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Fatigue resistance of the grain size transition zone in a dual microstructure superalloy disk

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ABSTRACT

Mechanical property requirements vary with location in nickel-based superalloy disks. In order to maximize the associated mechanical properties, heat treatment methods have been developed for producing tailored microstructures. In this study, a specialized heat treatment method was applied to produce varying grain microstructures from the bore to the rim portions of a powder metallurgy processed nickel-based superalloy disk. The bore of the contoured disk consisted of fine grains to maximize strength and fatigue resistance at lower temperatures. The rim microstructure of the disk consisted of coarse grains for maximum resistance to creep and dwell crack growth at high temperatures up to 704 °C. However, the fatigue resistance of the grain size transition zone was unclear, and needed to be evaluated. This zone was located as a band in the disk web between the bore and rim. Specimens were extracted parallel and transverse to the transition zone, and multiple fatigue tests were performed at 427 and 704 °C. Mean fatigue lives were lower at 427 °C than 704 °C. Specimen failures often initiated at relatively large grains, which failed on crystallographic facets. Grain size distributions were characterized in the specimens, and related to the grains initiating failures as well as location within the transition zone. Fatigue life decreased with increasing maximum grain size. Correspondingly, mean fatigue resistance of the transition zone was slightly higher than that of the rim, but lower than that of the bore. The scatter in limited tests of replicates was comparable for all transition zone locations examined.

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1. Introduction

In γ' strengthened superalloys, solution heat treatments at temperatures sufficient to dissolve all existing γ' precipitates allow enhanced grain growth [1], as the precipitates no longer constrain grain boundaries. This behavior is especially evident in powder metallurgy disk superalloys [2], where application of such a heat treatment after extrusion and forging can produce quite uniform grain sizes [3,4]. Disks heated to 20–40 °C below the γ' solvus in “subsolvus” solution heat treatments retain 10–20% of coarse “primary” γ' particles, which constrain grain growth to give uniform microstructures with grains near 5–10 μm in diameter. This fine grain size produces high strength and fatigue resistance at temperatures up to 550 °C, often typical requirements of disk bore and web regions. However, disks heated above the γ' solvus in “supersolvus” solution heat treatments lose these constraining coarse “primary” γ' particles, resulting in microstructures of larger grains near 30–70 μm in diameter. This coarse grain size gives lower strength and cyclic fatigue resistance, but

improved time-dependent properties such as creep and dwell fatigue crack initiation and growth at application temperatures of 600–700 °C, typical requirements for disk rims in high performance turbine engines [5–7].

The ability to vary the location specific microstructures to achieve a fine grain size in the bore and web of a disk, and coarse grain size in the rim of a disk, in order to maximize the associated mechanical properties as required at each location, is a promising approach to help optimize the disk design. Based on these perceived benefits, specialized heat treatment methods have been developed for producing tailored grain microstructures in the bore and rim portions of nickel-based superalloy disks [5–7]. The dual microstructure heat treatment (DMHT) method employed in the present study uses heat sinks to encourage a temporary temperature gradient between a disk's bore and rim regions, with the bore at lower temperature than the rim, Fig. 1. When combined with finite element modeling and positioning of thermocouples at key locations, this allows design of solution heat treatments that limit the bore to subsolvus temperatures producing grain sizes of near 10 μm diameter (ASTM 11–12), while allowing the rim to reach supersolvus temperatures resulting in grain sizes of 30–80 μm diameter (ASTM 5–7). This allows disk grain microstructure to be

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Fig. 1. Schematic of dual microstructure heat treatment (DMHT) assembly used for solution heat treatment of disk, with location of grain size transition zone indicated.

varied in accordance with the property requirements of disk bore and rim locations. This process has been successfully demonstrated on four different advanced powder metallurgy disk superalloys [7–10].

In order to validate the use of the DMHT process, it is necessary to verify the integrity of the transition zone by determining its fatigue resistance. The transition zone of the DMHT disk has a microstructure with variable grain size as a function of location. In coarse grain PM disk superalloys, fatigue failures can often initiate at grains which fail in a crystallographic manner due to concentrated slip [11,12]. These failing grains often appear to be relatively large with respect to the mean grain size for a given microstructure. Since grain size varies within the transition zone, it is therefore important to determine the fatigue resistance and fatigue failure modes of the transition zone.

