RESULTS OF PROFICIENCY TEST PROGRAMME ON FATIGUE CRACK GROWTH IN AN AIRCRAFT 7175-T7351 Al-ALLOY WITH PROBABILITY LIFE ASSESSMENT EXAMPLE

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Abstract

Existing exact knowledge on fatigue crack growth parameters and characteristics is an essential condition for an application of Damage Tolerance design philosophy in dynamically loaded structures. Measurement of fatigue crack growth (FCG) rates in an Al 7175-T7351 alloy of a particularly high homogeneity was carried out as a part of the Proficiency Test Programme organised by Exova in France. Results were evaluated in terms of parameters *C* and *m* of the Paris dependence in the stable growth region. To pass the test programme successfully, a particular attention was paid to improve and verify DCPD (direct current potential drop) method being used for the crack length measurement. The attention paid to the experimental methodology bored fruit - the results obtained were close to the average of results measured at different accredited worldwide aircraft laboratories. Additionally, the results of the FCG measurements generated by different participating laboratories were further analyzed. A distinct correlation between *C* and *m* values, so called “coupling”, was found and demonstrated. Some paradoxes of the assessment of laboratories were addressed, namely the fact that a laboratory assessed as unacceptable concerning one of the parameters generated much more accurate and useful data than another laboratory with a better assessment. Eventually, the results including their scatter were used to provide an example of probabilistic assessment of a simple beam residual life to show practical actual impacts of the scatter on the life assessment.

Keywords: Fatigue crack growth, Proficiency Test Programme, Al 7175 alloy, probability assessment

1. INTRODUCTION

Al 7075 alloy is a high strength material usually used for highly stressed components in lightweight structures, typically in aircraft, aerospace and defence applications [1]. It can be applied in different heat treatment conditions, but the T7351 temper state is most widely used because of improved stress-corrosion cracking resistance. The content of alloying element (weight %) is Cu 1.2 - 2, Mg 2.1 - 2.9, Zn 5.1 - 6.1 and Cr 0.18 - 0.28. Typical mechanical properties are R_m = 505 MPa, $R_{p\,0.2}$ = 435 MPa, elongation at break 13% and fatigue strength (limit) 150 MPa.

Damage Tolerance design philosophy, accepting an existence of defects or cracks with lengths below a danger limit, is being frequently used in connection with the necessity to reduce total weight of structures and to exploit their potential service life to the maximum extent not only in such industrial branches like aircraft, but also gradually in other fields, e.g. railway structures and components [e.g. 2]. Therefore, an exact knowledge about FCG rates, sufficient amount of correct and exact data being at disposal and knowledge about various affecting factors is a very important basis for an assessment of residual fatigue life of structures and their in-service safety and reliability.

Though experimental evaluation of FCG rates belongs to works being performed in a very large number of accredited laboratories, this measurement is sophisticated and exacting task. Therefore even laboratories performing tests for aircraft industry have to undergo audits on a regular basis. Very effective tools for verification of the laboratory quality are so called Proficiency Testing Programs (PTP) or Round Robin Tests (RRT). Note that Round Robin methods are also being used to make research targets more accurate, particularly in fatigue life predictions in aircraft industry [3], where the required precision is extremely high, e.g. one to million, but also in other industrial fields like marine [4] or elsewhere [5].

PTPs are statistical quality assurance programs that enable laboratories to assess their performance in conducting test methods within their own laboratories when their data are compared against other laboratories that participate worldwide in the same program. Proficiency testing, also called also called interlaboratory comparison, determines the performance of individual laboratories for specific tests or measurements and is used to monitor laboratories' continuing performance.

In a proficiency test one or more artifacts are sent around between a number of participating laboratories. Each laboratory measures the specified property according to a given set of instructions and reports its results to the administrator, where the results are compared to the reference value, which can be determined in various ways. The two most common ways are to use a reference laboratory or use the average of the values reported by the participants, the latter was the case of the PTP described in this paper.

In this paper, results of FCG measurement performed in sixteen worldwide laboratories accredited for aircraft industry according to GE Aviation rules on a 7175-T7351 Al alloy are presented, discussed and some problematic points are addressed. As an example of the practical issues of the scatter of results, probabilistic assessment of FCG in a rectangular beam is provided using the PTP data.

