Effect of Notch Orientation and Recrystallization on Thermal Fatigue Performance of a Directionally Solidified Cobalt-Based Superalloy (Postprint)

Authors: Pu Sheng, Wang Li, Xie Guang, Ding Xianfei, Lou Langhong, Feng Qiang

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

Abstract

In directionally solidified cobalt-based superalloys, plate-type thermal fatigue specimens with V-notches oriented both perpendicular and parallel to the solidification direction were employed, and recrystallized microstructure was pre-introduced at the notch locations. The influence of notch orientation and recrystallization on the thermal fatigue performance of directionally solidified cobalt-based superalloys was investigated under thermal cycling between a maximum temperature of 1000 °C and a minimum temperature of room temperature. The results show that when the notch orientation is perpendicular to the solidification direction, the matrix undergoes cyclic oxidation cracking under stress; when the notch is parallel to the solidification direction, the thermal fatigue performance deteriorates, with cracks propagating along interdendritic regions. Recrystallization degrades the thermal fatigue performance of directionally solidified cobalt-based superalloys; recrystallized grain boundaries undergo oxidation cracking, and voids formed by the oxidative spalling of M23C6-type carbides precipitated at grain boundaries accelerate crack propagation; recrystallized grain boundaries connecting interdendritic carbides become preferential propagation channels for thermal fatigue cracks when the notch is parallel to the solidification direction.

Full Text

Preamble

Acta Metallurgica Sinica, Vol. 51, No. 4, April 2015, pp. 449-457

Effect of Notch Orientation and Local Recrystallization on Thermal Fatigue Properties of a Directionally Solidified Co-Based Superalloy

PU Sheng[1,2], WANG Li[2,3], XIE Guang[2,3], DING Xianfei[4], LOU Langhong[2], FENG Qiang[1,4]

[1] State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, China
[2] Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China
[3] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China
[4] National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing 100083, China

Correspondent: FENG Qiang, professor, Tel: (010)82375850, E-mail: qfeng@skl.ustb.edu.cn

Supported by: National Basic Research Program of China (No. 2010CB631201), High Technology Research and Development Program of China (No. 2012AA03A513), National Natural Science Foundation of China (No. 50901079), and Supporting Technology Program of Chinese Ministry of Education (No. 625010337)

Manuscript received: 2014-08-01, in revised form 2014-12-10

Abstract

Directionally solidified (DS) Co-based superalloys are widely used in aircraft turbine vanes due to their good stress-rupture parameters and excellent hot corrosion resistance. During service, these vanes experience frequent thermal fatigue (TF) cracking caused by cyclic temperature changes and complex stress states. However, most research has focused on Ni-based superalloys, with limited reports on the TF behavior of DS Co-based alloys. Furthermore, due to residual strain accumulated during processing operations such as shot peening and grinding, recrystallization (RX) frequently occurs when DS components are exposed to high temperatures. Recrystallization is believed to alter the microstructure, particularly by introducing additional grain boundaries into DS alloys, thereby reducing their mechanical properties.

In this work, V-notch plate specimens with notch directions both perpendicular and parallel to the DS orientation were machined from DS plates. Local RX grains were prepared in the notch areas of some samples through local indentation followed by heat treatment. TF tests were conducted between 1000 °C and room temperature to investigate the effects of DS orientation and RX on the TF properties of a DS Co-based superalloy. The results indicate that cracks propagate along interdendritic regions in samples with notches parallel to the

DS direction, which exhibit lower TF properties than samples with notches perpendicular to the DS direction. In samples containing RX grains, TF cracks initiate and propagate along RX boundaries. Precipitation of M23C6 carbides occurs along RX boundaries during TF testing. Due to oxidation at the crack tip, M23C6 carbides desquamate, leading to the formation of microvoids that accelerate crack propagation and degrade TF properties. In samples with notches parallel to the DS direction, cracks preferentially propagate along RX grain boundaries that connect interdendritic carbides.

