Progress in the measurement of the cyclic R-curve and its application to fatigue assessment

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Progress in the measurement of the cyclic R-curve and its application to fatigue assessment

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Abstract

The cyclic R-curve describes the resistance of a material to fatigue crack propagation from the short to the long crack regimes and it is therefore an essential ingredient in any fracture mechanics-based fatigue assessment procedure. This work presents different testing procedures employed in the experimental determination of the cyclic R-curve, especially focusing on the comparison with long fatigue crack propagation thresholds obtained by means of the compression pre-cracking load reduction (CPLR) procedure. The tests were performed on the EA4T steel considering different stress ratios. The results show a good reproducibility of the cyclic R-curves at every stress ratio and for any testing procedure. In addition, the cyclic R-curves were used in a fracture mechanics-based assessment to predict the fatigue limits of specimens containing micro-notches.

Keywords:
Cyclic R-Curve, Fatigue Limit, Fatigue Propagation Threshold, EA4T Steel, Digital Image Correlation

Abbreviations

The following abbreviations are used in this manuscript:

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Email address: stefano.beretta@polimi.it (S. Beretta)
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polimi</td>
<td>Politecnico di Milano</td>
</tr>
<tr>
<td>BAM</td>
<td>Bundesanstalt für Materialforschung und -prüfung</td>
</tr>
<tr>
<td>SIF</td>
<td>Stress intensity factor</td>
</tr>
<tr>
<td>R</td>
<td>Load (or stress) ratio</td>
</tr>
<tr>
<td>EDM</td>
<td>Electrical discharge machining</td>
</tr>
<tr>
<td>SENB</td>
<td>Single-edge notched bending</td>
</tr>
<tr>
<td>PICC</td>
<td>Plasticity-induced crack closure</td>
</tr>
<tr>
<td>RICC</td>
<td>Roughness-induced crack closure</td>
</tr>
<tr>
<td>OICC</td>
<td>Oxide-induced crack closure</td>
</tr>
<tr>
<td>DIC</td>
<td>Digital image correlation</td>
</tr>
<tr>
<td>DCPD</td>
<td>Direct current potential drop</td>
</tr>
<tr>
<td>KT-diagram</td>
<td>Kitagawa-Takahashi diagram</td>
</tr>
<tr>
<td>EA4T</td>
<td>25CrMo4 steel</td>
</tr>
<tr>
<td>CPLR</td>
<td>Compression precracking Load reduction</td>
</tr>
<tr>
<td>Constant-ΔF</td>
<td>Constant range of applied force (or bending moment)</td>
</tr>
<tr>
<td>Constant-ΔK</td>
<td>Constant range of applied stress intensity factor</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
</tr>
</tbody>
</table>
Nomenclature

\begin{itemize}
\item \(a\) Crack length (depth)
\item \(c\) Semi-superficial crack length
\item \(a_0\) Notch and micro-notches lengths (depths)
\item \(\Delta a\) Crack extension
\item \(\Delta a_{CP}\) Crack extension during precracking
\item \(da/dN\) Crack growth rate
\item \(\varphi\) Boundary correction factor
\item \(\sigma\) Axial stress
\item \(\Delta \sigma\) Axial stress range
\item \(K_{\text{max}}\) Maximum SIF
\item \(\Delta K\) Applied SIF range
\item \(K_{\text{op}}\) SIF at the crack opening load
\item \(\Delta K_{\text{th,LC}}\) Long crack threshold SIF range
\item \(\Delta K_{\text{th,eff}}\) Long crack effective threshold SIF range
\item \(\Delta K_{\text{th}}\) Crack threshold SIF range
\item \(v_i\) Parameters of the R-curve equation
\item \(l_i\) Parameters of the R-curve equation
\end{itemize}

1. Introduction

The safe design of engineering components relies on different design philosophies according to how the initiation and evolution of the fatigue damage are quantitatively considered with respect to the safety and reliability level accepted for the component [1]. Under the assumption that most of the engineering components are inherently flawed due to material or fabrication defects [2, 3, 4], a damage tolerant approach based on fracture mechanics is well suited for fatigue life assessment. This approach finds major application in the determination of the residual life and inspection intervals [5] under the assumption of pre-existing flaws detected by nondestructive methods. Note, however, that a fracture mechanics-based approach can be used for the calculation of the total...
life of a component if small initial defects and short crack propagation are taken into account [6].

The damage tolerance approach can also be adopted in the infinite life regime as the fatigue limit can be interpreted as the non-propagating condition of the largest crack which can be find in a material (or component). This arrest condition depends on the different stages of crack propagation. Microstructurally short cracks arrest at microstructural barriers such as grain boundaries [7], while in the stage of mechanically and physically short cracks the main arrest mechanism is represented by crack closure [8]. While fracture mechanics cannot be applied to predict the fatigue behavior of microstructurally short cracks, the growth of mechanically short and long cracks can be described by elastic-plastic and linear elastic fracture mechanics, respectively [9]. It is also generally accepted that the time to nucleation and the propagation at the long crack stage give minor contributions to the overall lifetime [10]. Therefore, the understanding and modelling of crack closure is vitally important for the correct and reliable prediction of the fatigue limit conditions of a component.

Under the concept of fatigue crack closure, it is generally understood that propagation occurs just when a crack is open. From the early pioneering work by Elber [11] several studies demonstrated that mechanical contact of the fracture surfaces may take place even above the zero load level. This leads to the important conclusion that not all the applied $\Delta K$ contributes to crack propagation, but just an effective portion of it defined as $\Delta K_{\text{eff}} = K_{\text{max}} - K_{\text{op}}$, where $K_{\text{max}}$ is the maximum stress intensity factor (SIF) in a fatigue load cycle and $K_{\text{op}}$ the SIF at the crack opening load. The influence of fatigue crack closure on the crack propagation behavior is significant, especially in the near-threshold regime [8, 12]. The most important mechanisms contributing to crack closure are the plasticity-induced (PICC), the roughness-induced (RICC) and the oxide-induced (OICC). One or the other of these mechanisms is prevalent according to the mechanical properties of the material and the in-service environmental conditions. Recent investigations on the EA4T steel, which is the material considered in the present work, revealed that RICC and OICC, besides
PICC, have a prominent effect on the long fatigue crack propagation threshold \( \Delta K_{th,LC} \). In this regard, Pokorny et al. [13] and Vojtek et al. [14] showed that the crack closure function \( f \) proposed by Newman and implemented in NASGRO [15] (including plasticity-induced crack closure mechanism only) is not able to sufficiently describe the crack closure in threshold region. Similar mechanisms on the same material were observed by Beretta et al. in case of tests conducted under variable amplitude loading [16]. From the referenced studies, it is then evident that a more refined characterisation of the crack closure effects on the fatigue crack propagation threshold \( \Delta K_{th} \) in the mechanically short to long crack regimes is necessary.

