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Critical Assessment: oxygen-assisted fatigue crack propagation in turbine disc superalloys

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Abstract: Ni-based superalloys in turbine disc applications face increasing susceptibility to oxygen-assisted fatigue crack propagation due to increased turbine entry temperatures. The continued lack of understanding of the interplay between the factors operating during oxygen-assisted fatigue crack propagation limits: (1) development of lifing methodologies to accurately predict the fatigue performance of disc alloys/components and (2) associated disc alloy developments. An underpinning requirement to better understand the role of oxygen is to characterise the process of oxygen diffusion in the localised stress/strain state at the crack tip, which is related closely to microstructural features. The link between three-dimensional crack tomography, crack propagation rate and oxygen-related attack needs to be established. Quantitative models which include the interaction between fatigue-creep-oxygen attack need further development.

Keywords: Ni-based superalloys, oxidation, dynamic embrittlement, crack tip, localised deformation

Introduction

Ni-based superalloys are used widely for aeroengine turbine disc applications due to their good mechanical properties at elevated temperatures, exceptional oxidation and corrosion resistance as well as their processing versatility [1-9]. Amongst all of these properties, the mechanical properties, i.e. tensile strength at elevated temperatures, fatigue and creep resistance, have been studied extensively. In the past 60 years, considerable efforts have been made to improve the fatigue and creep resistance, and important improvements in fatigue and creep performance have been achieved by appropriate compositional design [3, 4] and microstructure modification in disc alloys [10-15]. In addition, by applying a dual microstructure heat treatment, the microstructures across the whole disc section can be tailored to optimise the fatigue-creep performance [7, 11, 16]. Although achievements in improving fatigue-creep performance of disc alloys have been significant, the resistance to oxidation or oxygen-related attack/embrittlement has received less attention, and is now a major limitation to application of disc alloys at the higher temperatures now required. Increases in the turbine entry temperature are needed to improve engine efficiency and reduce greenhouse gas emissions, so turbine disc alloys are increasingly being pushed to work at higher temperatures [1]. This temperature increase usually causes greater susceptibility to accelerated, environmentally related cracking [17-22], especially during the take-off and landing stages of a duty cycle in an aeroengine. Thus, fatigue failure processes with environmental attack, particularly in oxygen-containing environments, should be evaluated thoroughly. This will provide a basis for further disc alloy development to allow trade-offs between required mechanical properties and resistance to environmental attack and development of appropriate lifing philosophies for disc alloys and components.

Oxygen-assisted fatigue crack propagation

Oxygen-assisted fatigue crack propagation (FCP) is commonly observed in disc superalloys and is indicated by increased crack propagation rates, especially under dwell-fatigue conditions [6, 17, 21-23]. In general, oxygen-assisted FCP is a function of temperature [22, 24], oxygen partial pressure [17], composition [9, 25], microstructure of the disc alloys [15, 22, 26], and loading frequency [27, 28]. As shown in Fig.1, the FCP rates in 4 advanced disc superalloys (i.e. N18 [9, 21], U720Li [5], RR1000 [5] and LSHR [9, 22]) in air are usually one order of magnitude higher than that in vacuum under the same loading conditions. The microstructural characteristics of these 4 disc superalloys are summarised in Table 1. Enhanced crack propagation is usually associated with intergranular fracture features, which can be seen clearly in Fig. 2. Although creep damage is claimed to be partially responsible for these accelerated FCP processes and creep damage may also result in intergranular fracture [19, 23, 29], the creep effect can be distinguished from the oxidation effect by conducting fatigue tests in vacuum or low oxidation conditions under different loading wave-forms and frequencies [21, 22]. As shown in Fig. 1, where there is no apparent increase in FCP rate due to a 20s dwell at the peak load in vacuum, it appears that the creep effect on FCP processes is much less significant compared with the effects of oxygen attack. The oxygen-assisted FCP is related to temperature and alloy composition and microstructure. The discrepancies in resistance to oxygen-assisted FCP among different materials are more significant at higher temperature, as shown in Fig. 1. In addition, oxygen-assisted FCP is related closely to the localised deformation at the crack tips which is linked strongly to the crack tip microstructure [18, 20, 30-33]. As shown in Fig. 2, a transition from intergranular to mixed-inter-transgranular crack propagation is seen at 650 ^{o}C with a 20s dwell at the peak load as the stress intensity range (ΔK) increases. Moreover, a transition from intergranular to transgranular crack propagation is observed when a shorter dwell (1s) was applied at the peak load as reported in [22], and this transition is more likely to occur in disc superalloys with coarser microstructures. It appears that the sensitivity to oxygen attack may depend strongly on the interaction of the microstructure/local phase composition with the deformation mode at the crack tip.