2. EXPERIEMNTAL PROGRAMME

The Al 7075-T7351 alloy acquired for the experimental programme was of a particularly high quality. Since it was a material used for a PTP organized by Exova company for laboratories being involved in accredited testing for General Electric Aviation group, it had particularly homogeneous composition, mechanical and fatigue properties. Actual proof stress was 445 MPa, somewhat higher than typical average proof stress of this material. The only disadvantage was a very high price, but on the other hand, the characteristics affected reproducibility of experimental measurements very positively.

FCG measurement was performed according to the ASTM standard [6] on CT specimens of width $W = 75$ mm and thickness 12 mm [7]. Loading was of a sinusoidal type, load asymmetry $R = 0.1$, test frequency $f = 11\text{-}12$ Hz given by the resonance system of the SCHENCK PVQA fatigue machine, where the measurement was performed.

Four specimens were used for the implementation of the PTP programme. Crack length was measured using the modified direct current potential drop (DCPD) method [7, 8]. Basically, analytical calibration curves were used with a specific correction, carefully verified [7].

3. RESULTS AND DISCUSSION

3.1. Fatigue crack growth analysis

After evaluation of all FCG measurements of all participating laboratories, each PTP participant was provided with the results, which contained evaluated parameters C and m of the Paris dependence in the stable crack growth region with standard deviations (SD) for each of the two parameters. In general, the results only were indicated by the laboratory numbers, actual participating laboratories were not known. Number of the SVÚM a.s. laboratory was 300. Values of the parameters C and m are summarized in **Table 1**. Results were sorted to three classes considering the overall standard deviation of all the values. The first "green" class corresponded to the interval ± 1 SD, the second, "yellow" class ± 2 SD and the third "read" class contained results outside ± 2 SD. Graphical interpretation of C and m parameters shown in **Table 1** is in **Figures 1a), b)**, respectively, where mean values are plotted versus horizontal axes and repeatability on the vertical axis. Points corresponding to the SVÚM measurements (laboratory 300) are indicated by green point.

Table 1 Survey of coefficients *C* and *m* of Paris dependence measured at different laboratories

	C		m	
Lab#	**mean**	**SD**	**mean**	**SD**
9	1.469E-08	2.187E-09	3.908	0.05
30	3.593E-07	2.832E-08	2.702	0.04
63	1.234E-07	4.972E-08	3.147	0.18
120	2.436E-07	5.971E-08	2.701	0.12
156	5.545E-08	2.896E-08	3.497	0.18
183	4.730E-07	8.225E-08	2.606	0.06
196	2.956E-07	6.233E-08	2.795	0.08
221	2.326E-10	2.960E-11	2.865	0.05
236	1.305E-07	3.327E-08	3.033	0.09
238	5.783E-07	1.282E-07	2.516	0.08
239	1.290E-07	5.448E-08	3.138	0.15
269	1.476E-07	3.276E-08	3.033	0.08
276	6.006E-07	4.889E-08	2.638	0.03
286	2.126E-07	2.136E-08	2.948	0.03
300	1.517E-07	2.013E-08	2.960	0.01
431	4.499E-07	4.623E-08	2.599	0.05

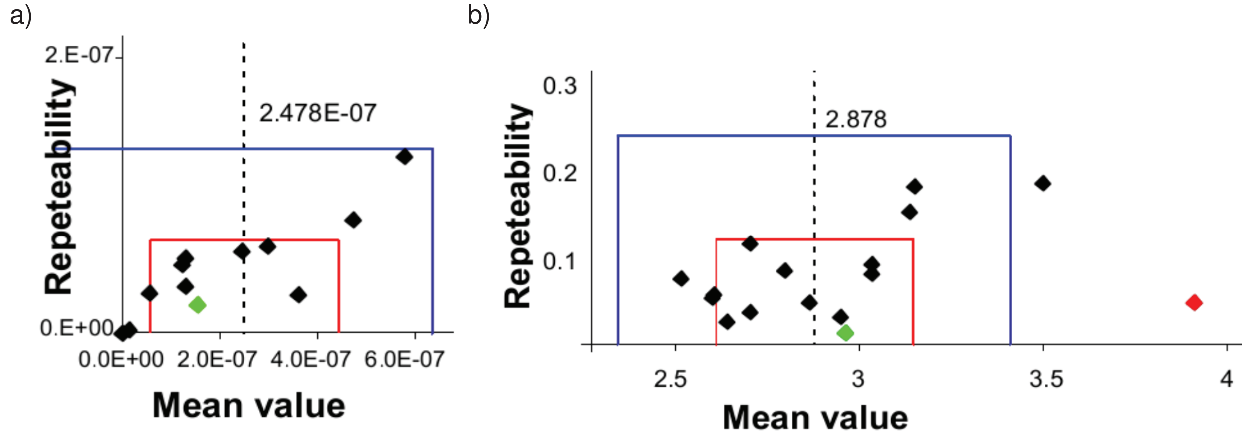

Figure 1 Graphical survey of parameters *C* and *m* measured by different participating laboratories, a) parameter *C*, b) parameter *m*