The fatigue crack propagation threshold \( \Delta K_{th} \) can be separated in two main contributions: i) an intrinsic one, \( \Delta K_{th,eff} \), and ii) an extrinsic one, \( \Delta K_{th,op} \), which describes the crack-tip shielding mechanisms:

\[
\Delta K_{th} = \Delta K_{th,eff} + \Delta K_{th,op}
\]  

While the intrinsic fatigue crack propagation threshold \( \Delta K_{th,eff} \) depends solely on the elastic material properties (Young’s modulus) and on the magnitude of the Burgers vector (\(|b|\)) [17], \( \Delta K_{th,op} \) increases in the mechanically-short crack regime due to contact shielding mechanisms (crack closure) which build up with the crack extension \( \Delta a \). The \( \Delta K_{th} \) generally reaches an asymptotic value which corresponds to the long crack threshold SIF range \( \Delta K_{th,LC} \). The crack length dependence of \( \Delta K_{th} \) was documented by several studies [18, 19, 20, 21, 22]. In analogy to static loading, this increase of \( \Delta K_{th} \) with crack extension is named cyclic R-curve, which was introduced by Tanaka et al. [23, 21].

The cyclic R-curve can be used to predict the fatigue limit of components containing small defects like casting porosity, inclusions, corrosion pits [24], or even in special applications such as fretting fatigue [25] and influence of the surface roughness (notch sensitivity) [26]. The most promising application of the cyclic R-curve method is undoubtedly the prediction of the threshold stress, \( \sigma_{th} \), as a function of the non-propagating crack length, which goes under the
name of Kitagawa-Takahashi (KT)-diagram [21, 27, 28, 29, 30, 31]. In fact, if the KT-diagram can be predicted based on the cyclic R-curve, the extensive fatigue tests on micro-notched specimens needed for the determination of the KT-diagram can be replaced by a single experimental test to obtain a cyclic R-curve. Recently, Maierhofer et al. [32] showed that particular attention should be paid when the KT-diagram is obtained on small artificial notches of finite depth.

There exist several studies in the literature dealing with the experimental determination of the cyclic R-curve [11, 33, 34, 35, 22, 36]. These studies are mostly based on indirect methods, such as the record of the load-deflection characteristic by means of a clip-on-gauge mounted at the mouth of the specimen, or the measure of successive crack-arrest events during crack extension. More recently, a direct methodology was proposed to measure with higher precision the opening stresses, $\sigma_{op}$, by adopting the concept of “crack-tip opening displacements” and “local strain cycles”, in which the strain cycles are measured by Digital Image Correlation (DIC) in proximity of the crack tip [37, 38, 39, 40]. However, the definition of the entire R-curve, along with the experimental techniques and procedures to be adopted to fully describe it, are still key aspects to be fully understood and this study aims particularly to provide new insights on them.

In the present paper, first a comprehensive overview of the basic methods for determining the cyclic R-curve is discussed. The different methods are used in an extensive experimental campaign conducted at Bundesanstalt für Materialforschung und -prüfung (BAM) and Politecnico di Milano (Polimi), devoted to the determination of the cyclic R-curve for the EA4T steel at load ratios $R= -2$, -1 and 0.05. The results of the different experimental techniques are compared with each other and with a set of fatigue long crack propagation thresholds obtained by compression precracking load reduction (CPLR) in a previous study. The fatigue limits of specimens with artificial defects were determined as well. The obtained R-curves were used in a fracture mechanics-based fatigue assessment to predict the fatigue limits of the artificial defects.
2. Experimental setup and specimens geometry

2.1. Fatigue crack propagation tests

The material under investigation was the commercial steel grade EA4T, a medium strength steel for railway axles production. The adopted single-edge notched bending (SENB) specimens are shown in Fig.1. Fig.1(a) shows the specimen used at Polimi ($L_1 = 110$ mm, $W_1 = 24$ mm and $B_1 = 12$ mm), while the geometry used at the BAM is depicted in Fig.1(b) ($L_2 = 108$ mm, $W_2 = 19$ mm and $B_2 = 6$ mm). The notch was machined by Electro Discharge Machining (EDM). It is important to notice that for the determination of the cyclic R-curve the initial crack should be nucleated from a very sharp notch. This is essential to limit the load history effects generated by an aggressive precracking procedure. For this reason, the razor blade technique was adopted to sharpen the initial EDM notch and a diamond polishing paste having a maximum grain size between 3 µm to 5 µm was used in conjunction with the razor blade to enhance the sharpening process. Thereafter, a compression precracking procedure was implemented to generate an initial closure-free crack [41, 42]. The execution of compression precracking was carried out differently in the two institutes according to own previous experience: a load ratio $R=10$ with a nominal SIF range of $\Delta K = 16.44$ MPa$\sqrt{m}$ were used at Polimi, whereas a load ratio $R=20$ and a $\Delta K = 18$ MPa$\sqrt{m}$ were employed at BAM. This enabled to nucleate precracks with lengths in the order of approximately 200 µm and 80 µm, respectively. An example of a precrack is reported in the micrograph of Fig.1a.

