Multiple Site Damage (MSD) crack growth: numerical evaluations and experimental tests

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ABSTRACT: This work is aimed to assess a numerical procedure for MSD crack propagation simulation of 2D pre-notched specimens (plates) undergoing a traction fatigue load, as defined by a general load spectrum. Experimental analyses on a fatigue machine were carried out in order to validate the numerical results and to provide the necessary material fatigue data for the aluminium plates. The numerical analyses were performed using a commercial code (BEASY) that is based on Dual Boundary Element Method. By means of a non-linear regression analysis, applied on in house obtained experimental data, a propagation law was defined, capable to effectively keep in account the threshold effect and the unstable final propagation. A satisfactory agreement between numerical and experimental crack growth rates was obtained even starting from a complex MSD scenario. Moreover the load introduction to the specimen was monitored by strain gauge equipment.

INTRODUCTION

With reference to fatigue and MSD (Multiple Site Damage) fracture mechanics, experimental fatigue tests were performed on a complex geometry notched plate undergoing cyclic axial load. The crack initiation process and crack propagation were monitored on a specimen undergoing a given traction load spectrum. Experimental crack growth rate and crack path were compared with those obtained with a numerical procedure based on DBEM (Dual Boundary Element Method) and the correct simulation of the load introduction to the specimen was checked by strain gauge measurements. The fatigue data necessary for the numerical analysis were previously obtained by experimental crack growth tests on simple geometry specimen [1].

A complex MSD initial scenario was artificially created on a rectangular plate, by means of notched holes and, after the pre-cracking process, four different cracks simultaneously propagating were obtained. The propagating crack lengths were monitored on both sides of the specimen in order to check the correctness of load introduction to the specimen: any misalignment between the machine grips could create a bending condition for the specimen and consequently an elliptical propagating crack front [2]. This check, together with the strain gauge measurements, allowed assessing the validity of the 2D hypothesis.

EXPERIMENTAL ANALYSIS ON SIMPLE GEOMETRY CRACKED PLATES FOR MATERIAL FATIGUE DATA ASSESSMENT

The first part of the fatigue experimental test was carried out on 3 simple notched (hole/slut) aluminium specimens, in such a way to work out, with statistical significance, the material fatigue parameters for crack growth simulation. The plate geometry (Fig.1) as well as the whole testing procedure was consistent with ASTM E 647 specification [3]. A constant amplitude fatigue traction load ($P_{max}=14\ kN$, $R=P_{min}/P_{max}=0.1$) was applied by a servo-hydraulic machine (Instron 8502), with a frequency $f=5\ Hz$, at ambient temperature.

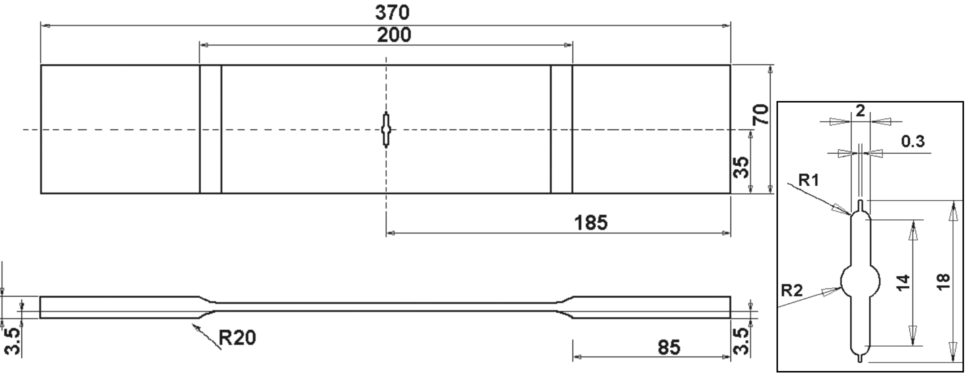


Figure1: Specimen geometry adopted for material fatigue property assessment.

