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Multiple crack initiation and propagation in weldments under fatigue loading

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Abstract

The work aims at addressing the modelling and implementation of criteria for multiple crack propagation, including interaction and coalescence, for a more reliable fracture mechanics-based prediction of stress-life curves for weldments.

A large experimental work is presented in which micro-cracks have been made visible by heat-tinting at successive stages of fatigue life of the welded specimens. Here the correlation between the number of initiation sites and the applied stress level has been also investigated.

The criteria have been implemented in in-house software, which allows multiple fatigue crack propagation, and validated against selected experimental tests. The results have shown that the modelling of multiple crack propagation and interaction is crucial for the prediction of the fatigue strength of weldments, both in finite and infinite life regime.

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Nomenclature

a	crack depth
a_i	initial crack depth
c	crack semi-length
h	excess weld metal
k	depth of the secondary notches
k_t	stress concentration factor
K_{LC}	stress intensity factor for long cracks
K_{SC}	stress intensity factor for short cracks
ℓ	width of each stripe in the modelling of the weld toe geometry
L	weld width
s	distance of the surface tips of two neighbouring cracks
T	thickness of the base plate
α	flank angle
ΔJ	cyclic J -integral
σ	stress
ρ	weld toe radius

1. Introduction

The investigation of multiple crack initiation and propagation is crucial for the structural integrity assessment of many engineering components subject to fatigue loading. Diverse metallic materials for technical applications are characterized by populations of defects which are dispersed in the metal matrix, like shrinkage cavities and gas pores in ductile cast iron [1] or micro-pores and un-melted powder in components obtained by additive manufacturing [2].

Micro-cracks initiate very often from these defects in the early stage of fatigue life, they propagate individually and simultaneously until they eventually coalesce with neighbouring cracks. Multiple crack initiation can be also triggered by irregularities of structural features, like weld ripples in weldments [3]. Here the initiation sites of micro-cracks are highly stressed regions at local stress raisers.

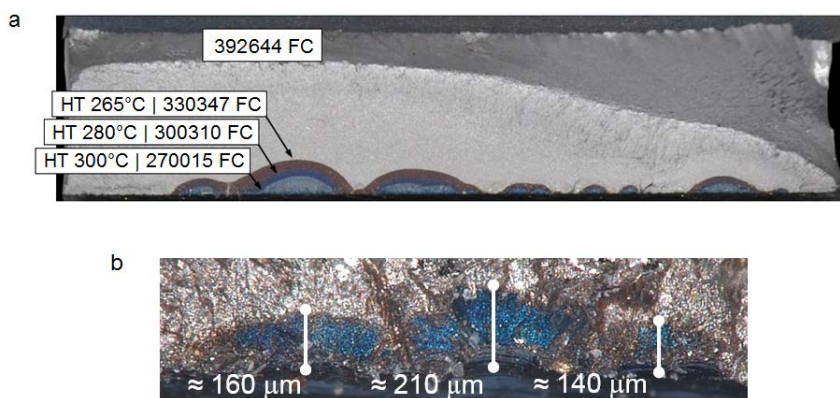


Fig. 1. Post-mortem analysis of the fracture surfaces in case of a cruciform joint made of medium strength steel (S355NL): (a) heat-tinting (HT) has been used to make the cracks visible for different fatigue cycles (FC); (b) small cracks marked by means of heat-tinting at about 40% of the total life of the joint.

The evidences reported in [3] have been confirmed by the findings of fatigue tests conducted in the project *IBESS*, in which experimental techniques like beach-marking and heat-tinting have been employed to mark cracks during different stages of their fatigue lives. In particular, the fractographic analysis of the specimens, which have been broken open after testing, revealed that multiple cracks initiate along the weld toe (see Fig. 1a). Furthermore, the use of the heat-tinting technique as early as 30 to 40% of the fatigue life of the joints could allow the visualization of small cracks starting from irregularities along the weld toe (see Fig. 1b). This represents a very important issue, as it yields to the conclusion that the fatigue life of the welded joints is spent mostly in the short crack propagation regime.

The experimental observations formed the basis for the fracture mechanics-based analytical modelling of the mechanisms leading to the failure of the welded joints. Of particular importance are the following aspects:

- The propagation of mechanically short cracks must be described adequately, which means that an elastic-plastic crack tip parameter such as the cyclic J -integral (ΔJ) should be employed, as the size of the plastic zone is comparable to the crack size in case of mechanically short cracks and therefore the conditions to apply the concepts of the linear-elastic fracture mechanics are no longer valid [4]. Correlated to this issue is also the gradual built-up of the crack closure effects, according to which the crack resistance to cyclic propagation increases gradually from the short to the long crack regime (the reader may refer to [5] for an overview).
- In order to model correctly the multiple crack propagation, the variability of the geometry at the weld toe must be considered in the calculations, because the nucleation of cracks along the weld toe correlates with the severity of the notch geometry and the presence of micro-notches, as already pointed out in Fig. 1b. This issue can be solved just by the statistical description of the local geometry, which in turn leads to a probabilistic fatigue strength assessment of the weldments.

