FATIGUE CRACK INITIATION IN ALLOY 718 AT 650°C

R. G. Andrews*, A. K. Koul** and P. Au**

*Department of Mechanical and Aerospace Engineering
Carleton University, Ottawa, Ontario, Canada
Presently with Hawker Siddeley Canada, Orenda Division

**Structures and Materials Laboratory
Institute of Aerospace Research
National Research Council of Canada
Ottawa, Canada

Abstract

Fatigue crack initiation life of Alloy 718 specimens, subjected to conventional and modified heat treatments, was determined using ASTM E606 small cylindrical specimens and an AGARD designed double edge notch (DEN) specimen in load control at 650°C. Crack initiation lives were monitored for the DEN specimens using a direct current potential drop technique while the ASTM E606 specimens were cycled to rupture. The DEN specimens were tested in two surface conditions. In one set of specimens the notch was lathe cut and in the other set of specimens the notch was electron discharge machined. It is shown that the notch surface condition can dominate the crack initiation life in Alloy 718 at 650°C. It is also shown that the modified heat treatment forms a notch sensitive microstructure which results in a loss in high cycle fatigue life of two orders of magnitude. However, under high strain low cycle fatigue conditions, normally encountered in aircraft gas turbine engine discs, the loss in fatigue life is less severe.

Introduction

High strain low cycle fatigue (LCF) is the major form of damage incurred by many rotating components such as discs, spacers and cooling plates in gas turbine engines during service. The LCF damage is the life limiting factor for over 75 percent of the major rotating components in advanced military engines [1,2]. In order to avoid catastrophic failures, engine manufacturers predict the design lives of discs and spacers on the basis of LCF crack initiation behaviour. With this design method, known as the safe life approach, a set of components is retired after a specified cyclic life has been exhausted. The safe life is typically based on the number of cycles required to initiate a LCF crack in 1 in 1000 components. A major disadvantage of this approach is that 999 components may be retired in a crack free condition. An alternative *damage tolerant* design approach, driven by USAF MIL-STD-1783, demands that in addition to conventional safe life, the components should be capable of withstanding propagating cracks without suffering catastrophic failures.

It has been argued that to take full advantage of the damage tolerance design approach the component microstructure should be redesigned to minimize crack propagation rates [3-6]. Recently, a heat treatment was developed for Alloy 718 which produced a microstructure that reduces creep and fatigue crack growth rates with limited loss in LCF initiation life relative to the conventional heat treatment [5]. This heat treatment was developed as an alternative to the conventional heat treatment presently used for turbine disc applications.

The LCF tests in this earlier work were conducted in strain control using smooth cylindrical specimens conforming to ASTM-E606-80 specifications. This specimen geometry may not have been entirely appropriate, since the LCF life of discs can be significantly influenced by the notch sensitivity of the material and the latter is not accounted for by smooth specimens [7,8]. Therefore, the present study was undertaken to establish the notch sensitivity of Alloy 718 subjected to the conventional and modified heat treatments.

Cracks initiate in discs at discontinuities such as bolt holes because of stress concentrations. Therefore it is important to use a specimen that properly simulates the influence of these discontinuities [9]. A double edge notch specimen (DEN) such as that normally used for fracture toughness testing was selected for this work following guidelines provided under a recent AGARD engine disc cooperative test program [10]. The decision to proceed in this fashion was made since there are no established standards for determining the influence of notch sensitivity on fatigue crack initiation data. The AGARD DEN specimen with its two semi-circular notches [10] is particularly well suited to simulate stress concentrations at bolt holes because of the similarities between notch and bolt hole geometries.

In this paper, the results of stress controlled fatigue tests obtained from the DEN specimens are compared with smooth specimen results with a view to determining the notch sensitivity of the conventional and modified microstructures of Alloy 718. The influence of notch surface preparation on notch sensitivity is also discussed.