Keywords: notch orientation, recrystallization, thermal fatigue, directional solidification, Co-based superalloy

---

Introduction

Cobalt-based superalloys exhibit excellent high-temperature corrosion resistance, good thermal conductivity, and low thermal expansion coefficients, making them suitable for manufacturing high-temperature guide vanes in aero-engines. During service, guide vanes operate at temperatures approximately 100 °C higher than turbine blades. The repeated temperature changes during engine start-up, shutdown, or afterburning subject guide vanes to severe thermal loads and thermal shocks. Cyclic variations in thermal stress and strain readily generate thermal fatigue cracks in vanes, leading to engine failure. Consequently, thermal fatigue performance represents a critical metric for evaluating guide vane materials.

The factors influencing thermal fatigue performance in superalloys are complex, and the underlying mechanisms are closely related to alloy type. Studies have shown that polycrystalline alloys generally crack along grain boundaries, but as grain size increases, thermal fatigue cracks transition to a transgranular propagation mode with reduced growth rates, thereby improving thermal fatigue performance. For directionally solidified Ni-based superalloys, V-notch specimens perpendicular to the DS direction are typically used to investigate thermal fatigue behavior, with cracks propagating primarily along crystallographic orientations or maximum shear stress directions. Carbides, eutectic phases, and even rafted γ phases can serve as crack initiation sites or promote crack propagation.

Xiao et al. studied DZ445 alloy using specimens with notches parallel to the solidification direction and found that thermal fatigue cracks mainly propagated along interdendritic regions; however, increasing the maximum test temperature caused cracks to switch to crystallographic orientation propagation. These findings demonstrate that both notch orientation and microstructure significantly influence thermal fatigue crack morphology in DS superalloys. Currently, most thermal fatigue research focuses on Ni-based alloys, with very limited studies on Co-based alloys, and no reports exist on the effect of notch orientation on thermal fatigue behavior in DS Co-based superalloys.

Additionally, plastic deformation accumulated during casting, core constraint, machining, straightening, and shot blasting operations can cause DS superalloy blades to recrystallize during solution heat treatment or ultra-high temperature service. Research has shown that recrystallization, as a defective microstructure, severely compromises the microstructural integrity of DS superalloys and significantly reduces their high-temperature tensile, creep, and fatigue properties. However, studies on the influence of recrystallized microstructures on thermal fatigue performance and the associated mechanisms in DS superalloys remain scarce.

Based on this background, the present work investigates a DS Co-based superalloy suitable for guide vane applications. Using V-notch specimens with orientations both perpendicular and parallel to the solidification direction, and with pre-fabricated recrystallized microstructures at the notch locations, we examine the effects of notch orientation and recrystallization on thermal fatigue performance. By observing crack propagation morphology and analyzing the failure mechanisms, this study provides theoretical references and experimental evidence for the processing and engineering application of this alloy in vane components.

---

1. Experimental Methods

The DS Co-based superalloy used in this study had a nominal composition (wt.%) of: Cr 25, Ni 10, W 7.5, Al 1.2, C 0.45, Ta 0.4, Mo 0.35, Ti 0.3, Zr 0.25, B 0.018, with Co as balance. DS plates were prepared by the high-rate solidification (HRS) method. Two groups of plate specimens measuring 25 mm × 17 mm × 3 mm were cut by wire electrical discharge machining, with the long edges oriented perpendicular and parallel to the DS direction, respectively.

Local deformation was introduced at the midpoint of the short edge (approximately 3 mm from the edge) on both sides of each plate using an HB-3000 Brinell hardness tester with a 5 mm diameter indenter under a load of 1250 kgf. The deformed plates were then heat-treated at 1250 °C for 90 min and air-cooled. Based on previous experiments, this treatment produces a recrystallized region approximately 2 mm in radius through the 3 mm thickness. After grinding both surfaces to remove indentations, standard thermal fatigue specimens were machined with the V-notch centered at the indentation location, as shown in [Figure 1: see original paper]. Specimens with V-notches perpendicular to the DS direction are referred to as transverse samples ([Figure 1: see original paper]a), while those with notches parallel to the DS direction are longitudinal samples ([Figure 1: see original paper]b). To evaluate the effect of recrystallization, transverse and longitudinal samples without plastic deformation were also prepared and subjected to the same heat treatment (1250 °C, 90 min, air-cooled). Five specimens were tested for each of the four conditions. All samples were mechanically polished and examined under an optical microscope to ensure no pre-existing cracks near the notch.

