, China

Correspondent: WANG Li, associate professor, Tel: (024)23971276, E-mail: wangli@imr.ac.cn

Supported by National Natural Science Foundation of China (No.51201164), National High Technology Research and Development Program of China (No.2012AA03A511) and National Key Scientific Instrument and Equipment Development Project (No.2012YQ22023304)

Manuscript received 2015-07-09, in revised form 2015-08-29

Abstract

Ni-based single crystal (SX) superalloys are widely used for production of blades in gas turbines and aircraft engines due to their superior mechanical performance at high temperatures. To obtain high cooling efficiency, most SX blades consist of thin walls with cooling holes. However, thermal fatigue cracks are commonly observed in blades with such structures. Thus, investigating crack initiation and propagation around holes during thermal fatigue tests in SX superalloys is of significant value. In the present work, a second generation SX Ni-based superalloy was used. Plate specimens parallel to the directional solidification (DS) direction and along (100) or (110) planes were prepared. A hole with a diameter of 0.5 mm was drilled vertical to the surface in the middle of each plate by electro-discharge machining (EDM). Thermal fatigue tests were performed between room temperature and 1100 °C to investigate the effect of crystal orientation on crack initiation and propagation behavior, and the underlying reasons were analyzed. It was found that a thin recast layer was produced around the EDM-drilled holes, with a maximum thickness of 15 μm. Crystal orientation has a significant effect on crack initiation sites and propagation kinetics. After 80 thermal fatigue cycles, cracks in (110) specimens initiated at the hole edge perpendicular to the DS direction, then grew rapidly and propagated along directions approximately 45° from the DS direction. After 200 cycles, crack length exceeded 2 mm. In contrast, no cracks were observed in (100) specimens even after 200 thermal fatigue cycles. This difference was mainly attributed to the combined effects of different thermal stresses caused by the anisotropy of single crystals and microstructural characteristics.

KEY WORDS Ni-based single crystal superalloy, crystal orientation, thermal fatigue, hole, crack initiation and propagation

Introduction

Single crystal superalloy blades are critical hot-section components in advanced aero-engines and industrial gas turbines. To meet the continuously increasing inlet temperature requirements [?, ?], researchers have investigated various approaches to enhance blade temperature capability, including improvements in blade materials, cooling structures, and coatings [?, ?]. Thin-walled multi-hole structures represent a typical feature of advanced aero-engine and industrial gas turbine blades [?, ?]. Since thermal fatigue cracks readily initiate around film cooling holes in single crystal superalloy blades, leading to blade failure [?], studying crack initiation and propagation around holes during thermal fatigue cycling provides a theoretical foundation for blade structural design and manufacturing process optimization.

Currently, thermal fatigue experiments primarily employ traditional notched specimens [?]. Generally, cracks in polycrystalline superalloys tend to propagate along grain boundaries [?], whereas in directionally solidified and single crystal superalloys, thermal fatigue cracks initiated at notches mostly propagate along directions approximately 45° to the directional solidification direction [?]. However, actual single crystal blades feature thin-walled structures with circular holes. Furthermore, during directional solidification of single crystal blades, only the primary orientation (solidification direction, blade axis) is controlled, while the secondary orientation (secondary dendrite direction, surface normal direction) is not. Numerous studies [?, ?] have demonstrated that the secondary orientation significantly affects tensile, creep, and fatigue properties of single crystal superalloys. The authors [?] previously investigated the effect of secondary orientation on thermal fatigue performance of third-generation Ni-based single crystal superalloy DD33 specimens with 2 mm open holes (referred to as “open holes” in this work). The results indicated that different crystallographic planes of specimen surfaces create different thermal stress states around open holes, leading to variations in crack initiation locations and propagation directions.

However, it has been reported [?] that the vast majority of blades in service contain un-notched circular holes with diameters of 0.3-1.0 mm and wall thicknesses of 0.5-4.0 mm. While studies on the effect of open holes on thermal fatigue performance have been reported, research on crack initiation and propagation behavior around un-notched circular holes during thermal cycling is scarce. Therefore, this work focuses on Ni-based single crystal superalloys, conducting thermal fatigue experiments to obtain crack initiation and propagation kinetic curves around holes in specimens with different crystallographic planes, examining crack behavior during thermal cycling, and analyzing the differences to provide a foundation for controlling secondary orientation during single crystal blade manufacturing.