The testing equipment used at Polimi consisted of a Rumul Craktronic resonant plane bending facility (working frequency equal to about 130 Hz) and the crack length was measured, at both sides of the crack, using crack-gauges by Rumul. The crack-gauges are thin resistance foils which were glued on the two lateral free surfaces of the SENB specimens by means of a two-component epoxy adhesive and were connected to a Fractomat unit which allowed to monitor continuously the crack length. In addition, a clip-on-gauge (model EXR 5-0, 5X by Rumul) was also mounted on the specimens to monitor the crack length.
from the real-time measurement of the specimen’s stiffness. The tests at BAM were conducted on a Rumul Testronic resonant fatigue testing machine with a maximum load capacity of 100 kN equipped with an 8-point bending fixture. The operating frequency was about 60 Hz in the present tests. The crack length was monitored by means of the direct current potential drop (DCPD) method, see Fig.1(b). A power supply (HP 6033A) works as current drive source that provides a constant current I flowing perpendicularly to the perspective crack plane in the SENB specimen. The difference in the electric potential (U) between two points at either side of the crack plane is measured by means of a nanovoltmeter (Keithley 2182A) connected to the specimen via potential probes. To compensate for thermoresistive effects, i.e., changes in electric potential due to temperature fluctuations, the measured difference in potential is corrected by assuming a linear relationship between the specific resistivity of the material and the specimen temperature. The latter is measured using PT100 sensors. Thermoelectric effects, i.e., electric potentials induced by temperature gradients between contact pairs in the measurement-chain, are compensated by periodically switching the direction of the current flow and averaging the potential-drop over one period. The averaging of the signal additionally reduces the noise in the signal. These measurements result in a fluctuation of the crack-length signal due to noise and temperature-influence of less than 3 µm.
Figure 1: Geometry of the SENB specimens adopted at Polimi (a) and at BAM (b).
A summary of the experimental campaign performed on the crack propagation specimens is presented in Tab 1. The tests regarding the long crack thresholds (labelled with CPLR) and the R-curve measurements by means of crack-gauges, optical microscope, clip-on-gauge and DIC techniques were performed in Polimi, whereas the R-curve experiments performed by means of the potential drop technique were carried out at BAM. The tested load ratios were R= -2, -1, 0.05 and 0.7. The number of dedicated specimens tested at R=-1 were noticeably higher then the number of specimens tested at other load ratios since the adoption of the present EA4T material for railway axles which are mainly subjected to rotary bending loading. Table 1 shows that the $\Delta a-\Delta K_{th}$ points used to construct the R-curve were obtained from different experimental techniques. In particular, the Constant-$\Delta F$ and Constant-$\Delta K$ techniques are herein introduced and they will be successively discussed more in detail.

<table>
<thead>
<tr>
<th>Load ratio</th>
<th>Technique</th>
<th>Crack measurement</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>R = -2</td>
<td>Constant-$\Delta F$ + Constant-$\Delta K$</td>
<td>Crack-gauges and Optical microscope</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potential drop</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>CPLR</td>
<td>Crack-gauges</td>
<td>1</td>
</tr>
<tr>
<td>R = -1</td>
<td>Constant-$\Delta F$ + Constant-$\Delta K$</td>
<td>Crack-gauges and Optical microscope</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clip-on-gauge</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CPLR</td>
<td>Crack-gauges</td>
<td>9</td>
</tr>
<tr>
<td>R = 0.05</td>
<td>Constant-$\Delta F$ + Constant-$\Delta K$</td>
<td>Potential drop</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIC</td>
<td>2</td>
</tr>
<tr>
<td>R = 0.7</td>
<td>CPLR</td>
<td>Crack-gauges</td>
<td>3</td>
</tr>
</tbody>
</table>
2.2. Fatigue limit tests

The R-curve was used to simulate the condition of short crack arrest at the endurance limit. To validate this model, a benchmark activity on artificially defected axial specimens was defined. A total number of 20 specimens were machined according the geometry depicted in Fig. 2. The specimens were initially turned into a cylindrical shape with a nominal diameter of 9 mm. Successively, two flattened parallel surfaces were machined in the central region, the distance between these two surfaces was 6 mm. Prior to machining the artificial defects, the specimens were electro-polished to remove the effect of residual stresses induced by machining. The electro-polishing was performed according to a solution of acetic acid (94%) and perchloric acid (6%). The target thickness of the superficial layer to be removed by the electro-polishing process was selected to be between 40 µm and 65 µm. The artificial micro-notches were obtained by EDM into two rectangular shapes with 0.1 mm (depth) x 0.5 mm (superficial length) and 0.2 mm x 2 mm dimensions, respectively.

Figure 2: Drawing of the specimen used in the fatigue limit tests with two artificial defect sizes: a) 0.1 mm (depth) x 0.5 mm (superficial length) and b) 0.2 mm x 2 mm.
The machine used was a Rumul Testronic resonant testing machine configured for axial specimens and a load capacity of 100 kN. The test frequency was about 112 Hz. The run-out condition was selected to $1.2 \cdot 10^7$ cycles, while the broken condition corresponds to a variation of the test frequency equal to $\pm 2$ Hz. The specimens were tested at two load ratios, namely $R=-1$ and $R=-2$ according to a short stair-case procedure.
3. Fatigue crack propagation results

3.1. Long crack threshold experiments

The CPLR experiments aimed at measuring the long crack threshold $\Delta K_{th,LC}$ which represents, in the concept of the R-curve, the asymptotic value for large crack extension $\Delta a$. The test procedure consisted in an initial precracking by the compression precracking technique. Successively, the crack was advanced by constant amplitude loading at the specific stress ratio under investigation. This initial step (often called homogenization stage) enabled to eliminate any potential transient crack propagation behavior due to the prior compressive loading, and to guarantee stabilized crack-opening stresses in the near-threshold regime. After the stabilisation step, a load shedding procedure was performed in accordance with the ASTM E-647 or ISO 12108 standard [43, 44]. Accordingly, the $\Delta K_{th,LC}$ was measured as the $\Delta K$ value for a crack growth rate at $10^{-11}$.

![Figure 3: Long fatigue propagation threshold test results: (a) Obtained $\Delta K_{th,LC}$ at different load ratios by adopting the CPLR method; (b) Dependence of $\Delta K_{th,LC}$ on $R$, interpolated by means of the NASGRO equation.](image-url)

Fig. 3 reports the trend of the $\Delta K_{th,LC}$ against the stress ratio and their

13
interpolations carried out adopting the NASGRO equation [15]. Table 2 summarizes all the evaluated $\Delta K_{th,LC}$ at different load ratios and the corresponding crack extension at the end of the CPLR procedure for each test. These data will be used to complement the experimental data of the cyclic $R$-curve.

Table 2: Summary of the long crack threshold obtained by CPLR method.