It follows from **Figure 1** and **Table 1** that one laboratory was completely excluded from the evaluation by Grubbs test and just one m parameter value exceeded the ± 2 SD interval. At first site, such result looks quite good. However, further analyses of the data to find actual impacts of the results on evaluation of residual fatigue life of a component containing crack pointed out some fairly problematic issues, which are discussed in the following part of the paper.

First of all, possible correlation between the *C* and m parameters was investigated. Couples of *C* and *m* values generated in individual laboratories were plotted against each other, namely as a dependence of parameter m on *C*. The results, interesting and quite surprising, are in **Figure 2**.

It follows from **Figure 2** that with the exception of the laboratory 221, values *C* and m are very distinctly correlated to each other. The dependence of *m* on *C* was evaluated by linear regression and can be expressed as $m = 0.395 \cdot C^{-0.130}$ with a high value of R^2 coefficient, namely $R^2 = 0.944$. Even the m value outside the 2 SD interval lies on the same regression line. On the other hand, value of *C* parameter evaluated by the laboratory 221 is exceptionally low and outside the regression line. What is interesting and definitely is a paradox of the whole PTP is the fact that the laboratory 221 was assessed as acceptable having just one parameter in the yellow class whilst the m parameter of the laboratory 156 was assessed as unacceptable. However, **Figure 3** shows that from practical and actual point of view, the situation is quite different.