Thermal fatigue testing was conducted in a box furnace with a cycle consisting of heating to 1000 °C, holding for 3 min, then water quenching to room temperature. After multiple thermal cycles, each specimen typically developed multiple cracks. At predetermined cycle intervals, specimens were mechanically ground, polished, and etched, and the main crack length was measured using a reading microscope. The main crack, which appeared at the notch location, was coarser and longer than other cracks. Reported crack lengths represent averages from 10 surfaces (both sides of 5 specimens) under identical conditions.

Microstructural characterization and crack morphology observation were performed using an Axiovert200MAT optical microscope (OM) and an S-3400N scanning electron microscope (SEM) with backscattered electron (BSE) imaging. Energy dispersive spectroscopy (EDS) analysis was conducted, and phase identification was performed using an XRD6000 X-ray diffractometer (XRD). The etchant used was 4 g $CuSO_4$ + 80 mL HCl + 20 mL C_2H_5OH.

---

2. Results

2.1 As-Cast and Recrystallized Microstructures

[Figure 2: see original paper] shows the as-cast microstructure of the DS Co-based superalloy. The alloy grew along the <001> direction, with primary dendrite arms parallel to the DS direction. Numerous carbides were distributed along columnar grain boundaries and interdendritic regions. [Figure 3: see original paper] presents SEM and BSE images of the carbides. The alloy contained three types of carbides: blocky and irregular M_7C_3 and MC carbides, with fine $M_{23}C_6$ carbides dispersed around these primary carbides. Cr-rich M_7C_3 carbides exhibited lower brightness, while MC carbides containing heavy elements (Ta, Ti, Zr, W) appeared brighter, as shown in [Figure 3: see original paper]b. [Figure 4: see original paper] shows EDS analysis of the M_7C_3 and MC carbides. Statistical analysis revealed a primary dendrite spacing of approximately 242 m and a total carbide content of about 7.3%.

XRD analysis of extracted carbides from as-cast DS Co-based superalloy after annealing at 1250 °C for 90 min confirmed that both M_7C_3 and MC carbides remained ([Figure 5: see original paper]). [Figure 6: see original paper] shows microstructures of as-cast and indented-deformed alloys after annealing at 1250 °C for 90 min. In the as-cast sample after annealing, fine $M_{23}C_6$ carbides nearly completely dissolved, while irregular M_7C_3 carbides evolved into blocky morphologies. MC carbides, containing high-melting-point elements, dissolved more slowly and retained their fine strip-like morphology ([Figure 6: see original paper]a). In the indented sample, the deformed region underwent complete recrystallization with relatively straight RX grain boundaries. $M_{23}C_6$ carbides also nearly completely dissolved, while some residual M_7C_3 and MC carbides remained distributed along grain boundaries ([Figure 6: see original paper]b). Carbide content measurements indicated that after annealing at 1250 °C, the carbide volume fraction decreased to approximately 2.1% in as-cast samples and about 2.0% in recrystallized regions, showing no significant difference.

2.2 Crack Propagation Behavior

During water quenching from high temperature, the V-notched region in DS Co-based superalloy specimens experienced contraction, generating stress concentration at the notch tip. After multiple thermal cycles, all four specimen groups (with and without RX, in both transverse and longitudinal orientations) developed varying degrees of thermal fatigue cracking. [Figure 7: see original paper] shows the relationship between average main crack length (L) and thermal cycle number (N). After 5 cycles, all four groups remained intact. At 15 cycles, transverse and longitudinal samples without RX remained crack-free, while both RX-containing groups had cracked. By 30 cycles, transverse and longitudinal samples without RX also developed cracks. With increasing cycle number, crack lengths in all four groups increased significantly.

