NDE Reliability using Laboratory Induced Natural Fatigue Cracks

Vamsi Krishna RENTALA [1], Phani MYLAVARAPU [2], Jai GAUTAM [1], Vikas KUMAR [2]

[1] University of Hyderabad, Hyderabad, India
[2] Defence Metallurgical Research Laboratory, Hyderabad, India

Contact e-mail: vamsikrishnarentala@uohyd.ac.in

Abstract. Successful implementation of damage tolerance methodology requires estimation of the reliability of the currently practiced non-destructive testing (NDT) techniques in the aero-engine industry. Reliability of the NDT techniques is measured in terms of probability of detection (POD). POD is dependent on material, geometry along with size, shape, location and type of the defect. Experimental estimation of POD usually requires large number of service expired aero-engine turbine disks. Alternatively, the POD studies can also be carried out using laboratory induced samples (as per MIL-HDBK-1823A) containing various sizes of defects. In the current study, 55 mm x 10 mm x 10 mm nickel based super alloy samples were extracted from a mid-life service expired turbine disc. A 2 mm radius circular notch was created at the centre of the specimen so as to represent the true stress concentration factor present near the bolt hole location of a turbine disc. Samples were subjected to repeated stress fatigue cycling using a 3-point bend set up with a constant load of -6.5 kN and stress ratio of R = 0.1. All these samples were subjected to constant number of fatigue cycles (1.05 x 10^5) under room temperature high cycle fatigue (HCF) conditions. 50 different cracks ranging from 0.1 mm – 2.0 mm sizes were observed in these fatigued samples. Fluorescent penetrant and eddy current inspection tests were carried out on the specimens for qualitative (Hit/Miss) defect indications. Further, Hit/Miss data obtained from both the techniques was analysed and the POD curve was plotted. Finally, the $a_{90/95}$ (flaw detection with 90 % probability and 95 % confidence) values of penetrant and eddy current inspection studies of naturally grown fatigue cracks were reported to be 1.13 mm and 0.98 mm, respectively.

1. Introduction

Extensive life revision programs has to be carried out for increasing the overall life of aero-engine components and in turn the whole aero-engine itself. Among the existing lifing methodologies, damage tolerance life design methodology is currently being adopted by all engine manufacturers and users globally. However, successful implementation of damage tolerance methodology for aero-engines requires the estimation of safe inspection intervals for carrying out NDT inspection of the components [1]. Hence, estimating the reliability of the currently practiced non-destructive testing (NDT) techniques is a must for adopting damage tolerance methodology. Probability of detection (POD) being a standard metric for measuring the non-destructive evaluation (NDE) reliability usually requires huge number of service expired aero-engine components. Several researchers [1-4] have used various service expired aero-engine components and in-service NDE inspection data for performing POD studies. However, carrying out this kind of methodology is a challenging task as it completely depends on the availability of the retired components. Alternatively, various researchers [5] and [6] have also used several methods of generating POD samples as per the methods and procedures mentioned in MIL-HDBK-1823A. According to MIL-HDBK-1823A, EDM notches and starter cracks can be introduced in to the laboratory samples and can be used for the POD studies. However, as the width of the EDM notches is fixed i.e., approximately 0.3 mm and cannot be varied, these notches are unfit for the purpose of replacing actual engine cracks. Real fatigue cracks have both the length and width variations. In addition, POD studies also accounts for both the dimensions of the cracks rather than only the length of a crack. Further, EDM notches also do not represent the actual stress concentrations present in the aero-engine components. Hence, it can be clearly understood that there is a need for samples with cracks representing the actual engine cracks for carrying out POD studies. The current authors had proposed a novel method of generating natural fatigue cracks in POD samples that represent the actual stress concentration present near the bolt hole location of a turbine disc [7] and [8]. However, their study varies number of fatigue cycles for generation of different lengths of fatigue cracks. It can be noted that the number of fatigue cycles that the actual aero-engine components experience is always a constant and does not vary. Hence, in the current study all the samples were prepared at a constant load and constant number of fatigue cycles. The statistical nature of fatigue aids in generating cracks of various dimensions and hence can be used as a valuable input for POD samples. Further, all these samples with laboratory induced natural fatigue cracks can be inspected using various NDT techniques. However, in the current study all these samples were inspected only with fluorescent penetrant inspection (FPI) and eddy current inspection (ECI) techniques. In addition, FPI being a qualitative inspection technique, ECI studies were also recorded only in the qualitative (HIT (defect detected) /MISS (defect undetected)) mode. Further, the HIT/MISS data obtained from both the techniques are processed for POD curve generation along with the 95 % lower confidence bounds using log-odds distribution method.