Experimental Materials and Test Methods

Materials

The materials for the study came from two sources including stock material in wrought bar form and a service exposed turbine disc. The chemical composition of the bar and the chemistry specification of the disc are given in Table 1. Each material was examined in

the conventional and modified heat treated conditions. In the case of the retired disc, this meant in the as-retired (service exposed) condition and after reheat treatment of half of the disc to obtain the modified microstructure. For the stock material, half of the test specimens were subjected to the conventional heat treatment, and the other half to the modified heat treatment, to produce the conventional and the modified microstructures, respectively. The two heat treatment schedules are presented in Table 2.

Table 1: Chemical compositions of Alloy 718 experimental materials in weight percent.

Material	C	Si	Cr	Fe	Co	Mo	Nb & Ta	Ti	Al	Ni
Wrought Bar (actual)	.04	.12	18.26	18.87	.27	2.92	5.14	1.00	.58	52.57
Turbine Disc (spec)	.02-.08	.35 max	17-21	15-21	1.0 max	2.8-3.3	4.75-5.5	.75-1.15	.3-.7	50-55

Table 2: Summary of Conventional and Modified heat treatment schedules and the overall microstructural features.

Heat Treatment	Heat Treatment Schedule	Average Grain Size (μm)	Grain Boundary Morphology
<i>Conventional</i>	955 °C/1h/AC + 718 °C/8h <u>1 °C/min</u> , 621 °C/10h/AC	10 - 20	Planar
<i>Modified</i>	1032 °C/1h <u>3 °C/min</u> , 843 °C/4h/AC + 926 °C/1h <u>3 °C/min</u> , 718 °C/8h <u>2 °C/min</u> , 621 °C/8h/AC	40 - 50	Serrated

Test Specimens

Details of the two test specimen geometries employed, i.e. the smooth cylindrical specimen and the AGARD recommended DEN specimen, are given in Figure 1. Specimens for the two geometries were produced from the stock material but only DEN specimens were produced from the disc.

For the smooth cylindrical specimens, one of the requirements of the ASTM standard E606-80 is that no circumferential scratches should be visible at a magnification of 25. This was achieved in two steps, first by specifying very light cuts during the machining process and then by polishing the specimens in their longitudinal direction with 400 and 600 grit abrasive paper successively.

The notches in the DEN specimens were lathe cut in the case of specimens machined from the bar stock while they were electron discharged machined (EDM) in the case of specimens produced from the retired disc. A summary of the type of fatigue specimen used including details of their surface condition for each material condition investigated is presented in Table 3.

Fatigue Crack Initiation Testing

Fatigue crack initiation tests were carried out on an MTS servo-hydraulic testing system, at 650 °C under load control using a triangular waveform and a stress ratio (R) of

NOTES

1. All dimensions in mm unless otherwise noted.
2. No undercut at fillets.
3. Use light passes on last several passes to minimize circumferential machine marks in gauge length and at radius.

(a) Smooth Cylindrical test specimen

NOTES

1. All dimensions in mm unless otherwise noted.
2. No undercut at fillets.
3. Reduced section to be smooth and free of scratches.

(b) Double Edge Notch test specimen

Figure 1: Crack initiation test specimen geometries.

Table 3: Summary of fatigue test specimens and material conditions used.

Specimen Material	Specimen Geometry					
	Smooth (Polished)		DEN (lathe notch)		DEN (EDM notch)	
Stock	CON (6)	MOD (6)	CON (7)	MOD (7)	-	-
Service Exposed Disc	-	-	-	-	SE (7)	SE+MOD (7)

CON - Conventional heat treatment

MOD - Modified heat treatment

SE - Service exposed (conventionally heat treated disc)

() - Number of specimens tested

+0.1 at a frequency of 0.1 Hz unless otherwise noted. Details of crack monitoring techniques for the two types of specimens used are as follows.

