ORAL REFERENCE: ICF100124OR

FATIGUE LIFE CALCULATION OF FILLET-ROLLED COMPONENTS AT AXIAL CYCLIC LOADING

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ABSTRACT

Fillet rolling is a mechanical surface strengthening method. Residual compressive stresses induced in the surface layer of a component are able to increase significantly the fatigue limit and the fatigue life. It is known that the residual stresses cannot prevent crack initiation in fillet-rolled notched areas at load levels lower than the fatigue limit. However, in the crack propagation phase the main working principle of fillet rolling occurs. After crack initiation the residual compressive stresses retard or prevent further crack propagation. Hence the calculation of the fatigue limit and the fatigue life is possible by means of fracture mechanics. To account for plasticity effects an elastic-plastic crack growth model based on the effective *J*-integral is formulated. It can be applied at all phases of the fatigue process by combining the description of crack propagation with methods of the local strain approach. Particular attention has to be drawn to the crack closure phenomenon to describe the positive effect of residual stresses. A new method is presented to calculate the crack opening load-level in notched areas with residual stresses considering notch plasticity effects. The crack growth model and its modules are verified by experiments. The model can be applied in the case of constant and variable amplitude loading to calculate the fatigue limit and the life until fracture (fracture fatigue life) or crack growth stop.

KEYWORDS: fatigue life prediction, fatigue crack growth, fillet rolling, residual stresses, crack closure, *J*-integral, local strain approach, variable amplitude loading

INTRODUCION

Fillet rolling is a mechanical surface strengthening method. It is used with success particularly in the case of notched structural parts which are symmetric in respect to rotation. During the fillet rolling process a profiled roller is pushed around the notched component in a rolling motion bearing a constant pressure load. Plastic deformation of the surface area and the elastic reaction of the core lead to residual compressive stresses in the surface area while residual tensile stresses act on the core.

The fatigue life of notched components is usually subdivided into crack initiation and crack propagation phases. In fillet-rolled components the fracture fatigue life is mainly determined by the latter due to the effect of the residual stresses. Figure 1 demonstrates the special fatigue behaviour of fillet-rolled components for constant and variable amplitude loading. In comparison to the non-rolled component the crack initiation load-level can be increased by about 15% in the case of constant amplitude loading. In addition to the surface improvement the residual stresses reduce the local loading of the notch root by shifting the local stress-strain-path in the compressive region. But the changes in mean stress in the notch root cannot explain the high endurance improvement, which can be reached by fillet rolling. This is in accordance with the experimental observation that crack initiation occurs at load levels lower than the fracture fatigue limit.

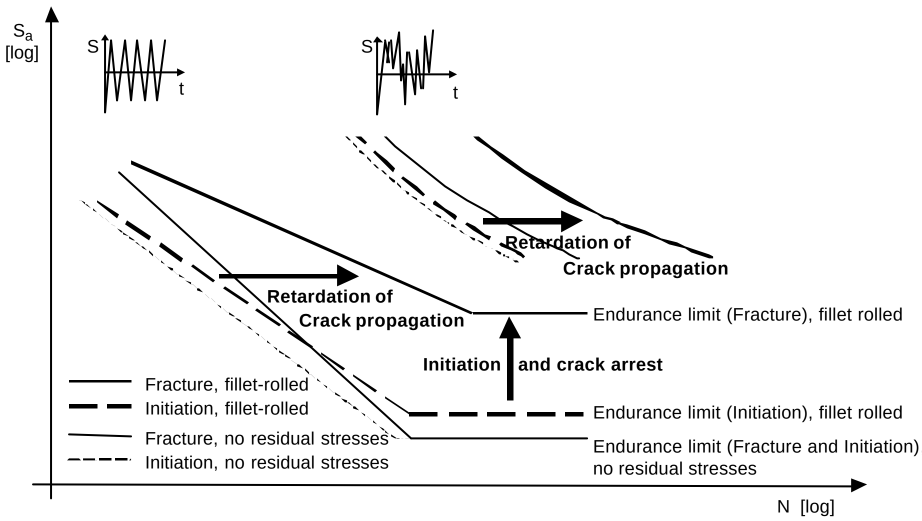

Figure 1: Enhancement of the fracture fatigue limit and the crack propagation fatigue lifetime due to fillet rolling in the case of notched components