<table>
<thead>
<tr>
<th>Load ratio</th>
<th>Specimen</th>
<th>Crack extension after stabilization Step 1 (mm)</th>
<th>Crack extension at the long crack threshold Step 2 (mm)</th>
<th>The obtained $\Delta K$ threshold MPa$\sqrt{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R= -2$</td>
<td>S16</td>
<td>3.18</td>
<td>5.30</td>
<td>21.20</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>1.71</td>
<td>4.41</td>
<td>12.47</td>
</tr>
<tr>
<td></td>
<td>S11</td>
<td>2.91</td>
<td>5.57</td>
<td>13.60</td>
</tr>
<tr>
<td>$R= -1$</td>
<td>S13</td>
<td>3.32</td>
<td>7.37</td>
<td>15.03</td>
</tr>
<tr>
<td></td>
<td>S15</td>
<td>2.72</td>
<td>6.13</td>
<td>14.93</td>
</tr>
<tr>
<td></td>
<td>S17</td>
<td>2.86</td>
<td>8.48</td>
<td>14.75</td>
</tr>
<tr>
<td>$R= 0$</td>
<td>S14</td>
<td>1.93</td>
<td>4.65</td>
<td>7.05</td>
</tr>
<tr>
<td></td>
<td>S9</td>
<td>1.80</td>
<td>4.76</td>
<td>6.70</td>
</tr>
<tr>
<td>$R= 0.7$</td>
<td>S12</td>
<td>1.60</td>
<td>5.90</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>S10</td>
<td>1.10</td>
<td>5.58</td>
<td>2.85</td>
</tr>
</tbody>
</table>

3.2. Experimental determination of the cyclic $R$-curve by means of Constant-$\Delta F$ procedure

The cyclic $R$-curve is generally obtained applying cyclic loadings at constant range (Constant-$\Delta F$) until the initial precrack arrests due to the built-up of the different crack closure mechanisms. This procedure can be implemented considering one crack extension for one specimen (single-step procedure), or multiple crack extensions (multi-step procedure). These two methodologies provided consistent results [36] and for this reason, in the following, the multi-step procedure was adopted.

The cyclic $R$-curve experiments were carried out adopting the compression precracking stepwise increasing constant load amplitude test procedure [20, 36, 28]. In order to minimize the load history effects, each specimen was subjected
to a maximum of four loading steps at Constant-ΔF considering a sufficient increment of ΔK that guarantees the crack extension between the loading steps. Fig. 4a demonstrates the details of a particular test which was started at ΔK=6 MPa√m, the load ratio was R=-1. After running 14.53 million cycles, a crack extension of 0.193 mm was observed. Successively, the load range was increased to give an initial ΔK=8.50 MPa√m for the second step. After 15 million cycles a further crack extension of 1.25 mm was observed. Finally, by increasing to ΔK=10.2 MPa√m, the crack started to propagate indefinitely.

Considering other specimens, and different initial ΔK, the preliminary cyclic R-curve at the load ratio R=-1 was obtained, see Fig. 4b. The Δa-ΔKth points are shown in the figure with the long crack thresholds ΔKth,LC scatter (see Table 2). The results show that there is a steep increase in the threshold up to crack extension of 1 mm, then it gradually increases up to 3 mm. It is worth stating that one specimen was tested with the initial ΔK=9.6 MPa√m which was well below the long crack threshold. However, the crack continued propagating without arresting, which implies that the cyclic R-curve must be below this load curve. Another important observation is that there is a clear gap between the maximum threshold evaluated by the Constant-ΔF approach and the ΔKth,LC values obtained by the CPLR procedure. This highlights the limitation of adopting the Constant-ΔF approach for the determination of the cyclic R-curve, and the need for developing a new procedure to evaluate the upper region of the R-curve.
Figure 4: a) Loading history for a test conducted at load ratio R=-1 and subsequent crack extension in each step (Constant-ΔF method), b) summary of the R-curve tests performed adopting the Constant-ΔF test method.
3.3. Proposed modification of the experimental procedure

The schematic reported in Fig. 5 illustrates that the limitation of adopting the Constant-ΔF procedure is determined by the so-called tangency condition. The evolution of the crack driving force ΔK with the crack extension Δa is plotted along with the cyclic R-curve. The tangency point represents the point at which the values of the crack driving and resistance forces are the same, therefore determining the non-propagating condition of a growing crack. The crack extension at the tangency point represents the maximum Δa that can be obtained with Constant-ΔF test procedure. This matter of fact poses the problem how to determine the region of the R-curve between the point of tangency and the asymptotic ΔK_{th,LC}.

![Figure 5: Schematic representation of the proposed methodology which combines the constant ΔF and constant ΔK techniques to describe the cyclic R-curve up to ΔK_{th,LC}.](image)

Consequently, it is proposed to determine the second region of the R-curve by using a Constant-ΔK procedure. The red dashed lines in Fig. 5 indicate the perspective Δa-ΔK_{th} points obtained according Constant-ΔK steps. This procedure requires precise real-time crack length measurements and a dedicated
software for the testing machine which enables to reduce the applied load range to keep the $\Delta K$ constant while the crack is growing. The main advantage is the possibility to determine $\Delta a - \Delta K_{th}$ points very close to the long crack threshold, which would have been impossible with the Constant-$\Delta F$ technique, except for very large specimens where the increase of $K$ with crack extension is small or in cases of materials where the R-curve behavior is limited to small crack extensions. However, it has to be pointed out that the initial points are more suited to be captured by the Constant-$\Delta F$ since it is difficult to control the $\Delta K$ at constant levels when the crack extension is very small and hard to measure.

![Figure 6: Summary of the R-curve tests performed adopting the combination of Constant-$\Delta F$ and Constant-$\Delta K$ procedures. A more accurate representation of the cyclic R-curve up to the region of $\Delta K_{th,LC}$ is obtained.](image)

Adopting the new experimental procedure, two additional tests were performed at $R=-1$. For these tests, the crack extension was monitored with the crack-gauges and the clip-on-gauge techniques. As shown in Fig.6, the results corroborate the previously evaluated R-curve points from the Constant-$\Delta F$ procedure. The key point is that the two procedures can be adopted sequentially during the same test. In fact, some of the $\Delta K$-paths shown in Fig.6 (dashed...
red lines) indicate that the first crack extension was obtained according the Constant-\(\Delta F\) technique (circular blue dots), while the following crack extensions were performed with the Constant-\(\Delta K\). As it can be seen, the upper region of the R-curve was well captured by using constant \(\Delta K\) steps. Moreover, by using the new technique, it was possible to reach the threshold levels that were obtained by the CPLR procedure reported in correspondence of the crack extension measured at the end of each CPLR test.