Smooth Cylindrical Specimen Testing

The smooth cylindrical tests were carried out at three different maximum initial stress levels: 740, 950 and 1100 MPa, which correspond to alternating stress levels of 666, 855 and 990 MPa, respectively at a load ratio (R) of +0.1. These stress levels were selected on the basis of the tensile properties of the modified material, which has a lower ultimate tensile strength (UTS) than the conventional material, Table 4. Due to extremely long test periods, the test frequency for the 666 MPa tests was increased to 5 Hz. The criteria for crack initiation was defined to be specimen rupture. In a small section specimen, Figure 1(a), the crack propagation interval represents a small fraction of the total fatigue life and therefore, the use of specimen rupture as the initiation criterion is considered reasonable.

Table 4: Tensile properties of Alloy 718 at 650°C.

Material	Heat Treatment	Yield Strength (MPa)	Ultimate Strength (MPa)	Yield Strain (%)
Stock Material	Conventional	1060	1170	0.67
	Modified	940	1100	0.60
Turbine Disc	Conventional	1070	1160	0.80
	Modified	950	1100	0.80

Double Edge Notch Specimen Testing

The lathe cut stock specimens were tested at maximum initial notch root stress levels of 775, 1000 and 1060 MPa, which correspond to alternating stress levels of 698, 900 and 954 MPa, respectively at an R value of +0.1. The EDM disc specimens were tested at maximum initial notch root stress levels of 740, 950 and 1100 MPa, which correspond to alternating stress levels of 666, 855 and 990 MPa, respectively at an R value of +0.1. The test frequency was increased to 2 Hz for specimens tested at 666 MPa due to extremely long test periods.

Crack initiation was monitored using a computer controlled, three channel, direct current potential drop (DCPD) technique developed in the laboratory [11]. Four stock material specimens were used to calibrate the DCPD technique and one disc material specimen was used to verify the calibration. The calibration tests were stopped at four different voltage increases ranging from 1 to 1.75% and the specimens were then ruptured by overload. After rupture, fatigue crack demarcations on the specimen fracture surfaces were measured using a scanning electron microscope. The crack initiation criterion was defined as a 1% increase in voltage. The sensitivity of this technique was such that an equivalent straight front crack of depth $50 \pm 20 \mu\text{m}$ (50 ± 3 standard deviations) could be detected repeatedly.

Results

Material Response to Heat Treatment

Optical micrographs showing the microstructure of the stock material subjected to the conventional and modified heat treatments are presented in Figures 2(a) and 2(b). The

average grain size for the stock material was found to be $8.1\text{ }\mu\text{m}$ for the conventional heat treatment and $51\text{ }\mu\text{m}$ for the modified heat treatment. The grain size of the service exposed disc ranged between 10 and $60\text{ }\mu\text{m}$ while the grain size of the modified reheat treated disc material ranged between 45 and $65\text{ }\mu\text{m}$, Figures 2(c) and 2(d) respectively. The modified heat treatment gave rise to a serrated grain boundary structure along with an increased number of annealing twins that were decorated with Ni_3Nb needles.

Smooth Cylindrical Test Results

The stock material fatigue crack initiation data for the conventional and modified microstructures are represented by dotted lines in Figure 3. At the lowest alternating stress level, 666 MPa , the fatigue life of the conventionally heat treated material was 25 times higher than material subjected to the modified heat treatment. Internal crack initiation was found to occur in all specimens tested at this stress level which is a typical feature of high cycle fatigue failure [12,13], Figure 4. At the medium stress level, 855 MPa , the difference between the conventional and the modified material lives was reduced to between ten percent and a factor of three. At the higher stress level, 990 MPa , the modified material initiation lives were an order of magnitude lower than the conventionally treated smooth specimens, Figure 3, because the maximum stress level of 950 MPa is close to the modified material UTS, Table 4. At the medium and high stress levels, both microstructures revealed multiple crack initiation sites where the cracks invariably initiated at the specimen surface.

