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Local fatigue assessment of butt-welded joints between additively manufactured 316L stainless steel parts

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Abstract

Additive manufacturing (AM) has seen a rapid increase in application for many applications in recent years; nevertheless, there are still technical limitation with respect to widespread industrial applications. One important aspect is the relative limited building volume of the laser powder bed fusion (LPBF) process. Thus, the joining of AM parts makes it possible to increase the volume of AM structures; however, it is currently unclear whether welded AM parts can be assessed using fatigue assessment concepts typically applied for welded components. In particular, local fatigue assessment concepts seem to be suitable for this task, as they are capable to assess complex part and weld geometries. In this study, local concepts based on the micro-structural support effect hypothesis are applied as they also account for support effects at weld transitions. The considered methods are the critical distance and the IBESS approach. To investigate their applicability, fatigue tests were performed on butt-welded joints of 316L AM steel plates made by gas metal arc welding. To account, for the different weld seam position relative to the LBPF building process, joints were produced with weld seams parallel and vertical to the layer orientation of AM plates. For all three test series, the local fatigue assessment concepts lead to conservative results; however, the comparison between numerical and test results also reveal some shortcomings of the chosen concepts.

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1. Introduction

Due to the limited building volume of powder bed AM processes, welding may be required to combine several AM parts into larger components. Laser powder bed fusion (LPBF) is a promising method for producing nearly full-density components, but it can induce additional residual stresses and production defects. These factors can affect the mechanical and fatigue behavior of welded AM parts. In a previous study (Braun et al. 2023), the butt joints of 316L AM steel plates produced by gas metal arc welding were characterized. Welded specimens were made with seams parallel and vertical to the layer orientation of AM plates. The nominal stress results were compared to joints of conventionally rolled steel plates produced with the same welding parameter. The fatigue design curve for butt joints from international standards was exceeded by all three test series, but the fatigue strength of the butt joints made by LPBF and hot rolling varied significantly. This variation is thought to be related to differences between the AM and conventional joints in microstructure, static strength, residual stress level, and small crack-like defects that partially interact with stress concentrations at the weld transition.

In real components, the component geometry is more complex. Thus, it is not possible to use the nominal stress approach and fatigue design curves for fatigue assessment. The goal of this study, therefore, is to investigate whether the fatigue test results can be predicted accurately by local fatigue assessment methods. For this purpose, two local fatigue assessment concepts based on the micro-structural support effect hypothesis are applied to assess the aforementioned test results of the butt-welded AM and hot-rolled 316L steel specimens. The benefit of the applied critical distance and the IBESS approach is that they are capable of considering the part and weld geometries as well as the support effects at weld transitions.

Nomenclature

ρ	weld toe radius	ε_a	strain amplitude
α	flank angle	σ_a	stress amplitude
u	secondary notch depth	n', K'	Ramberg-Osgood parameter
$\Delta K_{th,LC}$	Long crack SIF threshold	ΔK_{eff}	Effective stress intensity factor
$\Delta K_{th,eff}$	Intrinsic fatigue crack propagation threshold	C, m	Paris-law material parameter
a_{LC}	Transition crack length		
A, b	Material parameter for cyclic R-curve		

2. Fatigue assessment methods

2.1. Critical distance approach

The critical distance approach is based on the work of Peterson (1959) and has lately gained more attention thanks to an increase in the computational power of personal computers, see Taylor (2007) and Baumgartner et al. (2015). In principle, the effective stress (σ_{eff}) is obtained by selecting a stress value in a fixed distance from a notch root. Often, this is performed perpendicular to the notch root using the maximum principal stress gradient $\sigma_1(\theta, s)$ and polar coordinates.

Herein, the distance is chosen with respect to the micro-structural support effect of the material surrounding notches, e.g., at weld toes and roots. For the critical distance approach, it is assumed that failure occurs, if the effective stress range $\Delta\sigma_{eff}$ at the critical distance a is equal or exceeds the fatigue limit $\Delta\sigma_0$ (Taylor 2007). Based on fracture mechanics, it can be shown that the critical distance a is related to the fatigue crack propagation threshold ΔK_{th} and the fatigue limit of plain specimens $\Delta\sigma_0$ with:

$$a \approx \frac{1}{2\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_0}\right) \quad (1)$$

A typical values for welded joints that is frequently found in literature $a = 0.1$ mm (Baumgartner et al. 2015). It can be shown that the critical distance a is linked to the short and long crack growth transition by introducing the El Haddad-Smith-Topper parameter a' (El Haddad et al. 1979).