As previously mentioned, due to the very slow crack propagation and the small crack extension in the first steps of the Constant-\(\Delta F\) procedure, the crack depth has to be measured with high accuracy and steadily over a longer period of time. This can be accomplished using the optical microscope, even if this operation requires the specimen to be un-mounted from the testing machine. Consequently, the potential drop method was applied for monitoring the crack propagation during the tests. Additional R-curve tests were carried out at BAM by adopting a combination of Constant-\(\Delta F\) and Constant-\(\Delta K\) approaches. Details of two tests carried out at \(R=0.05, R=-1\) and \(R=-2\) are depicted in Fig.7. The applied crack driving force was stepwise increased (dark grey curve) after each crack arrest event denoted by crack propagation rate values \(da/dN\) below \(10^{-11}\) m/cycle (blue points). Eventually, at a given \(\Delta K\) level the crack extended indefinitely and the crack propagation curve in the Paris’ regime was described. All the arrest points, in terms of \(\Delta a\) and \(\Delta K_{th}\), were used to build up the cyclic R-curve.
Figure 7: Variation of crack propagation rate $da/dN$ subsequent to increasing load steps (plotted in terms of crack driving force $\Delta K$) in R-curve tests performed at BAM.
3.4. Crack closure measurements by means of DIC

DIC is a non-contact technique utilised to measure full-field displacement and strain fields. Depending on the specific application, DIC can be adopted for micro- to macro-scale observations. In the present work, DIC was used to track the crack tip (and consequently the crack length) and perform crack closure measurements during a test performed at load ratio $R=0.05$. The specimen was initially pre-cracked and successively sprayed with white and black paints to create a random speckle pattern on the specimen’s surface adapted for image correlation. The paint was sprayed on the target area by means of an Iwata airbrush with a nozzle diameter of 0.18 mm. The images were captured by means of a 2 Megapixel Allied Vision Manta CCD camera which was equipped with a system of lens produced by Navitar. To allow a precise positioning of the microscope at the crack tip region, two linear micro-stages were also used. The region of interest was set to approximately 1.24 mm x 0.94 mm. The test was conducted at a frequency of 30 Hz. At specific test interruptions, the frequency was lowered to allow the DIC images acquisition process. The images at the crack tip were then acquired continuously according a frequency of acquisition that guaranteed 100 images captured for each fatigue cycle. Further details of the DIC experimental set-up and data analysis are given in [40]. The specimen was loaded under an Instron Electronpulse machine (load capacity of $\pm 10$ kN) with a four-points bending fixture. The present test was conducted at a constant $\Delta K=5 \text{ MPa\sqrt{m}}$.

Fig 8 shows the crack extension as a function of the number of cycles, where each point corresponds to a test interruption. The crack was observed to propagate at a constant growth rate of approximately $5 \times 10^{-10}$ m/cycle until a total crack extension from the notch of $\Delta a_{CP} + \Delta a = 2.76$ mm. Further crack propagation was then observed with crack growth rates below $10^{-12}$ m/cycle indicating that the threshold condition was reached.

The DIC images captured during each test interruption were successively used to calculate the displacement fields in proximity of the crack tip. Virtual extensometers were then positioned behind the crack tip, close to the crack.
flanks. The reading of each extensometer indicates the relative displacement between the crack flanks and, once plotted together with the applied remote load, it can be used to track the crack opening and closing loads. The strategy adopted to analyse the virtual extensometer readings versus the applied load data is reported in [40].

The SIF at the point of crack opening $K_{op}$ can be readily calculated from the opening load. The effective range of SIF, $\Delta K_{eff}$, is then determined according $\Delta K_{eff} = \Delta K - K_{op}$. $\Delta K_{eff}$ values as a function of the crack extension are reported in Fig.9. Remarkably, the $\Delta K_{eff}$ remained in the range of 2.1 – 2.5 MPa$\sqrt{m}$ until, at a crack extension of $\Delta a_{CP} + \Delta a = 2.76$ mm, it reached a minimum value of 2 MPa$\sqrt{m}$ which corresponded to the crack arrest.
Figure 9: Applied $\Delta K$ and effective $\Delta K$ as measured by means of DIC during crack growth.
The points refer to the DIC measurements for the opening load. The solid lines are used as reference trend-line to show how the effective crack driving force decreased to $\Delta K_{\text{eff}} = 2 \text{ MPa}\sqrt{\text{m}}$ towards the end of the test.
3.5. Comparison of R-curves

The $\Delta a - \Delta K_{th}$ points obtained from all the experimental techniques previously discussed were used to fit the equations of the R-curves according to the model proposed by Maierhofer et al. [45]. The equation considers the $\Delta K_{th,eff}$ as the initial $\Delta K_{th}$ for the nominal crack extension $\Delta a = 0$. For long crack extensions ($\Delta a \to \infty$), the asymptotic condition for $\Delta K_{th}$ corresponds to the long crack threshold measured from the CPLR tests $\Delta K_{th,LC}$. The model is written according to the following equation:

$$
\Delta K_{th} = \Delta K_{th,eff} + (\Delta K_{th,LC} - \Delta K_{th,eff}) \left[ 1 - \sum_{i=1}^{n} \nu_i \exp \left( -\frac{\Delta a}{\ell_i} \right) \right] \quad (2)
$$

with the constraint

$$
\sum_{i=1}^{n} \nu_i = 1 \quad (3)
$$

Equation 2 was fitted separately for the three load ratios using the maximum likelihood method, see Fig.10.

