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PROBABILISTIC APPROACHES TO ASSESSMENT OF FATIGUE CRACK GROWTH IN SELECTED HIGH PRESSURE PIPELINES STEELS

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Abstract: Linear fracture mechanics enables to transfer experimental laboratory measurement of defect growth performed on standard specimens on actual structures. In case of cyclic loading, Paris – Erdogan dependence of crack growth rate on stress intensity factor amplitude is being used. An application of purely deterministic crack growth assessment based on average value of regression line for an evaluation of residual life can be, however, dangerous because of material inhomogenity and scatter of local crack growth values. The residual life assessments can be several times more optimistic than the reality in an actually evaluated structure. Therefore, probabilistic approaches have to be used. In the contribution, probabilistic evaluation of a specific set of crack growth rate measurement in three different types of high-pressure pipeline steels is presented, namely an evaluation by deterministic integration using statistically evaluated tolerance limits of regression lines. A good agreement of this method with another one, more sophisticated, by the Monte – Carlo simulations using the ALIAS HIDA software elaborated within the Framework Programme project "HIDA Applicability" is shown. Results are discussed from the viewpoint of experimental specimen sampling as regards number and position in the intermediate product.

1. Introduction

Estimation of safety and reliability of engineering structures and components containing cracks or crack-like defects are one of the most important application field of fracture mechanics particularly in components, where limited defects can be accepted due to the component size, their high costs and, first of all, loading character. Such the design philosophy, usually called "damage tolerance", formerly "safe life", enables to postpone partial or general repair or put out the structure of operation, which is connected with significant financial savings. In such cases, safety and reliability of further operation, residual life assessment, eventually specification of interval of damage development inspections are important issues.

Linear fracture mechanics is a powerful tool enabling, with a considerable extent, to transfer results measured in standard laboratory specimens to actual structures in operation. In case of cyclic loading, the damage process is described by the well known Paris-Erdogan equation of fatigue crack growth (FCG) rate on stress intensity factor range $da/dN = C\ \Delta K^m$, when dependencies of K-factor on crack length in standard specimens are known and for complicated components, it can be calculated mostly by finite element method or, even better, by boundary integral equations. If inaccuracies caused by different constraint factors are not considered, such transfer of results is basically quite correct.

There is, however, a problem consisting in different type and extent of material inhomogeneity and related scatter of local FCG rate values. In Figure 1, taken from [1], three different characters of material variability are schematically shown, namely low, medium and high variabilities, whereas this classification is dependent on specimen size, where FCG rate

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is evaluated. For example, in small size specimens, the case 3 occurs much more frequent than in large scale components of the same material. Therefore, data basis of FCG rate has to be evaluated using more than one specimen and mean FCG rates are eventually statistically evaluated with regression line. An application of purely deterministic crack growth assessment and evaluation of residual life in a real component just on the basis of the regression line is dangerous and irresponsible, because due to the material inhomogeneity and scatter of local FCG rates, such the assessment can be several times more optimistic than the reality. Therefore, probabilistic approaches have been recently further intensively studied and applied particularly for service life of structures and components exploited to the maximum extent, which is typical for recent years [2-5].

2. Probabilistic Assessment using Tolerance Limits

Besides probabilistic methods of FCG using random simulations, there is another method of the probabilistic assessment, not too complicated and therefore suitable for usual engineering application: a method of FCG calculation using tolerance limits along the regression line given by the Paris law.

FCG rate in a material is determined by the parameters C and m of the Paris law, which specify the dependence on the stress intensity factor range. However, an instantaneous value of FCG can differ from the mean value very significantly, because it is affected by scatter. The scatter can be influenced by the experimental method used, but even if the measurement method is very exact, the source of the scatter comes from a material variability and inhomogenity.

During FCG measurements, fatigue crack length, depending on number of fatigue loading cycles, is measured or monitored at defined intervals. In comparison with these intervals, the material variability can be divided into three groups [1]: (i) fine or intermediate variability, when material properties change in distances comparable with individually measured crack increments, (ii) rough variability, when material properties are different at larger mutual distances, but still within a single specimen and (iii) extreme rough variability, when two different specimens of the same material and orientation have different FCG properties. The three types of variability are schematically shown in Figure 1.