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

2.2. IBESS-approach

The acronym IBESS stands for "integral fracture mechanics determination of the fatigue strength of welds" (Zerbst et al. 2019). This method was developed by the IBESS research cluster to cover the basic mechanism and novel aspects of fatigue failure of welded joints: crack propagation of mechanical/physical short cracks (and thereby support effects at notches), the phenomena of crack closure, meaningful definition of the initial crack size, multiple crack propagations and coalescence between multiple cracks, and the variation of the weld toe geometry, to mention the most important ones. For detailed description, the reader may refer to Zerbst et al. (2019) or Madia et al. (2018).

The modeling strategy adopted in the IBESS approach is based on partitioning the weld toe in a finite number of equidistant sections to reproduce the variation of the local geometrical parameters, as shown in Fig. 1(a). The weld toe radius ρ, the flank angle α, and the depth of the secondary notch u have been determined by semi-random sampling from their statistical distributions per each section (lognormal distribution for ρ and normal distribution for α and t). According to Zerbst et al. (2019), the values of the secondary notch depth u can be determined by a roughness measurement based on ISO 4287:1997 using the total height of the roughness profile P_t near the weld toe. For the determination of the stress concentration factor (SCF) and the stress-trough thickness profile, the solution of Kiyak et al. (2016) was used.

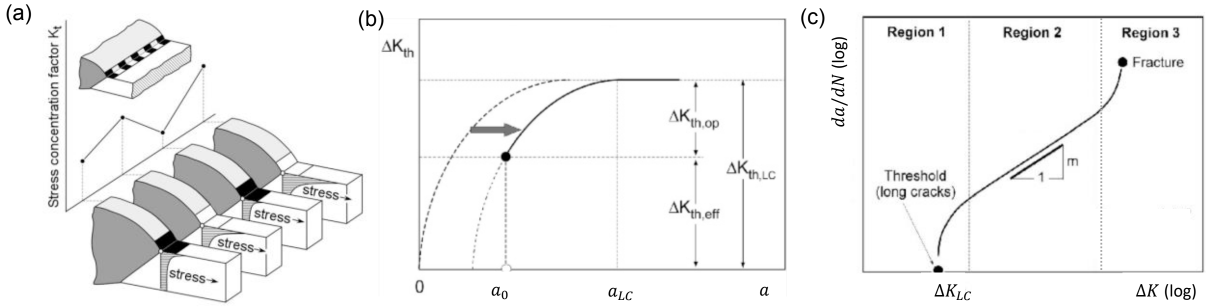

Fig. 1. Modeling of weld geometry [2] with the IBESS approach (a), evolution of the fatigue crack propagation threshold in the short crack regime and (b) fatigue crack propagation rate in the long crack regime (c) as given in the IBESS approach [4].

The cyclic stress-strain behavior is modelled according to the Ramberg–Osgood equation:

$$\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \quad (3)$$

The material parameters K' and n' were be determined for the heat-affected zone based on hardness measurements according to Lopez and Fatemi (2012). In the current version of the IBESS approach (Madia et al. 2018; Zerbst et al. 2019), the cyclic R-curve (Tanaka and Akiniwa 1988) was used to cover the fatigue crack propagation in the physically short crack regime, where a power law function (Zerbst et al. 2014) was used for the fit of the threshold ΔK_{th}, illustrated in Fig. 1(b):

$$\Delta K_{th} = \begin{cases} A \cdot \Delta a^{b} + \Delta K_{th,eff} & for \quad \Delta a < a_{LC} \\ \Delta K_{th,LC} & for \quad \Delta a \geq a_{LC} \end{cases} \tag{4}$$