The main working principle of fillet rolling occurs in the crack propagation phase because after fillet rolling the maximum of the residual stresses is beneath the surface. After crack initiation the residual compressive stresses retard or prevent further crack propagation which can be explained by the crack closure phenomenon. For the fillet-rolled component this leads to a reduction of the effective load amplitude in comparison to the non-rolled case, which causes a reduction of the effective fracture mechanical loading of the system. The effective load amplitude is regarded as the part of the total load amplitude in which the crack is fully open. From the description of the failure mechanism in fillet-rolled components it can be concluded that the calculation of the fatigue limit and the fatigue life can be predicted by means of fracture mechanics.
Even though there are a lot of models describing crack growth in residual stress fields little attention has been given to describe the phenomena in a unified way for the initiation and propagation phases considering the crack opening and closure behaviour in plastically deformed notches with residual stresses.

ELASTIC-PLASTIC CRACK GROWTH MODEL

The basis of the model is the equation

$$\left(\frac{da}{dn};\frac{dc}{dn}\right) = C \cdot \left(\Delta J_{eff}\right)^m \quad \text{if} \quad \Delta J_{eff} > \Delta J_{eff,th} \tag{1}$$

This describes the crack growth rate in a unified way for the initiation and the propagation phases. C and m are material constants from standard experiments, J_{eff} is the effective amplitude of the cyclic J-integral, a the crack depth, c the half surface crack length and $J_{eff,th}$ the effective threshold value of the cyclic J-integral. The value of J_{eff} is calculated by means of approximation formulae

$$DJ_{eff} = f\,(DS_{eff}, \text{geometry , cyclic ó–å–curve}\ ) \tag{2}$$

being dependent on the effective load amplitude for the crack depth and the crack length direction and on the notch geometry and the cyclic --curve . During the analysis the crack growth is determined incrementally in both directions starting from an initial crack length until the fracture of the component. As Eqn. 1 is formulated in terms of J_{eff} rather than J, the material parameters m and C are independent of the mean stress of the cyclic loading and therefore can be applied for the determination of crack propagation in areas with residual stresses.

A description of the developed model is shown schematically in figure 2, the essential elements of which are outlined below.

- Calculation of the residual stresses due to fillet rolling.
- Calculation of the elastic stress distribution in the crack propagation area.
- Calculation of the redistribution of the residual stresses and the S--paths and --paths for the crack propagation area due to the applied cyclic loading by means of an approximation approach.
- Calculation of the effective load amplitude considering the crack opening and closure behaviour in elastic-plastic, inhomogeneous loaded notched areas.
- Calculation of the effective range of the *J*-integral by means of approximation formulae.
- Calculation of the crack propagation.