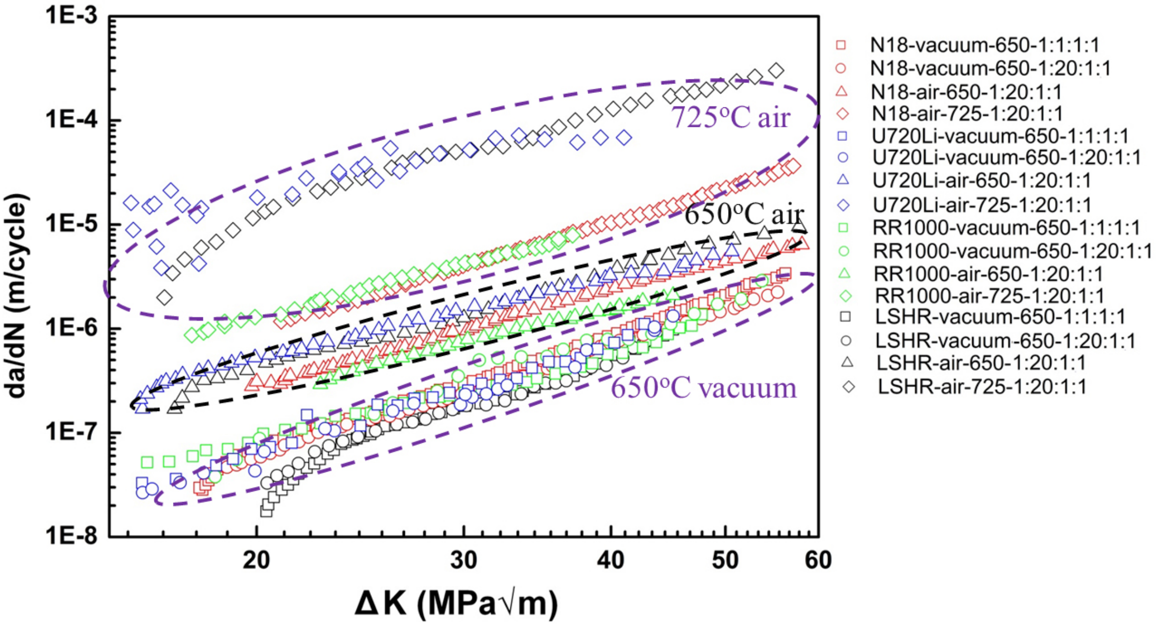

Fig. 1 Fatigue crack propagation rates in 4 advanced turbine disc superalloys [5, 9, 21, 22], where the figure legend indicates: alloy-environment-test temperature (in °C) - loading waveform (where 1:x:1:1 indicates a trapezoidal waveform: 1s ramp up, x s at maximum load, 1s ramp down and 1s at minimum load).

Table 1 Grain size and γ´ size in the disc superalloys presented in Fig.1 [5, 9, 21, 22]

	Grain size (μm)	Primary γ´ (μm)	Secondary γ´ (nm)	Tertiary γ´ (nm)
N18	8.7±4.7	2.19±0.98	188± 112	25
U720Li	6.4±1.8	1.99±0.9	102	16
RR1000	7.4±2.8	1.75±0.9	140	18
LSHR	36.1±18.1	N/A	153± 29	15

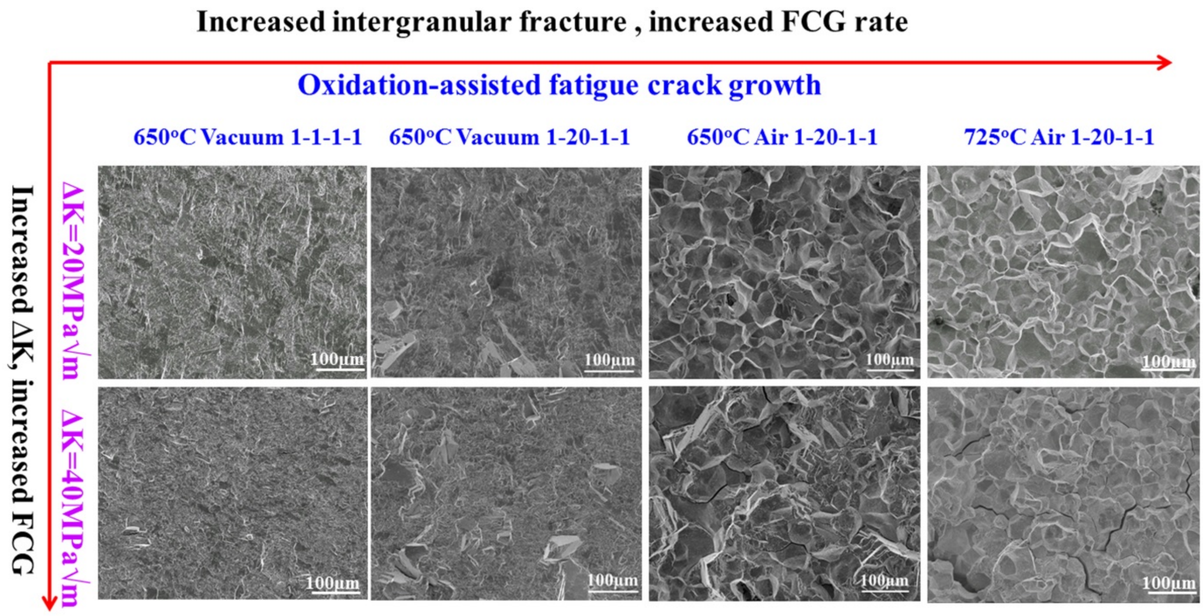

Fig. 2 Fractography of supersolvus heat treated LSHR alloy tested in vacuum and air at 650 and 725 °C using 1-1-1-1 and 1-20-1-1 loading waveform [22].

