

Full paper**Numerical fatigue strength investigation of wire and arc additive manufactured (WAAM) specimens based on 3D-scans and implicit gradient model**Sulaiman Shojai¹ | Hessam Moshayedi² | Moritz Braun¹ | Elyas Ghafoori²**Correspondence**

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Abstract

The calculation of fatigue strength based on the actual local quality of a component offers the advantage of a more accurate fatigue assessment. For wire arc additively manufactured (WAAM) components, however, the incorporation of local quality into fatigue calculations is challenging due to the strong variability of the as-built surface geometry. As a result, conventional local methods such as the Theory of Critical Distances, which require the evaluation of individual stress paths, are not readily applicable when a large number of surface notches are present. To overcome this limitation, a methodology is required that allows all surface notches to be considered simultaneously. In this work, a surface-based local fatigue assessment approach is applied for the first time to WAAM components made of ER70S-6 steel. The method combines high-resolution 3D laser scanning, reverse engineering of the as-built geometry, and numerical stress evaluation using the IGM to identify fatigue-relevant surface regions without prior knowledge of crack initiation sites. The predicted locations of maximum effective notch stress were compared with experimentally observed crack initiation sites from fatigue tests. An agreement was found for 9 out of 15 failed specimens, indicating that the approach can identify critical surface regions despite geometric complexity and modeling uncertainties. This demonstrates the potential of the method for improving fatigue assessment and supporting the industrial application of WAAM components. Further investigations, particularly regarding material-dependent model parameters, are required to improve the robustness of the method for WAAM components.

Keywords

Local Fatigue Approaches, Wire Arc Additive Manufacturing (WAAM), 3D Laser Scanning, Reverse Engineering, Effective Notch Stress, Fatigue Assessment

1 Introduction

The WAAM process is an additive manufacturing method based on welding technologies. In this process, a continuously fed welding wire is melted by an electric arc and deposited layer by layer onto a substrate. This method enables high deposition rates of several kilograms per hour and is particularly suitable for large-scale metallic components. The main advantages of WAAM include high material efficiency, comparatively low investment costs, and good integrability into existing production lines.

The surfaces of WAAM-produced components are characterized by irregularities such as waviness, thickness variations, and surface roughness, which are influenced by various process parameters. Waviness, defined as the variation of the mean line, increases with both the melting

speed and the deposition rate of the process [1; 2]. These irregularities represent geometric notches and generate local stress concentrations at the specimen surface, which significantly affect the fatigue behavior [3]. Hence, the fatigue strengths of components are directly related to the local quality.

The local quality of a component can be taken into account independently of the manufacturing process by means of local fatigue assessment methods. Recent research has extended local fatigue assessment methodologies to additively manufactured components by incorporating local quality and stress gradient effects. Lipiäinen et al. [4] applied the theory of critical distances (TCD) within a finite element framework to DED-Arc specimens, demonstrating improved fatigue strength prediction compared to nominal stress approaches. In this investigation, this could only be

achieved because the stress gradient could be evaluated directly at the crack initiation sites identified from fatigue tests. In the design of such components, however, the actual crack initiation site is unknown, and the application of the Theory of Critical Distances (TCD) is not feasible due to the large number of potential notches present in an additively manufactured component. Recent developments in fatigue strength assessment based on local methods therefore aim to capture entire components using 3D scanners and, on this basis, to numerically determine the notch stresses for all potential critical locations and incorporate them into fatigue life calculations [5–14].

In the present work, for the first time these methods are applied to additively manufactured components produced by WAAM.

2 Background of the notch stress methods

2.1 Notch stress analysis methods

With local fatigue methods such as the notch stress method, it is possible to consider the stress concentrations arising from geometrical discontinuities. In the notch stress method, the analysis of the notch stresses concentration is based on the notch geometry and on linear elastic material behaviour, leading to the elastic notch stress σ_k . In case of sharp notches, the yield stress in the surface crystallites can be exceeded and lead to micro cracks, which do not propagate with continued cyclic loading. This behaviour is called micro-support effect, which reduces the stress concentrations and supports the fatigue resistance [15; 16]. Various hypotheses related to micro-support effects exist in the literature for calculating the effective fatigue notch stress, here denoted as σ_f . Among these methods are the point method (PM) by Peterson [17], the line method (LM) by Neuber [18], the volume method (VM) by Bellet [19], and the fictitious notch stress approach by Radaj [20].