2. Experimental Procedure

2.1. Material Selection

A representative Nickel based super alloy material was chosen for the current POD studies. It was extracted from an aero-engine turbine disc at mid-life service. Typical chemical composition of the material comprises of C (0.04-0.08 wt %), Fe (1 wt %), Mn (0.4 wt %), Si (0.6 wt %), Ti (2.65-2.9 wt %), Cr (19-22 wt %), Al (0.7-1 wt %) and Ni as the remaining with minor additions of Pb, B, Cu and Ce.

2.2. Specimen Design

The material extracted from the used turbine disc was designed as per the standard specimen typically used for an turbine disc bolt hole location. The specimen is designed with dimensions of 55 mm x 10 mm x 10 mm with a 2 mm radius circular notch at the center so as to represent the actual stress concentration factor (k_t = 3 for a circle) present near the bolt hole location of an aero-engine turbine disc. Figure 1 shows the specimen geometry.

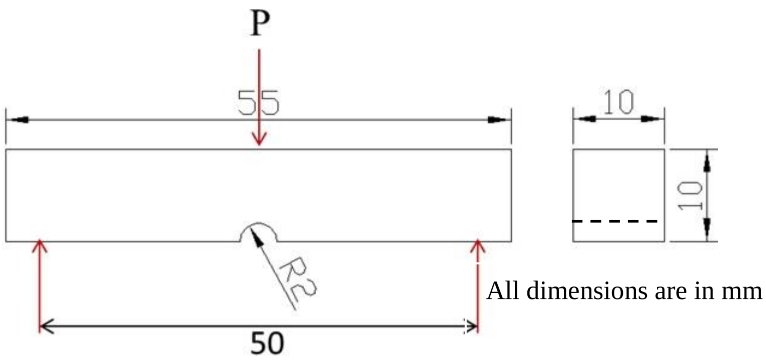

Figure 1: Specimen design showing load point and supports

2.3. Fatigue loading and generation of natural fatigue cracks

Conventionally, as the fatigue failure is mainly a surface phenomenon, any sample is usually mirror finished before carrying out fatigue testing. However, in the current study, samples were used in the as received condition so as to maintain the same surface roughness values as that of service expired disk (R_a~0.8 µm (measured using surface profilometer)). In addition, all the samples were fatigue tested by applying a 3-point bend loading phenomenon. From Figure 1, it can be observed that the load is applied at the centre of the sample whereas the supporting points were positioned at 25 mm on each side from the centre of the notch or sample. All the samples were fatigue tested at a constant load of -6.5 kN with a stress ratio of R = 0.1and 1.05 x 10^5 constant number of fatigue cycles. Due to the statistical nature of fatigue, various cracks were initiated with different dimensions.

2.4. NDT inspection of natural fatigue cracks

2.4.1. Fluorescent Penetrant Inspection (FPI)

The natural fatigue cracks generated on all the samples were used for the HIT/MISS POD studies. These fatigue cracks were initially inspected using FPI technique. A high sensitive commercially available penetrant was applied on all the samples after thoroughly cleaning them. The applied penetrant is left for a dwell time of 20 minutes such that the penetrant can penetrate in to the defects. Further, on completing the dwell time, the sample surface is gently cleaned so as to not remove the penetrant from the defects. Finally, developer was applied on the samples for a dwell time of 10 minutes. All the HIT/MISS indications were tabulated accordingly.