The objective of this study was to evaluate the low cycle fatigue resistance of the grain size transition zone in a DMHT disk. Specimens were extracted from the transition zone in the circumferential and radial directions. Grain size distributions were determined for each specimen location. Fatigue tests were performed at 427 and 704 °C to assess comparative fatigue lives and failure modes.

2. Materials and methods

Powder of LSHR superalloy having the composition in weight percent of 3.5Al, 0.03B, 0.03C, 20.7Co, 12.5Cr, 2.7Mo, 1.5Nb, 1.6Ta, 3.5Ti, 4.3W, 0.05Zr, bal. Ni and trace impurities was atomized in argon by PCC Special Metals Corp. and passed through screens of –270 mesh to give powder particle diameters of no more than about 55 µm. The powder was then sealed in a stainless steel container, hot compacted, and extruded at a reduction ratio of 6:1 by PCC Wyman–Gordon Forgings. Segments of the extrusion billet were machined to segments approximately 15 cm dia. and 20 cm long, then isothermally forged into flat disks approximately 31 cm in diameter and 6 cm thick. A contoured disk was then machined with an outer diameter of 30 cm, maximum bore thickness of 5 cm, and rim thickness of 3.8 cm [9]. The disks were heat treated by Ladish Company, Inc. They were first conventionally subsolvus solution heat treated at 1135 °C for 2 h then air cooled, to give a uniform fine grain microstructure of ASTM 11–12. The DMHT process was then applied [7], along with an aging heat treatment of 815 °C/8 h.

Specimen blanks were extracted as shown in Fig. 2. Using rotational symmetry, they were located in three different tangential-oriented rings parallel to the transition zone of inner, mid, and outer radius, and in radial spokes perpendicular to the transition zone. Machining and testing of low cycle fatigue specimens, having a uniform gage diameter of 6.4 mm across a gage length of 19 mm, was performed by Mar-Test, Inc. and NASA GRC. The low cycle fatigue (LCF) specimens were machined using a low stress grinding procedure, and the gage sections were finally

Fig. 2. Schematic showing location of inner, mid, and outer ring specimens in transition zone.

polished to an 8 rms finish with all polishing performed parallel to the loading direction. They were then tested using uniaxial closed-loop servo-hydraulic testing machines with induction heating and axial extensometers. Low cycle fatigue tests were performed at 427 and 704 °C.

The maximum, minimum, and range of stresses generated during conventional strain-control fatigue tests can vary among repetition tests, due to slight differences in yield strength among individual specimens. Such variations in cyclic stress can influence fatigue life, and complicate comparisons of fatigue life between locations. Therefore, the first three fatigue tests for each specimen location were initiated with strain-controlled to fixed limits. The remaining three tests were run with load-controlled to fixed limits, to give a total of six tests performed for each location at each temperature. The first three of six tests for each location were performed according to ASTM E606, with strain initially controlled to fixed limits. A triangular waveform was employed for the first 6 h of cycling, varying strain at a frequency of 0.33 Hz over a total strain range of 0.6% at a strain ratio ($R_e = \epsilon_{\min}/\epsilon_{\max}$) of 0. After 6 h of testing in this manner, surviving specimens were interrupted and then cycled using a triangular load-controlled waveform at a faster frequency of 10 Hz until failure, maintaining the stresses stabilized before interruption. The average stabilized maximum and minimum stresses were calculated for the three specimens tested in strain control for each specimen location and test temperature. These defined constant maximum and minimum stress limits for running the other three specimens of the group using a waveform controlling load, according to ASTM E466. A triangular waveform having a frequency of 10 Hz was employed here.

Fracture surfaces of all specimens were evaluated by scanning electron microscopy to determine crack initiation and propagation mechanisms. Grain sizes were determined on metallographically prepared sections. Linear intercept grain size distributions were determined from gage sections of representative test specimens according to ASTM E112 linear intercept procedures using circular grid overlays, grain area distributions were determined using image thresholding, and As-Large-As (ALA) grain sizes were determined according to ASTM E930. Grain size distributions and texture were also assessed using Electron Back Scatter Diffraction (EBSD), on a field emission scanning electron microscope equipped with a backscatter detector and EDAX[®] TSL electron backscatter diffraction analysis software.