Beside the aforementioned aspects, other variables play a prominent role in the fracture mechanics-based assessment of welded joints, such as residual stresses generated by the welding process and the choice of the material parameters (base metal or heat affected zone). Nevertheless, these aspects will not be discussed in the present work, which focuses instead on the analytical modelling of multiple crack propagation.

2. Measurement and characterization of the geometry at the weld toe

The local geometry at the weld toe plays a prominent role in the initiation of surface cracks, which can eventually lead to the failure of the welded joint subject to fatigue loading. Therefore, a thorough experimental characterization of the weld toe geometry was conducted for different weld joints, which comprised the idealization of the geometry according to the sketch depicted in Fig. 2a, the measurement of the local geometrical parameters (see example in Fig. 2b) and the statistical treatment of the sampled values (see Fig. 2c). The important parameters were: the weld toe radius ρ , the flank angle α , the excess weld metal h , the weld width L and the secondary notch k , which could be the effect of undercuts or weld ripple, for example. More specifically, in the case of the present research, it has been found that also the surface roughness of the hot-rolled plates used in the fabrication of the welded joints could play a major role as crack initiation sites. This is shown in Fig. 3, where, beside the presence of weld ripples, a homogeneous distribution of micro-holes can be observed from the base plate up to the weld toe.

The toe radii ρ and flank angles α have been determined by using line scans executed by means of a stylus instrument, whereas the excess weld metal h and the weld width L have been measured with a laser scanner. For the secondary notch depths k , optical 3D scans with a confocal microscope have been used. The experimental data have been fitted by statistical distributions for the implementation in the analytical procedure for the probabilistic assessment of the fatigue strength of the welded joints; typically, a lognormal distribution has been found to fit well to the values of the weld toe radii, whereas a normal distribution has been employed in the case of the flank angles. This applied well also to the distribution of the secondary notches.

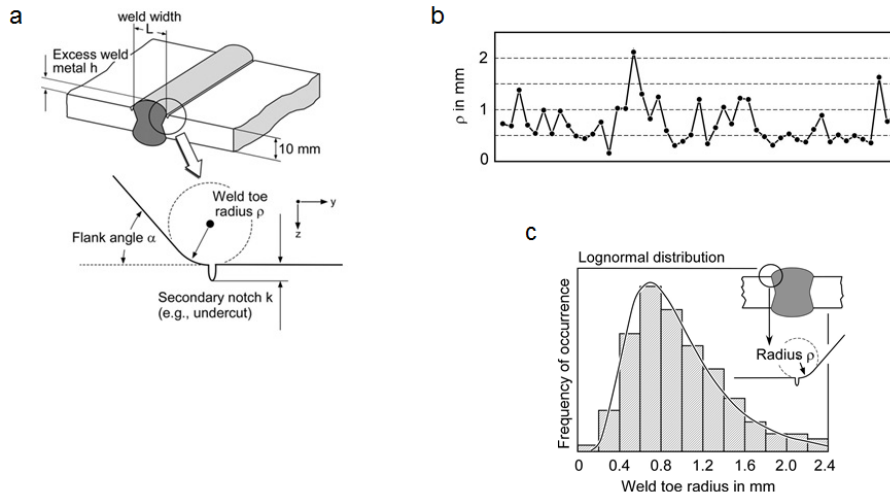


Fig. 2. Characterization of the local geometry at the weld toe: (a) idealization and definition of the local geometrical parameters; (b) example of the measurements for the weld toe radius ρ in a butt-weld; (c) example of the statistical treatment of the weld toe radius ρ in a butt-weld made of steel S355NL.