What does oxygen do at the crack tip?

Oxygen-assisted FCP is associated usually with an intergranular crack path. The mechanisms responsible for this accelerated intergranular crack propagation are mainly ascribed to stress-assisted grain boundary oxidation (SAGBO) [6, 17, 18, 20, 33-38] or dynamic embrittlement [39-42]. SAGBO is involved with *long-range* diffusion of oxygen and formation of grain boundary oxides. The role of stress is then to help accommodate the volume change for oxide formation. Crack advance is achieved by cracking the oxide/matrix interface or the oxides themselves. The dynamic embrittlement hypothesis is related to the *short range* diffusion of oxygen along grain boundaries with the assistance of local stress and reduction in boundary cohesion strength due to the segregation of oxygen. The susceptibility to cracking caused by dynamic embrittlement is shown to depend strongly on grain boundary character [42]. Moreover, gas phase embrittlement is sometimes also used to explain oxygen-assisted FCP, where oxygen attack may be regarded as arising from boundary immobilisation by oxides or gas bubbles leading to the prevention of accommodation of grain boundary sliding rather than an intrinsic reduction in grain boundary cohesion [43-45]. Although these mechanisms are reported and discussed in literature, it seems that the mechanism responsible for oxygen-assisted FCP may vary significantly from alloy to alloy and also depends on the loading conditions and rates.

Both SAGBO and dynamic embrittlement (or gas phase embrittlement) involve the diffusion of oxygen under stress/strain conditions often within the plastic zone ahead of the crack tip [37, 40, 46, 47]. Accurate measurement of oxygen diffusion ahead of the propagating crack tip is critical to quantitatively describe oxygen-assisted FCP, especially from a standpoint of simulation of this failure problem to assess the combination of the damage arising from cyclic load and oxygen attack [48, 49]. However measurement of oxygen diffusion is still a major challenge. Although oxygen isotopes (i.e. ^{18}O) have been used successfully to measure oxygen diffusion during oxidation in disc alloys with/without static load [50], the dynamic advancement of the crack tip makes it much less feasible to measure oxygen diffusion along grain boundaries and/or dislocation networks using ^{18}O. Additionally, identification of the status of oxygen existing at the crack tip may also be helpful to distinguish between the SAGBO and dynamic embrittlement mechanisms.

In terms of SAGBO, the oxides formed ahead of the crack tip vary from alloy to alloy due to the complexity of the composition of disc superalloys, although it is generally believed that layered oxides form at the crack tip with thermodynamically unstable oxides at the centre and thermodynamically stable oxide at the matrix/oxide interface [18, 20, 33, 51]. In addition, the formed oxides and oxide intrusion penetration depth ahead of the crack tip also depends on loading conditions, oxygen partial pressure, microstructures, FCP rate and more importantly local deformation at the crack tip [17, 18, 20, 37, 46]. Studies of oxidation at the propagating crack tip are still scarce, and the investigated crack tips in different materials at different ΔK levels which correspond to different FCP rates usually lead to a wide range of factors affecting the results and make the obtained results not directly comparable. This further limits the development of better understanding of the oxidation processes at the crack tip. Due to our lack of knowledge of the nature of the oxides formed ahead of the crack tip and their formation processes, it is difficult to quantitatively describe the oxidation processes ahead of the crack tip, and current models for predicting oxygen-assisted FCP fail to reflect accurately the actual physics occurring there. Oxide formation ahead of the crack tip is usually accompanied by the dissolution of γ′, particularly tertiary and secondary γ′ [20, 38, 50, 52]. Hence, this dissolution process and the diffusion of oxide-forming elements (such as Ni, Al, Ti, Cr, Co) also needs to be considered along with the segregation of these oxide-forming elements at γ/γ′ interfaces and grain boundaries. More importantly, it seems that the observed oxide intrusion penetration depth is relatively short in comparison to the crack advancing distance in each fatigue loading cycle [20, 33]. Although dynamic oxide formation and cracking may occur during crack propagation, in some cases, discrepancy between the oxide intrusion depth and crack advancing distance in a single loading cycle is so significant that it cannot be simply explained by dynamic oxide formation and cracking. Such differences may arise from significant crack branching at the crack tip during intergranular crack growth and the interlinking of the crack tip with uncracked ligaments (which are not captured by most currently employed crack detection techniques) [53, 54]. Better, systematic visualisation of the crack tip morphology in three dimensions would be helpful to reveal the discontinuity of the crack tip and to understand the true interplay between oxide intrusions and the three dimensional nature of crack advance during fast crack propagation, especially at high ΔK levels.