Statistical analyses of variance were performed using JMP[®] software, with significance assessed at a probability $p = 0.05$, representing 95% confidence.

3. Results and discussion

3.1. Material and microstructures

Typical grain microstructures are shown in optical images from etched metallographic sections of LCF specimen sections, Fig. 3. Linear intercept lengths for grains at each location are compared in Fig. 4. Inner, mid, and outer ring specimens had increasing mean

intercept grain diameters of 5.8, 38, and 55 μm , respectively, and had corresponding increasing ALA grain diameters of about 22, 410, and 413 μm , respectively. Because these disks were machined from flat pancake forgings of relatively uniform forging strains, no consistent changes in non-metallic inclusion content or morphology were observed across the fatigue tested locations.

The grain size transition zone was abrupt in this disk, and was usually captured within the gage cross sections of specimens at

Fig. 3. Typical grain microstructures observed for inner, mid, and outer ring transition zone locations.

Fig. 4. Linear intercept grain size versus estimated cumulative probability of occurrence for inner, mid, and outer ring transition zone locations.

the mid location. Within this mid location, a bimodal grain size distribution mixing large and small grains was observed, giving a lower slope and more non-linearity in cumulative probability versus $\log(\text{grain size})$ than for inner and outer locations, Fig. 4. The grain size – cumulative probability plots were comparable for individual specimens of a fixed location. Inner ring specimens also had coarse, undissolved “primary” γ' particles widely spaced along grain boundaries and sometimes scattered within grains, Fig. 3. As shown in Fig. 3, the most abrupt plane of transition in grain size was located parallel to the loading axis in the gage sections of mid ring specimens. This shows as a line of transition in the image of a transverse section. However, this plane of grain transition was

located normal to the loading axis near the middle of the gage sections in radial specimens. This shows as a line of transition in the presented image of a longitudinal section. This enabled fatigue loading of the grain size transition plane in the parallel and transverse directions, respectively.

3.2. Low cycle fatigue response

The general monotonic and fatigue properties of these disks were previously compared for bore and rim locations in Ref. [9]. This discussion will therefore remain focused on the fatigue properties of the grain size transition zone. Typical hysteresis loops measured at the beginning of strain-controlled tests are shown with indicated maximum and minimum stresses in Fig. 5. Maximum and minimum stresses stabilized at 7200 cycles are listed in Tables 1 and 2. Fatigue life is also compared for the different specimen locations within the transition zone in Tables 1 and 2, and in the cumulative probability plots of Fig. 6. The fatigue lives have a log normal distribution as is evident by the linear fit of the data shown in a plot with a logarithmic life cycle axis. Modest scatter in life was observed for each specimen location. No difference was consistently observed between strain-controlled (open symbols) and load-controlled (filled symbols) test lives. The resulting lives were therefore grouped together in all analyses.

As shown in Fig. 6, for tests conducted at both 427 and 704 °C, the inner location specimens had significantly higher mean fatigue lives than mid, outer, and radial specimens at both test temperatures. Inner specimens had over 10× higher mean lives than mid, outer, and radial specimens at 427 °C, and over 50× higher mean lives at 704 °C. Mid, radial, and then outer specimens ranked in order of decreasing mean fatigue lives at both test temperatures, however the differences in lives between these three locations

Fig. 5. Typical stress–strain hysteresis loops at beginning of strain-controlled tests, with maximum and minimum stresses indicated.

Table 1
Fatigue test results at 427 °C.