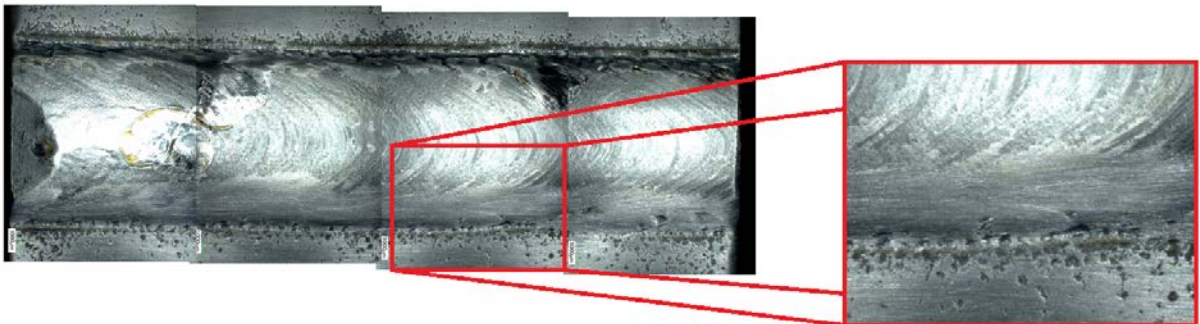


Fig. 3. Evidence of the presence of secondary notches at the weld toe for a double-V butt weld made of S355NL. The magnification shows the major role played by the surface roughness of the base plate in the proximity of the weld toe.

3. Analytical modeling of multiple crack propagation

3.1. Random sampling of the local geometry

The main modelling issue was to account for the variation of the geometry along the weld toe of the welded joints (here the geometry of the tested pieces has been considered, the width of which was 50 mm). It has been decided to partition the weld toe in a finite number of equidistant stripes as depicted in Fig. 4. Note that a similar procedure was already proposed in [6]. The width ℓ of each stripe depends on the variation of the local geometry and consequently on the number of crack initiation sites. Depending of the welding process (shape of the weld beads) more crack initiation sites can be triggered, which means that the density of small cracks at the initial stage of the fatigue life of the joints is higher and, therefore, the distance between adjacent cracks shorter. Note that this yields to an earlier crack coalescence at the weld toe and consequently to a smaller crack aspect ratio, as reported in [3].

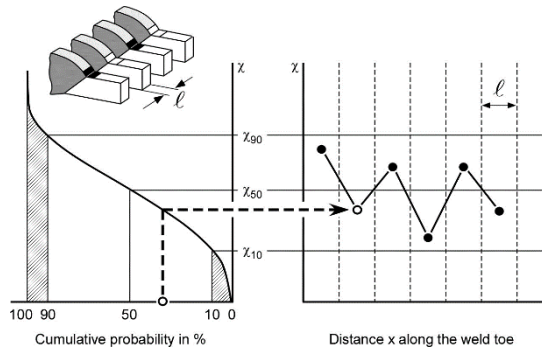


Fig. 4. Partition of the weld toe in stripes and semi-random assignment of the local geometrical parameters.

The variability of the weld toe geometry has been reproduced by a semi-random sampling of the weld toe radius ρ , the flank angle α , and the depth of the secondary notches k . The term “semi-random” refers to the fact that the random sampling of the stochastic variables has been performed taking into account two constraints in order to produce a regular geometry along the weld toe: i) values with a cumulative probability less than 10% and greater than 90% have been discarded; ii) the values for adjacent stripes have been sampled alternatively below and above the 50% cumulative probability to model the waviness of the weld beads. The procedure is schematically described in Fig. 4. Each stripe was characterized by a set of geometrical parameters, which have been used for the calculation of weld toe stress concentration factors and through-thickness stress profiles employed in the determination of the stress intensity factors by means of weight functions [7,8].

3.2. Treatment of secondary notches

The presence of secondary notches at the weld toe can be generally regarded as multiple stress concentration problem, as two stress raisers, namely the weld toe and the secondary notches, occur at the same location. In a fracture mechanics analysis, the problem can be tackled following two possible options (see also Fig. 5a): Option A, the effect of the secondary notches is incorporated in the through-thickness stress profile and the initial crack depth is defined by a_i ; Option B, the through-thickness stress profile accounts only for the stress distribution due to the weld toe and the initial crack depth is taken as a_i+k .