During the experimental fatigue test on simple specimens (Fig.1), crack length data, measured by optical systems, were recorded and used to work out, by analytical formula, the corresponding SIF's (Stress Intensity Factors) and crack growth rates. The overall specimen size was chosen sufficiently large in order to get a mainly elastic behaviour, with plasticity effects confined to the final part of crack propagation, whose monitoring can start only after a pre-cracking phase, as prescribed by the ASTM E 647 standard. The observed rectilinear crack propagation path turned out to be consistent with symmetric boundary conditions but, whenever out of tolerance deviations from the ideal rectilinear path came out, the corresponding specimens were discarded from the analysis. In the final part of crack propagation, due to high plasticity effects, a 45° deflection of the crack surface preceded the ductile failure [4]. For each valid specimen (N° 5-7), according to the mentioned standard, a chart with crack length against the number of cycles was plotted, in order to assess crack growth rates da/dN, calculated by the secant method, while SIF's were calculated by analytical formulas. Crack growth rate values were then plotted against ΔK in a bilogarithmic chart and a linear regression was performed to estimate the Paris law material constants *C* and *n* (Fig.2).

NUMERICAL-EXPERIMENTAL ANALYSIS FOR MSD COMPLEX GEOMETRY CRACKED PLATES

The material fatigue parameters, obtained by the experimental analysis previously described, are useful to perform an MSD crack growth simulation on a complex geometry specimen made of the same material (Fig.3). In our case the results of such numerical analysis were compared with those from the experimental tests, in order to validate and improve the numerical procedure, based on DBEM [5-7]. Two loading conditions were considered on different specimens:

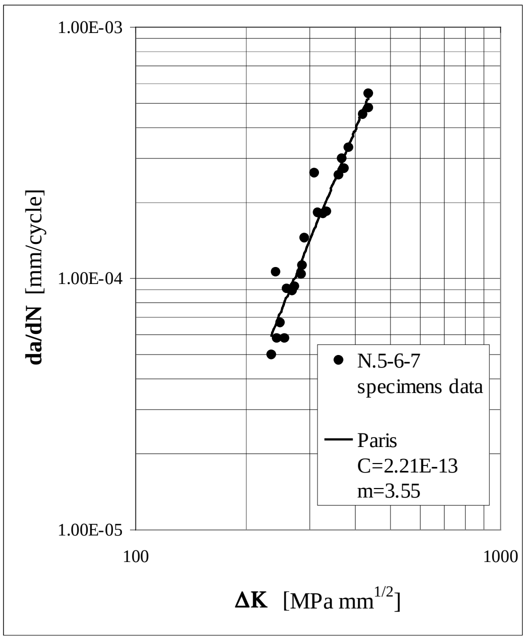
1. Cyclic load with constant amplitude (P_{max}-P_{min}=12.6 KN) and stress ratio (*R=0.1)*, the same values were used for the simple notched specimens, with Paris law adopted for numerical crack growth assessment. Crack paths (Figs.4-5) and propagation times (Figs.6-9), obtained by BEASY code [8], were compared with the experimental ones from specimen N.1, getting a satisfactory agreement;
2. Cyclic load with variable amplitude and stress ratio with NASGRO law adopted for numerical crack growth assessment (in this case the Paris law did not give satisfactory results). The crack paths are the same as for the previous case (Figs. 4-5) and the propagation times (Figs. 6-9), obtained by BEASY code [8], were compared with the experimental ones from specimen N°2, getting a satisfactory agreement especially in the first part of the propagation. The differences (however limited) in the final part suggest improving the correlation by increasing the experimental data.

For that concern the specimen N°2, with the same experimental data (coming from simple notched specimens) a non-linear regression was attempted in order to model the threshold phenomena and the fracture toughness for the final unstable crack propagation. More precisely the NASGRO 2.0 equation was adopted (Eq. 1), with no crack closure effect and using the parameter values indicated in Table 1. Such parameters were extracted from the NASGRO database (in correspondence of Al 2219-T87, which was reputed the most similar to the aluminium used), in order to get the unknowns *C* and *n* from the non-linear regression (made with MATHEMATICA):

$$\frac{da}{dN}=\frac{C\cdot\Delta K^{n}\cdot\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^{p}}{\left(1-\frac{\Delta K}{(1-R)\cdot K_{c}}\right)^{q}}\rightarrow C=4.26E-11, n=2.69 \qquad (1)$$