2.4.2. Eddy Current Inspection (ECI)

In addition to FPI inspection technique, ECI was also carried out on all the POD samples. M/s. Olympus, U.S.A made ECI test set up was used for the inspection purpose. A pencil probe of 500 kHz was used to scan over the sample surface for the defect detection purpose. Presence of a surface defect on the scanned surface results in a change in impedance which can be recorded and identified as corresponding to a defect. In the current study, only qualitative defect indications such as a HIT/MISS of the Eddy current inspection technique were noted.

2.5. Crack Size Measurements

Laboratory induced natural fatigue cracks were measured for the crack dimensions such as length and width using field emission scanning electron microscope (FESEM) made by M/s. FEI Ltd, Netherlands after all the NDT inspections were carried out. As all the fatigue cracks are surface cracks, the depth of the crack is unknown or negligible. Hence, efforts were made only to measure the crack length and crack width. However, unlike the crack length, the crack width cannot be measured directly due to the random crack opening at the crack origin and crack tip locations. Hence, in the current study, all the crack width values reported were average crack width at origin, middle of the crack and at the crack tip.

3. Results and Discussion

Minimum detectable crack size is an essential requirement for the calculation of safe inspection intervals in the implementation of damage tolerance methodology. However, the minimum detectable crack size by an NDT technique is completely dependent on its reliability. POD being a standard measure of NDT reliability requires large number of service expired components as samples for carrying out this task. In the current study, an alternative method of generating natural fatigue cracks for carrying out the POD studies was proposed. The results obtained in the current study were discussed below.

3.1. NDT inspection of natural fatigue cracks

Table 1 shows the HIT/MISS defect indications obtained from both the FPI and ECI techniques. In Table 1, the HIT (defect detected) indications are represented with "H" whereas the MISS (defect undetected) indications are represented with "M". From Table 1, it can be observed that the total numbers of fatigue cracks detected by FPI and ECI techniques are 13 and 18, respectively. Further, crack sizes measurements obtained using FESEM are also shown in Table 1.

3.2. Crack sizes generated

Table 1 shows the crack dimensions measured using FESEM. From Table 1, it can be observed that the samples 1, 11,16 and 20 does not contain any fatigue cracks on both the sides whereas for some samples cracks were initiated only on one side i.e., either side1 or side 2. In addition, multiple cracks were also initiated in most of the samples. This kind of variation in the generation of fatigue cracks for the same loading conditions can be attributed to the random or statistical nature of fatigue. This randomized nature of fatigue represents the true engine conditions as the cracks cannot be observed at every bolt hole location after a certain number of fatigue cycles. In addition, the total number of fatigue cracks generated is 52. Further, it can also be observed that the minimum and the maximum crack lengths were 0.09 mm and 1.66 mm, respectively whereas the crack widths are 0.32 µm and 4.05 µm, respectively. Figure 2 shows the natural cracks originated in the sample 6-side1 and sample 19-side 2. From Figure 2, it can be observed that the largest crack lengths in sample 6 and sample 19 are 0.65 mm and 1.61 mm, respectively. In addition, the crack widths are 4.05 µm and 0.92 µm, respectively. It can also be observed that the notch location consists of multiple fatigue cracks. Moreover, crack branching and tortuosity can also be clearly observed. These cracks were exactly similar to the actual fatigue cracks originated in a turbine disc [7], [9-11]. Hence, these cracks can be readily used for carrying out the POD studies.