The majority of the data points were determined for the load ratio $R=-1$ which covers the typical load condition of railway axles subjected to rotating bending. Notably, all the experimental techniques determine values which are contained into the 90% scatter bands. It is also worth remarking that, at the load ratio of $R=-1$, the $\Delta K_{th,LC}$ values obtained by means of the CPLR procedure show some dispersion. Once these data points are reported in the R-curve plot according to their total crack extension, it is evident that they nicely fit the asymptotic condition of the cyclic R-curve (equation 2). Finally, also the experimental point determined by means of the DIC technique is contained in the scatter band for the load ratio $R=0.05$. 

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Figure 10: Comparison of the cyclic R-curves obtained for different stress ratios R.
4. Estimation of fatigue limit based on the cyclic R-curve method

In the short crack regime, the R-curve can be applied to predict the condition of crack propagation/crack arrest for a crack nucleating from a pre-existing defect. In fact, the R-curve depicts the increment of the material resistance to crack propagation in the threshold region induced by the built-up of crack closure, and this represents the same condition for a crack nucleating from a defect. To verify the applicability of the R-curve, an experimental campaign on artificially defected specimens was then performed and is herein presented. The R-curve was used to predict the crack propagation/crack arrest condition and the predictions were successively compared with the experimental results.

4.1. Fatigue limit test results

All the experimental results obtained on the micro-notched specimens are given in the Appendix 6. In particular, the results for the load ratio $R=-1$ are reported in Table 5, while the results for the load ratio $R=-2$ are reported in Table 6. The results obtained at load ratio $R=-1$ were complemented by 16 additional test results obtained during the Euraxle project for the same material, specimen and defect geometries [46]. The summary of the results obtained on the artificial micro-notched specimens, along with the range of the measured crack extensions for the run-out specimens, is reported in Table 3. Since the limited number of specimens for each combination of defect dimension and load ratio is not sufficient to calculate the endurance limit, a fatigue limit range is provided according to the observation of the run-out stress level and the first failure level detected above it. As expected, the fatigue limit ranges are higher for the load ratio $R=-2$. However, it can be observed that the relative difference is smaller for the fatigue limit range of the small defect (approximately +10%), while it is relatively higher in the case of the large defect (approximately +40%).
Table 3: Summary of obtained fatigue limits and non-propagating crack ranges for run-out conditions.

<table>
<thead>
<tr>
<th>load ratio</th>
<th>Defect size</th>
<th>Fatigue limit range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[µm]</td>
<td>[MPa]</td>
</tr>
<tr>
<td>R=-1</td>
<td>Small defect (100×500)</td>
<td>395-430</td>
</tr>
<tr>
<td></td>
<td>Large defect (200×2000)</td>
<td>260-320</td>
</tr>
<tr>
<td>R=-2</td>
<td>Small defect (100×500)</td>
<td>440-470</td>
</tr>
<tr>
<td></td>
<td>Large defect (200×2000)</td>
<td>392-422</td>
</tr>
</tbody>
</table>
The run-outs were heat-tinted and successively broken by fatigue cycles at higher load levels to observe the extension of the non-propagating cracks in the fracture surfaces. Examples of non-propagating cracks derived from run-out specimens are shown in Fig.11. For each fracture surface reported, one image was captured with the stereo microscope while the second one with the scanning electron microscope. Fig.11(a) shows the fracture surface for the larger defect tested at load ratio $R=-2$. The crack front is characterised by the same aspect ratio as the original artificial defect. In particular, in the central region, the crack is observed to be straight and characterised by an extension in depth of approximately $103 \, \mu m$. Similarly, the small defect tested at the same load ratio of $R=-2$ displays the same geometrical shape in terms of aspect ratio as the original artificial defect Fig.11(b). In this case, the crack extension was measured to be approximately $82 \, \mu m$ at the deepest point. For the load ratio $R=-1$, the crack extensions were observed to be generally smaller. For example, Fig.11(c) shows that for the larger defect, a crack extension of $39 \, \mu m$ was measured.

![Figure 11: Non-propagating cracks in run out specimens.](image)

The fracture surfaces micrographs show that the crack extensions for the $R=-1$ run-outs are much smaller than the ones measured for the $R=-2$ run-outs.
In view of these results, it would be arguable to adopt analytical solutions for the calculation of the SIFs of such small cracks which extend few microns from the artificial micro-notch root. For this reason, in the next section, a finite element (FE) model is described, which was developed to calculate precisely the SIF solution for cracks that are still embedded in the stress field determined by the presence of the artificial micro-notch.

4.2. Micro-notch effect and SIFs determination along the crack front

The FE model of the micro-notched specimens, including various crack depths at the notch-tip, was developed and calculated using ANSYS workbench 19.0. Fig.12(a) shows the geometrical global model which considers an axial length of 26 mm along which the cross section is homogeneous. The material was modelled as purely elastic with Young’s modulus $E = 210$ GPa and Poisson’s ratio $\nu = 0.3$. To perform a local mesh refinement in the micro-notch and crack tip region, a submodel was developed in which the artificial micro-notch and the crack are embedded, see Fig.12(b). The crack geometry is modelled considering a simple straight crack front at the micro-notch root. This modelling strategy for the crack geometry can be implemented as, for the aspect ratios of the artificial defects selected in this study ($a/c = 0.4$ and $a/c = 0.2$, i.e. shallow cracks), the deepest point shows the largest SIF which is equivalent with a straight crack having the same depth. The FE mesh was generated using Solid186 quadratic elements. The number of elements is variable and depends on the specific crack extension considered. However, an average FE size of 3 to 5 $\mu$m about the crack tip region was adopted for all the models. A remote stress of 100 MPa was applied along the axial direction.

Fig.12(c) depicts an example of the von Mises stress field visualised for a longitudinal section at the midspan of the micro-notch. In the same figure it is also indicated the total crack size which is the notch length $a_0$ plus the crack extension $\Delta a$. To the aim of analysing the shielding effect of the micro-notch thoroughly, a total of 8 FE simulations for both the small and big artificial defects were performed with crack extensions equal to $\Delta a = 25, 37.5, 50, 75, 100, 150, 200$
and 300 µm. For each simulation, the SIFs were obtained for 15 contours around the crack tip according the J-integral calculation based on the Ansys Pre-meshed techniques [47]. The path independence of the J-integral values was generally achieved after 4 contours from the first one corresponding to the crack tip.