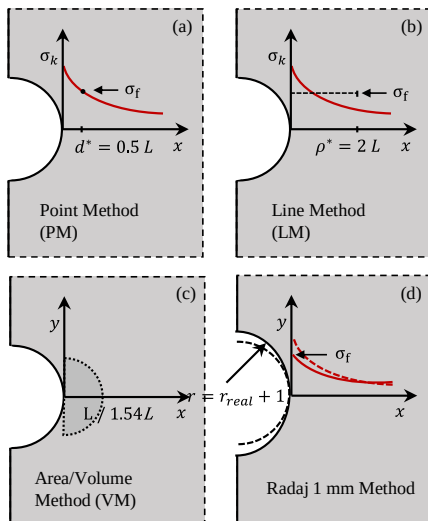


Figure 1 Notch stress analysis methods (a) point method, (b) line method, (c) area/volume method, summarized in [21] and (d) Radaj 1 mm method [20], from [11]

In the PM, the effective notch stress σ_f is considered as the stress at a critical distance d^* (equation (1), Figure 1 (a)), while in the LM the effective notch stress is considered to

be the stress averaged over the length of a microstructure particle ρ^* in the notch base (equation (2), Figure 1 (b)). Analogously, in VM the stresses are averaged over a hemisphere defined by a radius of $1.54L$ (Figure 1 (c)). With the critical distance $d^* = L/2$ and the equivalent averaging length $\rho^* = 2L$, PM, LM, and VM can be related to the intrinsic material length L , derived from linear elastic fracture mechanics [22] and defined in equation (3). Here ΔK_{th} is the fatigue crack propagation threshold and $\Delta\sigma_0$ is the fatigue limit.

In the fictitious notch stress approach by Radaj, the notch stresses are calculated based on fictitious notch radius r_f . Therefore, the existing notch radius r_{real} is increased by 1 mm (equation(4), Figure 1 (d)). Assuming a worst-case scenario with $r_{real} = 0$ for welded components, this leads to a fictitious radius of $r_f = 1$ mm as recommended in various standards including the IIW recommendations [23]. The fictitious radius varies depending on material behaviour and the nominal plate thickness between 0.05 mm to 1.0 mm as reported in [24; 25].

$$\sigma_f = \sigma_k(d^*) \quad (1)$$

$$\sigma_f = \frac{1}{\rho^*} \int_0^{\rho^*} \sigma_k dx \quad (2)$$

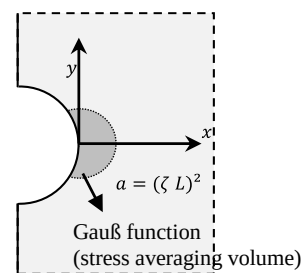
$$L = \frac{1}{\pi} \left(\frac{\Delta K_{th}}{\Delta\sigma_0} \right)^2 \quad (3)$$

$$r_f = r_{real} + 1 \quad (4)$$

However, all presented methods show deficiencies when the effective stresses shall be investigated on the basis of a real 3D geometry. The application of 1 mm approach of Radaj requires a change of geometry, which is not possible for 3D-models. The analysis with PM, LM, and VM is possible, but requires a lot of post processing because of the great number of notches in real WAAM surface geometries, requiring all the stress paths to be evaluated individually.