Crack propagation characterisation

Due to the competing mechanisms of oxygen attack and mechanical processes contributing to fatigue failure, a transition between intergranular and transgranular crack propagation occurs [6, 15, 17, 22-24]. Generally, intergranular crack propagation is observed at relatively low ΔK level, whilst transgranular crack propagation is more likely to occur at high ΔK level [22]. As crack propagation rate determines the available diffusion time (per loading cycle) of oxygen ahead of the crack tip [46], an accurate measurement of FCP rate is important to understand the kinetics of oxygen attack processes.

Conventionally, FCP rate has been measured by the direct current potential drop method, which is a measurement of the overall *averaged* crack length [55]. This method usually underestimates the crack length, especially in the case where oxygen-assisted FCP is dominant, due to crack branching at the propagating intergranular crack tip or micro-cracking processes ahead of the crack tip with interlinked uncracked ligaments [53, 54]. Therefore, the FCP rate obtained from the method may not be able to truly reflect the influence of oxygen. More accurate assessment of crack propagation will be needed in terms of the crack morphology and crack propagation rate. X-ray or synchrotron radiation computed tomography is increasingly used in material science investigations and has been used to characterise crack morphologies in three dimensions [56-59]. Although tomography can provide deeper insight into local crack propagation behaviours, crack tip stress/strain states and three dimensional crack morphology, its application to disc alloys is limited by the attenuation effects brought about by the high density of disc alloys, which restricts the observable volumes which provide an acceptable resolution. Challenges also exist in producing the appropriate environment, temperature and loading conditions within an X-ray computed tomography set-up. The grain orientation ahead of the crack tip in three dimensions can be captured by diffraction contrast computed tomography and/or phase contrast tomography [60]. Once crack tomography and grain orientation ahead of the crack tip are obtained, they can be integrated with crystal plasticity models to assess the localised strain accumulation and oxygen-assisted FCP [48, 49]. In addition, secondary cracks around crack tips can be captured with tomography, and will be helpful to assess stress redistribution at the crack tip and stress relaxation, which is also closely related to the oxidation at the crack tip and fatigue crack propagation [22, 61].

Deformation ahead of crack tip

As mentioned previously, the operation of SAGBO or dynamic embrittlement or other mechanisms is closely related to oxygen diffusion in the strain/stress field around the crack tip [6, 15, 18, 40, 43]. Oxygen transportation at the crack tip is facilitated by strain/stress [38, 50]. The variation of fracture mode (Fig. 2) with ΔK also indicates the dependence of oxygen attack on the local strain/stress state. As outlined in an important early review by Ghonem et al [15], the oxidation process is related to the degree of homogeneity of plastic deformation and associated slip density at the crack tip. For conditions promoting homogeneous plastic deformation, with a high degree of slip density, the environmental damage contribution is shown to be limited, thus permitting the dominance of cyclic damage effects which are characterized by a transgranular crack growth mode and a lower crack growth rate. Under conditions leading to inhomogeneous plastic deformation and lower slip density the crack tip damage is described in terms of grain boundary oxidation and related intergranular fracture mode. Therefore, characterisation of strain/stress on a grain level as a consequence of microstructural inhomogeneity (e.g. grain size, precipitate size and grain orientation) at the crack tip is needed and believed to be critical to assess and understand the role of oxygen in enhanced FCP. The challenge lies in obtaining the *localised* heterogeneous deformation at elevated temperature, which rules out the usage of long established techniques such as strain gauges or extensometers. Digital image correlation has been developed to map strains across surfaces [62], however, characterisation of the localised deformation requires a fine speckle pattern of fiduciaries to achieve higher resolutions. Some efforts have been made to produce this fine speckle pattern via Au particle sputtering [63, 64], etching of intrinsic microstructures in Ni-based superalloy such as secondary γ' [65, 66], and electron beam lithography of hafnium oxide [67, 68]. These all show the possibility of using digital image correlation for strain characterisation at a grain level, although the application of speckle patterns prepared by Au particle sputtering and etching of the intrinsic microstructures at elevated temperatures still need further investigation. Alternatively, the localised strain at the crack tip can be characterised by high resolution electron backscatter diffraction which is developed to assess strain on a grain level by analysing Kikuchi pattern variation/degradation after a post-test characterisation [69-71].

If detailed information concerning the localised deformation at the crack tip along with the oxygen diffusion at the crack tip can be obtained, the next step will be to develop appropriately complex quantitative models to describe the oxygen-assisted FCP process. These quantitative models can be integrated into current mechanical models which mainly only consider the damage arising from fatigue or fatigue-creep interaction for fatigue life and/or FCP rate prediction. A more realistic model which combines the influence of fatigue-creep-environmental attack on FCP may yield a cost-effective and safe prediction of the fatigue performance of turbine disc alloys/components.