Experimental Procedures

Materials and Sample Preparation

The experimental alloy was a second-generation single crystal superalloy developed by the Institute of Metal Research, Chinese Academy of Sciences, with a chemical composition (mass fraction) of Al+Ti+Ta=10%, W+Mo=9.5%. Master alloy was melted in a ZG-0.05 vacuum induction furnace, and single crystal bars with a diameter of 16 mm were directionally solidified at a withdrawal rate of 3 mm/min. The crystal orientation of the bars was determined using electron backscatter diffraction (EBSD) Channel 5 system in an S-3400N scanning electron microscope (SEM). To minimize the effect of orientation deviation, all bars used in this study had a deviation from the [001] dendrite growth direction within 3°. After full heat treatment (solution treatment: 1280 °C, 4 h, air cooling + two-stage aging: 1100 °C, 4 h, air cooling + 850 °C, 24 h, air cooling), plate specimens measuring 20 mm × 10 mm × 2 mm were machined parallel to the dendrite growth direction [001] and along either (100) or (110) planes, referred to as (100) and (110) specimens, respectively. A circular hole with a diameter of 0.5 mm was drilled at the center of each specimen perpendicular to the plate surface. To ensure hole shape and minimize taper, all holes were fabricated by electro-discharge machining. A schematic of the specimens is shown in [Figure 1: see original paper]. Five specimens were prepared for each condition and tested simultaneously.

Thermal Fatigue Testing

Thermal fatigue experiments were conducted according to the aviation industry standard HB6660-92. The maximum test temperature was 1100 °C with a furnace temperature error of ± 3 °C. After every 20 cycles, the specimen surfaces were mechanically ground and polished, and crack lengths were measured using the surface crack method. The reported crack length values represent the average of 10 measurements taken on both sides of five specimens. After measurement, thermal fatigue testing was resumed, and crack propagation kinetic curves were plotted. An AXIO Vert.A1 optical microscope (OM) and an S-3400N SEM equipped with INCA X-sight energy dispersive spectroscopy (EDS) were used for microstructural observation after each interruption.

Results

Microstructure and Recast Layer

The microstructure of the Ni-based single crystal superalloy after heat treatment is shown in [Figure 2: see original paper]. The fully heat-treated microstructure exhibits no residual eutectic, with regularly arranged cubic γ phases distributed in the γ matrix. The microstructure around the hole is presented in [Figure 3: see original paper]. The EDM-drilled holes are relatively round with uniform surrounding microstructure, and a thin recast layer is observed locally ([Figure

3a: see original paper]), reaching a maximum thickness of approximately 15 mm ([Figure 3b: see original paper]).

Crack Growth Kinetics

Crack propagation kinetic curves around holes in (100) and (110) specimens are shown in [Figure 4: see original paper]. The crack growth behavior differs significantly between the two specimen orientations. In (110) specimens, cracks initiated around the hole after 80 cycles and propagated rapidly with continued thermal fatigue testing. After 200 thermal cycles, crack length around the hole in (110) specimens exceeded 2 mm. In contrast, no cracks were observed around holes in (100) specimens even after 200 cycles.

Crack Initiation and Propagation Behavior

The holes in specimens with different crystallographic planes before thermal fatigue testing are shown in [Figure 5a: see original paper] and [Figure 5b: see original paper]. The holes exhibit good roundness, smooth surfaces, and uniform dimensions, with no obvious differences in the microstructure around holes between the two specimen types. However, distinct differences emerged during thermal cycling. After 80 thermal cycles, (100) specimens developed a uniform, dense oxide layer approximately 100 nm thick around the hole edge ([Figure 5c: see original paper]). After 120 cycles, the oxide layer thickness increased to about 150 nm, with no cracks observed at the hole edge ([Figure 5e: see original paper]).