2.2 Implicit gradient model (IGM) approach

An alternative approach is the implicit gradient model (IGM) introduced by Peerlings [26; 27], shown in Figure 2. In contrast to the TCD-based methods, which require the evaluation of predefined stress paths or local assessment regions, the IGM enables the simultaneous consideration of the full surface in a single numerical analysis and is therefore particularly suitable for WAAM components with numerous interacting surface notches.



$$\sigma_f(\mathbf{x}) = \frac{1}{V_r(\mathbf{x})} \int_V G(\mathbf{x}, \mathbf{y}) \sigma_k(\mathbf{y}) dV_y$$

Figure 2 Implicit Gradient Model, according to [26]

The IGM allows considering the micro-support effect for all notches of a component in a single analysis. Different approaches like PM, LM, or VM can be used by selecting appropriate weighting functions [21]. In the case of three-dimensional FE-models, the VM approach is suitable, as it can be implemented in commercial numerical software (see Figure 2). Considering this, the effective stress $\sigma_f(\mathbf{x})$ at the point $\mathbf{x} = (x_1, x_2, x_3)$ can be described as the integral over the volume V of the weighting function G , that is dependent on the distance $||\mathbf{x} - \mathbf{y}||$ between point $\mathbf{x}$ and any point $\mathbf{y} = (y_1, y_2, y_3)$, and a reference volume V_r as follows:

$$\sigma_f(\mathbf{x}) = \frac{1}{V_r(\mathbf{x})} \int_V G(\mathbf{x}, \mathbf{y}) \sigma_k(\mathbf{y}) dV_y \quad (5)$$

Assuming a Gaussian function for the weighting function G , that approximates the hemisphere in Figure 1 (c), this leads to the following differential equation:

$$\sigma_f(\vec{x}) - \sigma_k(\vec{x}) - a \nabla^2 \sigma_f(\vec{x}) = 0 \quad (6)$$

The total volume of the body is considered as the solution domain and the surface is defined as the boundary. Usually the Neumann boundary condition is used [26; 28]:

$$\frac{\partial \sigma_f(\mathbf{x})}{\partial \mathbf{x}} \cdot \mathbf{n} = 0 \quad (7)$$

where $\mathbf{n}$ is the normal to the surface of the solution domain.

Considering this, the differential equation (6) can be solved to σ_f for any given stress σ_k under specification of the weighting scale factor a . The weighting scale corresponds to the surrounding volume at the notch and is linked to the intrinsic material length L defined in equation

(3) with:

$$a = (\zeta \cdot L)^2 \quad (8)$$

where ζ considers the stress criterion, which is equal to 0.545 for the maximum principal stress as well as for the Tresca stress criterion and 0.456 for the von Mises stress criterion [29]. With this, the impact of the material can be considered on the basis of linear elastic fracture mechanics. A detailed derivation of the method is provided in the literature [21; 26; 27; 30; 31] and is not discussed here. The application of this method on the examined specimens is described in section 3.4.

It should be noted, that for the IGM approach there is no recommendation for choosing a specific stress criterion. However, as the stress analysis is based on 3D-models, which leads to multiaxial stress conditions, the von Mises stress criterion was used in this study. According to Sonsino [32] and Radaj and Vormwald [16] the application of the von Mises criterion for consideration of multiaxial stresses leads to reliable results, if it is applied to ductile materials and in-phase loading.

3 Numerical analysis and fatigue strength assessment

The specimens investigated within the scope of the present work were fatigue-tested by Huang et al. [3]. These specimens consisted of as-built WAAM-manufactured fatigue coupons with a nominal thickness of 3 mm, which were extracted from flat plates produced by a robotic multi-axis Wire Arc Additive Manufacturing process using