Summary:

Oxygen-assisted fatigue crack propagation is commonly observed in Ni-based superalloys for turbine disc application. However, the processes controlling this failure problem have not yet been established unambiguously, which limits the development of quantitative models to predict this failure and also influences targeted, further disc alloy development. To better understand the oxygen-assisted fatigue crack propagation, the following aspects should be further studied:

(1) The nature of oxygen attack at the crack tip and the oxygen diffusion processes within the plastic zone ahead of the crack tip should be further studied, which is necessary to quantitatively describe the oxygen attack in terms of thermodynamics and kinetics.
(2) Oxygen diffusion ahead of the crack tip is closely related to strain/stress state. Characterisation of strain/stress ahead of the crack tip at a grain level and the study of the influence of microstructural inhomogeneity (such as grain orientation, grain boundary character, precipitates) on the localised deformation should clarify the strain/stress assisted oxygen diffusion processes and diffusion of the relevant oxide-forming element in the case of stress-assisted grain boundary oxidation.
(3) The fatigue crack propagation rate determines the time available in each loading cycle for oxygen attack to occur. Conventional direct current potential drop techniques usually underestimate the overall crack length due to crack branching and micro-cracking with interlinked ligaments at the crack tip. More accurate measurement of crack growth rate is required along with the visualisation of crack morphology in three dimensions. The link between three dimensional crack tomography studies, local fatigue crack propagation rate and oxygen attack at the crack tip needs to be established.
(4) Quantitative models which consider the damage arising from fatigue, creep and oxygen attack are required to better predict the performance (fatigue life/fatigue crack propagation rate) of turbine disc superalloys and/or components.
(5) The alloy to alloy variation in likely oxidation mechanisms and diffusion processes needs to be acknowledged by the community, there is a tendency to assume the same processes occur in all alloy systems and at all crack growth rates. Dynamic embrittlement as well as stress-assisted grain boundary oxidation processes need to be considered across the range of crack propagation rates being considered.

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Reference

1. R. C. Reed: 'The Superalloys: Fundamentals and Applications', 2006, Cambridge University Press.
2. J. Y. Guedou, J. C. Lautridou, and Y. Honnorat: 'N18, Powder metallurgy superalloy for disks: Development and applications', *Journal of Materials Engineering and Performance*, 1993, **2**(4), 551-556.
3. J. Y. Guédou, I. Augustins-Lecallier, L. Nazé, P. Caron, D. Locq: ' Development of a new fatigue and creep resistant PM Nickel-base superalloy for disk applications', TMS Superalloy 2008. Warrendale (PA): The Minerals, Metals & Materials Society, (2008), 21-30.
4. Y. Gu, H. Harada, C. Cui, D. Ping, A. Sato, and J. Fujioka: 'New Ni–Co-base disk superalloys with higher strength and creep resistance', *Scripta Materialia*, 2006, **55**(9), 815-818.
5. S. Everitt, M. J. Starink, H. T. Pang, I. M. Wilcock, M. B. Henderson, and P. A. S. Reed: 'A comparison of high temperature fatigue crack propagation in various subsolvus heat treated turbine disc alloys', *Materials Science and Technology*, 2007, **23**(12), 1419-1423.
6. A. Pineau and S. D. Antolovich: 'High temperature fatigue of nickel-base superalloys – A review with special emphasis on deformation modes and oxidation', *Engineering Failure Analysis*, 2009, **16**(8), 2668-2697.
7. T. P. Gabb, P. T. Kantzos, J. Telesman, J. Gayda, C. K. Sudbrack, and B. Palsa: 'Fatigue resistance of the grain size transition zone in a dual microstructure superalloy disk', *International Journal of Fatigue*, 2011, **33**(3), 414-426.
8. J. H. Chen, P. M. Rogers, and J. A. Little: 'Oxidation behavior of several chromia-forming commercial nickel-base superalloys', *Oxid Met*, 1997, **47**(5-6), 381-410.
9. S. Everitt, R. Jiang, N. Gao, M. J. Starink, J. W. Brooks, and P. A. S. Reed: 'Comparison of fatigue crack propagation behaviour in two gas turbine disc alloys under creep–fatigue conditions: evaluating microstructure, environment and temperature effects', *Materials Science and Technology*, 2013, **29**(7), 781-787.
10. S. L. Semiatin, K. E. McClary, A. D. Rollett, C. G. Roberts, E. J. Payton, F. Zhang, and T. P. Gabb: 'Microstructure Evolution during Supersolvus Heat Treatment of a Powder Metallurgy Nickel-Base Superalloy', *Metall and Mat Trans A*, 2012, **43**(5), 1649-1661.
11. J. Gayda, T. P. Gabb, P. T. Kantzos: ' The effect of dual microstructure heat treatment on an advanced Nickel-based disk alloy', TMS Superalloy 2004. Warrendale (PA): The Minerals, Metals & Materials Society, 2004, 323-329.
12. M. P. Jackson and R. C. Reed: 'Heat treatment of UDIMET 720Li: the effect of microstructure on properties', *Materials Science and Engineering: A*, 1999, **259**(1), 85-97.
13. N. Bozzolo, N. Souaï, and R. E. Logé: 'Evolution of microstructure and twin density during thermomechanical processing in a γ-γ’ nickel-based superalloy', *Acta Materialia*, 2012, **60**(13–14), 5056-5066.
14. T. Osada, Y. Gu, N. Nagashima, Y. Yuan, T. Yokokawa, and H. Harada: 'Optimum microstructure combination for maximizing tensile strength in a polycrystalline superalloy with a two-phase structure', *Acta Materialia*, 2013, **61**(5), 1820-1829.
15. H. Ghonem, T. Nicholas, and A. Pineau: ' Elevated temperature fatigue crack growth in alloy 718—part II: effects of environmental and material variables', *Fatigue & Fracture of Engineering Materials & Structures*, 1993, **16**(6), 577-590.
16. T. P. Gabb, J. Gayda, and J. Telesman: 'Thermal and Mechanical Property Characterization of the Advanced Disk Alloy LSHR', *NASA/TM—2005-213645*, 2005.