Figure 12: Finite element model used for the calculation of SIFs for cracks of different depth at notches: (a) general view of the submodel in the global geometry; (b) detail of the mesh in the submodel containing the notch; (c) detail of the crack at the notch.
Fig. 13(a) summarises the FE results in terms of SIF solution for a remote stress equal to 100 MPa. As a comparison, the SIF solution for a semi-elliptical crack with the same nominal dimensions is reported in the same figure. The solution was calculated according the weight functions of Wang & Lambert [48] and Shiratori [49], respectively. As expected, the FE solution shows lower SIFs for small crack extensions, in particular for $\Delta a < 50 \mu$m. On the other hand, in between 50 to 100 $\mu$m crack extensions, the FE and weight function solutions are overlapped clearly indicating that the shielding effect of the micro-notch disappears. For longer crack extensions, the FE and the weight function solutions tend to diverge as, in the simplified scenario of the FE model, the crack is only extended in the depth direction. This simplification is valid when the crack is small and embedded in the micro-notch stress field, while when the crack extension is larger than 100 $\mu$m it should be considered a crack front that extends also till the free surface. However, as it will be shown in the following, this assumption is valid as, for the application of the R-curve, only the first crack extension steps are required to be precisely modelled.

From the SIF solution provided in the Fig. 13(a), the boundary correction factor $\varphi$ was calculated, which is reported in the Fig. 13(b) for both the small and large defects according the equation $\varphi = \frac{K}{\sigma \sqrt{\pi a}}$. 

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Figure 13: Calculation of the SIFs at the deepest point of the crack front: (a) comparison of numerical and analytical solutions for different crack depths; (b) boundary correction factors derived by means of finite element analysis.
4.3. Prediction of the fatigue limit based on the cyclic R-curve

The cyclic R-curve was used to predict the endurance limits for the micro-notched specimens (section 4.1). Fig.5 depicts the concept of the assessment procedure which is based on finding the so-called tangency condition between the crack driving force curve (labelled as applied $\Delta K$) and the R-curve. Early applications of the method can be found in [21, 28]. The applied $\Delta K$ curve represents the $\Delta K$ calculated for the perspective crack extension from the artificial micro-notch (depth $a_0$) according the equation $\Delta K = \phi \Delta \sigma \sqrt{\pi (a_0 + \Delta a)}$ where $\Delta \sigma$ is the constant applied range of remote stress and $\phi$ is the boundary correction factor determined by means of the FE models, see Fig.13(b). The applied $\Delta K$ curve was parameterised according to different levels of $\Delta \sigma$ and the endurance limit was given for the curve that satisfies the tangency condition. This model is capable to predict the occurrence of cracks that initially propagate and then stop. In fact, until the crack driving force $\Delta K$ is higher than the R-curve, the crack can propagate. If the remote stress range $\Delta \sigma$ is not sufficiently high, the crack will stop since, with crack extension, the R-curve becomes higher than the applied $\Delta K$.

The preceding procedure was implemented to predict the endurance limits of the fatigue tests performed on the micro-notched specimens. Fig.14 summarises all the experimental results and the endurance limit predictions. The four plots highlight the four stair-cases which consider the combined effect of the two defect sizes (0.1 mm x 0.5 mm and 0.2 mm x 2 mm) and the two load ratio ($R = -1$ and $R = -2$). The R-curves are shown according to the experimental points (circular solid black points), the fitted curve with a solid black line (see equation 2) and the scatter bands with two black dashed lines. It is important to highlight that the points displayed in Fig.14 refer only to those in between crack extensions from 0 mm to 0.4 mm which are not clearly visible in Fig.10 due to the different scale of the horizontal axis. The crack driving force (applied $\Delta K$) curves were calculated for four stress levels $\Delta \sigma$ which correspond to, respectively, the tangency condition with the mean R-curve, the two scatter band curves and an additional $\Delta K$ curve above the top scatter band curve which indicates a stress...
level $\Delta\sigma$ leading to a failure condition ($\Delta K$ always higher than the R-curve).

The experimental data obtained from the tests on the micro-notched specimens are indicated with two vertical solid lines. The blue lines represent the band of applied $\Delta K$ leading to a run-out condition, while the red one to the failures. The crack extensions for positioning the experimental data were taken from the fracture surface analyses (Fig.11). The results were also compared in terms of $\Delta\sigma$ in the Tab.4. Comparing the experimental fatigue limit ranges with the predicted values performed for the load ratio $R=-1$, a certain degree of conservatism in the predictions can be noticed. In particular, this is observed with the predictions performed with the average R-curve. For the small defect, the average fatigue limit prediction is equal to 273 MPa, while the experiments
indicate that the value is expected in the range between 395 and 430 MPa. However, if the prediction is performed with the R-curve corresponding to the scatter band, it is observed that the predicted value is equal to 350 MPa, which is close to the lowest run-out condition observed experimentally, 395 MPa. For the large defect, the predictions is slightly more accurate as, adopting the average R-curve, the predicted value is 222 MPa, while the lower value of the experimental fatigue limit range is 260 MPa. For the load ratio R=-2, the predictions and experimental values are in an excellent agreement. For the small defect, the prediction performed with the average R-curve indicate a fatigue limit of 468 MPa which is consistent with the experimental range of 440-470 MPa. Finally, also for the large defect, it is observed that the prediction (335-418 MPa) overlaps well with the experimental fatigue limit 392-422 MPa.

Table 4: Comparison between the experimental results and the predictions performed by means of the R-curve (between parentheses the predictions performed adopting the R-curves in correspondence of the scatter bands).

<table>
<thead>
<tr>
<th>load ratio</th>
<th>Defect size [μm]</th>
<th>Fatigue limit range [MPa]</th>
<th>R-curve Predictions [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R=1</td>
<td>Small defect (100×500)</td>
<td>395-430</td>
<td>(227) 273 (350)</td>
</tr>
<tr>
<td></td>
<td>Large defect (200×2000)</td>
<td>260-320</td>
<td>(188) 222 (258)</td>
</tr>
<tr>
<td>R=-2</td>
<td>Small defect (100×500)</td>
<td>440-470</td>
<td>(416) 468 (522)</td>
</tr>
<tr>
<td></td>
<td>Large defect (200×2000)</td>
<td>392-422</td>
<td>(335) 376 (418)</td>
</tr>
</tbody>
</table>
To summarise, the results clearly show that a large crack size effect on the
crack growth resistance in the physically short crack regime was observed in
this material. In particular, for the small and large defects investigated in this
study, we observed that failures occurred at applied ΔK much lower than the
long crack threshold $\Delta K_{th,LC}$. For example, at $R=-1$, the failures for the small
defected specimens were promoted by applied ΔK between approximately 6
and 9 MPa $\sqrt{m}$ (Fig.14), while the $\Delta K_{th,LC}= 14$ MPa $\sqrt{m}$. For the load ratio
$R=-2$, the applied ΔK leading to failure the defected specimens were in the
range of approximately 10.5 to 12.5 MPa $\sqrt{m}$ (Fig.14), while the $\Delta K_{th,LC}= 22.6$
MPa $\sqrt{m}$.