In contrast, (110) specimens behaved differently. After 80 thermal cycles, a uniform dense oxide layer approximately 100 nm thick formed at the hole edge, but the oxide layer cracked locally. In all specimens, the dendrite growth direction was along the [001] direction indicated in the figures. Statistical analysis revealed that cracks initiated at the hole edge perpendicular to the dendrite growth direction ([Figure 5d: see original paper]). Once initiated, cracks propagated rapidly along directions approximately 45° to the dendrite growth direction. After 120 cycles, crack length at the hole edge exceeded 2 mm ([Figure 5f: see original paper]).

Discussion

Thermal fatigue processes are primarily influenced by high-temperature oxidation, thermal stress, and microstructure [?]. Research has shown that crack initiation life is longer in vacuum, while in atmospheric conditions, high-temperature oxidation significantly shortens crack initiation life. Oxidation behavior is mainly related to alloy composition. Since both specimen groups in this work had identical compositions and equivalent oxidation levels, the effect of high-temperature oxidation can be neglected. Microstructure also significantly affects crack propagation. In polycrystalline superalloys, thermal fatigue cracks readily propagate along grain boundaries, with carbides and

residual eutectic serving as primary crack paths. In single crystal alloys, the elimination of grain boundaries results in slower thermal fatigue crack propagation rates compared to polycrystalline alloys [?].

Thermal stress σ depends primarily on notch geometry, elastic modulus, and temperature difference [?], and can be expressed as [?]:

where K is the constraint coefficient, α is the thermal expansion coefficient, E is the elastic modulus, and ΔT is the temperature difference. The constraint coefficient K is mainly affected by notch geometry and curvature radius. Under identical thermal cycling conditions, smaller notch radii produce greater stress concentration at the notch tip, facilitating crack initiation [?]. In this study, both specimen groups had identical external dimensions, notch shapes, and curvature radii, resulting in the same constraint coefficient. The difference in thermal expansion coefficients between orientations is small [?]. With increasing maximum temperature and holding time, thermal fatigue crack propagation rates increase, but when temperature and holding time reach certain levels, the crack propagation rate decreases [?]. In this work, both specimen groups were tested under identical conditions from room temperature to 1100 °C with the same holding time, resulting in the same temperature difference. However, due to different crystallographic planes and the anisotropic nature of single crystal alloys, the elastic modulus E varies significantly between orientations, thereby affecting thermal stress. The typical elastic modulus ratio for different orientations in single crystal superalloys is approximately $E_{\langle 001 \rangle} : E_{\langle 011 \rangle} : E_{\langle 111 \rangle} \approx 1 : 1.7 : 2$ [?]. Consequently, the thermal stress ratio between different orientations is approximately $\sigma_{\langle 001 \rangle} : \sigma_{\langle 011 \rangle} : \sigma_{\langle 111 \rangle} \approx 1 : 1.7 : 2$. According to the Tresca yield criterion, the thermal stresses at the hole edge perpendicular to the dendrite growth direction for the two specimen types are: $\sigma_{\langle 100 \rangle} = \sigma_{max} - \sigma_{min} = \sigma_{\langle 001 \rangle} - \sigma_{\langle 001 \rangle} = 0$ (where σ_{max} is the maximum principal stress and σ_{min} is the minimum principal stress at a point on the hole edge), while $\sigma_{\langle 110 \rangle} = \sigma_{max} - \sigma_{min} = \sigma_{\langle 011 \rangle} - \sigma_{\langle 001 \rangle} = 0.7\sigma_{\langle 001 \rangle}$. Clearly, (110) specimens experience greater thermal stress than (100) specimens, leading to earlier crack initiation during thermal cycling.

In this alloy, thermal fatigue cracks primarily form through oxidation ([Figure 5d: see original paper]). EDS analysis revealed that the crack surface is enriched in O, Al, Cr, and Ni. During oxidation, an oxide film forms on the surface. Due to the different thermal expansion coefficients between the oxide film and the substrate alloy [?], the oxide film easily spalls from the alloy surface during thermal cycling. Simultaneously, oxide film formation consumes Al from the substrate, reducing the Al content near the oxide layer and decreasing the γ phase volume fraction around the hole, thereby weakening the local alloy strength. The combination of reduced alloy strength around the hole and non-uniform thermal stress distribution leads to crack initiation at locations with relatively high thermal stress.