17. R. Molins, G. Hochstetter, J. C. Chassaigne, and E. Andrieu: 'Oxidation effects on the fatigue crack growth behaviour of alloy 718 at high temperature', *Acta Materialia*, 1997, **45**(2), 663-674.
18. E. Andrieu, R. Molins, H. Ghonem, and A. Pineau: 'Intergranular crack tip oxidation mechanism in a nickel-based superalloy', *Materials Science and Engineering: A*, 1992, **154**(1), 21-28.
19. K. Maciejewski, J. Dahal, Y. Sun, and H. Ghonem: 'Creep–Environment Interactions in Dwell-Fatigue Crack Growth of Nickel Based Superalloys', *Metall and Mat Trans A*, 2014, **45**(5), 2508-2521.
20. H. S. Kitaguchi, H. Y. Li, H. E. Evans, R. G. Ding, I. P. Jones, G. Baxter, and P. Bowen: 'Oxidation ahead of a crack tip in an advanced Ni-based superalloy', *Acta Materialia*, 2013, **61**(6), 1968-1981.
21. R. Jiang, S. Everitt, N. Gao, K. Soady, J. W. Brooks, and P. A. S. Reed: 'Influence of oxidation on fatigue crack initiation and propagation in turbine disc alloy N18', *International Journal of Fatigue*, 2015, **75**, 89-99.
22. R. Jiang, S. Everitt, M. Lewandowski, N. Gao, and P. A. S. Reed: 'Grain size effects in a Ni-based turbine disc alloy in the time and cycle dependent crack growth regimes', *International Journal of Fatigue*, 2014, **62**, 217-227.
23. D. G. Leo Prakash, M. J. Walsh, D. Maclachlan, and A. M. Korsunsky: 'Crack growth micro-mechanisms in the IN718 alloy under the combined influence of fatigue, creep and oxidation', *International Journal of Fatigue*, 2009, **31**(11–12), 1966-1977.
24. B. A. Lerch, N. Jayaraman, and S. D. Antolovich: 'A study of fatigue damage mechanisms in Waspaloy from 25 to 800°C', *Materials Science and Engineering*, 1984, **66**(2), 151-166.
25. J. Gayda and R. V. Miner: 'Fatigue crack initiation and propagation in several nickel-base superalloys at 650°C', *International Journal of Fatigue*, 1983, **5**(3), 135-143.
26. J. Gayda and R. V. Miner: 'The effect of microstructure on 650 °C fatigue crack growth in P/M astroloy', *Metallurgical Transactions A*, 1983, **14**(11), 2301-2308.
27. Tong and Byrne: 'Effects of frequency on fatigue crack growth at elevated temperature', *Fatigue & Fracture of Engineering Materials & Structures*, 1999, **22**(3), 185-193.
28. J. Dahal, K. Maciejewski, and H. Ghonem: 'Loading frequency and microstructure interactions in intergranular fatigue crack growth in a disk Ni-based superalloy', *International Journal of Fatigue*, 2013, **57**, 93-102.
29. T. Billot, P. Villechaise, M. Jouiad, and J. Mendez: 'Creep–fatigue behavior at high temperature of a UDIMET 720 nickel-base superalloy', *International Journal of Fatigue*, 2010, **32**(5), 824-829.
30. H. Y. Li, J. F. Sun, M. C. Hardy, H. E. Evans, S. J. Williams, T. J. A. Doel, and P. Bowen: 'Effects of microstructure on high temperature dwell fatigue crack growth in a coarse grain PM nickel based superalloy', *Acta Materialia*, 2015, **90**, 355-369.
31. J. D. Carroll, W. Abuzaid, J. Lambros, and H. Sehitoglu: 'High resolution digital image correlation measurements of strain accumulation in fatigue crack growth', *International Journal of Fatigue*, 2013, **57**, 140-150.
32. Y. W. Lu, C. Lupton, M. L. Zhu, and J. Tong: 'In Situ Experimental Study of Near-Tip Strain Evolution of Fatigue Cracks', *Exp Mech*, 2015, **55**(6), 1175-1185.
33. L. Viskari, M. Hörnqvist, K. L. Moore, Y. Cao, and K. Stiller: 'Intergranular crack tip oxidation in a Ni-base superalloy', *Acta Materialia*, 2013, **61**(10), 3630-3639.
34. R. Jiang, N. Gao, and P. A. S. Reed: 'Influence of orientation-dependent grain boundary oxidation on fatigue cracking behaviour in an advanced Ni-based superalloy', *J Mater Sci*, 2015, **50**(12), 4379-4386.
35. L. Ma and K.-M. Chang: 'Identification of SAGBO-induced damage zone ahead of crack tip to characterize sustained loading crack growth in alloy 783', *Scripta Materialia*, 2003, **48**(9), 1271-1276.
36. C. F. Miller, G. W. Simmons, and R. P. Wei: 'Evidence for internal oxidation during oxygen enhanced crack growth in P/M Ni-based superalloys', *Scripta Materialia*, 2003, **48**(1), 103-108.