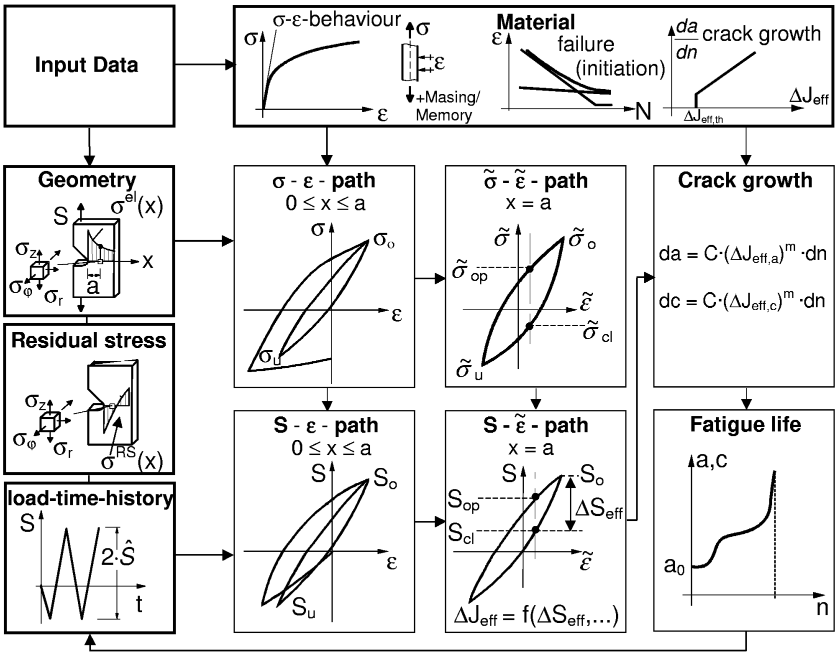

Figure 2: Crack growth model

Due to the improvements in computing power it is now possible to simulate the fillet rolling process and to determine the residual stresses after fillet rolling by Finite-Element-Analysis (FE-Analysis). The initial stress distribution changes due to the cyclic loading and the maximum of the residual compressive stresses is reduced and is pushed away from the surface. In the case of variable amplitude loading this redistribution occurs permanently. Therefore the load-strain curve and the corresponding local stress-strain curve due to the cyclic loading are calculated by approximation formulae, because a FE-analysis is not applicable for every cycle in a variable amplitude load sequence. As only axial loaded notched components symmetrical with respect to rotation are considered, a one-dimensional approach is sufficient. Therefore the crack propagation area is divided into k linear elements with $k+1$ nodes. The local stresses and strains are calculated at these nodes and are assumed to be linear between the nodes. At every reversal of the applied load a generalised Neuber Rule is applied. The increases of equivalent stress $_v$ and equivalent strain $_v$ at every node (i) are thereby formulated as:

$$E \cdot \Delta \boldsymbol{s}_v^{(i)} \cdot \Delta \boldsymbol{e}_v^{(i)} = p \cdot (\Delta \boldsymbol{s}_{e,v}^{(i)})^2 \qquad i = 1,\ldots,k+1 \tag{3}$$

where $_{ev}$ is the equivalent elastic stress at the node (i) and E the modulus of elasticity. So the elastic stress distribution in the crack propagation direction is essential for the application of the approximation formulae. The factor p is determined from the demand that the ligament stresses in the axial direction are in equilibrium with the applied load. For the application of Eqn. 3 it is assumed that the material is already cyclically stabilized. Hence Masing and Memory behaviour for the equivalent stress and strain is assumed to be valid. For the calculation of the increases of the stress and strain components the finite deformation law of Hencky is applied. To obtain the principal stresses and strains at the nodes further assumptions have to be made: In addition to Henckys law and the Mises yield criterion it is also assumed, as in [1], that $^{(i)}/_z^{(i)}$ = const. and

$_{r}{}^{(i)}/_{z}{}^{(i)}$ = const. is valid. The residual stresses after the fillet rolling process are considered by assigning every node (i) an equivalent stress and strain at the beginning of the load time history . Based on suggestions made by McClung [2] and Dankert [3], calculation of the local elastic-plastic loading path neglects the crack. In [4] it its shown that the procedure is able to describe the --paths as well as the residual stress reduction and removal in a fillet-rolled specimen subjected to cyclic loading.

Every closed hysteresis loop is regarded as a damaging event which causes crack propagation. The calculation starts with a semicircular surface crack with the radius a_0. Following Vormwald's local strain approach damage-parameter P_J [5] the value of a_0 is determined from the results of constant strain amplitude tests for an unnotched specimen without residual stresses by "backward" integration of the crack growth law, Eqn. 1.

In [6] it is shown that the determination of the crack opening load in notched areas can be done on the basis of approximation formulae which are originally formulated for the unnotched case. For this the formulae are applied using local stress and strain values at the point of the crack tip in the uncracked structure. However, if residual stresses lead to a high stress gradient in the crack growth area, the total stress and strain distribution acting on the crack surfaces have to be considered. In the case of small-scale yielding conditions this can be done by using a normalized stress intensity factor as proposed in [7] but at progressively higher stresses this parameter becomes less effective in characterizing the crack-tip stress and deformation fields. Therefore the Newman-formulae [8] is formulated in so called effective stress $\tilde{s}$ and effective strain $\tilde{e}$. For the crack depth direction (a-direction) they are computed from

$$\tilde{s} = \int_0^a s(x) \cdot G(x,a)\,dx$$
$$\tilde{e} = \int_0^a e(x) \cdot G(x,a)\,dx \tag{4}$$

The local stresses (x) and strains (x) are determined by means of the approximation formulae Eqn. 3. For the crack length direction (c-direction) the effective stress and strain are equivalent to the local values. The function $G(x,a)$ is proportional to the weight function $m(x,a)$ used to determine the stress intensity factor for an edge crack in a semi-infinite plate. The factor of proportionality is determined from the demand that

$$\int_0^a G(x,a)\,dx = 1 \tag{5}$$

is valid. So in the case of homogenous stress and strain loading in a unnotched component the effective stress and strain are equivalent to the local values.