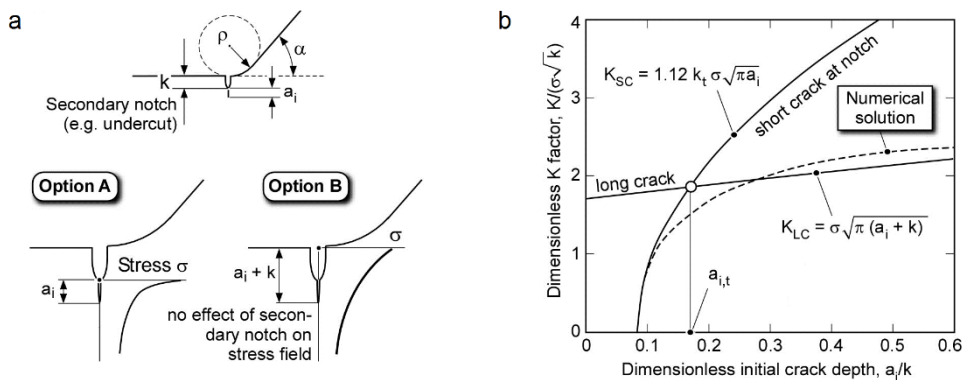


Fig. 5. Treatment of secondary notches in a fracture mechanics-based assessment: (a) possible options; (b) dimensionless stress intensity factor for an initial crack a_i at the edge of a circular hole of radius k in an infinite plate subject to uniaxial tension σ (modified from [11]).

The Option B has been employed in the analytical procedure, as various analytical solutions can be found in the literature for stress concentration factors and through-thickness stress profiles for welded joints [7,9,10]. However, some requirements need to be fulfilled in order to apply Option B, namely the problem of cracks emanating from notches must be considered [11,12], which is schematically described in Fig. 5b in case of a crack emanating from a circular hole in an infinite plate. The initial crack depth a_i must be long enough compared to the secondary notch depth k to avoid any effect of the notch field on the stress intensity factor, assuming a_i+k as crack depth. Note that the statistical analysis of the secondary notches tested in this study revealed a maximum secondary notch depth of about 100 μm , which, therefore, can be considered completely embedded in the notch field of the weld toe. The result is that a crack depth a_i of few microns is already sufficient to allow the use of Option B in the calculation of the crack driving force.

3.3. Modelling of crack coalescence

The process of multiple crack interaction is a complex issue to be modelled analytically, especially in case of small cracks. In fact, despite conventional coalescence criteria can be found in the literature [13], these have to be applied carefully in case of small cracks, where the concept of linear elastic fracture mechanics cannot be employed. Furthermore, in case of welded joints, it must be considered that superficial cracks initiate at the weld toe, where the stress field is not homogeneous due to the variability of the local geometry and steep stress gradients are often found.

The multiple crack growth problem is schematically described in Fig. 6. As far as two cracks are distant from each other, they grow independently of each other (step 1). As the crack tips come closer, the cracks start interacting, which means that the growth of neighbouring tips is speeded up (step 2). As the cracks come into contact ($s = 0$), they coalesce (step 3) until a new single crack is formed (step 4).

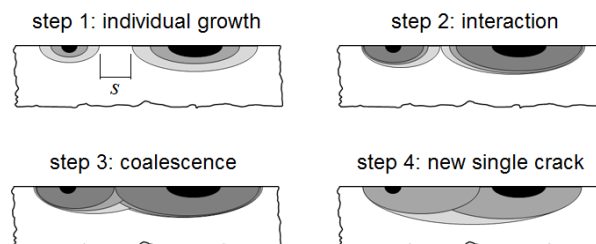


Fig. 6. Schematic description of multiple crack growth.

Experimental tests with pairs of artificial defects and finite element simulations have been conducted to quantify the effect of the crack interaction and coalescence. In particular, heat-tinting has been used to investigate the interaction and the coalescence of neighbouring cracks (Fig. 7a), whereas the finite element simulations have been employed to derive simple approximation formulas for the variation of the J -integral due to the mutual interaction and coalescence of cracks compared to single crack growth (Fig. 7b). Two factors have been derived numerically, namely the interaction factor and the coalescence factor, which depend on the dimensions of the cracks and on the values of the local geometrical variables.

Note, however, that these factors have not been implemented in the analytical procedure yet. At the present stage, two cracks are recharacterized as single crack as soon as the distance s between the surface crack tips equals zero. At this point, the surface length of the new crack is calculated as the sum of the individual crack lengths and the crack depth is taken as the depth of the deepest crack.