Spec ID	Disk-location	Temperature (°C)	Starting control mode	Stab. max. stress (MPa)	Stab. min. stress (MPa)	Smith–Watson–Topper stress (MPa)	Total strain range (%)	Fatigue life (Cycles)	Prime initiator type	Prime initiator min. depth (μm)	Prime initiator area (μm ²)	Prime initiator max. length (μm)	Prime initiator width (μm)	Prime initiator perimeter (μm)
L36	DMHT-inner	427	Load	1124	−41	809		290,379	Inclusion	2650	639	36	29	155
L29	DMHT-inner	427	Strain	1132	−27	810	0.598	325,908	Inclusion	468	628	38	25	150
L5	DMHT-inner	427	Strain	1134	−39	816	0.599	327,202	Inclusion	1636	711	43	23	117
L17	DMHT-inner	427	Load	1124	−41	809		349,760	Inclusion	48	176	24	10	66
L12	DMHT-inner	427	Load	1124	−41	809		355,313	Inclusion	352	67	19	5	44
L24	DHHT-inner	427	Strain	1116	−52	807	0.600	483,703	Facet	28	202	21	14	66
L33	DMHT-mid	427	Strain	1032	−173	788	0.600	24,505	Facet	173	28,579	355	122	929
L4	DMHT-mid	427	Load	1055	−131	791		26,342	Facet	67	24,035	244	146	813
L28	DMHT-mid	427	Load	1055	−131	791		26,991	Facet	84	40,594	336	173	953
L21	DMHT-mid	427	Load	1055	−131	791		27,057	Facet	895	19,297	237	107	668
L9	DMHT-mid	427	Strain	1067	−123	796	0.600	27,061	Facet	262	30,386	297	172	895
L16	DMHT-mid	427	Strain	1082	−93	797	0.599	30,799	Facet	0	63,359	399	238	1302
L8	DMHT-outer	427	Load	993	−179	763		12,307	Facet	0	34,199	278	204	849
L20	DMHT-outer	427	Strain	1037	−142	782	0.594	14,881	Facet	0	72,257	372	287	1298
L13	DMHT-outer	427	Load	993	−179	763		17,036	Facet	0	35,224	297	215	859
L37	DMHT-outer	427	Strain	1043	−117	778	0.599	18,463	Facet	0	18,518	182	164	636
L32	DMHT-outer	427	Load	993	−179	763		19,925	Facet	0	17,868	201	139	609
L1	DMHT-outer	427	Strain	951	−210	743	0.601	25,287	Facet	57	13,347	163	140	530
RL16	DMHT-radial	427	Load	1055	−131	791		18,898	Facet	91	69,345	438	311	1549
R17	DMHT-radial	427	Strain	1074	−124	802	0.600	18,901	Facet	0	57,086	432	246	1448
RL13	DMHT-radial	427	Load	1055	−131	791		22,010	Facet	96	16,887	208	160	732
RL2	DMHT-radial	427	Load	1055	−131	791		22,921	Facet	151	27,332	254	170	810
R3	DMHT-radial	427	Strain	1041	−154	789	0.601	25,042	Facet	185	32,234	273	183	943
R6	DMHT-radial	427	Strain	1054	−108	783	0.601	31,883	Facet	352	15,180	315	70	765
A1BL3	Supersolvus	427	Strain	957	−272	767	0.598	48,725	Facet	0	7547	111	94	368
A1RL8	Supersolvus	427	Strain	1014	−148	767	0.597	77,950	Facet	0	4971	100	94	332
A1BL4	Supersolvus	427	Strain	880	−302	721	0.598	81,939	Facet	0	6696	113	98	348
A1BL5	Supersolvus	427	Strain	933	−233	737	0.598	94,733	Facet	61	13,598	176	112	514

Table 2

Fatigue test results at 704 °C.