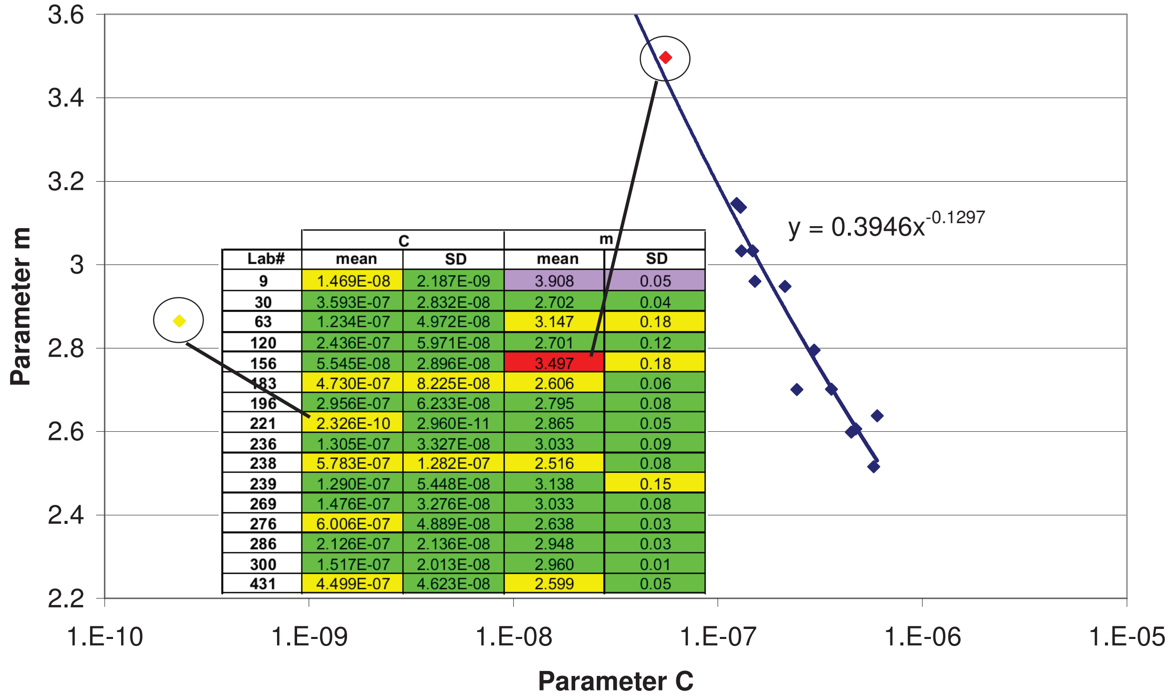

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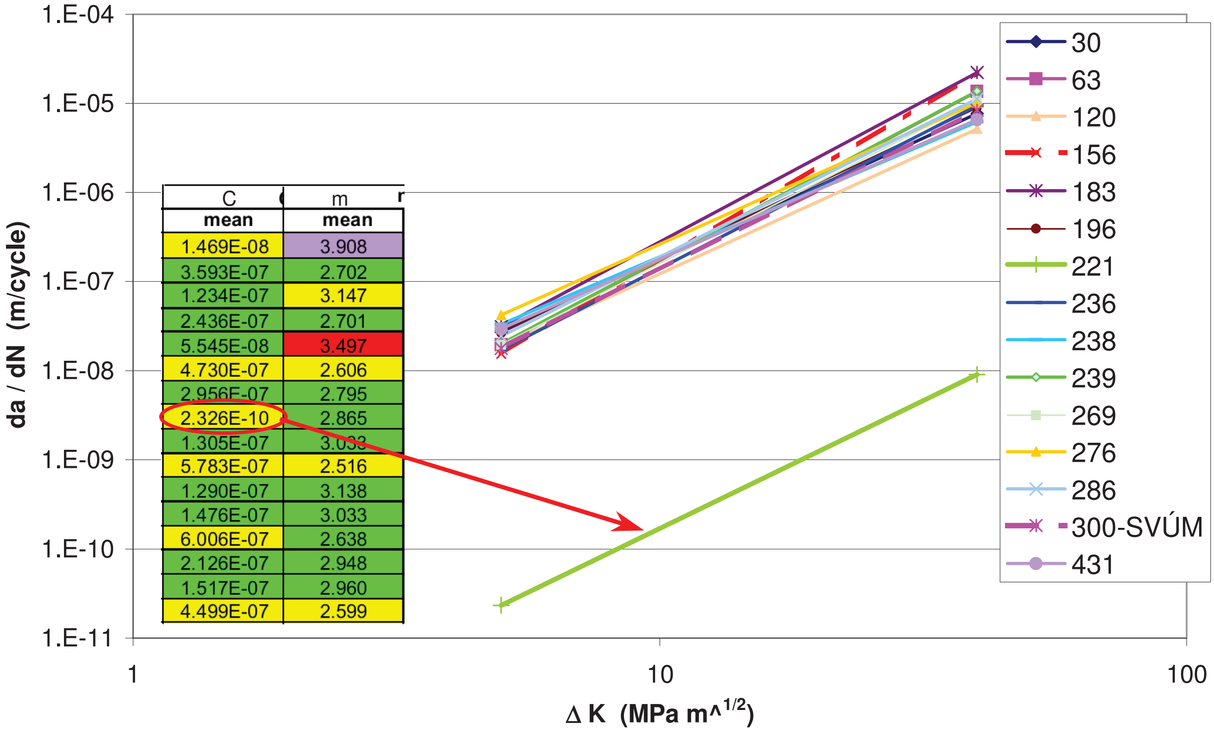
Figure 2 Diagram of mutual correlation between *C* and *m* parameters evaluated at different laboratories



C	m
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Figure 3 Actual FCG lines of different laboratories plotted on the basis of *C* and *m* values

In **Figure 3**, actual FCG regression lines of different laboratories are plotted on the basis of *C* and *m* values evaluated by the individual laboratories. By the way, such results provide a very good and valuable information on FCG values in the material including possible scatter affected more or less just by different experimental methods, as the material itself was very homogeneous. Concerning the SVÚM results of FCG rates, they correspond almost exactly to the average at high stress intensity factor range ΔK, at low ΔK values, the FCG rates are slightly below the average. The regression line of the laboratory 156 with the m value in the read class lies completely within the range of FCG rates of all other laboratories. Therefore, from the practical point of view, its poor classification seems not to be fair. On the contrary, the data of the laboratory 221, evaluated as acceptable, are lying completely outside the scatter bound of the average common regression line and in the whole stable FCG rage, they are practically by three orders lower. Use of such data for assessment of a component residual life could have immense impacts as such estimations would be extremely inconservative. This is one of paradoxes of the C and m coupling and quality assessment of laboratories, if just pure statistics is applied without any thinking.