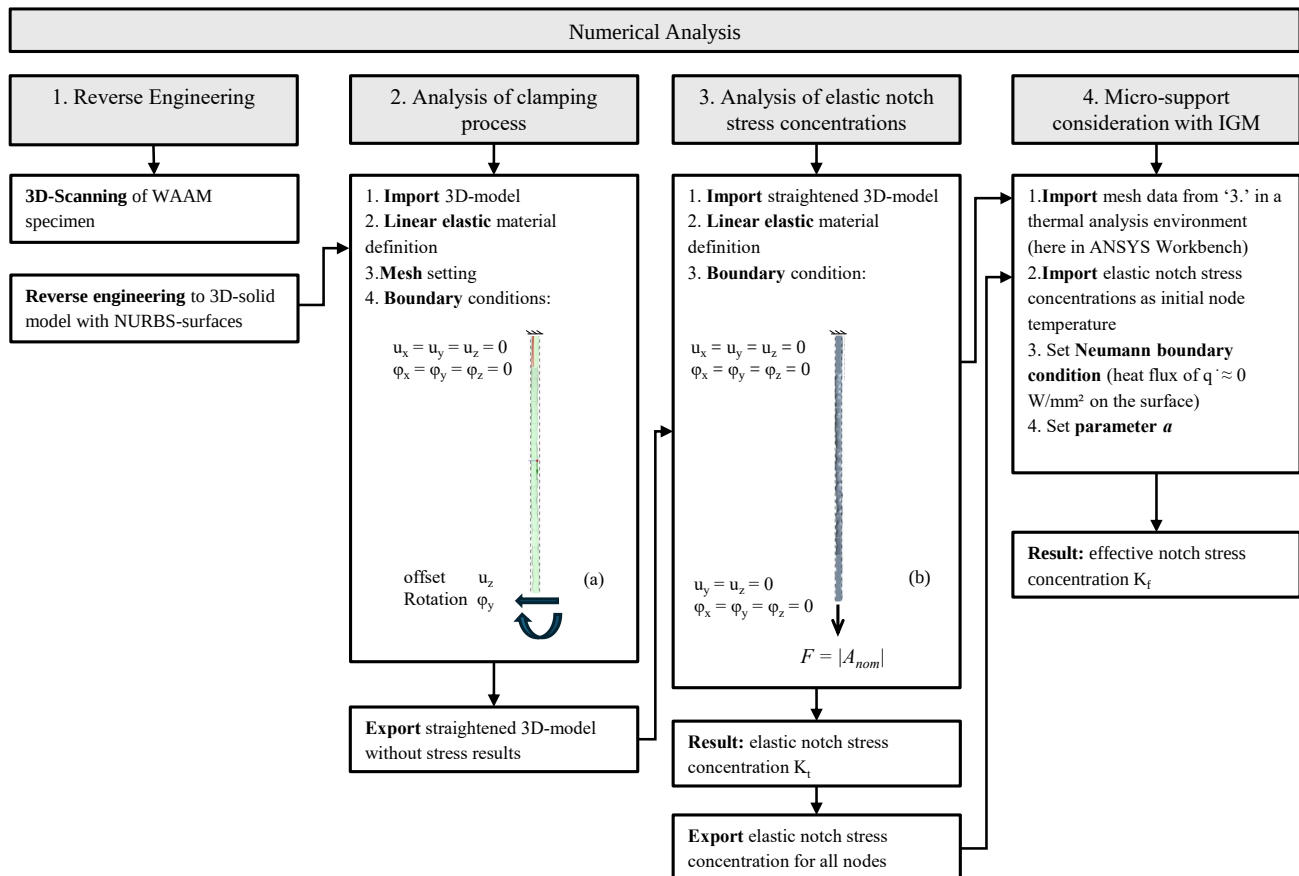


Figure 3 Flowchart of numerical analysis using the IGM approach

ER70S-6 steel welding wire as feedstock. A parallel deposition strategy with periodic reversal of the deposition direction was applied to control heat input and geometric stability. The fatigue coupons were cut from the additively manufactured plates by water-jet cutting, with the longitudinal specimen axis oriented perpendicular to the deposition direction. The fatigue coupon is illustrated in Figure 4 (a) [3]. Up to 18 specimens (FN1 – FN18) were tested under uniaxial tensile loading with constant amplitude. The fracture surfaces were documented photographically.

The schematic overview of the numerical analysis using the IGM approach is shown in Figure 3 and is described in the following sections.

3.1 Reverse engineering and numerical model

The geometry of the specimens was digitally captured prior to testing using 3D laser scanning with a Faro ScanARM [3]. The scan data were converted from point clouds into a polygon object, saved as an STL file, and further analyzed in this format.