3.3. Correlation of Crack sizes with respect to NDT response

From Table 1, it can be observed that the minimum detectable crack sizes by FPI and ECI techniques are 0.57 mm and 0.43 mm, respectively. In addition, it can also be observed that there are crack sizes higher than the minimum detectable crack sizes that go undetected. This can be attributed to the narrow width (< 1μm) of these fatigue cracks [7]. Figure 2(c) and 2(d) shows the crack widths of sample 6-side 1 and sample 19-side 2. From Figure 2(d), it can be observed that the crack width of sample19-side2 is 0.92 μm i.e., < 1 μm. Hence, this study is in well agreement with the literature [7]. Further, the HIT/MISS POD data of both the techniques was processed using log-odds distribution function for plotting the POD curves and hence the $a_{90/95}$ (flaw size with 90 % probability and 95 % confidence) value.

Table 1: Crack Dimensions along with FPI and ECI HIT/MISS indications

ID	side 1		FPI	ECI	side 2		FPI	ECI
	L, mm	W, µm			L, mm	W, µm		
S1	-	-	-	-	-	-	-	-
S2	0.09,0.61,0.61	1.1, 1.2	H	H	1.59	1.65	H	H
S3	-	-	-	-	0.31	0.68	M	M
S4	-	-	-	-	0.24	0.76	M	M
S5	0.75	1.32	H	H	0.13	0.66	M	M
S6	0.65,0.19	3.45,0.79	H	H	1.66	3.17	H	H
S7	1.57	1.79	H	H	-	-	-	-
S8	0.17,0.78	0.68,1.38	H	H	0.14	0.77	M	M
S9	0.31	0.64	M	M	0.17	0.51	M	M
S10	0.46	0.47	M	H	0.09	-	M	M
S11	-	-	-	-	-	-	-	-
S12	0.43,0.11,0.09	0.66,0.40,0.39	M	H	0.72	1.65	H	H
S13	0.12	0.44	M	M	0.18,0.35	-	M	M
S14	-	-	-	-	1.20	1.69	H	H
S15	0.26	0.68	M	M	0.57	2.28	H	H
S16	-	-	-	-	-	-	-	-
S17	0.12,0.39,0.09	0.46,0.36,0.64	M	M	0.26	0.53	M	M
S18	0.08,0.05, 0.48,0.20,0.06	0.86,0.55,0.35	M	H	0.61,0.16	0.99,0.42	H	H
S19	0.22,0.19,0.22,1 .15	0.99	H	H	1.61,0.17 ,0.17	0.92,0.62	M	H
S20	-	-	-	-	-	-	-	-
S21	0.53, 0.23,0.34	0.40	M	H	0.47,1.04	0.38,1.13	H	H