Within 75 cycles, the longest main crack propagation occurred in longitudinal samples with RX, followed by longitudinal samples without RX, then transverse samples with RX, with transverse samples without RX showing the shortest cracks. Further analysis revealed that after 75 cycles, the average crack length in longitudinal samples with RX reached 1.70 mm, approximately 2.8 times that of transverse samples with RX. In samples without RX, longitudinal specimens had an average crack length of 1.14 mm, 4.4 times greater than transverse specimens (0.26 mm). Additionally, transverse samples with and without RX reached average crack lengths of 0.61 mm and 0.26 mm, respectively. Under identical cycle numbers, the presence of RX also increased crack length and propagation rate in longitudinal samples. Notably, both longitudinal groups consistently showed greater crack lengths and propagation rates than the two transverse groups. These results demonstrate that thermal fatigue performance is always superior when the notch orientation is perpendicular to the solidification direction, and this trend persists even with recrystallization. Under the same orientation, recrystallization significantly accelerates crack propagation and degrades thermal fatigue performance.

2.3 Crack Morphology

[Figure 8: see original paper]a shows thermal fatigue crack morphology in a transverse DS Co-based superalloy sample without RX after 30 thermal cycles. Two cracks were present at the notch: a shorter crack perpendicular to the primary dendrite direction (normal to the principal stress direction) and another crack at 45° to the primary dendrite growth direction, propagating along the maximum shear stress direction. After 75 cycles, the crack along the maximum shear stress direction grew slowly, while the crack perpendicular to the primary dendrites extended inward with increased width, becoming the main crack ([Figure 8: see original paper]b). SEM observation of the main crack front revealed that the crack terminated in the alloy matrix ([Figure 9: see original paper]a). EDS analysis showed high oxygen content near the crack tip, indicating oxidation of the matrix ahead of the crack ([Figure 9: see original paper]b).

[Figure 10: see original paper]a shows crack propagation morphology in a transverse DS Co-based superalloy with RX after 15 thermal cycles. Unlike matrix cracking in transverse samples without RX ([Figure 9: see original paper]a), RX grain boundaries at the notch tip cracked and propagated along the grain boundaries. After 75 cycles, multiple cracks appeared at the notch with branching during propagation, though the main propagation directions generally aligned with the principal stress and maximum shear stress directions ([Figure 10: see original paper]b). The longest crack extended along the principal stress direction (perpendicular to primary dendrites). SEM imaging ([Figure 10: see original paper]c) revealed numerous nanosized $M_{23}C_6$ secondary carbides precipitated within RX grains. Thermal fatigue cracks propagated along RX grain boundaries, with $M_{23}C_6$-depleted zones near the crack path. Blocky carbides on grain boundaries cracked and underwent severe oxidation. [Figure 10: see original paper]d shows $M_{23}C_6$ secondary carbides precipitated along RX grain boundaries; however, at the crack front, previously precipitated $M_{23}C_6$ carbides detached, pre-forming intergranular voids that accelerated crack propagation.

[Figure 11: see original paper]a shows crack propagation morphology in a longitudinal DS Co-based superalloy without RX after 30 thermal cycles. Cracks initiated in interdendritic regions at the notch tip. After 75 cycles, the main crack morphology confirmed propagation along interdendritic regions ([Figure 11: see original paper]b). [Figure 11: see original paper]c presents an SEM image of the main crack front, showing large blocky M_7C_3 carbides and smaller strip-like MC carbides. Primary carbides were densely distributed along the crack path, and during propagation, interfacial decohesion between primary carbides and the matrix caused carbide detachment, leaving voids that arrested crack growth near MC carbides.

[Figure 12: see original paper] shows crack initiation, propagation, and carbide morphology near cracks in longitudinal DS Co-based superalloy with RX. After 15 thermal cycles, stress concentration at the V-notch tip caused cracking of nearby RX grain boundaries, with carbide cracking on grain boundaries promoting crack propagation ([Figure 12: see original paper]a). After 75 cycles, the main crack extended from the notch into the specimen interior, parallel to the primary dendrite direction ([Figure 12: see original paper]b). [Figure 12: see original paper]c shows an SEM image of the main crack front, revealing that the main crack propagated from left to right along RX grain boundaries. At triple junctions, secondary cracks formed along RX grain boundaries approximately parallel to the principal stress direction, making propagation difficult and arresting at carbide-matrix interfaces. Additionally, carbides on grain boundaries exhibited interfacial cracking under the influence of the main crack stress field, and larger carbides impeded crack propagation.