Every time the local --hysteresis closes the corresponding S-$\tilde{e}$- and $\tilde{s}$-$\tilde{e}$-hysteresis is calculated for the point of the actual crack tip by means of Eqn. 4. Then the effective crack opening stress $\tilde{s}_{op}$ is calculated by means of Newman's approximation formula formulated in local effective values. Figure 2 shows that the crack closure load S_{cl} is determined with the aid of the equality of the effective crack opening strain and the effective crack closure strain $\tilde{e}_{op} = \tilde{e}_{cl}$ and the known S-$\tilde{e}$ and the $\tilde{s}$-$\tilde{e}$-paths for the closed hysteresis. The validity of the equation $_{op} = {}_{cl}$ is proven experimentally for the case of notched specimens without residual stresses [9] but in the case of residual stresses the local values are regarded to be not representative for the description of the crack-tip stress and deformation fields. However, the application of local values ($_{op} = {}_{cl}$) is also possible as the deviations in the determined fatigue life are small.

Following [3] the effective load amplitude results from the difference between the maximum load of the closed hysteresis and the crack closure load, $S_{eff} = S_o - S_{cl}$. To obtain the value of the crack driving force per cycle, the approximation formulae (Eqn. 2), described and verified for circumferential and surface cracks in circumferentially notched round bar specimens [4] are applied. The basis of the approach is the superposition of the so-called elastic and plastic part of the J-integral.

VERIFICATION

Crack opening loads

The algorithm for the determination of the crack opening load is verified by experimental results for cracks growing from notches at CA loading at the nominal stress ratio R = -1 for two different materials and two notch geometries shown in Figure 3a. The measured values, material data and further details are reported in [6]. Figure 3b demonstrates that the developed algorithm is able to describe the crack opening behaviour. In accordance with the experimental results the calculated crack opening level (S_{op}) normalized with respect to the maximum load (S_{max}) increases the longer the crack grows and stabilises at a nearly constant level. Further examples show similar quality [4]. Following [5,8,10,11] the crack opening load is defined as the load level which opens the crack completely.