In this single crystal alloy, crack propagation exhibits a preferred orientation approximately 45° to the dendrite growth direction, as shown in [Figure 5f:

see original paper]. This occurs because Ni-based superalloys have an FCC structure where $\{111\}$ planes are close-packed and $\langle 110 \rangle$ directions are the close-packed directions within $\{111\}$ planes. In this study, the thermal fatigue crack propagation direction $\langle 110 \rangle$ corresponds to the maximum shear stress direction, facilitating crack extension due to higher resolved shear stress. Unlike most previous studies, the cracks in this work propagated straight without changing direction or branching, indicating minimal microstructural influence on crack propagation. Compared with results from specimens containing 2 mm open holes, although both studies show faster crack initiation and propagation in (110) specimens, differences in notch geometry (hole diameter and shape) cause significant variations in crack propagation direction even for specimens on the same crystallographic plane. For (110) specimens with 2 mm open holes, cracks approximately 200 μm long initiated at the hole edge perpendicular to the dendrite growth direction after 40 thermal cycles and subsequently propagated along the dendrite growth direction [?]. In contrast, for (110) specimens with 0.5 mm closed holes, cracks nearly 200 μm long initiated at the hole edge perpendicular to the dendrite growth direction after 80 cycles and propagated along directions 45° to the dendrite growth direction. This difference may arise because oxide layers form at the hole edge during thermal cycling and thicken with continued testing. Due to different thermal expansion coefficients between the oxide layer and substrate [?], rapid temperature changes generate deformation mismatch that promotes crack initiation. During propagation, cracks more readily extend along carbides or residual eutectic at dendrite boundaries [?, ?]. The dendrite spacing in the single crystal superalloy used in this study is approximately 300 μm . The 0.5 mm hole affects a region of about 1-2 dendrites, while a 2 mm open hole affects approximately 7-8 dendrites. Therefore, microstructural effects must be considered. For 2 mm open holes encompassing multiple dendrites, cracks preferentially propagate along interdendritic regions, resulting in propagation parallel to the dendrite growth direction. For 0.5 mm holes existing within only 1-2 dendrites with uniform microstructure, cracks tend to propagate along specific crystallographic directions. Since Ni-based alloys have an FCC structure with 011 slip systems, cracks preferentially extend along the maximum shear stress direction—the $\langle 110 \rangle$ direction [?]. For (100) specimens, those with 2 mm open holes developed cracks at the hole edge 45° to the dendrite growth direction after 80 cycles, which propagated rapidly along this direction, reaching approximately 1 mm after 200 cycles. However, (100) specimens with 0.5 mm holes showed no cracking even after 200 cycles. This may be attributed to different temperature change rates during thermal cycling for different hole sizes. Larger open holes experience faster temperature changes at the hole edge, creating greater temperature differences between the hole edge and substrate, thereby generating higher constraint stresses and facilitating cracking.

In summary, thermal fatigue crack initiation locations and propagation modes in single crystal superalloys are closely related not only to microstructure and notch geometry but also result from the combined effects of secondary orientation and microstructural features.

Conclusions

1. The crystallographic plane of Ni-based single crystal superalloys significantly affects crack initiation and propagation around holes during thermal cycling.
2. In (110) specimens, cracks initiated after 80 thermal cycles and subsequently propagated rapidly along directions 45° to the directional solidification direction. In contrast, (100) specimens showed no significant cracking around holes even after 200 cycles.
3. The essential reason for this difference is the combined effect of thermal stress variations caused by the anisotropic crystal structure of single crystal superalloys and microstructural characteristics.