For the numerical investigation of the specimens, the software Ansys Workbench, version 2023 R1, and its subprogram SpaceClaim were used in order to reverse engineer the STL-file of the as-built WAAM specimen into a CAD model. For this purpose, the faceted surface is approximated in SpaceClaim by NURBS (Non-Uniform Rational B-Spline) surfaces [11]. An example of a surface approximated in this manner is shown in Figure 4 (b-c). This step is necessary because the 3D surface consists of triangular elements whose transitions are not continuous, which would otherwise lead to edge singularities. The surface was not converted into a single NURBS surface, but rather into many small, approximately square surface patches, as shown in Figure 4 (c).

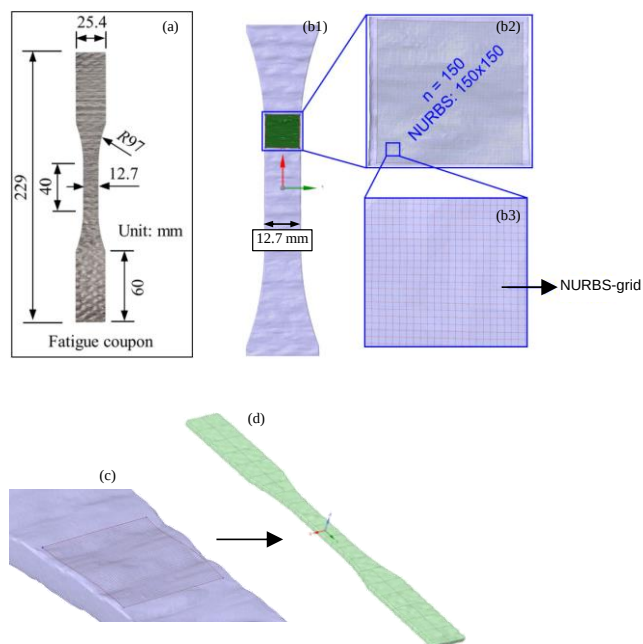


Figure 4: (a) Fatigue coupon from Huang et al. [3], (b1) STL-file from 3D-scan, (b2) approximation of the STL-surface with a NURBS-patch with a 150x150 grid, (b3) detailed illustration of the NURBS-grid, (c) illustration of one NURBS-patch on the STL-file, (d) resulting 3D-model with several NURBS-patches combined to one solid model

Once the entire surface has been covered or approximated, the individual surfaces merge to form a solid body, as illustrated in Figure 4 (d).

To determine a suitable mesh size for the approximated surfaces used in the reverse-engineering process, a parameter study was carried out for specimen FN1. In this study, the selected number of NURBS surfaces was divided by the surface width, which here corresponds approximately to the width of the narrow section of the specimen and can be referred to as the NURBS-grid rate. The higher the grid rate, the more curves per length or area are used to describe the surface topology, see Figure 4 (b3).

In Figure 5 the results of the parameter study are shown. It can be observed that beyond a grid rate of 8/mm the notch stress concentrations are changing only marginally. The analysis of the stress concentrations in this study was carried out using a grid rate of 12/mm. This ensures a sufficient approximation of the STL surface. If the mesh is too coarse, notches are approximated too roughly, resulting in stress concentrations that are either lower or even higher than they should be from a mathematical standpoint. Further refinement of the surface approximation does not lead to changes in the stress concentrations, but it significantly increases the model size and, consequently, the computational time. The selected NURBS-grid rate was chosen based on the conducted stress convergence study for the investigated specimen 3D-scan. It should therefore be understood as a case-specific modelling choice, which may differ for different specimens and also 3D-scan resolutions.

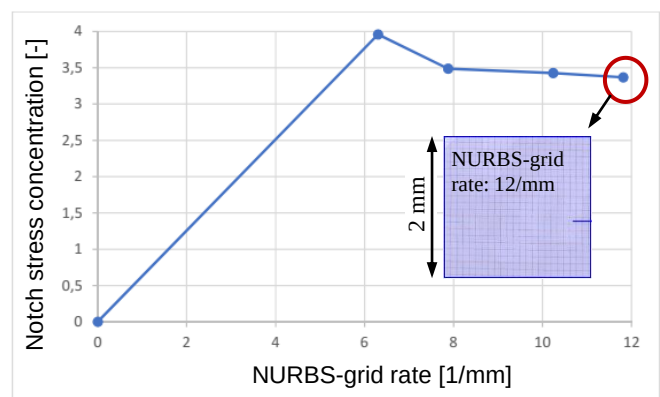


Figure 5 Parameter study with varying NURBS-grid rates.