Double Edge Notch Test Results

The fatigue crack initiation lives of the service exposed and modified reheat treated disc DEN specimens machined by EDM are compared with the smooth specimen lives in Figure 3 (solid lines versus dotted lines). This figure shows that the conventionally heat treated smooth specimen lives and DEN specimen lives are within the test scatter at 855 MPa but at 666 MPa , i.e. under HCF conditions, the DEN specimen crack initiation lives are lowered by a factor of 5. The initiation lives of DEN specimens machined from the modified reheat treated disc are an order of magnitude lower than the modified smooth specimen lives at 666 MPa and a factor of 2 lower at 855 MPa . These observations are indicative of the increased notch sensitivity of the modified microstructure relative to the conventional microstructure at low stresses.

The fatigue crack initiation lives of lathe cut stock DEN specimens are represented by solid lines in Figure 5. The conventional and modified stock material initiation lives are similar at comparable stress levels and the cracks always initiated at the machining marks in all DEN specimens, Figure 6. The smooth specimen stock material results are also superimposed on Figure 5 (dotted lines) for comparison. The initiation life of the conventionally heat treated DEN specimens was over two orders of magnitude lower than the conventionally heat treated smooth specimens at the low stress level and an order of magnitude lower at the medium stress level. However, the DEN specimen initiation life at the high stress level was within experimental scatter of the smooth specimen results for both microstructures.

In all DEN specimens crack initiation occurred straight across the notch face with only small out of plane transitions. It was observed that most specimens contained a limited number of secondary cracks on the notch face.

(a) Conventional heat treatment

(b) Modified heat treatment

(c) Service exposed disc material

(d) Modified reheat treated material

Figure 2: Optical micrographs showing stock and disc material Alloy 718 microstructures.

Etchant - 40 ml distilled water, 20 ml Hydrogen Peroxide and 60 ml Hydrochloric Acid

Figure 3: Smooth cylindrical and double edge notch disc material fatigue crack initiation results for different material conditions at 650°C.

(a) Conventional microstructure

(b) Modified microstructure

Figure 4: Fatigue crack initiation regions of smooth specimens tested at low stress (666 MPa) and 650°C. The faceted surface of the modified microstructure in (b) may suggest separation along the Ni_3Nb decorated noncoherent twin boundaries.

Figure 5: Smooth cylindrical and double edge notch stock material fatigue crack initiation results at 650°C.

Discussion

Smooth Specimen Fatigue Crack Initiation

The stress controlled fatigue tests conducted in the present study reveal a similar trend to that found by Au et al. [4] and Koul et al. [5] where the LCF lives of the conventional microstructure were marginally longer than those for the modified microstructure in strain controlled tests. The longer LCF life of the conventionally heat treated specimens at

855 MPa can be attributed to their higher yield strength and smaller grain size [4,12,13]. The medium stress level of 855 MPa is about 20% lower than the yield strength of the conventionally heat treated material but only about 10% lower than the modified material yield strength. As a result, crack initiation in the modified material specimens occurs at ~ 20,000 cycles whereas crack initiation in the conventionally heat treated specimens occurs at ~ 50,000 cycles. A pronounced decrease in the high cycle fatigue (HCF) initiation life of the modified microstructure relative to the conventional microstructure at the lowest stress level of 666 MPa is perhaps related to the difference in the twin frequency and Ni_3Nb needle density because these microstructural features can act as preferential crack nucleation sites.

Double Edge Notched Fatigue Crack Initiation

The fatigue life of DEN specimens can be influenced by the notch sensitivity of the notch. Despite significant differences in the microstructure and defective machining of the notch. Despite significant differences in the Ni_3Nb precipitate distribution between the conventional and modified microstructures of the lathe cut DEN specimens, Figure 2, their initiation lives were similar at comparable stress levels, Figure 5. Alloy 718 has been found to become notch sensitive as a result of an increase in the size, amount and distribution of the Ni_3Nb precipitates [7] but the present results, suggest that the lathe cut machining marks controlled the fatigue lives of the stock material DEN specimens. Therefore, it is suggested that the reduction in the initiation lives of the stock material DEN specimens relative to the smooth specimens was caused by the presence of machining marks which acted as stress raisers and increased the notch root stress. The machining marks also influence crack initiation by forming straight crack fronts with marginal curvature through the specimen thickness, Figure 6.