Where A and b are material-dependent parameters and determined according to by Zerbst et al. (2014) based on the El-Haddad model (El Haddad et al. 1979). Δa_{LC} is the extension crack length from the physical short to long crack regime. The lower bound of this relation is $\Delta K_{th} = \Delta K_{th,eff}$, and the values of the intrinsic fatigue crack propagation threshold of $\Delta K_{th,eff} = 2.7$ MPa mm. The fatigue crack propagation in the physically long crack regime in the IBESS procedure, illustrated in Fig. 1(c), is described by the following equation:

$$\frac{da}{dN} = C \cdot \left(\Delta K_{eff}\right)^{m} \cdot \left(1 - \frac{\Delta K_{th}(a)}{\Delta K}\right)^{p} \tag{5}$$

where ΔK_{eff} is the effective stress intensity factor (SIF) range including the crack closure factor $U(a)$ (with ΔK_{eff} = $\Delta K\ U(a)$). The parameter p is used for fitting experimental data to the crack threshold regime and is set to p = 1.0 for all calculations in this study. The material parameter C and m were evaluated based on the investigations for hot-rolled and additive manufactured 316L of Riemer et al. (2014) and Gnanasekaran et al. (2021). The parameters for the IBESS calculations are summarized in Table 1.

Table 1. Fracture mechanics input parameter for fatigue life assessment of 316L welded joints with the IBESS approach

Material condition	K' MPa	n' -	$K_{th,LC}$ MPa mm$^{1/2}$	A -	b -	$\mathrm{Log}(C)_{10}$*	m -	u (Mean) mm	u (std) mm
Hot-rolled	1274	0.201	4.8	1.909	0.324	-9.5833	6.051	0.065	0.015
LBPF-ver	1390	0.189	4.0	1.380	0.351	-8.7438	4.062	0.110	0.056
LBPF-par	1390	0.189	4.5	1.809	0.345	-8.7438	4.062	0.110	0.056

* given for da/dN in mm/cycle and ΔK in MPa mm$^{1/2}$

3. Results

3.1. Nominal stress results

The fatigue test results from Braun et al. (2023) are presented in Fig. 2 together with stress-life (S-N) curves. Tests reaching ten million cycles without failure were terminated and classified as run-outs (marked by arrows). The test evaluation was performed by linear regression with:

$$N = 2 \times 10^{6} \left(\frac{\Delta\sigma_n}{\Delta\sigma_R}\right)^{-k} \tag{6}$$

where N is the endured number of cycles on the nominal stress range level $\Delta\sigma_n$, $\Delta\sigma_R$ is the reference fatigue strength at 2×10^{6} cycles, and k the free inverse slope. The LPBF parallel data point exceeding 2×10^{6} was omitted in the regression, as it could be beyond the knee point of the S-N curve.

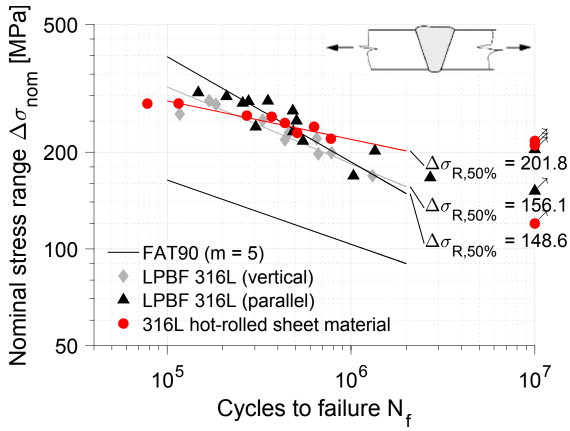

Fig. 2. Nominal stress results of the butt joint fatigue test specimens, modified from Braun et al. (2023)

The fatigue behavior of all three test series exceeds the fatigue design class FAT90 for butt welded joints, as per the recommendations of the International Institute of Welding (IIW) (Hobbacher 2016); yet, there are variations in fatigue performance among the test series. The butt joints made from conventionally hot-rolled steel plates exhibit a shallower S-N curve slope and higher fatigue strength at 2×10^6 cycles. Interestingly, the slopes of both LPBF butt joint test series are similar, but specimens with layer orientation parallel to the weld seam demonstrate higher fatigue strength.