As it was demonstrated, the adoption of the R-curve led to a precise es-
timation of the endurance limits. In particular, for the load ratio $R=-2$, the
predictions precisely captured the observed fatigue limits. On the other side,
the predictions performed for the load ratio $R=-1$ were observed to be slightly
conservative. One of the reasons for this discrepancy can be explained in view
of the observed experimental crack extensions for the defected specimens that
survived. The fracture surfaces (Fig.11) indicate that the crack extensions for
the runout specimens tested at $R=-2$ (from 80 to 100 µm) were longer than the
crack extension for the specimens tested at $R=-1$ (approximately 40 µm). The
shielding effect produced by the notch was properly quantified by FE analyses,
however, other local effects could have been still present and slightly influenced
the crack tip at the early stages of propagation. For example, the local plas-
ticity induced by the presence of the micro-notch, or local effects induced by
the EDM process which might have determined a different local material mi-
crostructure in proximity of the micro-notch root. These effects are difficult to
quantify and to be considered in the present model which is based on the linear
elastic fracture mechanics theory.
5. Conclusion and Remarks

The present paper discusses the progress in the measurement of the cyclic R-curve for the EA4T steel used for railway axles. Different experimental techniques were used to determine the $\Delta a-\Delta K_{th}$ points for three load ratios: -2, -1 and 0.05. Such R-curves were successively used to predict the condition of propagation-non propagation of short cracks emanating from artificially micro-notched specimens. The outcomes of this work are summarised as follows:

- The conventional Constant-$\Delta F$ procedure cannot capture the upper region of the R-curve (large crack extensions $\Delta a$), as a result a gap was observed between the $\Delta a-\Delta K_{th}$ points and the long crack threshold obtained by the CPLR procedure.

- The cyclic R-curves were determined according a new procedure that combines loading steps with Constant-$\Delta F$ and Constant-$\Delta K$.

- The $\Delta K_{th,LC}$ data obtained with the CPLR technique are fully consistent with the R-curves when they are plotted considering the total crack advancement.

- The R-curve measurements were employed by different experimental techniques to monitor the crack extension and control the tests: the potential drop, the clip-on-gauge, the crack-gauges and the DIC technique; all $\Delta a-\Delta K_{th}$ points determined with these techniques resulted to be consistent leading to robust measurements of the R-curves.

- Based on the comparison with the results of a benchmark activity, we demonstrated that the R-curve can be adopted to estimate the endurance limits for micro-notched specimens, under the assumption that the notch stress field is correctly considered in the calculations.
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6. Appendix

Table 5: Summary of staircase test performed at load ratio of $R = -1$.

<table>
<thead>
<tr>
<th>Small defects (100 × 500µm)</th>
<th>Large defects (200 × 2000µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress Range $\Delta\sigma$ [MPa]</td>
<td>Cycles</td>
</tr>
<tr>
<td>353</td>
<td>10,000,000 run-out</td>
</tr>
<tr>
<td>395</td>
<td>2,927,000 failed</td>
</tr>
<tr>
<td>374</td>
<td>10,320,000 run-out</td>
</tr>
<tr>
<td>395</td>
<td>10,000,000 run-out</td>
</tr>
<tr>
<td>490</td>
<td>1,426,900 failed</td>
</tr>
<tr>
<td>460</td>
<td>1,128,000 failed</td>
</tr>
<tr>
<td>430</td>
<td>10,000,000 run-out</td>
</tr>
<tr>
<td>460</td>
<td>1,093,700 failed</td>
</tr>
<tr>
<td>430</td>
<td>1,562,300 failed</td>
</tr>
<tr>
<td>400</td>
<td>1,324,900 failed</td>
</tr>
<tr>
<td>370</td>
<td>10,000,000 run-out</td>
</tr>
<tr>
<td>400</td>
<td>1,324,900 failed</td>
</tr>
<tr>
<td>370</td>
<td>10,000,000 run-out</td>
</tr>
<tr>
<td>300</td>
<td>1,440,800 failed</td>
</tr>
<tr>
<td>300</td>
<td>1,440,800 failed</td>
</tr>
<tr>
<td>Stress Range</td>
<td>Cycles</td>
</tr>
<tr>
<td>--------------</td>
<td>--------</td>
</tr>
<tr>
<td>Δσ [MPa]</td>
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<tr>
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<td>500</td>
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<td>440</td>
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<tr>
<td>470</td>
<td>10,000,000</td>
</tr>
<tr>
<td>500</td>
<td>1,800,000</td>
</tr>
<tr>
<td></td>
<td>392</td>
</tr>
</tbody>
</table>
References


• The crack propagation threshold depends on the crack length
• A new experimental methodology to determine the R-curve is presented
• The R-curve is used to predict the endurance limits of micro-notched specimens
Author statement for manuscript:

"Progress in the measurement of the cyclic R-curve and its application to fatigue assessment"

by A. Pourheidar et al.

The authors state that this work is not under consideration elsewhere and has not been published in any form before.

We approve the submission and declare no conflict of interests in this work.

The contributions to the paper:
1) A. Pourheidar: R-curve and micro-notched specimen experiments, analysis, manuscript preparation;
2) L. Patriarca: manuscript preparation, experiments and analysis with DIC;
3) M. Madia: project direction at BAM, manuscript preparation;
4) T. Werner: R-curve experiments, manuscript revision;
5) S. Beretta: project direction at Politecnico di Milano, manuscript revision.

On the behalf of all the co-authors

Prof. Stefano Beretta