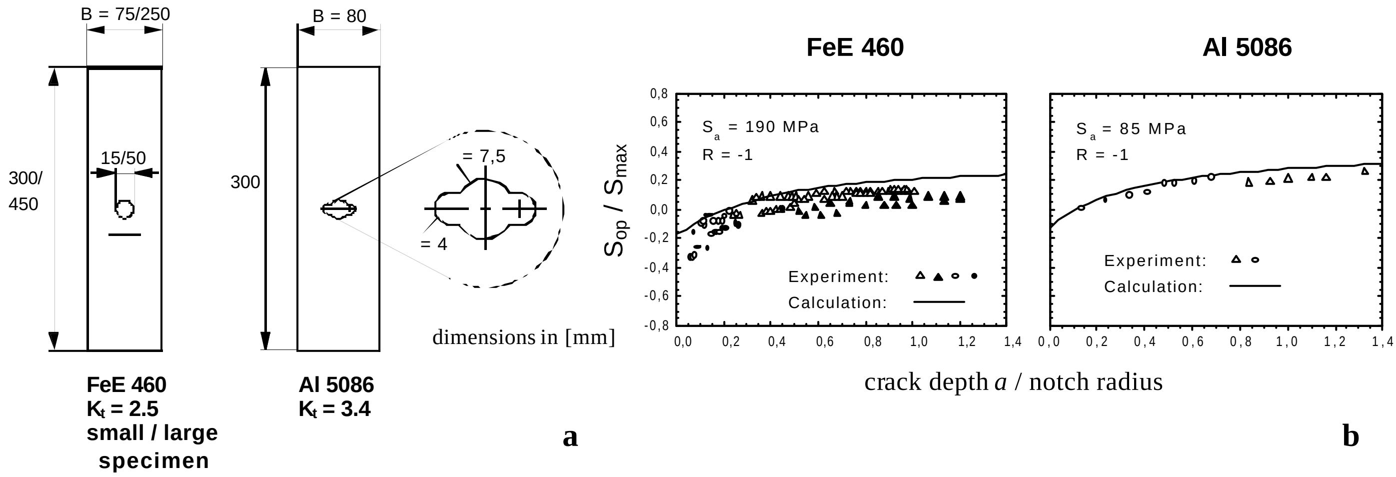

Figure 3: Specimen (a), Comparison of experimentally [6] and calculated crack opening loads (b)

Crack growth

The crack growth model is verified by experimental results described in [12]. The notched cylindrical specimen (material: German grade 42CrMo4, R_m=1065 MPa) is shown in Figure 4a. The fillet rolling force is F_W = 5 kN leading to compressive residual stresses of approx. –650 MPa at the notch root surface and a maximum of –1100 MPa approx. 0,4 mm beneath the surface after fillet rolling. These values are determined by FE-analysis performed by Schaal [13] and the residual stress distribution is employed as input data.

Figure 4b shows the result of the crack propagation calculation at the nominal stress ratio R = -1 in comparison to the experimentally determined crack propagation curve and describes the typical crack growth behaviour in notched fillet-rolled components. After crack initiation the crack grows with relative high crack growth rates, crack growth retardation occurs at the time the crack tip reaches the area of the maximum compressive stresses which are redistributed due to the cyclic loading. In the case of amplitudes which are lower than the fracture fatigue limit the crack stops. Otherwise the crack retardation phase is followed by a phase of crack growth acceleration ending in the fracture of the specimen. Figure 4c shows the results of the crack propagation calculation in the form of S-N-curves for different R ratios. The flat slope of the S-N-curves, which are typical for notched fillet-rolled components, and the endurance limit are quite accurately calculated by the developed model.

The crack growth model can also be applied in the case of variable amplitude loading. Load sequence effects are considered by an approach whereby the algorithm proposed in [5] is reformulated in terms of effective strains, in the way that the effective crack closure strain of the actual hysteresis depends on the effective crack closure strain of the actual hysteresis at CA loading and also on the effective crack closure strain of the previous hysteresis loops. Figure 5a shows the comparison between experimentally and numerically determined fracture fatigue life for a Gaussian load sequence (H_0 = 10^6, I = 0.99, $\overline{R}$ = -1). Figure 5b shows experimentally and calculated crack propagation curves for a blocked program test load sequence ($\overline{R}$ = -1). For all comparisons the measured crack growth can be fairly accurately described, particularly considering the high slope exponent of the S-N-curves for fillet-rolled components.