37. H. E. Evans, H. Y. Li, and P. Bowen: 'A mechanism for stress-aided grain boundary oxidation ahead of cracks', *Scripta Materialia*, 2013, **69**(2), 179-182.
38. A. Karabela, L. G. Zhao, J. Tong, N. J. Simms, J. R. Nicholls, and M. C. Hardy: 'Effects of cyclic stress and temperature on oxidation damage of a nickel-based superalloy', *Materials Science and Engineering: A*, 2011, **528**(19–20), 6194-6202.
39. D. Bika and C. J. McMahon Jr: 'A model for dynamic embrittlement', *Acta Metallurgica et Materialia*, 1995, **43**(5), 1909-1916.
40. J. A. Pfaendtner and C. J. McMahon Jr: 'Oxygen-induced intergranular cracking of a Ni-base alloy at elevated temperatures—an example of dynamic embrittlement', *Acta Materialia*, 2001, **49**(16), 3369-3377.
41. U. Krupp, W. M. Kane, C. Laird, and C. J. McMahon: 'Brittle intergranular fracture of a Ni-base superalloy at high temperatures by dynamic embrittlement', *Materials Science and Engineering: A*, 2004, **387–389**, 409-413.
42. U. Krupp, W. M. Kane, X. Liu, O. Dueber, C. Laird, and C. J. McMahon Jr: 'The effect of grain-boundary-engineering-type processing on oxygen-induced cracking of IN718', *Materials Science and Engineering: A*, 2003, **349**(1–2), 213-217.
43. D. A. Woodford: 'Gas phase embrittlement and time dependent cracking of nickel based superalloys', *Energy Materials*, 2006, **1**(1), 59-79.
44. R. H. Bricknell and D. A. Woodford: 'Grain boundary embrittlement of the iron-base superalloy IN903A', *Metallurgical Transactions A*, 1981, **12**(9), 1673-1680.
45. R. H. Bricknell and D. A. Woodford: 'The embrittlement of nickel following high temperature air exposure', *Metallurgical Transactions A*, 1981, **12**(3), 425-433.
46. H. Ghonem and D. Zheng: 'Depth of intergranular oxygen diffusion during environment-dependent fatigue crack growth in alloy 718', *Materials Science and Engineering: A*, 1992, **150**(2), 151-160.
47. C. J. McMahon Jr: 'Comments on "Identification of SAGBO-induced damage zone ahead of crack tip to characterize sustained loading crack growth in alloy 783"', *Scripta Materialia*, 2006, **54**(2), 305-307.
48. L. G. Zhao, J. Tong, and M. C. Hardy: 'Prediction of crack growth in a nickel-based superalloy under fatigue-oxidation conditions', *Engineering Fracture Mechanics*, 2010, **77**(6), 925-938.
49. A. Karabela, L. G. Zhao, B. Lin, J. Tong, and M. C. Hardy: 'Oxygen diffusion and crack growth for a nickel-based superalloy under fatigue-oxidation conditions', *Materials Science and Engineering: A*, 2013, **567**, 46-57.
50. B. J. Foss, M. C. Hardy, D. J. Child, D. S. McPhail, and B. A. Shollock: 'Oxidation of a Commercial Nickel-Based Superalloy under Static Loading', *The Journal of The Minerals, Metals & Materials Society*, 2014, **66**(12), 2516-2524.
51. H. S. Kitaguchi, M. P. Moody, H. Y. Li, H. E. Evans, M. C. Hardy, and S. Lozano-Perez: 'An atom probe tomography study of the oxide–metal interface of an oxide intrusion ahead of a crack in a polycrystalline Ni-based superalloy', *Scripta Materialia*, 2015, **97**, 41-44.
52. A. Sato, Y. L. Chiu, and R. C. Reed: 'Oxidation of nickel-based single-crystal superalloys for industrial gas turbine applications', *Acta Materialia*, 2011, **59**(1), 225-240.
53. S. Y. Yu, H. Y. Li, M. C. Hardy, S. A. McDonald, and P. Bowen: 'Mechanisms of dwell fatigue crack growth in an advanced nickel disc alloy RR1000', Eurosuperalloys 2014, 03002; 2014.
54. E. Storgärds and K. Simonsson: 'Crack Length Evaluation for Cyclic and Sustained Loading at High Temperature Using Potential Drop', *Exp Mech*, 2015, **55**(3), 559-568.
55. 'Standard Test Method for Measurement of Fatigue Crack Growth Rates', *ASTM E647*.
56. E. Marie and P. J. Withers: 'Quantitative X-ray tomography', *International Materials Reviews*, 2014, **59**(1), 1-43.
57. B. Y. He, O. L. Katsamenis, B. G. Mellor, and P. A. S. Reed: '3-D analysis of fatigue crack behaviour in a shot peened steam turbine blade material', *Materials Science and Engineering: A*, 2015, **642**, 91-103.