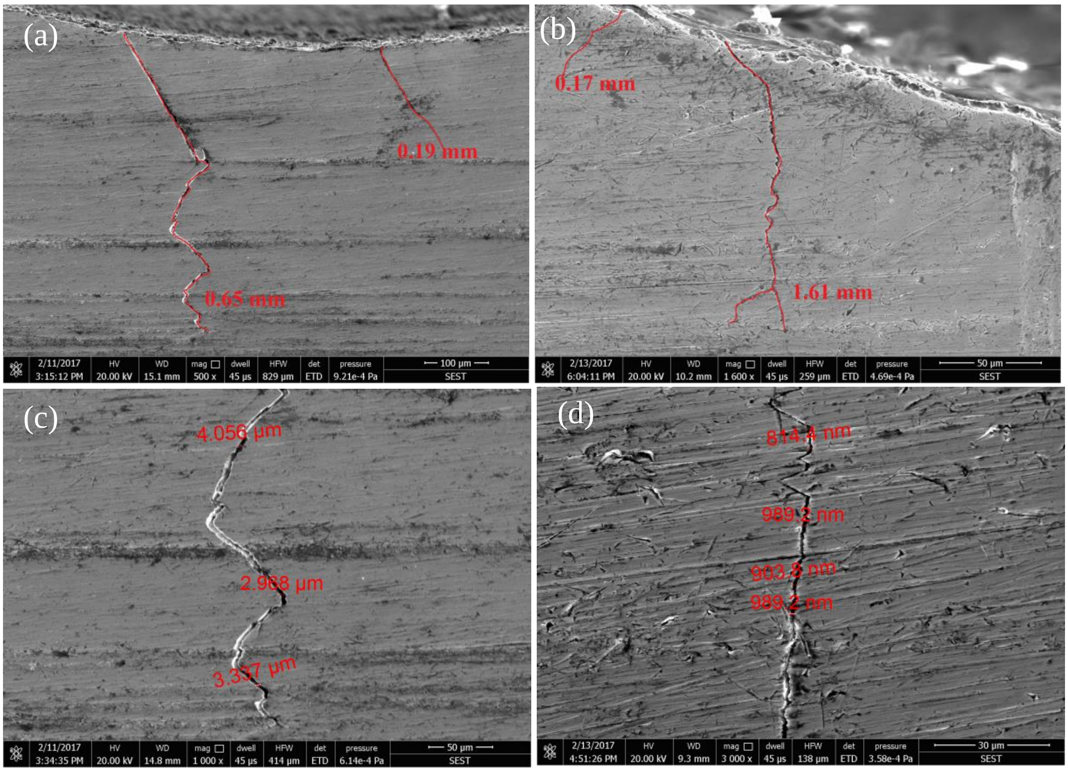

Figure 2: SEM Micrographs of fatigue cracks in (a) & (c) sample 6- side1, (b) & (d) sample 19-side 2 showing the measured crack dimensions

3.4. POD of FPI and ECI Techniques

As a conventional procedure for carrying out HIT/MISS POD studies, in the current study log-odds distribution was used for plotting POD curves. The functional form of the log-odds distribution function is represented as

$$P_i = \left[\frac{e^{(\alpha+\beta.\ln(a_i)}}{\left(1+e^{(\alpha+\beta.\ln(a_i))}\right)}\right] \tag{1}$$

From the Equation 1, the regression parameters such as α and β were estimated using a logit link function. The functional form of the logit link function is represented as

$$\text{logit(p)} = \log\left(\frac{p}{1-p}\right) = \alpha + \beta.\ln(a_i) \tag{2}$$

Using the HIT/MISS data obtained from both FPI and ECI inspection techniques, the cumulative distribution function (CDF) of log-odds distribution function was plotted with the regression parameters obtained from the logit link function. The CDF of the log-odds distribution function actually represents the POD vs. a curve. Figure 3 shows the POD curves of both FPI and ECI inspection techniques. From Figure 3, it can be observed that the POD values i.e., the $a_{90/95}$ (flaw size detected with 90 % probability and 95 % confidence) were 1.13 mm and 0.98 mm for FPI and ECI inspection techniques, respectively. In addition, it can also be observed that the $a_{90/95}$ value obtained from ECI technique was less than the value obtained from FPI. This can be attributed to the high sensitivity of the ECI technique than the FPI technique.