Typically, welded joints of thin plates (thickness $t < 7$ mm) exhibit a shallower slope, as reported by Baumgartner et al. (2020). This is also observed in the case of hot-rolled plates. Therefore, the FAT90 curve is presented here with a recommended slope of $m = 5$for thin joints. Fractographic investigations have confirmed the presence of small defect-like imperfections near the weld toes of the additive manufacturing (AM) specimens. Furthermore, higher tensile residual stresses in the loading direction were measured in the AM specimens. Consequently, the differences in fatigue strength and S-N curves are believed to be related to disparities in static strength, residual stress levels, and possibly small crack-like defects.

3.2. Results of the critical distance approach

The results for the critical distance approach using the recommended critical distance for welded joints ($a = 0.1$ mm) is presented in Fig. 3.

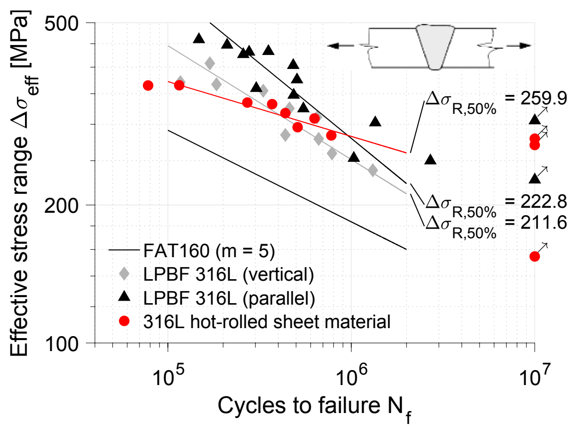

Fig. 3. Effective stress results based on the critical distance approach using $a = 0.1$ mm

For reference, the mean geometry determined by the curvature method (Schubnell et al. 2020; Renken et al. 2021) was used in connection with reference weld toe and root radii $\rho_{ref} = 0.05$ mm for the finite element models, see (Baumgartner et al. 2015; Baumgartner 2017). Here, the mean geometry was used in order to allow a comparison with the IBESS approach, which is based on mean and standard deviation of geometry parameters. For both failure locations (weld toe and root), the radii were meshed with 32 elements over 360° according to (Braun et al. 2020).

The results are clearly above the FAT160 design curve recommended for this approach. Again, a slope exponent of $m = 5$ was used for the design curve. In principle, the results are similar to the nominal stress results; however, the difference between the three test series is more pronounced. Thus, larger differences in fatigue strength would be predicted using the mean geometry parameters of each test series. This might be related to the fact that mean geometry parameters are prone to outliers; however, the results prove to be conservative. Thus, fatigue assessment of welded connections between AM parts seems to be feasible using the critical distance approach.

3.3. Results of the IBESS-approach

As shown in Fig. 4, the fatigue life assessment with the IBESS-approach yields different results for the three test series. The behaviour of the hot-rolled steel specimens is accurately predicted, while there are larger deviations for the two L-PBF test series. Several reasons may responsible for this and are discussed in detail by Schubnell et al. (2023): First, the current version of the IBESS approach do not cover the effect of residual stresses.