58. H. Proudhon, A. Moffat, I. Sinclair, and J.-Y. Buffiere: 'Three-dimensional characterisation and modelling of small fatigue corner cracks in high strength Al-alloys', *Comptes Rendus Physique*, 2012, **13**(3), 316-327.
59. A. J. Moffat, B. G. Mellor, I. Sinclair, and P. A. S. Reed: 'The mechanisms of long fatigue crack growth behaviour in Al–Si casting alloys at room and elevated temperature', *Materials Science and Technology*, 2007, **23**(12), 1396-1401.
60. J. L. Olivier M.D.M. Messé , Andrew King, Jean Yves Buffière, Cathie M.F. Rae: 'Investigation of Fatigue Crack Propagation in Nickel Superalloy Using Diffraction Contrast Tomography and Phase Contrast Tomography', *Advanced Materials Research* 2014, **891**, 923-928.
61. J. Telesman, T. P. Gabb, A. Garg, P. Bonacuse and J. Gayda: 'Effect of Microstructure on Time Dependent Fatigue Crack Growth Behavior In a P/M Turbine Disk Alloy', TMS Superalloy 2008. Warrendale (PA): The Minerals, Metals & Materials Society, 2008, 807-816.
62. P. Bing, Q. Kemao, X. Huimin, and A. Anand: 'Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review', *Measurement Science and Technology*, 2009, **20**(6), 062001.
63. F. Di Gioacchino and J. Quinta da Fonseca: 'Plastic Strain Mapping with Sub-micron Resolution Using Digital Image Correlation', *Exp Mech*, 2013, **53**(5), 743-754.
64. F. Di Gioacchino and J. Quinta da Fonseca: 'An experimental study of the polycrystalline plasticity of austenitic stainless steel', *International Journal of Plasticity*, 2015, **74**, 92-109.
65. J. C. Stinville, M. P. Echlin, D. Texier, F. Bridier, P. Bocher, and T. M. Pollock: 'Sub-Grain Scale Digital Image Correlation by Electron Microscopy for Polycrystalline Materials during Elastic and Plastic Deformation', *Exp Mech*, 2015, 1-20.
66. J. C. Stinville, N. Vanderesse, F. Bridier, P. Bocher, and T. M. Pollock: 'High resolution mapping of strain localization near twin boundaries in a nickel-based superalloy', *Acta Materialia*, 2015, **98**, 29-42.
67. J. L. Walley, R. Wheeler, M. D. Uchic, and M. J. Mills: 'In-Situ Mechanical Testing for Characterizing Strain Localization During Deformation at Elevated Temperatures', *Exp Mech*, 2012, **52**(4), 405-416.
68. J. L. W. Carter, M. W. Kuper, M. D. Uchic, and M. J. Mills: 'Characterization of localized deformation near grain boundaries of superalloy René-104 at elevated temperature', *Materials Science and Engineering: A*, 2014, **605**, 127-136.
69. M. Kamaya, A. J. Wilkinson, and J. M. Titchmarsh: 'Quantification of plastic strain of stainless steel and nickel alloy by electron backscatter diffraction', *Acta Materialia*, 2006, **54**(2), 539-548.
70. A. J. Wilkinson, G. Meaden, and D. J. Dingley: 'High-resolution elastic strain measurement from electron backscatter diffraction patterns: New levels of sensitivity', *Ultramicroscopy*, 2006, **106**(4–5), 307-313.
71. T. Zhang, J. Jiang, B. A. Shollock, T. B. Britton, and F. P. E. Dunne: 'Slip localization and fatigue crack nucleation near a non-metallic inclusion in polycrystalline nickel-based superalloy', *Materials Science and Engineering: A*, 2015, **641**, 328-339.