Figure 6: Fracture surface of lathe cut conventional microstructure DEN specimen tested at low alternating stress (698 MPa) and 650°C.

The fact that the service exposed turbine disc DEN specimen LCF initiation lives, at medium to high stresses in Figure 3, were generally similar to the conventionally heat treated smooth specimen lives suggests that the conventional Alloy 718 microstructure is not notch sensitive. The corollary to this observation is that the smooth specimen can be used to simulate the effect of material defects at the notch root so long as the material is not notch sensitive [4,5,13,14].

Under HCF conditions, i.e. at 666 MPa in Figure 3, the service exposed DEN specimen lives were observed to be 5 times lower than the lives of the conventionally heat treated stock material smooth specimens in spite of their similar tensile properties. The notches in the service exposed disc material specimens were machined by EDM and then finished

with 600 grit paper to remove any debris from the notch surface. It will be recognized that EDM leaves a thin cast material layer on the specimen surface which is often brittle and this brittle layer is only partially removed by the 600 grit paper polishing. Under HCF conditions, where near surface microstructural features dominate crack initiation, this cast layer could be expected to promote early initiation in the DEN specimens. The HCF life of the service exposed disc specimens could also have been lowered due to damage accumulation during service. The relative contribution of cast layer formation due to EDM and service induced damage towards the overall decrease in HCF life remains unclear at this stage.

Figure 7: Disc material fatigue crack initiation regions in DEN specimens tested at 650°C. Note initiation sites at cleaved grain facets in (b) and (d) and at the surface in (a) and (c).

Relative to the modified smooth specimen lives the initiation lives of disc DEN specimens subjected to the modified reheat treatment were shorter by an order of magnitude under HCF conditions and by a factor of 3 under LCF conditions, Figure 3.

This loss in fatigue life in notched specimens is considerably greater than that observed in as exposed, i.e. conventionally heat treated, notched specimens suggesting that the modified heat treatment makes Alloy 718 notch sensitive. The modified microstructure contains profuse amounts of Ni_3Nb precipitates at the grain boundaries and abundant twinning and these microstructural features may give rise to a notch sensitive material [7,8]. In fact, the DEN modified specimens initiated transgranular cracks at the notch root along cleaved grain facets at medium and high stresses, while the conventionally heat treated specimens appear to have initiated cracks at the specimen surface, Figure 7. These observations further indicate that the modified material becomes notch sensitive due to Ni_3Nb decorated twin boundaries.

The DEN fatigue crack initiation results suggest that the modified heat treatment significantly reduces the initiation life of both stock and disc Alloy 718 materials. In the preceding discussion it has become clear that surface quality of DEN specimens, i.e. lathe machining, can completely overshadow the effects of microstructure on crack initiation life. In addition, the EDM of DEN specimens also contributes to a loss in fatigue life in both conventionally and modified heat treated materials. Currently, work is being planned to test DEN specimens machined using the same techniques as those used to machine the turbine disc bolt holes. These specimens will be tested in a shot peened condition using shot peening parameters similar to those used to process the turbine discs.

Conclusions

- The technique used to machine the notches in the DEN specimens was found to significantly affect the crack initiation life of Alloy 718 material. The lathe cut notches in the stock material specimens significantly reduced the initiation life because the machining marks on the notch face acted as stress raisers, while the electron discharge machined notches in the disc specimens did not reduce the initiation life to the same extent.
- The results confirm that a smooth cylindrical specimen can be used to study the effect of notch root stress concentrations on the fatigue life of materials that are not notch sensitive.
- The initiation life of the modified heat treated material was lower than the conventionally heat treated specimens in the case of both smooth cylindrical and DEN specimens. This loss in initiation life was considerably larger for the DEN specimens because the modified heat treatment renders Alloy 718 notch sensitive. The notch sensitivity of the modified microstructure decreases with increasing stress. Further work is required to precisely quantify the notch sensitivity of the modified Alloy 718 microstructure using specimens representative of a turbine disc bolt hole and rim slot surface condition.

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