3.2 Consideration of the clamping procedure

Before analysis of the stress concentrations external displacements are applied to the support surfaces in order to simulate the clamping process and bring both specimen ends to the same height and to eliminate any inclination in the support regions. The adjustment of the support alignment is applied stepwise, as shown in Figure 6 for the solid model of FN16. The rotations applied during the support alignment range between 0 and 2.43°, while the displacements range between 0 and 1.4 mm. As illustrated in Figure 6, a visual verification can be performed using horizontal reference lines at the upper and lower edges of the support regions. The remaining curvature outside the support regions is not further corrected, as it represents a

surface profile irregularity typical of WAAM products that was present during the experimental testing.

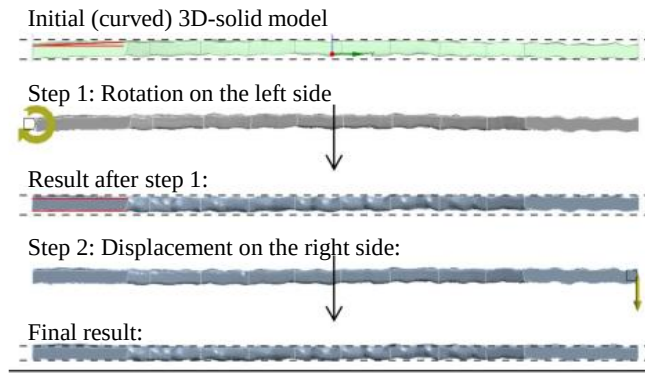


Figure 6 Simulation of the clamping process and elimination of inclinations.

3.3 Numerical analysis of stress concentration

After simulation of the clamping process the support conditions of the fatigue experiments and the applied load are introduced in order to evaluate the elastic stress concentrations. The stress concentrations are calculated based on linear elastic material formulation. Therefore, the deformed model from the clamping process is utilized for the analysis. Analogous to the fatigue test, the model is fixed on both sides, allowing only axial deformation, Figure 7 (a). To simplify the determination of the elastic notch stress concentrations, the load is selected such that a nominal stress of approximately 1 N/mm² is obtained, i.e., the applied force is equal in magnitude to the cross-sectional area of the specimen in the narrow section. Since the cross-sectional area varies both between different specimens and along a single specimen, the cross-sectional area was measured at the specimen mid-length as well as at positions 10 mm and 20 mm away from it, and an average value was determined. This average deviates by only $\pm 2\%$ from 37 mm². Based on this, a simplified load of $F = 37$ N was applied in the numerical calculations for all specimens.

For the mesh, quadratic tetrahedral elements (SOLID187 in ANSYS) with an initial element size of 0.3 mm over the whole surface of the specimen were used. An adaptive convergence study led to element sizes of 0.03 mm at the high stressed areas, see Figure 7 (b1-b2), and about 10^6 to 10^7 nodes for each specimen.

The elastic notch stress concentrations are presented in Figure 7 (c) using the von Mises criterion because a multi-axial stress state exists at the notch root.