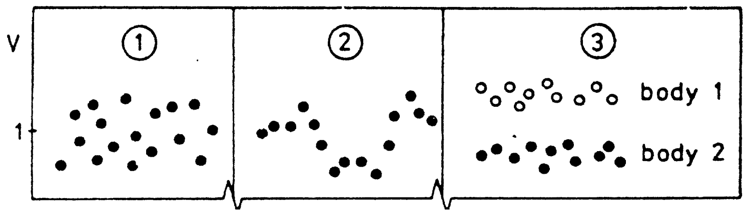

Figure 1: *Schematic diagrams of FCG rates for a constant ΔK at different positions along the crack: (1) fine or intermediate variability, (2) rough and (3) extremely rough variability*

If FCG measurement is performed on more than one specimen of a single type of material, all the experimental points of the batch are usually put into a single diagram and the parameters C and m of the Paris equation are evaluated by linear regression analysis in logarithmic co-ordinates. The parameters evaluated by such the method provide an information on the mean value of FCG in the material, but nothing about the scatter. However, the regression analysis can be carried out with an evaluation of tolerance limits. Tolerance limits for a probability P (percentage of all experimental points), evaluated with a certain significance level α, are values defining with a certain probability, how many percents

(P) of experimental points will lay on the left side (or above) the tolerance limit and how many points (1-P) will be on the right side (or bellow) the limit. Equations for the tolerance limit evaluation can be found in numerous publications on mathematical statistics (e.g. [6]).

It is supposed that for selected points x_i there are random values Y_i, $Y_i = \beta_0 + \beta_1 x_i + e_i$. Medium value $E(e_i) = 0$ and its scatter is σ^2. This model represents linear regression. The coefficients β_0 and β_1 are estimated using minimum square method:

$$b_0 = (\sum x_i^2 \sum Y_i - \sum x_i \sum x_i Y_i) / (n \sum x_i^2 - (\sum x_i)^2) \quad \text{and}$$
$$b_1 = (n \sum x_i Y_i - \sum x_i \sum Y_i) / (n \sum x_i^2 - (\sum x_i)^2). \quad (1)$$

The scatter σ^2 can be estimated by s according to the following expression:

$$s^2 = (\sum Y_i^2 - b_0 \sum Y_i - b_1 \sum x_i Y_i) / (n - 2) \quad (2)$$

where b_0 is an estimation of β_0 and b_1 is an estimation of β_1. All the sums are from i = 1 to n, n being the number of experimental points.

On the assumption that e_i has a normal distribution with the mean value equal to 0 and scatter σ^2, tolerance limits can be estimated by the points:

$$Y \pm \sqrt{(1/n + (x-x_m)^2 / (\sum x_i^2 - n x_m^2))} \; t'(n-2, \delta, \gamma) \; s, \quad \text{where}$$
$$\delta = u_P \; / \; \sqrt{(1/n + (x-x_m)^2 / (\sum x_i^2 - n x_m^2))} \quad (3)$$
$$x_m = \sum x_i / n ,$$

where u_P is normal distribution quantile corresponding to the probability P,
$t'(n-2, \delta, \gamma)$ is quantile of non-central t-distribution,
δ is parameter of non-centrality and
γ is significance level.

The described method is not complicated and can be easily used for any evaluated FCG experiments provided that the basic assumptions about the standard distribution are valid. The method is therefore suitable for applications, if a corresponding computer programme is prepared. The quantile of the non-central t-distribution can be either taken from statistical tables or, better, its calculation by numerical integration of two variables can be included into the programme, too.

3. Experimental Material and Data

The probabilistic assessment method was applied on a batch of FCG experimental measurement, performed using CT-specimens of width 75 mm. Three types of high-pressure gas pipeline steel were used, namely X60, X65 and X70 according to the API 5L standard nomenclature. Corresponding marking according to the EN 10208-2 standard is L 415 MB, L 450 MB and L 485 MB, respectively. Concerning the X60 steel, specimens were taken from three different locations of a long steel sheet – the intermediate product to be used for spiral welded pipes. Specimens taken from the beginning of the sheet were marked *p*, specimens from the sheet center and its end were marked *s* and *z*, respectively. The three steels differ in chemical composition and mechanical properties. The actually evaluated chemical composition and mechanical properties [7] are in the following Tables 1 and 2.

Table 1: *Chemical composition of experimental material in weight percentage*

Steel	C	Si	Mn	S	P	Mo	Al	V	Nb	Ti
X60	0,086	0,24	1,36	0,02	0,005	0,005	0,044	0,014	0,034	0,017
X65	0,12	0,19	1,44	0,014	0,012	0,089	0,044	0,075	0,045	0,039
X70	0,097	0,43	1,64	0,008	0,002	0,079	0,05	0,057	0,055	0,049

Table 2: *Mechanical properties of experimental material*

Steel	Yield Stress (MPa)	Strength (MPa)	Ductility (%)	Area Reduction (%)
X60	434	538	29.2	74.5
X65	454	591	25.1	61.8
X70	491	605	25.1	72.7

The initial crack length in all the specimens was identical, namely 17 mm. All the specimens were loaded with the same nominal stress range, 14.29 MPa. Specimen thickness was 7 mm in case of the X65 and X70 steel, respectively, unlike the X60 steel, where it was 6 mm. Load asymmetry was R = 0.5. Load frequency was between 25 and 30 Hz. Crack growth was recorded as a dependence on number of cycles using DCPD method and computer controlled device developed in the laboratory in the past [8,9]. All the experimental data are shown in Figure 2.