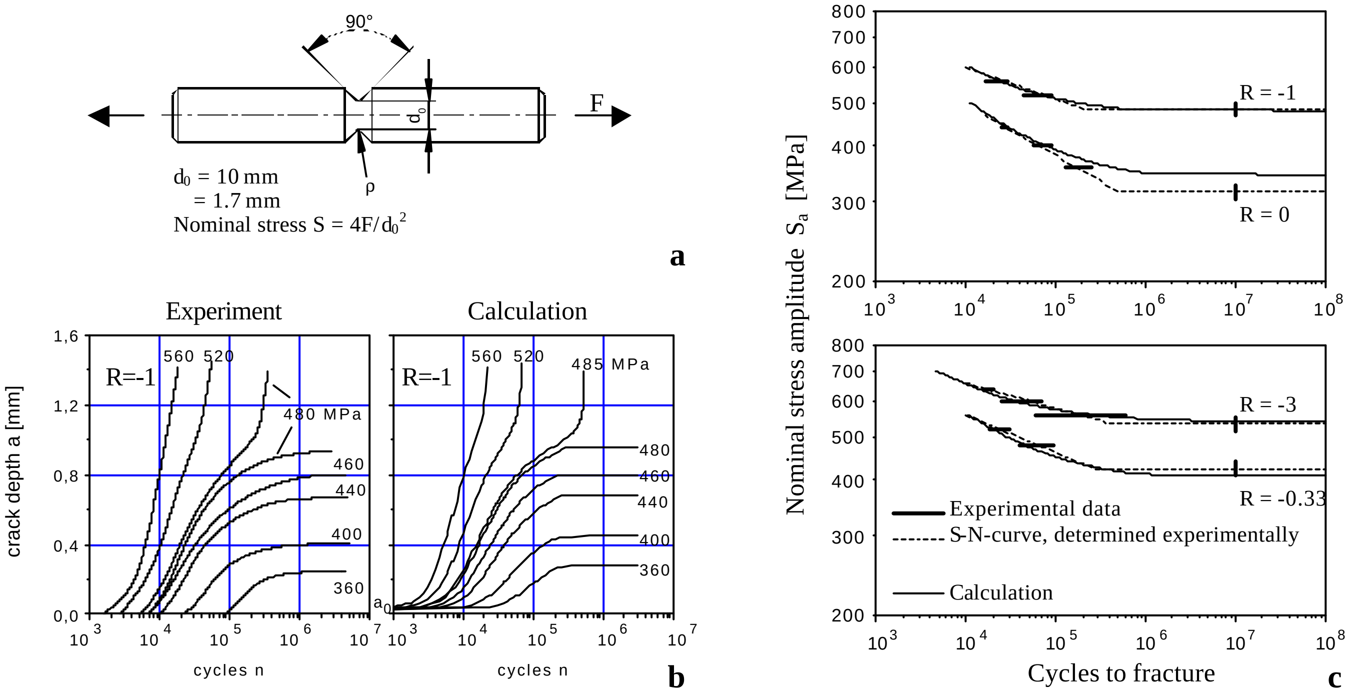

Figure 4: Specimen Geometry (a), Comparison of calculated and experimentally [12] determined crack propagation curves (b) and S-N-curves (c) for constant amplitude axial loading

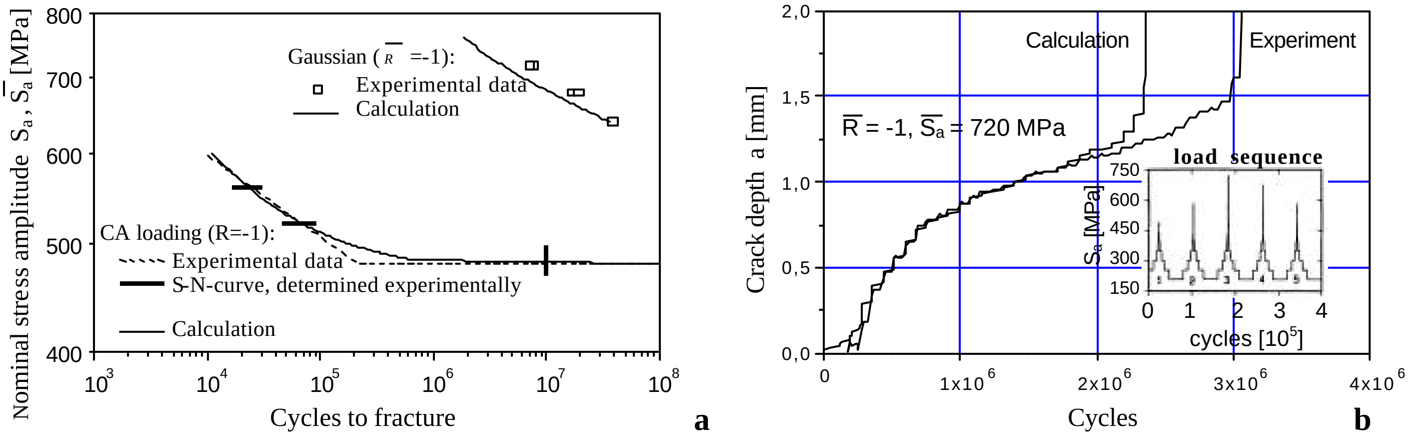

Figure 5: Comparison of calculated and experimentally [12] determined fatigue life curve for a Gaussian type random sequence (a), Comparison of calculated and experimentally [12] determined crack propagation curve for a blocked program test load sequence (b)

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