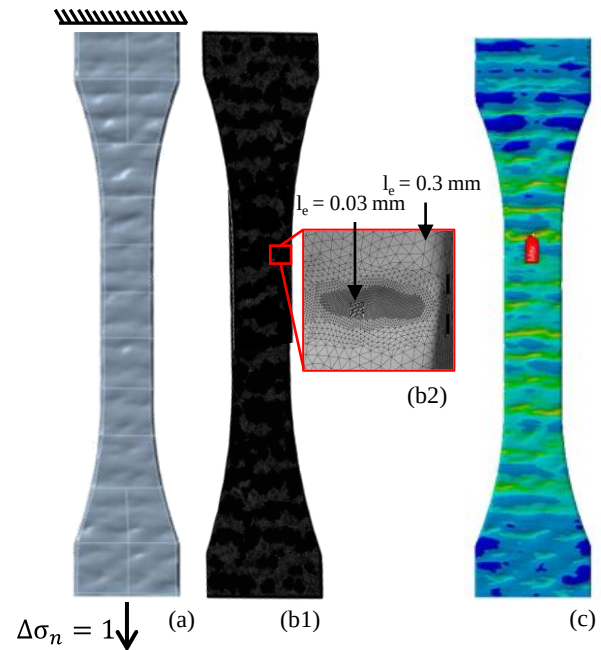


Figure 7 (a) Reverse engineered 3D-solid model with boundary conditions for stress concentrations analysis, (b1 and b2) discretization of the 3D-solid model, (c) results for elastic notch stress concentration K_t .

3.4 Consideration of micro-support effect with IGM

For consideration of the micro-support effect with IGM, the differential equation (6) has to be solved to σ_f . For one- or two-dimensional problems, the equation can be solved by implementation in MATLAB. For three-dimensional problems, it is recommended to use the solvers of commercial FE-software. According Lang et al. [33] and Lener et al. [34] it can be solved with the thermal analysis module of commercial FE-software, as equation (6) is similar to the differential equation of the thermal diffusion problem. For more information on the numerical implementation, it is referred to Shojai et al. [35].

In this study, the thermal analysis module of ANSYS Workbench is used to solve equation (6). For this purpose, the elastic notch stresses $\sigma_k (= K_t \sigma_n)$ are used as input values for the diffusion analysis for each individual node of the numerical model Figure 7 (b1). The Neumann boundary condition according equation (7) is considered with a 'heat flux' boundary condition of $\dot{q} \approx 0$ applied to the surface of the specimen. In ANSYS Workbench, this was achieved by setting $\dot{q} = 10^{-20}$ as a numerical approximation of the Neumann boundary condition. In the investigated models, this value provided stable solutions without observable influence on the resulting stress distribution. The weighting factor a is linked to the thermal properties with $a = \frac{\lambda}{\rho_d \cdot c_p}$ and is considered with the thermal conductivity parameter λ , as the specific heat capacity and density were set to $c_p = 1.0$ and $\rho_d = 1.0$.

The weighting factor for this study was set to $a = 0.01$ mm² based on literature review [21; 27; 31].

3.5 Results

The results of the numerical investigations are shown exemplarily for specimens FN1, FN2, and FN3 in Figure 8. For each of the three specimens, the fractured specimen and the corresponding crack initiation site are presented. Below these, the effective notch stresses numerically determined using the IGM are shown, with the location of the maximum notch stress indicated by a red marker. All three specimens exhibit similarly high notch stress values. For specimens FN1 and FN2, the location of the maximum notch stress coincides exactly with the crack initiation site observed in the experiments, whereas no such agreement is found for specimen FN3. Possible reasons include uncertainties in surface reconstruction, clamping representation, and the possibility of crack initiation from internal defects.