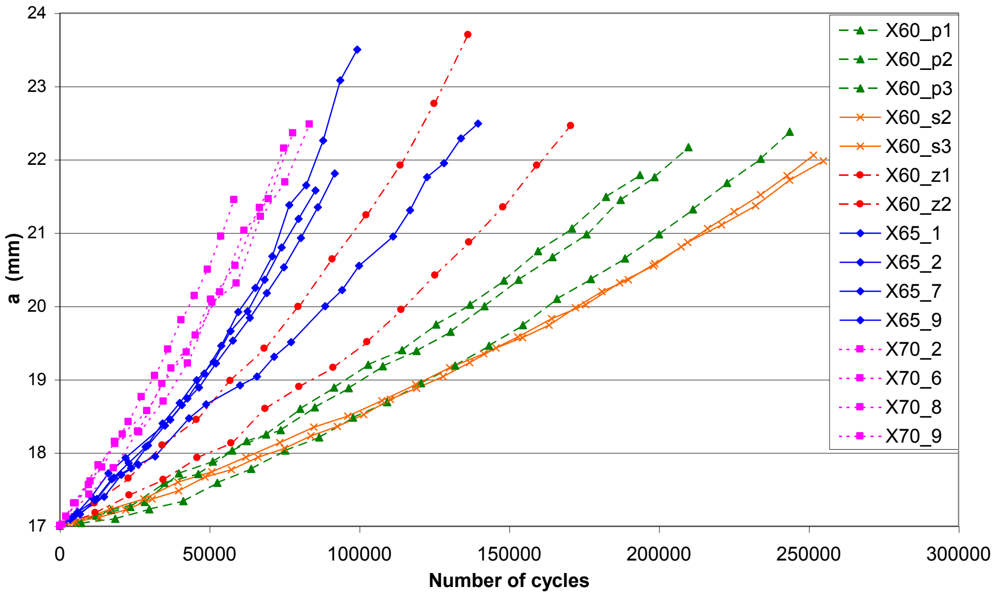

Figure 2: *Set of experimentally measured dependencies of crack length on number of cycles for individual specimens of different steels*

4. Results and Discussion of Probabilistic Assessment in the Pipeline Steels

The agreement of the assessment performed using the method of integration of tolerance limits along the regression line with the more sophisticated method using the

ALIAS HIDA software, i.e. Monte Carlo simulations with the randomised parameter C of the Paris equation, was verified using another set of FCG data in an Al-Cu4-Mg alloy [10]. The results are shown in Figure 3. There is a very good agreement between the two methods with the exception of very high probability of failure over 99 %.