References

- [1] He G, Li J G, Mao X M, Fu H Z. *Mater Rev*, 1994; (1): 12
- [2] Yue Z F, Yin Z Y, Yang Z G. *Aeroengine*, 1997; (4): 32
- [3] Ohyszko A, Kubiak K, Sieniawski J. *J Achievements Mater Manuf Eng*, 2009; 32(1): 66
- [4] Shah D M, Cetel A. In: Pollock T M, Kissinger R D, Bowman R R, Green K A, McLean M, Olson S, Schirra J J eds., *Superalloys 2000*, Warrendale: TMS, 2000: 295
- [5] Duhl D N, Cetel A D. US Pat, 4719080, 1988
- [6] Harris K, Wahl J B. In: Strang A, Banks W M, Conroy R D, McColvin K, Neal J C, Simpson S eds., *Proc 5th Int Charles Parsons Turbine Conf*, London: Cambridge University, 2000: 832
- [7] Walston W S, O' hara K S, Ross E W, Pollock T M, Murphy W H. In: Kissinger R D, Deye D J, Anton D L, Cetel A D, Nathal M V, Pollock T M, Woodford D A eds., *Superalloys 1996*, Warrendale: TMS, 1996: 27
- [8] Fuchs G E. *J Mater Eng Perform*, 2002; 11(1): 19
- [9] Hollwarth B R, Dagan L. *ASME J Eng Power*, 1980; 102: 994
- [10] McNally C A, Folkes J, Pashby I R. *Mater Sci Technol*, 2004; 20: 917
- [11] Kim Y J, Kim S M. *Int J Heat Mass Transfer*, 2004; 47: 245
- [12] Hou N X, Wen Z X, Du Z X, Yue Z F. *Theor Appl Fract Mech*, 2007; 47: 164
- [13] Das D K, Pollock T M. *J Mater Proc Technol*, 2009; 209: 5661
- [14] Zhou Z J, Wang L, Wen J L, Lou L H, Zhang J. *J Alloys Compd*, 2015; 628: 158

- [15] Wang J L, Chen M H, Yang L L, Zhu S L, Wang F H. *Corros Sci*, 2015; 98: 530
- [16] Alamn M Z, Satyanarayana D V V, Chatterjee D, Sarkar R, Das D K. *Mater Sci Eng*, 2015; A641: 84
- [17] Wang L, Zhou Z J, Jiang W G, Wang D, Shen J, Lou L H. *Chin J Mater Res*, 2014; 28: 663
- [18] Sabnis P A, Maziere M, Forest S, Arakere N K, Ebrahimi F. *Int J Plast*, 2012; 28: 102
- [19] Li Y L, Yuan C, Guo J T. *Acta Metall Sin*, 2006; 42: 1056
- [20] Xia P C, Yu J J, Sun X F, Guan H R, Hu Z Q. *Rare Met Mater Eng*, 2008; 37: 50
- [21] Liu Y, Yu J J, Xu Y, Sun X F. *Rare Met Mater Eng*, 2009; 38: 59
- [22] Xiao X, Xu H, Qin X Z, Guo Y A, Guo J T, Zhou L Z. *Acta Metall Sin*, 2011; 47: 1129
- [23] Liu J L, Jin T, Zhang J H, Hu Z Q. *Acta Metall Sin*, 2001; 37: 1233
- [24] Zhao N R, Wang Z H, Li J G, Jin T, Sun X F, Yang H C, Hu Z Q. *J Mater Eng*, 2008; (2): 58
- [25] Li J R, Shi Z X, Yuan H L, Liu S Z, Zhao J Q, Han M, Liu W W. *J Mater Eng*, 2008; (12): 6
- [26] Jia Y X, Jin T, Liu J L, Sun X F, Hu Z Q. *Acta Metall Sin*, 2009; 45: 1364
- [27] Hu G X, Cai X, Rong Y H. *Fundamentals of Materials Science*, 3rd Ed., Shanghai: Shanghai Jiaotong University Press, 2010: 431
- [28] Jin Z X. *Central Iron Steel Res Inst Tech Bull*, 1985; 5: 205
- [29] Academic Committee of the Superalloys, The Chinese Society for Metals. *China Superalloys Handbook*, Beijing: Standards Press of China, 2012
- [30] Chao J, Gonzalez-Carrasco J L. *Mater Sci Eng*, 1997; A230: 39

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.