TABLE 1

Youngs Modulus [MPa]	E	7.20E+04
Poissons ratio	ν	0.3
Yield stress (Ys) [MPa]	σ_{YS}	283
Ultimate tensile strength (UTS) [MPa]	σ_{UTS}	309
Plane strain fracture toughness [MPa mm$^{1/2}$]	K_{Ic}	900
Empirical constant	A_k, B_k	1
Exponent	p, q	1
Threshold SIF at R=0 [MPa mm$^{1/2}$]	ΔK_0	120
Cut off stress ratio	R_{cl}	0.7
Intrinsic crack length [mm]	a_0	0.102



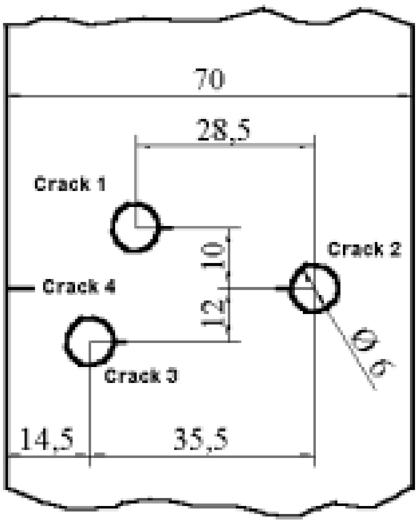


Figure 2: Interpolation curve using Paris law.

Figure 3: Notched specimen: initial scenario (dimensions *mm).*

In table 2 the load spectrum adopted for the specimen N° 2 is illustrated. From Fig.6, related to crack 1, which is the first appearing, it is possible to note the little difference between initiation times for the two complex geometry specimens.

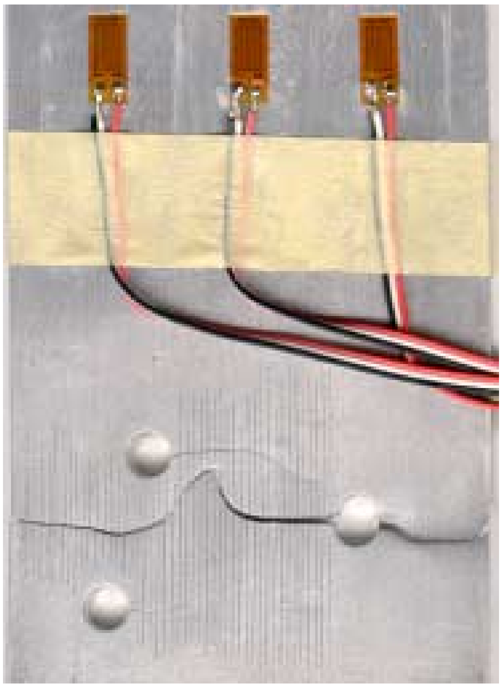


Figure 4: Experimental crack propagation paths (specimen N°2).

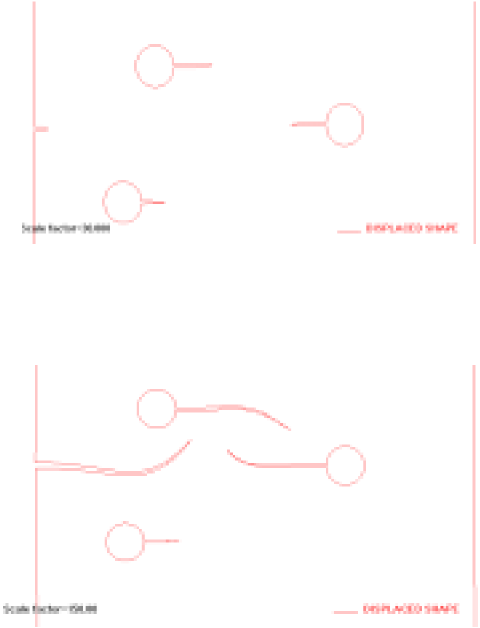


Figure 5: Numerical crack propagation paths at 774000 (upper) and 1070000 cycles (specimen N°2).