Spec ID	Disk-location	Temperature (°C)	Starting control mode	Stab. max. stress (MPa)	Stab. min. stress (MPa)	Smith–Watson–Topper stress (MPa)	Total strain range (%)	Fatigue life (cycles)	Prime initiator type	Prime initiator min. depth (μm)	Prime initiator area (μm ²)	Prime initiator max. length (μm)	Prime initiator width (μm)	Prime initiator perimeter (μm)
L6	DMHT-inner	704	Strain	1023	−51	741	0.600	1,062,332	Inclusion	1333	973	59	23	144
L35	DMHT-inner	704	Load	1021	−41	736	0.600	1,072,677	Inclusion	2283	451	38	25	209
L18	DMHT-inner	704	Load	1021	−41	736	0.600	1,130,332	Inclusion	951	598	43	23	174
L23	DMHT-inner	704	Strain	1025	−25	734	0.597	1,762,377	Inclusion	2017	683	40	24	116
L30	DMHT-inner	704	Strain	1018	−49	737	0.601	1,834,651	Inclusion	1983	1346	61	36	200
L11	DMHT-inner	704	Load	1021	−41	736	0.600	2,635,233	Inclusion	398	489	38	20	130
L39	DMHT-mid	704	Load	986	−69	721	0.600	24,372	Lost					
L3	DMHT-mid	704	Load	986	−69	721	0.600	31,000	Facet	0	16,480	175	156	523
L22	DMHT-mid	704	Load	986	−69	721	0.600	34,519	Facet	36	55,352	343	241	1090
L34	DMHT-mid	704	Strain	992	−72	726	0.598	35,736	Facet	69	13,350	174	131	553
L10	DMHT-mid	704	Strain	990	−61	721	0.600	63,939	Facet	589	36,701	326	184	1113
L15	DMHT-mid	704	Strain	996	−63	726	0.598	94,741	Facet	146	23,169	210	177	665
L31	DMHT-outer	704	Load	966	−89	714	0.600	18,894	Facet	0	21,447	242	136	698
L19	DMHT-outer	704	Strain	993	−83	731	0.600	25,110	Facet	1171	38,010	315	219	1018
L14	DMHT-outer	704	Load	966	−89	714	0.600	26,125	Facet	80	25,131	219	174	677
L7	DMHT-outer	704	Load	966	−89	714	0.600	29,635	Facet	1485	51,533	379	251	1113
L2	DMHT-outer	704	Strain	957	−108	714	0.597	31,168	Facet	1137	42,561	345	179	1043
L26	DMHT-outer	704	Strain	947	−85	699	0.600	37,300	Facet	352	7105	127	79	372
RL14	DMHT-radial	704	Load	986	−69	721	0.600	21,998	Facet	0	33,147	310	204	1139
RL1	DMHT-radial	704	Load	986	−69	721	0.600	23,988	Facet	595	31,963	290	184	960
R4	DMHT-radial	704	Strain	969	−86	715	0.600	26,881	Facet	128	61,000	421	232	1377
R5	DMHT-radial	704	Strain	981	−70	718	0.601	40,310	Facet	1264	39,273	350	239	1590
RL15	DMHT-radial	704	Load	986	−69	721	0.600	47,177	Facet	0	14,110	167	114	502
RL18	DMHT-radial	704	Strain	991	−68	724	0.600	49,988	Facet	226	24,777	220	195	728
A1BL7	Supersolvus	704	Strain	925	−152	706	0.598	223,970	Facet	2196	12,355	157	131	486
A1RL7	Supersolvus	704	Strain	980	−112	731	0.599	246,425	Facet	1791	7229	143	84	386
A1BL6	Supersolvus	704	Strain	985	−103	732	0.597	332,061	Facet	203	4188	123	55	328

were relatively modest. Outer samples had lower mean lives than those of mid and radial specimens at a 95% significance level for tests at 427 °C, but at lower significance levels in tests at 704 °C.

Mean fatigue lives were significantly lower at 427 °C than at 704 °C for all transition zone specimen locations. This has been observed in other studies of this [9] and other [13] PM disk superalloys, and will be considered with respect to the failure modes and locations, and the stresses generated at each temperature. Several additional specimens extracted and tested from the bore of the disk had lives comparable to the inner ring specimens at 427 °C [7], indicating fatigue life was likely comparable over this inward region of the disk.

3.3. Failure modes

Typical failure initiation sites are shown in Fig. 7. Two predominant failure modes were observed. The fine grain inner ring specimens usually failed from small internal non-metallic inclusions. The inclusions initiating failures were usually granulated, aluminum-rich oxide type 2 inclusions [14,15]. For the coarse grain outer specimens as well as mid and radial specimens which contained at least some coarse grains, the failures initiated at the crystallographic grain facets of large grains (Fig. 6a).