3. Discussion

3.1 Effect of Notch Orientation on Thermal Fatigue Performance

Research on notch orientation effects in DS superalloys is limited. Previous studies on Ni-based alloy DZ22 reported that thermal fatigue performance decreased significantly when the angle between notch direction and solidification direction was less than 45°. Robert and Richard found that DS Ni-based alloys exhibited superior thermomechanical fatigue life when notches were perpendicular to the solidification direction, while cracks propagated along columnar grain boundaries near the notch when oriented parallel to the solidification direction. Similar behavior was observed in the present study. The alloy' s columnar grain boundaries and interdendritic regions contained numerous blocky MC and M_7C_3 carbides ([Figure 6: see original paper]a), which served as crack initiation and propagation paths ([Figure 11: see original paper]a and b). However, when the notch was perpendicular to the solidification direction ([Figure 8: see original paper]b), cracks propagated through dense dendrite cores perpendicular to the principal stress direction, being less influenced by microstructural features. This fundamental difference in failure mechanisms explains the performance variation between the two notch orientations.

Xia et al. observed that in Ni-based alloy DZ319, cracks propagated by linking oxidized voids through dense dendrite cores. In contrast, the present work on Co-based alloy with notches perpendicular to the solidification direction ([Figure 8: see original paper]b) showed oxidation near cracks but no oxidized voids ahead of the crack front ([Figure 9: see original paper]a), possibly due to the excellent oxidation resistance of Co-based alloys. Studies have shown that static oxidation products on Co-based alloys below 1000 °C consist primarily of continuous, dense CoO and Cr_2O_3 layers. In the present work, under severe temperature fluctuations and stress concentration at the V-notch, brittle oxide films fractured, exposing fresh alloy surfaces at the crack tip. Reuchet and Remy calculated that oxygen diffusion to the crack tip in Co-based alloys at 900 °C in air reaches saturation in only 5$×10^{-8}$ s. Kang et al. found that stress can accelerate oxygen diffusion into the alloy, exacerbating high-temperature oxidation. Simultaneously, oxidation consumption of Al, Ti, and Cr in the matrix reduces alloy strength. The combined effects result in the most severe oxidation at the V-notch, where oxide layers repeatedly form and fracture during thermal cycling. Continuous oxidation of the crack tip leads to crack initiation at the notch and propagation perpendicular to the principal stress direction, which is the primary cracking mechanism in transverse samples ([Figure 8: see original paper]).

For longitudinal samples with notches parallel to the solidification direction, microstructure significantly influences crack initiation and propagation in addition to oxidation effects. The coefficient of thermal expansion (CTE) of Co-based superalloys at 980 °C is approximately 1.7$\times10^{-5} °C^{-1}, higher than that of Cr-rich M_7C_3 or $M_{23}C_6$ carbides (1.1$\times10^{-5} °C^{-1}) and about twice that of MC carbides containing Ta, Ti, Zr, and W (0.7$\times10^{\{-5\}-0.8\times10}$\{-5\}$ °C^{-1}). Due to this CTE mismatch, carbides experience compressive stress during heating and tensile stress during cooling, reducing interfacial bonding strength between carbides and matrix. When cracks encounter carbides during propagation, the stress at the crack tip exceeds the interfacial bonding strength, causing interfacial decohesion. In DS Co-based alloys with numerous carbides distributed in interdendritic regions, crack propagation along carbide interfaces requires less energy compared to cracking through dense dendrite cores, as observed in transverse samples ([Figure 8: see original paper]). Consequently, interdendritic cracking is favored when notches are parallel to the solidification direction ([Figure 11: see original paper]b).