TABLE 2

Number of cycles	P_{max} (KN)	R
581000	14	0.10
774000	16.3	0.22
866000	21.5	0.41
968000	19.2	0.58
1046000	17.2	0.77
1076000	19.2	0.58

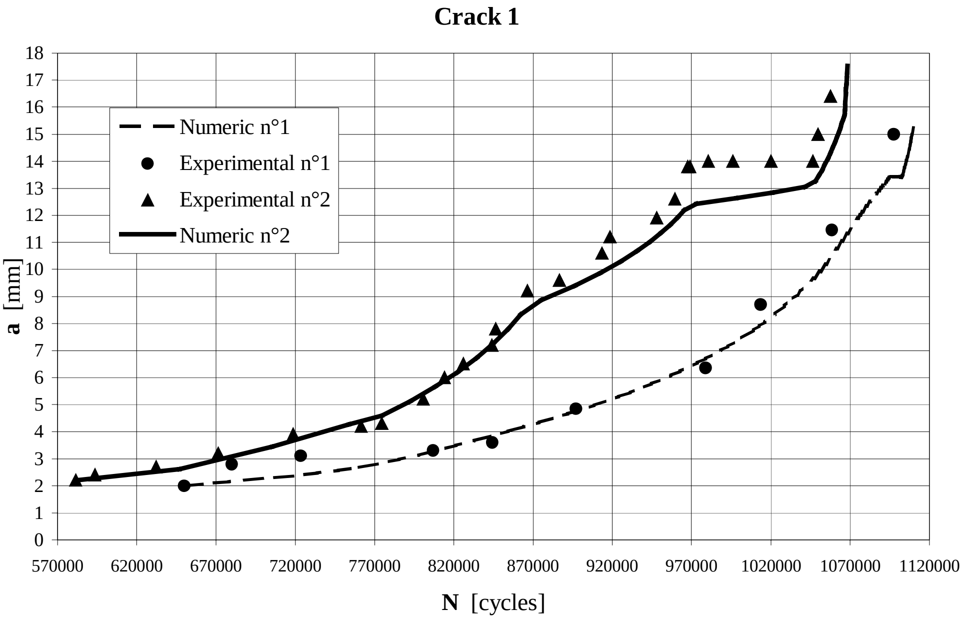


Figure 6: Crack length versus number of cycles, as obtained by numerical simulation with Paris (specimen 1) and NASGRO (specimen 2) laws and by experimental tests.

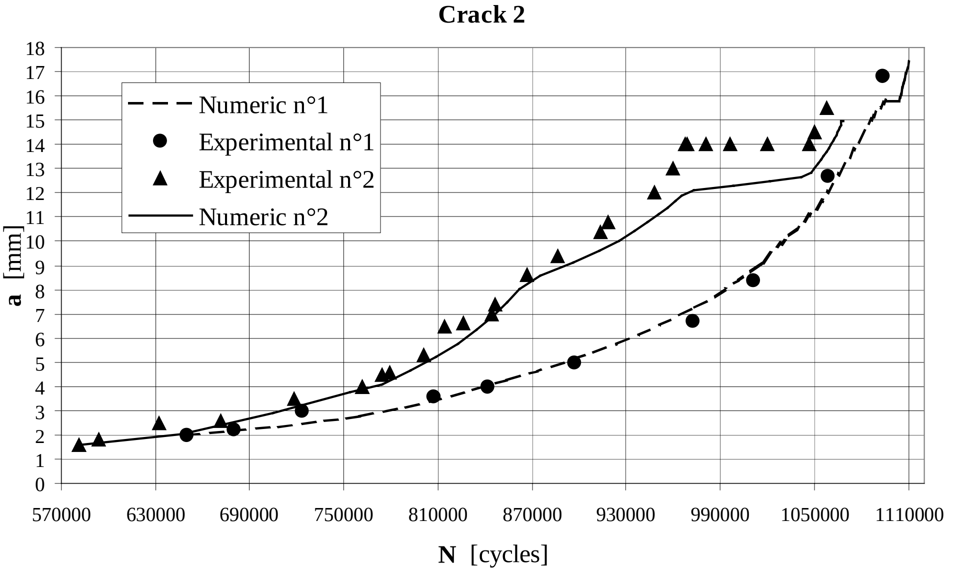


Figure 7: Crack length versus number of cycles, as obtained by numerical simulation with Paris (specimen 1) and NASGRO (specimen 2) laws and by experimental tests.