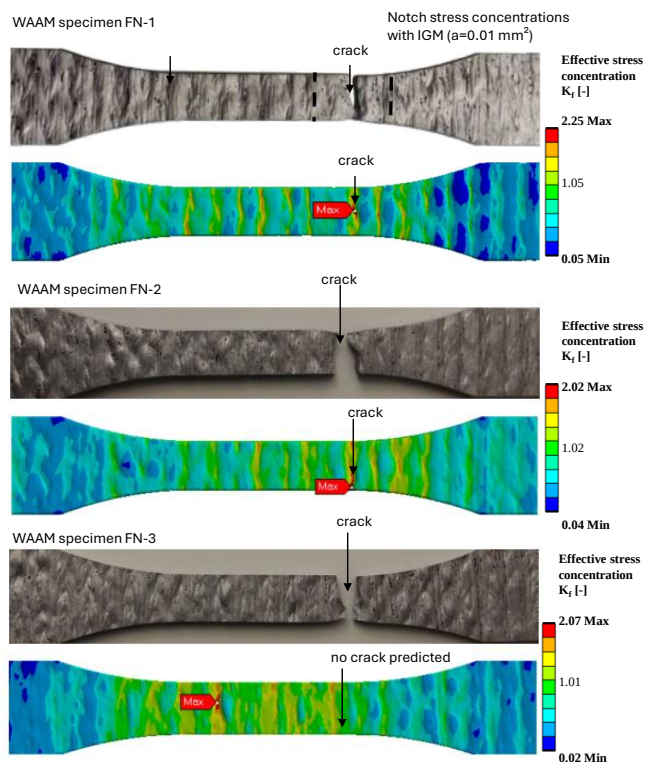


Figure 8 Results of effective stress concentrations K_t based on numerical analysis with implicit gradient approach for specimen FN-1, FN-2, and FN3 as representative examples for all specimens.

In total, 18 specimens were tested, of which 15 ultimately failed by cracking. Among these 15 specimens, an agreement between the numerically predicted maximum notch stress location and the experimentally observed crack initiation site was achieved for 9 specimens, while no agreement could be obtained for the remaining 6 specimens.

3.6 Discussion

The shown results must be interpreted in light of the uncertainties introduced throughout the numerical modelling process. Limitations arise from the resolution of the 3D scans, the loss of geometric detail during NURBS-based surface reconstruction, and uncertainties in the representation of the clamping conditions. Since the actual installation state of the specimens in the testing machine is not

known, misalignment and surface waviness in the clamping regions may introduce bending effects that are not fully captured in the simulations. Additional uncertainty is associated with the weighting factor a used in the IGM, which was set to 0.01 mm^2 in this study based on values reported for mild steel. This assumption may not be fully applicable to additively manufactured components, whose material properties can deviate due to process-related effects. Furthermore, crack initiation from internal defects cannot be excluded, in which case a surface-based stress evaluation would not be expected to correctly identify the crack initiation location. A general limitation of the present surface-based approach is that it cannot capture crack initiation governed by internal defects. Accordingly, agreement between predicted and observed crack initiation locations can only be expected where fatigue failure is primarily controlled by surface geometry. Given the large number of potential surface notches present on additively manufactured specimens, an exact spatial correspondence between simulation and experiment cannot be expected for all cases. It should also be noted that in fatigue research, the agreement between predicted and observed crack initiation locations is not commonly used as a primary criterion for evaluating assessment methods; instead, the focus is typically placed on fatigue life prediction. Within this context, the IGM provides a basis for identifying critical surface regions in complex WAAM components.

4 Conclusion

The present work was motivated by the need to account for local quality effects in the fatigue assessment of additively manufactured components. While local fatigue assessment methods such as the Theory of Critical Distances have shown improved predictive capability for additively manufactured structures when evaluated at known crack initiation sites, their application in component design is limited by the unknown location of fatigue-critical defects. To address this limitation, recent approaches aim to capture the full component geometry and evaluate local stresses at all potential critical locations.

In this study, such an approach was applied for the first time to WAAM-manufactured components. The methodology combined high-resolution 3D laser scanning, reverse engineering of the as-built geometry, and numerical stress evaluation using the IGM. The complete surface geometry of fatigue coupons was captured, reconstructed, and analyzed to identify locations of maximum effective notch stress and compared with the fatigue test data.

The numerical results showed an agreement between the predicted maximum effective notch stress location and the experimentally observed crack initiation site for 9 out of 15 failed specimens. This indicates that the applied methodology is capable of identifying fatigue-relevant surface regions despite geometric complexity and modeling uncertainties. At the same time, deviations highlight the influence of assumptions related to surface reconstruction, boundary conditions, and material modeling.

In the longer term, the presented workflow offers the potential for further automation, from 3D surface acquisition

and geometry reconstruction to numerical identification of fatigue-critical surface regions. Future work should focus on a systematic investigation of the weighting factor α used in the IGM, particularly with respect to its applicability to additively manufactured materials. This requires a larger experimental database and may contribute to improving the robustness of local fatigue assessment methods for WAAM components.

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