These crystallographic facet fatigue failures usually initiated near or at the specimen surface in tests of mid, outer, and radial specimens at 427 °C. However, several of these specimens failed

from internal facet locations in tests at 704 °C, which resulted in longer lives than for surface-initiated failures. This change of failure location with temperature can help explain the lower lives observed at 427 °C than for 704 °C. The facet failure mode, associated with the coarse grain microstructures, resulted in lower fatigue lives at both 427 and 704 °C than for inclusion-initiated failures of fine grained inner and bore specimens.

Coarse grain microstructure is well known in these type alloys to decrease the low cycle fatigue life in comparison to fine grain microstructure. Here, not only did the coarse grain microstructure of the outer specimens result in low lives, but it also gave low fatigue lives for both the radial and mid specimens which contained both fine and coarse microstructures. For this apparent reason, radial specimens failed at locations corresponding to outer ring specimens, where larger grains were present to give earlier failures, Fig. 8. Also, in case of the mid specimens, the crack initiation leading to failure was always located in the coarse grain section of the specimen cross section, also shown in Fig. 8.

3.4. Fatigue lives of DMHT and uniform grain size disks

In addition to the fatigue testing of the DMHT disk, fatigue tests were previously performed at these temperatures in another study of LSHR [16], from disks of exactly the same chemistry, extrusion,

Fig. 6. Fatigue life versus estimated cumulative probability for tests at 427 and 704 °C. Strain-controlled tests are indicated in open symbols, fully load-controlled tests by filled symbols.

Fig. 7. Typical fatigue failure initiation sites: (a) grain facet failure initiating near the specimen surface of coarse grain specimens, and (b) non-metallic inclusion failure initiating away from the surface of fine grain specimens.

Fig. 8. Typical fatigue failure initiation sites: (a) facet failures initiating at coarse grains near or at the specimen surface for outer and mid specimens, internal inclusion failures for inner specimens, and (b) near-surface facet failures at coarse grain ends (red lines) of radial specimens. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and size, having microstructures with uniform grain size. Comparisons of the results from these two studies can shed further light on the mechanisms governing low cycle fatigue behavior.

The uniform grain size disks had been given conventional isothermal subsolvus and supersolvus heat treatments, before the same 815 °C/8 h aging heat treatment used in the DMHT disk tested here. The observed fatigue lives from those isothermal subsolvus and supersolvus heat treated disks are compared to DMHT transition zone lives in plots of strain range versus life in Fig. 9. DMHT inner ring and bore lives were comparable to that of the subsolvus disk. Yet, DMHT mid, outer, and radial specimens had consistently lower fatigue lives than those for the supersolvus disk.

Several issues were explored to gain an understanding why fatigue lives were lower for the DMHT disk at these transition zone locations than for the uniform supersolvus disk. Tensile and creep fatigue properties of the DMHT disk rim were previously determined to be comparable to those for the supersolvus disk [9]. The disks were also shown to have similar γ' precipitate morphologies. However, the differences in fatigue life between the two disks could still be due in part to variations of cyclic stress range and mean stress response in fatigue tests of a given strain range. Such differences in cyclic stresses can be accounted for using a stress parameter proposed by Smith–Watson–Topper [17]:

$$SWT = (\sigma_{\max} \Delta \sigma / 2)^{0.5}$$

This relationship accounts for differences in maximum stress as well as stress range. Fatigue life is compared for these cases using SWT stress in Fig. 10. No consistent variations in SWT stress versus life were observed that could account for the differences in life between the DMHT and supersolvus disks. However, SWT stresses were usually higher at 427 °C than for 704 °C at a given strain range, which could help explain the lower strain-life responses observed at 427 °C for both disks.

As previously described, the failures of the DMHT disk fatigue specimens were typically initiated on the crystallographic facets of large grains. The relationship between the size of the facets initiating failure and fatigue life for both the DMHT and supersolvus uniform grain size fatigue specimens is shown in Fig. 11. As shown for both 427 °C and 704 °C, the fatigue specimens removed from the supersolvus disk had smaller facet sizes than those for specimens excised from the DMHT disk. Also note that the size of the facets seemed to be related to the corresponding fatigue lives, with the increase in size resulting in shorter lives.