Actually, the source of the differences of the laboratory 221 should be find elsewhere, namely in the FCG units used for the evaluation of the *C* parameter. FCG rates can be plotted either in mm/cycle or in m/cycle. The PTP conditions were described clearly and requested mm/cycle. The laboratory 221 evidently used m·/·cycle and so, the *C* parameter was by three orders lower. It follows from **Figure 3** that if the line was shifted by three orders higher, even this line would lie within the scatter band of the regression line of all the other laboratories quite well. It was namely a mistake of the PTP organiser that they did not find the actual mistake and included the incorrect results into the statistical evaluation of all other laboratories.

3.2. Example of fatigue life probabilistic assessment

The PTP results including their scatter were used to provide an example of probabilistic assessment of a simple beam residual life to show practical actual impacts of the scatter on the life assessment and to show an idea, how the role of scatter is important. The probabilistic assessment was performed using a special ALIAS HIDA software [9], developed and verified within the 5th Framework Programme projects HIDA and HIDA Applicability [10, 11]. SVÚM a.s. has the software at disposal as a partner of the HIDA Applicability project.

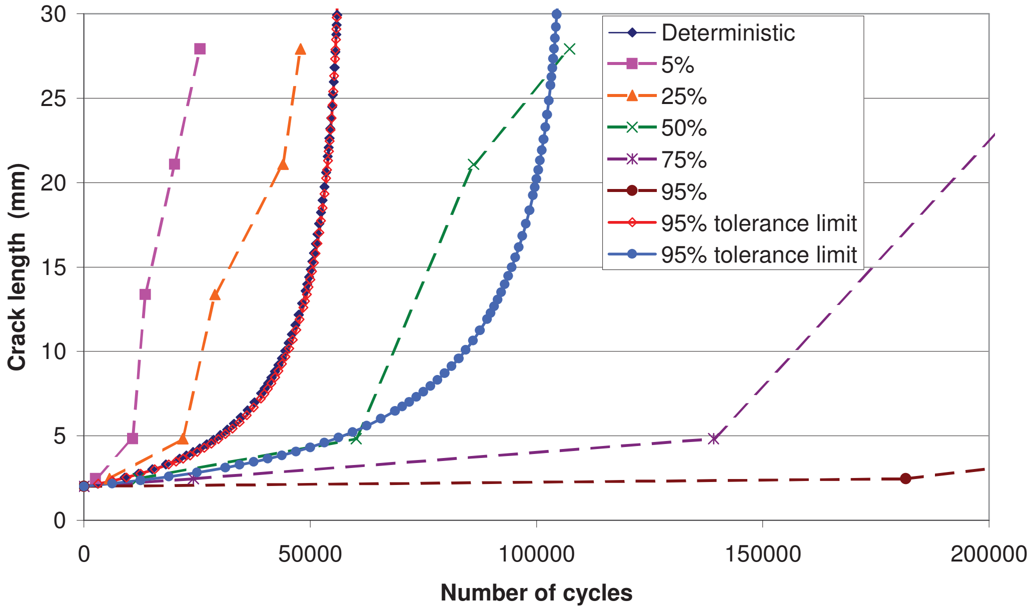

Figure 4 Example of probabilistic FCG assessment in a edge cracked rectangular beam

The ALIAS HIDA probabilistic assessment is being performed using Monte Carlo simulations [9]. Using the PTP results, the *C* and m parameters were randomised considering the best fitting distribution, which was exponential for *C* and normal for m, respectively. Probability of FCG in rectangular beam of 50 mm width and 20 mm thickness with side crack of initial length 2 mm loaded by 70 MPa stress range with load asymmetry

$R = 0$ was calculated. Results are in **Figure 4**. It follows from **Figure 4** that (i) deterministically calculated FCG using average C and m values are within lines calculated using 95 % tolerance limits of data generated at SVÚM and (ii) the range of assessed residual life is very large, likely due to the exponential distribution of the C parameter affected also by the wrong value included into the statistical evaluation, as mentioned in the previous chapter.

4. CONCLUSIONS

Results of PTP on FCG rate measurement with sixteen participating laboratories including SVÚM a.s., with an aircraft accreditation were analysed. A distinct mutual correlation between C and m was found. Some paradoxes were addressed, like very incorrect data of a laboratory with results accepted by the PTP on one hand and quite correct data of a laboratory with an unaccepted result on the other hand. A mistake of the PTP organiser made during the evaluation process was found. The example of the probabilistic assessment confirmed significant effects of the scatter on fatigue life predictions.

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