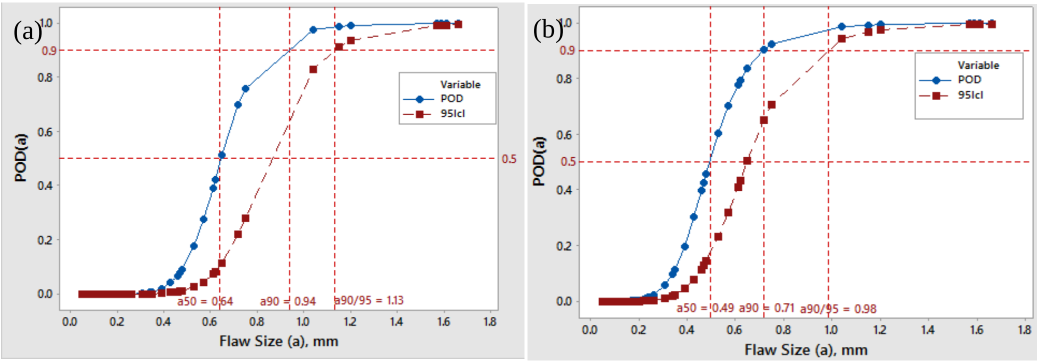

Figure 3: POD curves indicating $a_{90/95}$ values of (a) FPI (b) ECI Techniques

4. Conclusions

- Conventional procedures for carrying out the POD studies pose certain challenges and drawbacks associated with it.
- In the current study, an alternative approach for generating POD samples was demonstrated.
- These laboratory induced natural fatigue cracks comprise of similar morphological features as that of actual engine fatigue cracks.
- $a_{90/95}$ values obtained from FPI and ECI techniques were 1.13 mm and 0.98 mm, respectively. As the ECI technique is highly sensitive than FPI, the $a_{90/95}$ value is lower for ECI such that it represents high probability of detecting a crack with same size than FPI.

Acknowledgements

The authors express their gratitude to Director, DMRL for the encouragement provided to publish this work. The funding provided by Defence Research and Development Organization (DRDO) to carry out the work is acknowledged. One of the authors, Mr.Vamsi Krishna Rentala is also thankful to the Council of Scientific and Industrial Research (CSIR), India (ACK. No.: 141308/2k15/1, File No.:09/414(1124)/2016 EMR-I) for the financial support extended.

References

[1] A.K. Koul, N.C. Bellinger, A. Fahr, Damage-tolerance-based life prediction of aero-engine compressor discs: I. A deterministic fracture mechanics approach, International Journal of Fatigue 12(5) (1990) 379-387.
[2] B. Sasi, B.P.C. Rao, T. Jayakumar, Dual-frequency eddy current non-destructive detection of fatigue cracks in compressor discs of aero engines, Defence Science Journal 54(4) (2004) 563.
[3] M. Şimşir, A. Ankara, Comparison of two non-destructive inspection techniques on the basis of sensitivity and reliability, Materials & Design 28(5) (2007) 1433-1439.
[4] D.S. Forsyth, A. Fahr, D.V. Leemans, K.I. McRae, S. Kallsen, C. Nessa, D.O. Thompson, D.E. Chimenti, L. Poore, Development of POD from in-service NDI data, AIP Conference Proceedings 509(1) (2000) 2167-2174.
[5] R.J. Lord, Evaluation of the Reliability and Sensitivity of NDT Methods for Titanium Alloys, DTIC Document, (1974).
[6] G.R. Romanoski, The fatigue behaviour of small cracks in aircraft turbine disk alloys, Massachusetts Institute of Technology, (1990).
[7] Vamsi Krishna Rentala, Phani Mylavarapu, J.P.Gautam, Vikas Kumar, " POD estimation of NDT techniques using natural fatigue cracks", submitted to Engineering Failure Analysis in July (2017).

[8] Phani Mylavarapu, Vamsi Krishna Rentala, M.Sundararaman, Vikas Kumar, H. Gokhale, Sensitivity evaluation of NDT techniques on naturally initiating fatigue cracks-An experimental approach for a POD framework, in: DRDO-DMRL-NDTG-083, DMRL Technical Report, Hyderabad, (2015).
[9] M. Kemppainen, I. Virkkunen, J. Pitkanen, R. Paussu, H. Hanninen, Comparison of Realistic Artificial Cracks and In-Service Cracks, Journal of Nondestructive Testing 8(3) (2003) 1-6.
[10] M. Kemppainen, I. Virkkunen, J. Pitkänen, R. Paussu, H. Hänninen, Advanced flaw production method for in-service inspection qualification mock-ups, Nuclear Engineering and Design 224(1) (2003) 105-117.
[11] A.A. Shanyavskiy, Y.A. Potapenko, In-service fatigue fracture mechanisms in covered disks of a TV3-117VK helicopter turbine engine, Strength of Materials 40(1) (2008) 158-161.