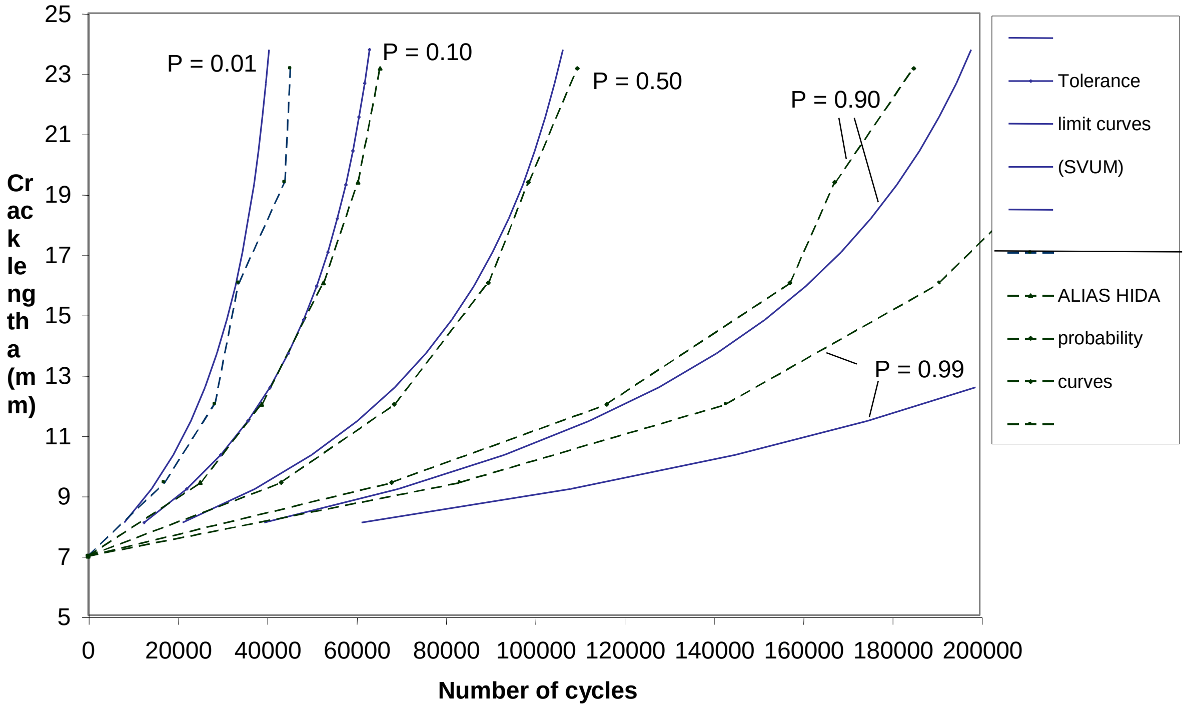

Figure 3: *Comparison of probabilistic assessment using integration of tolerance limits with ALIAS HIDA software using Monte Carlo simulation with randomized C parameter of Paris equation*

As the method using tolerance limits was successfully verified, it was used for further calculations. Results of probabilistic assessment of crack growth with probability of 10 % and 90 %, respectively, applied on the batch of X60 steel specimens is shown in Figure 4.

Both Figures 2 and 4 document a high scatter of results. There is, however, a systematic dependence of the resistance against FCG rates on the position in the sheet. The best results correspond to the center of the sheet, where FCG rates are low and very self-consistent. Somewhat worse resistance against FCG were obtained with specimens taken from the sheet beginning. The highest FCG rates were measured in the specimens taken from the end of the sheet. In addition, FCG rates in two specimens were different to each other. These results indicate that technological parameters during the sheet manufacture are not ideally constant and some changes exist, particularly at the end of the sheet rolling. Figure 4 shows, how significant errors in crack growth assessment can occur, if just mean value of regression line is applied or, even worse, the measurement is performed just on one or two specimens randomly selected from the sheet. Due to the high material variability, the crack growth interval limited by the 10% and 90% probability is wide: the number of cycles corresponding to a crack increment in the sheet center is more than twice higher in comparison with the sheet end.

If the material variability was classified according to Figure 1, the situation in the X60 steel sheet would correspond to the very rough variability. There was no considerable scatter of FCG results in each of the specimen and area of FCG measurement, but significant differences were connected with the different specimen location.