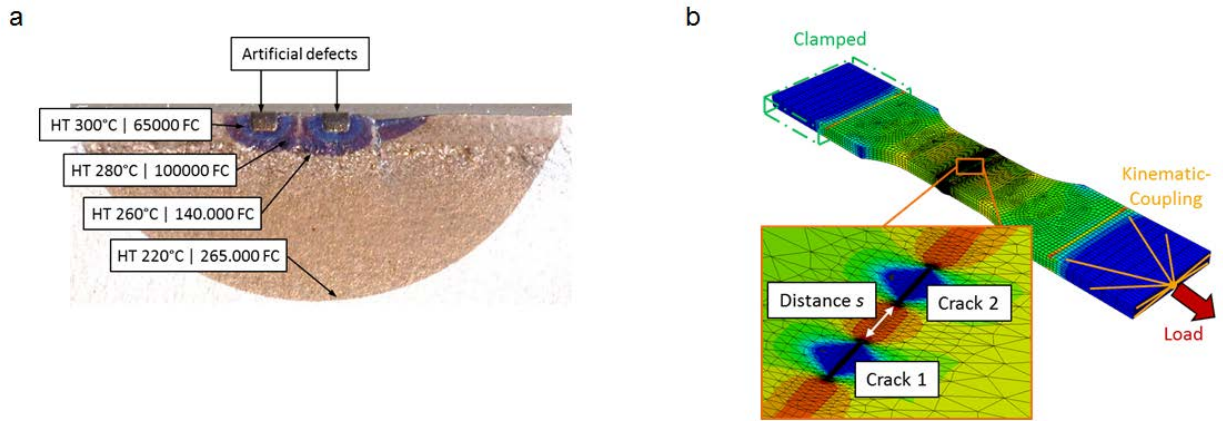


Fig. 7. Characterization of multiple crack growth: (a) experimental tests in which the propagation of paired artificial defects has been marked by heat-tinting; (b) finite element simulations to quantify the mutual influence of neighbouring cracks in terms of J -integral.

4. Validation

In order to validate the procedure a number of interrupted tests on welded joints have been performed. The tests have been interrupted at a very early stage of the fatigue life to mark by heat-tinting potentially small cracks. Then, the tests have been continued up to the final rupture performing intermediate blocks with beach-marking technique. After that the specimens have been broken open, the fracture surfaces have been analyzed and the position and size of each crack has been recorded. The cracks detected by heat tinting have been provided as input for the analytical calculations and the complete experimental test has been simulated.

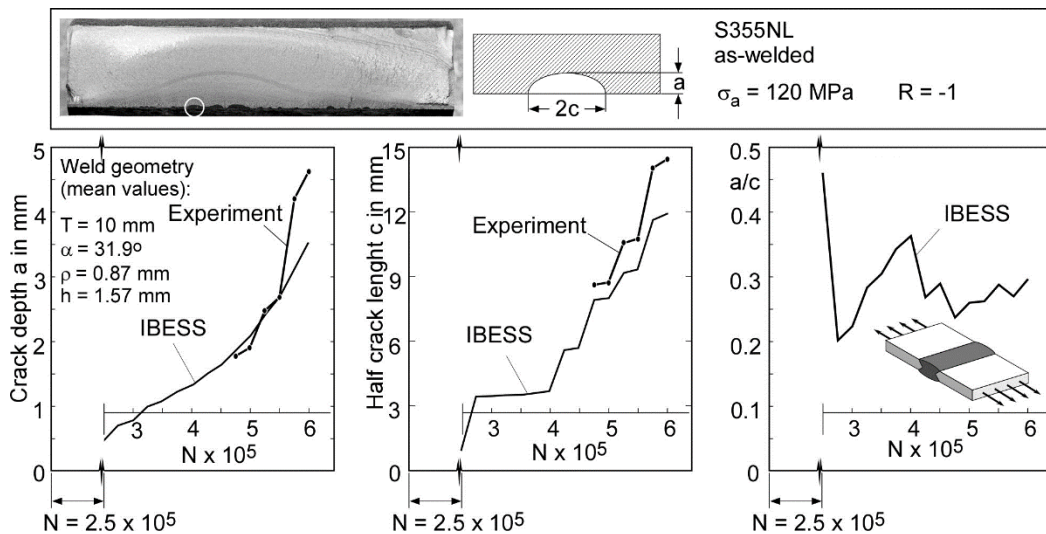


Fig. 8. Simulation of multiple crack growth for a double-V butt weld.

An example of calculation for a double-V butt weld is presented in Fig. 8, where the measurements of the experimental cracks marked by means of beach-marking have been compared to the results of the multiple crack simulations. A fairly good correlation can be observed for the crack depth a and the crack semi-length c up to the last block of beach-marking, where a larger deviation is recorded. A thorough comparison of the crack contours

along the weld toe per each propagation stage revealed that the interaction of neighbouring cracks is underestimated in case of the present calculations. The implementation of the interaction and coalescence factor in the analytical procedure should be beneficial at this point, leading to better predictions. A further remark is given regarding the evolution of the crack shape a/c in Fig. 8. It can be observed that the propagation is characterized by stages of individual crack propagation, in which the crack grows more in the depth (a/c increases), and stages of crack coalescence, where an abrupt drop of a/c is observed.

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