3.2 Effect of Recrystallization on Thermal Fatigue Performance

Generally, recrystallization severely degrades the properties of DS superalloys. Xie et al. found that in DS Ni-based superalloy DZ125L with surface recrystallization, RX grain boundaries perpendicular to the stress axis readily cracked during high-temperature creep. Zheng et al. proposed that dendrite cores are the primary load-bearing structure in DS alloys, and RX layers have extremely low load-bearing capacity. If dendrite cores are intersected by RX grain boundaries, these regions become weak links. In the present study on transverse samples, the pre-fabricated RX grains at the notch region created numerous grain boundaries intersecting dendrite cores, destroying the original columnar grain structure ([Figure 6: see original paper]b). Thermal cycling induced periodic thermal stress variations, causing cracks to initiate and propagate along RX grain boundaries ([Figure 10: see original paper]). However, [Figure 7: see original paper] shows that the crack propagation rate in recrystallized transverse samples was lower than in non-recrystallized longitudinal samples, indicating that RX grain boundaries in DS Co-based superalloys possess some load-bearing capacity.

Unlike Ni-based alloys, Co-based alloys under cyclic stress generate numerous slip bands and dislocations during thermal fatigue testing, promoting Cr segregation to slip planes and grain boundaries. This Cr reacts with C in the matrix to precipitate nanosized secondary $M_{23}C_6$ carbides in the matrix and along grain boundaries ([Figure 10: see original paper]d). The presence of RX grain boundaries facilitates $M_{23}C_6$ precipitation, which can enhance high-temperature creep strength. However, grain boundaries also exhibit high solubility and diffusivity, providing rapid diffusion paths for oxygen that reduce grain boundary strength and promote thermal fatigue crack propagation. Cr in Co-based alloys is chemically active and oxidizes readily at high temperatures. In the present experiments, oxidation-induced Cr loss from the matrix caused previously precipitated $M_{23}C_6$ carbides near cracks to redissolve, creating $M_{23}C_6$-depleted zones ([Figure 10: see original paper]c). Simultaneously, $M_{23}C_6$ carbides on RX grain boundaries at the crack front decomposed, reducing interfacial bonding and causing carbide detachment that left intergranular voids ([Figure 10: see original paper]d). Crack propagation by linking these voids reduced propagation resistance and accelerated cracking, degrading thermal fatigue performance in recrystallized transverse samples.

In the two recrystallized sample groups, longitudinal specimens with notches parallel to the solidification direction exhibited the highest crack propagation rates ([Figure 7: see original paper]), and crack morphology ([Figure 12: see original paper]b) differed significantly from transverse specimens ([Figure 10: see original paper]b). This indicates that the original microstructure substantially influences thermal fatigue performance in recrystallized samples with different notch orientations. After introducing local recrystallization, primary MC and M_7C_3 carbides became connected through RX grain boundaries ([Figure 6: see original paper]b and [Figure 11: see original paper]a), creating carbide-rich paths along certain grain boundaries. Since primary carbides distribute along interdendritic regions, these paths were approximately aligned with the solidification direction. As previously discussed, cyclic stress and strain reduce interfacial strength between carbides and matrix. Combined with oxidation-induced cracking of RX grain boundaries and detachment of secondary $M_{23}C_6$ carbides, the minimum energy principle dictates that cracks in recrystallized longitudinal samples preferentially propagate along RX grain boundaries connecting interdendritic carbides ([Figure 12: see original paper]b), resulting in the lowest thermal fatigue performance.

In summary, notch orientation and recrystallization induce different thermal fatigue damage mechanisms in DS Co-based superalloys. The performance difference between notch orientations depends on whether cracks propagate along primary carbides distributed in interdendritic regions. The two recrystallized sample groups are also affected by primary carbide distribution along the notch direction. However, [Figure 7: see original paper] shows that even recrystallized transverse samples exhibit lower crack propagation rates than non-recrystallized longitudinal samples, demonstrating that regularly aligned primary carbides along the notch direction represent a critical factor degrading thermal fatigue performance, regardless of recrystallization. Based on these results, aero-engines and ground gas turbines using DS Co-based superalloy components must consider the combined effects of stress state, alloy orientation, surface recrystallization, and operating environment. Prevention of surface recrystallization and avoidance of large angles between component loading directions and columnar grain orientations are essential.

---

4. Conclusions

1. Within 75 thermal cycles, recrystallized longitudinal specimens of DS Co-based superalloy exhibited the longest main crack propagation, followed by non-recrystallized longitudinal specimens, then recrystallized transverse

specimens, with non-recrystallized transverse specimens showing the shortest cracks.