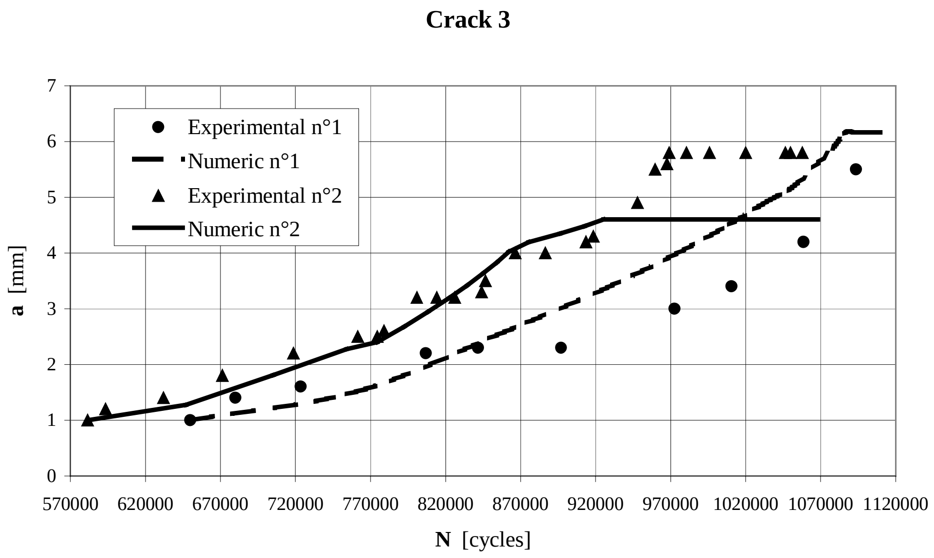


Figure 8: Crack length versus number of cycles, as obtained by numerical simulation with Paris (specimen 1) and NASGRO (specimen 2) laws and by experimental tests.

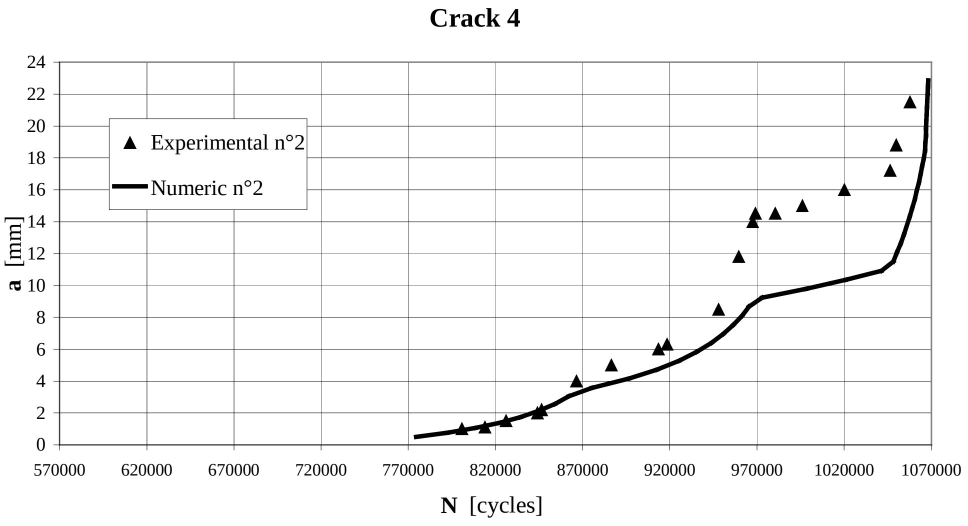


Figure 9: Crack length versus number of cycles, as obtained by numerical simulation with Paris (specimen 1) and NASGRO (specimen 2) laws and by experimental tests.

CONCLUSIONS

Satisfactory agreement was obtained between numerical and experimental crack propagation rates on specimen 1 when using the Paris formula, with the related constants provided by in house made experimental tests. Such formula was not anymore accurate for variable amplitude load cycles (as applied to specimen 2) because unable to keep in account the load ratio variability. That is why a more complex correlation based on the same experimental data and on information from NASGRO database (without the need to model crack closure effect), was attempted with a satisfactory agreement between numerical and experimental results. The later approach could be improved by increasing the experimental data by cycling some simple notched specimen with different R values (at this stage only data with $R=0.1$ were available). Another possibility would be to use also the experimental data coming from the specimen N°1 in order to set up a propagation law to be tested with results coming from specimen N°2.

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