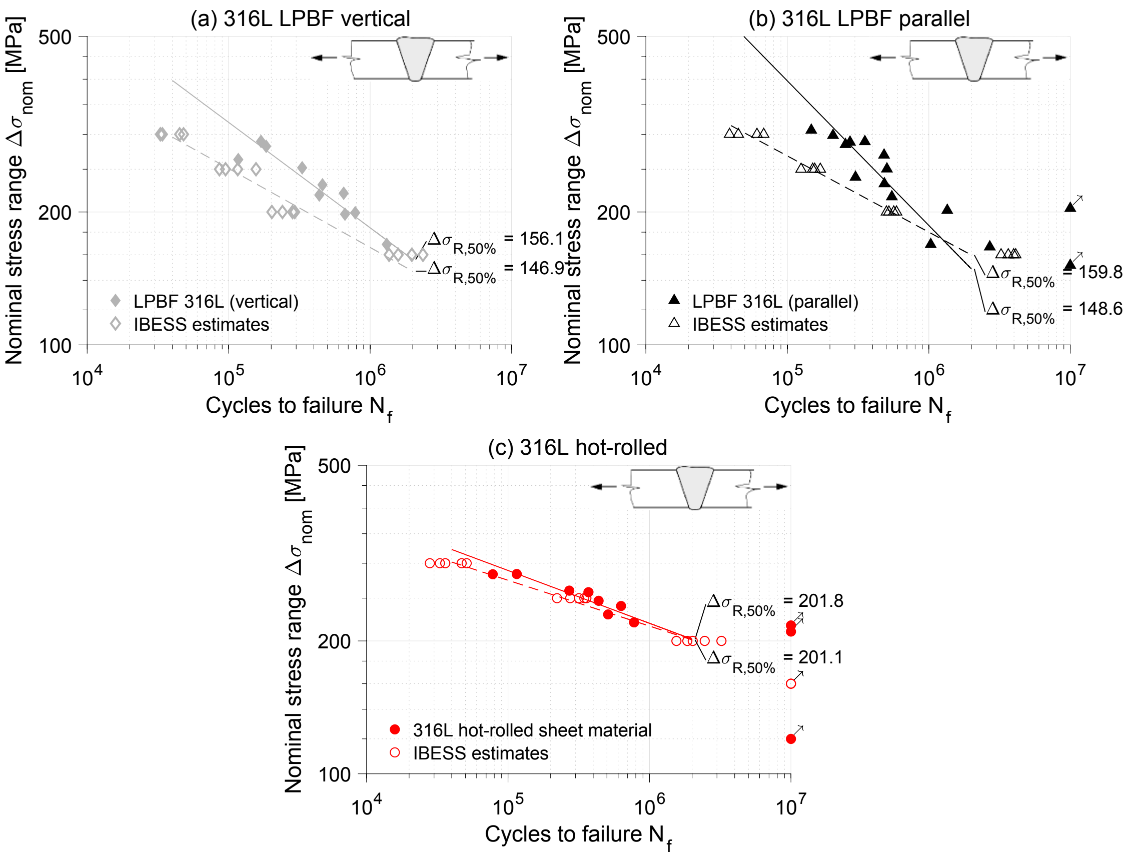

Fig. 4. Comparison of nominal stress results with the IBESS results

A previous study (Braun et al. 2023) determined high residual stresses state in the different conditions (hot-rolled, LBPF). In hot-rolled condition, compressive residual stresses were determined that may decrease the crack propagation rate, while tensile residual stresses in LBPF-condition leads to an increase. Second, fractographical analysis revealed that near surface inner defects in the HAZ lead to crack initiation. This phenomenon is not covered by the IBESS approach, as it is only able to describe crack propagation from the surface cracks at weld toes. Third, fatigue crack growth parameters were adopted from literature.

4. Conclusions

Gas metal arc welding of 316L steel sheets made by laser powder bed fusion and hot rolling was performed to investigate the possibility to combine several additive manufactured parts due to a limited building volume. Three parent material conditions after welding were investigated: Hot-rolled steel plates, AM steel plates in vertical and horizontal building direction. From the investigation, the following conclusions are drawn:

- The butt joints fabricated from conventionally hot-rolled steel plates exhibit a shallower S-N curve slope but demonstrate higher fatigue strength at 2×10^6 cycles in comparison to the LPBF material with layer orientation parallel and vertical to the weld seam. As the fatigue regime transitions to the low-cycle range, the hot-rolled specimens display lower fatigue strength compared to the two LPBF series. Although the slope of both LPBF butt joint test series remains similar, specimens with layer orientation parallel to the weld seam show a higher fatigue strength. This variation in fatigue strength is thought to be related to differences in microstructure, residual stress level, and possibly small crack-like defects.
- Local fatigue assessment methods based on the micro-structural support effect hypothesis are capable of accounting for various influencing factors on fatigue strength of welded AM parts. They consider the part and weld geometries as well as the support effects at weld transitions; however, both methods are not capable of accounting for internal defects that might interact with the stress concentration at weld transitions.
- The IBESS approach is currently also not able to account for residual stress effects on fatigue strength. This becomes eminent when comparing the results of the IBESS approach for the different test series. The predicted fatigue strength of the hot-rolled steel plate with negligible residual stresses is closer to the actual test results than the prediction for the AM specimens.

In summary, local fatigue assessment methods based on the micro-structural support effect hypothesis are suitable tools to assess the fatigue strength of welded AM parts. This is mainly related to the fact that they are capable of accounting for various influencing factors on fatigue strength; however, more research is required to determine the best suitable fatigue assessment method for welded AM components.

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