2. When the notch orientation was perpendicular to the solidification direction, the alloy underwent cyclic oxidation cracking under stress, with cracks propagating perpendicular to the solidification direction, demonstrating excellent thermal fatigue performance. When the notch was parallel to the solidification direction, thermal fatigue cracks propagated along interdendritic regions, where primary carbides were densely distributed, resulting in inferior performance.

3. Recrystallization degraded the thermal fatigue performance of DS Co-based superalloy through oxidation cracking along RX grain boundaries. During thermal fatigue, $M_{23}C_6$ carbides precipitated along grain boundaries and their oxidative detachment created voids that accelerated crack propagation. RX grain boundaries connecting interdendritic carbides served as preferential crack propagation paths when notches were parallel to the solidification direction.

References

[1] Badger F S. J Met, 1958; 10: 512
[2] Ratna V, Sarma D S. Scr Metall, 1993; 29: 467
[3] Glover N E, Davis C L. Scr Metall, 1996; 34: 675
[4] Li Y L, Yuan C, Guo J T. Acta Metall Sin, 2006; 42: 1056
[5] Beck C G, Santhanam A T. Scr Metall, 1978; 12: 255
[6] Bhattachar V S. Int J Fatigue, 1995; 17: 407
[7] Woodford D A, Mowbray D F. Mater Sci Eng, 1974; A16: 5
[8] Xia P C, Yu J J, Sun X F, Guan H R, Hu Z Q. Rare Met Mater Eng, 2008; 37: 50
[9] Reuchet J, Remy L. Mater Sci Eng, 1983; A58: 19
[10] Miao J S, Pollock T M, Jones J W. Acta Mater, 2009; 57: 5964
[11] Pedron J P, Pineau A. Mater Sci Eng, 1982; 56: 143
[12] Xiao X, Xu H, Qing X Z, Guo Y A, Guo J T, Zhou L Z. Acta Metall Sin, 2011; 47: 129
[13] Xia P C, Yu J J, Sun X F, Guan H R, Hu Z Q. Rare Met Mater Eng, 2011; 40: 152
[14] Panwisawas C, Mathur H, Gebelin J, Putman D, Rae C M F, Reed R C. Acta Mater, 2013; 61: 51
[15] Wang L, Pyczak F, Zhang J, Lou L H, Singer R F. Mater Sci Eng, 2012; A532: 487
[16] Xie G, Wang L, Zhang J, Lou L H. Metall Mater Trans, 2008; 39A: 206
[17] Khan T, Caron P, Nakagawa Y G. J Met, 1986; 38: 16
[18] Pu S, Zhang J, Shen Y F, Lou L H. Mater Sci Eng, 2008; A480:
[19] Guo X F, Wang H Q. Aeronaut Mater, 1984; (6): 1

[20] Robert A K, Richard W N. Int J Fatigue, 2010; 32: 1330
[21] Xia P C, Yang L, Yu J J, Sun X F, Guan H R, Hu Z Q. Rare Met, 2011; 30(special issue): 472
[22] Liu P S, Chen G F, Liang K M. J Chin Soc Corros Prot, 1999; 19: 339
[23] Reuchet J, Remy L. Mater Sci Eng, 1983; A58: 19
[24] Kang B, Liu X B, Cisloiu C, Chang K M. Mater Sci Eng, 2003; A347: 205
[25] Brandes E A, Brook G B. Smithells Metals Reference Book. 7th Ed., London: Butterworths Press, 1992: 11
[26] Chen K Y, Zhao L R. J Phys Chem Sol, 2007; 68: 1805
[27] Zheng Y R, Ruan Z C, Wang S C. Acta Metall Sin, 1995; 31(suppl): 325
[28] Lu Z, Lu L, Xu Y B, Hu Z Q. Fatigue Fract Eng Mater Struct, 1998; 21: 1589
[29] Jiang W H, Yao X D, Guan H R. Mater Sci Eng, 1999; A271: 101
[30] He L Z, Zheng Q, Sun X F. Mater Sci Eng, 2005; A397: 297
[31] Mishin Y, Herzig C. Mater Sci Eng, 1999; A260: 55
[32] Parthasarathy T A, Shewmon P G. Scr Metall, 1983; 17: 943

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