One-way analysis of variance comparisons of $\log(\text{facet area})$ indicated supersolvus specimens had significantly smaller mean facet areas than mid, outer, and radial specimens at both test

Fig. 9. Fatigue life versus total strain range for fatigue tests in transition zone of DMHT disk, compared to that for tests from uniform subsolvus fine grain and supersolvus coarse grain disks at 427 and 704 °C (15).

temperatures. The mean facet areas of mid, outer, and radial DMHT disk specimens did not differ significantly. This may explain the very small variation in mean fatigue lives for these three DMHT locations, as was noted earlier.

Facet sizes did not significantly vary between the two testing temperatures. Inner specimens had over 10× higher mean lives than mid, outer, and radial specimens at 427 °C, and over 50× higher mean lives at 704 °C. One-way analysis of variance comparisons of log(life) indicated supersolvus disk specimens correspondingly had significantly higher mean fatigue lives than mid, outer, and radial specimens at both test temperatures. Increasing fatigue life significantly correlated with decreasing facet size for all facet failures at both test temperatures. The correlation as indicated by the coefficient of determination was higher at 427 °C than for 704 °C. This appeared related in part to the locations of failure initiations. Most failure initiations were consistently near or at the surface for tests at 427 °C. However, several specimens failed from internal grain facets at 704 °C, producing lives significantly longer than for surface failures. Such variations in life based on failure location have been observed in other disk superalloys [13,18,19].

The grain facet size was of course related to the grain size distribution of the samples. A micrograph of the grain structure in the supersolvus disk rim is shown in Fig. 12. The mean linear intercept grain size of the supersolvus disk was approximately 33 μm, with an ALA grain size of 150 μm. Grain area size distributions are compared for DMHT mid and outer locations and the supersolvus disk in Fig. 13. The grain area sizes of the supersolvus disk were significantly smaller than that of mid and outer ring specimens of the DMHT disk, due to the different heat treatment temperature-time paths of these two disks. Facet grain area sizes of the failed specimens are also included for mid, outer, radial, and supersolvus disk specimens in Fig. 13. Grains causing facet failures were in the upper 30% of grain areas measured for each location. Thus, it was apparent that relatively large grains failed in specimens of each location. Such response has been observed in other disk superalloys [11,12]. It would be expected that crystallographic orientation of the large grains would also be important, in order to produce high resolved shear stress to cause facet failures on operative slip planes, and this was proven the case for high cycle fatigue failures of René 88DT in [12]. The stress state within a grain could also be

Fig. 10. Fatigue life versus Smith–Watson–Topper (SWT) stress for fatigue tests in transition zone of DMHT disk, compared to that for tests from uniform subsolvus fine grain and supersolvus coarse grain disks at 427 and 704 °C (15).

affected by the resolved shear stresses of surrounding grains, including their magnitudes and orientations. But clearly, the relative large size of a grain was a first order determinant for facet failures in the current test conditions. Therefore, a properly calibrated correlation of facet size versus fatigue life at relevant conditions could perhaps be analytically combined with the measured distribution of grain sizes at a disk location, to generate probabilistic life predictions there.

It should be noted that grain texture and the percentage of twins and low angle grain boundaries were also compared for the supersolvus and DMHT disks. Texture, twin, and low angle grain boundary content were comparable for the supersolvus and DMHT mid and outer disk locations. Therefore, differences in grain size seemed to be mainly responsible for the differences in fatigue life between the DMHT transition zone and supersolvus disk specimens.

Since relatively large grains within the grain size distribution caused failures, ALA grain size as determined according to ASTM E930 could be used as a simple, well established measurement

for bounding fatigue life in these conditions [19]. The correlation of mean fatigue life is shown versus ALA grain areas for the supersolvus disk and DMHT disks in Fig. 14. ALA grain size correlated well with fatigue life at each temperature, and could be used as a practical predictor for upper bounds of facet grain size. However, it should be understood that facet size will approach but often be smaller than actual ALA size for each disk and specimen location.

Cyclic crack growth rates have been found to moderately decrease with increasing grain size in tests of this LSHR material, and decrease with decreasing temperature [16]. Therefore, the lower fatigue life of the coarser grain DMHT material could not be attributed to reduced crack propagation life, and must be linked in some way to reduced crack initiation life. The lower fatigue life observed at 427 °C compared to 704 °C has also been previously observed in this and other PM superalloys [13,16], and also appears related to crack initiation life differences, including the greater propensity for surface facet failures and higher cyclic stresses observed at 427 °C. Interrupted testing would be necessary to help understand and confirm how crack initiation

Fig. 11. Relationship of grain facet failure size versus life for DMHT and supersolvus disks at 427 and 704 °C. Open symbols indicate surface-initiated failures, filled symbols indicate internal-initiated failures.