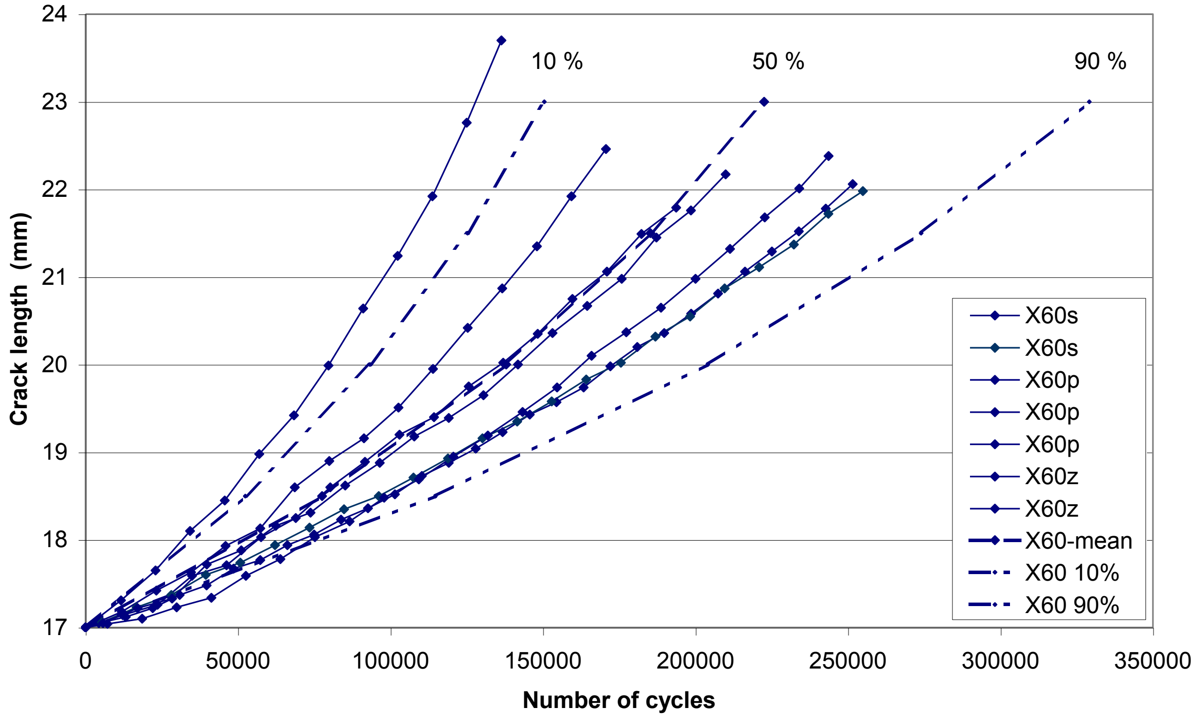

Figure 4: *Experimentally measured crack growth curves in X60 steel with probability curves obtained by integration of mean regression line (50%), 10% and 90% tolerance limits, respectively*

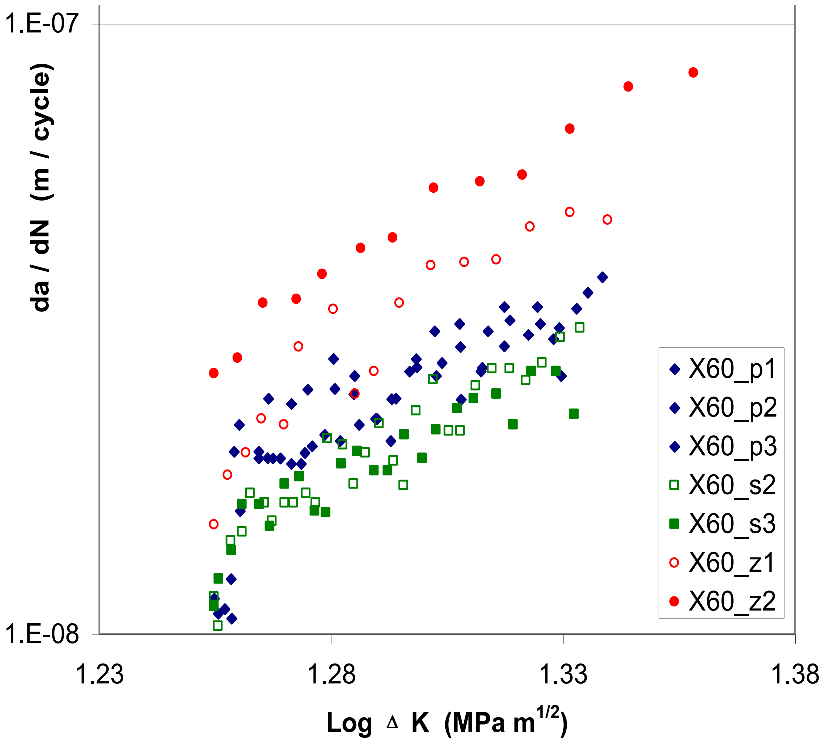

Figure 5: *Paris FCG diagram of X 60 steel*

The significant material variability resulting in different resistance against FCG also took effect in the Paris diagram – Figure 5. The extremely rough variability between the beginning and end of the sheet (specimen groups *p* and *z*) resulted in almost no interface of the points in the diagram, unlike the scatter within the groups *p* and *s*, which corresponds to fine or intermediate variability.

The final comparison of FCG in the three steels with 10% probability curves is in Figure 6. The lowest resistance against FCG corresponds to the X70 and X65 steels. As usually, this characteristics is connected with the higher strength of the steels. The average resistance of the X60 steel against FCG is significantly better, however, due to the large variability, 10% probability curve of this steel is not too much different from the X70 and X65 steels, respectively.

5. Conclusions

The main results of the probabilistic evaluation of FCG in three pipeline steels, X60, X65 and X70 can be summarised as follows:

- The method of integration of statistically evaluated tolerance limits along regression line provides quite satisfactory results, in a good agreement with results obtained using ALIAS HIDA probabilistic software with randomised parameter C of Paris dependence and Monte-Carlo simulations.
- Extremely rough material variability as regards resistance against FCG rates was shown for the X60 steel. FCG resistance of the X65 and X70 steels, respectively, was significantly lower, but with a low scatter.

Acknowledgement

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