Fig. 12. Grain structure of supersolvus disk, showing ALA grain.

life is reduced with increasing grain size and decreasing temperature in these materials.

3.5. Potential future work

Additional work could be performed to improve the understanding and balance of microstructure-fatigue life relationships in the transition zone of disks having location specific microstructures, such as the DMHT disk process. Interrupted testing would allow better understanding of how crack initiation life is reduced with increasing grain size in these materials. Longitudinal sectioning could perhaps uncover multiple cracked grains, to allow an understanding of grain size, crystallographic orientation, and surrounding grain constraints necessary for fatigue crack initiation.

Such knowledge could then be applied to help guide enhancement of transition zone and rim microstructures and

Fig. 13. Comparisons of overall and facet failure grain areas versus cumulative probability for mid, outer, and radial specimens tested at 427 and 704 °C.

Fig. 14. Relationships of ALA grain area versus mean life for DMHT and supersolvus disk specimens tested at 427 and 704 °C.

fatigue properties. Varied disk forging conditions have been found to significantly influence grain size response in powder metallurgy disk superalloys during subsequent heat treatments [20,21]. Therefore, varied forging conditions could be used to tailor grain size and fatigue properties in the transition zone and rim. Cooling rate and aging heat treatments have been found to strongly influence the balance of mechanical properties in most disk superalloys [1,2,22,23], by altering the sizes and volume fractions of secondary and tertiary γ' precipitates. Modified heat treatments such as location-specific air quenching [8] and increased aging time and temperature [24] could be applied to potentially improve fatigue life of the transition zone.

However, cyclic fatigue crack initiation properties would need to be balanced with many other mechanical properties of importance for mechanical design of location specific microstructure disks. Depending on the location and service conditions of a transition zone, these could include cyclic fatigue crack growth, dwell fatigue crack initiation, dwell fatigue crack growth, and also strength and creep resistance, at both uniform and notched locations. Variations in grain microstructure at a fixed location of a location specific microstructure disk have been shown in the present study to have a key influence on cyclic fatigue life. Yet, some other mechanical properties such as tensile and creep resistance may be less sensitive to grain size variations.

4. Summary and conclusions

The fatigue life, failure modes and microstructure of the transition zone of a DMHT disk were characterized using LCF tests, quantitative fractography, and metallography. Specimens located at an inner ring just within the transition zone had fatigue lives comparable to bore specimens, and were much longer than specimens located at mid and outer rings of the transition zone. The bore and inner ring specimens had a fine grain size and failed mostly from internal inclusions. The mid and radius specimens contained both coarse and fine grain size microstructures, but always failed from coarse grain facets. The coarse grain outer ring specimens also failed from large grain crystallographic facets. The grain facet failure initiations resulted in substantially lower fatigue lives.

The grain facets initiating failure were generally larger than the mean grain size, extending to near ALA grain size. The lives of specimens located mid way in the transition zone, with near bimodal grain size, appeared to still be limited by these large grains, with no additional complications due to wider grain size variations.

It can be concluded from this work that the cyclic fatigue failure response of the transition zone region behaves in a predictable manner for this DMHT disk, varying with maximum grain size for the current material and test conditions. Simple screening of mean and ALA grain size may be useful to initially estimate mean cyclic fatigue life in such location specific microstructure disks. Subsequently, a carefully calibrated correlation of facet size versus fatigue life could be analytically combined with measured distributions of grain sizes versus disk location, to generate probabilistic life predictions. Thus, careful control, measurement, and then prediction of grain size distribution as a function of location will be important for accurate cyclic fatigue life prediction of DMHT and other disks having location specific microstructures and mechanical properties. Several processing avenues may offer further refinements of microstructure for enhancing fatigue life. However, other mechanical properties need to be considered for such refinements and optimizations.

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