Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 34 (2021) 259–265

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

The second European Conference on the Structural Integrity of Additively Manufactured Materials

Representative structure elements for the fatigue assessment of additively manufactured components

Rainer Wagener[a,]*, Andrea Chiocca[b]

[a]Fraunhofer Institute for Strucutral Durability and System Reliability LBF, Bartningstr. 47, 64289 Darmstadt, Germany
[b]Department of Civil and Industrial Engineering, University of Pisa, Largo Lucio Lazzarino 2, 56122 Pisa, Italy

Abstract

The fatigue life estimation of additively manufactured structures can be a very challenging task, because the component behaviour will be influenced by many parameters, such as surface roughness, imperfections and inhomogeneous properties. Furthermore, the loading conditions and the component geometry have to be taken into account. The problem of considering the singular influences adequately is intensified by their interactions, which invokes a simultaneous treatment of all relevant influencing factors. Without predefinition of the fatigue approach, properties to describe the cyclic aspects of component behaviour and the fatigue life are required. Even in the case of using small sized specimens, it is not possible to produce a defect-free material for studying the behaviour of sound material in order to derive cyclic material properties as a requirement for the local strain-based fatigue concept, or in order to derive a reference SN-curve and knock-down factors for load-based concepts.
Analysing the microstructure offers additional information about the local material state, because, depending on the lightening strategy, the material can be divided into different areas (up-skin, down-skin, contour, core, etc.) with characteristic distributions of imperfections. In order to use a conventional fatigue approach method, this information is not sufficient, because the interaction of statistically distributed imperfections is superimposed on the effect of singular defects. Due to these reasons and after introducing a new interpretation of the measured stress and strain, a fatigue approach will be discussed, which is based on a combined experimental and numerical derivation of the required local properties of the so-called representative structure elements.
In addition to the reduced numerical effort compared to the conventional approaches, a combined experimental and numerical derivation of RSE properties is enabled.

* Corresponding author. Tel.: +49-6151-705-444; fax: +49-6151-705-214.
E-mail address: rainer.wagener@lbf.fraunhofer.de

2452-3216
10.1016/j.prostr.2021.12.037

Keywords: representative strucutre elements; additive manufacturing; fatigue strength; material defects; incremental step test;

1. Introduction

Many parameters have an influence on the material behaviour of cyclically loaded components. Compared to conventional manufacturing technologies, the number of parameters is increased drastically in the case of additively manufactured components. In order to perform a high quality numerical fatigue approach, it is important to consider these influencing factors in an adequate manner. Apart from the mean stress and notch geometry, influences caused by the production process, such as, for example, a gradient of material properties along the cross section or the influence of the load frequency, should be considered for a proper fatigue estimation. To take advantage of the lightweight potential of additive manufacturing technologies, the local component-related material behaviour should be characterised. The capabilities of current and up-coming computer generations allow a more detailed consideration of the (cyclic) material behaviour during the process of numerical stress and strain analyses. To take advantage of these possibilities and with respect to an improved fatigue approach, existing experimental limits, such as limited test frequencies, have to be overcome. Furthermore, the industrial needs of reducing the number of material properties and increasing the relation between numerical fatigue approach accuracy and experimental effort have to be taken into account. Therefore, an increased knowledge of the component-related material behaviour is required in order to improve the conventional experimental procedure to derive the cyclic material properties as well as the numerical fatigue approach methods, especially in the case of additively manufactured structures, including also the multitude of influences on the fatigue behaviour of those components. With respect to an optimised degree of utilisation and, perhaps, a service life extension under service loading conditions, the damage mechanisms from Low Cycle Fatigue up to the Very High Cycle Fatigue regime have to be considered. Due to the pores and surface roughness of additively manufactured structures, the Very High Cycle Fatigue regime is a matter of particular interest, because the existence of an endurance limit is more than questionable.

2. Representative Structure Elements

In order to perform a fatigue approach of cyclically loaded components, a variety of more or less different methods exists. These methods can be stress- or strain-based and can differ in the assumed material behaviour. The stress-based fatigue approach concepts use linear-elastic stress-strain behaviour and presume a homogeneous property distribution. On the other hand, the basic idea of strain-based fatigue approach concepts is to describe the local material behaviour assuming an identity between the material behaviour of a homogeneously loaded cross section of finite dimensions and an infinitesimally small, and therefore homogenously loaded, material volume at the notch root. Independent of the fatigue approach concept used and important for a high quality fatigue approach, it is important to consider the main effects on the fatigue in a suitable manner.

In the case of additively manufactured components, the microstructures are diverse, because the exposure strategy can influence the resulting microstructure. Therefore, the cyclic properties should be evaluated by considering the local scanning parameters, in order to generate suitable local material properties for a numerical fatigue approach. Dealing with local material properties implies the use of a local strain-based fatigue approach concept to evaluate the damage impact of a load-time history. Thus, the Fatigue Life Curve, a continuous S-N curve from the Low Cycle Fatigue up to the Very High Cycle Fatigue regime, should be used to describe the strain amplitude vs. the number of cycles to failure relation. Due to the basic idea of the local strain-based fatigue approaches, the cyclic properties usually describe the fatigue behaviour of an infinitesimally small material volume. Therefore, polished specimens with a homogeneous microstructure are required. Even through the use of sub-sized or small specimen geometries, it is, in most cases, impossible, or at least very challenging, to generate such specimens. Normally, the microstructures of additively manufactured specimens look like the laser powder bed fusion specimen shown in Fig. 1.

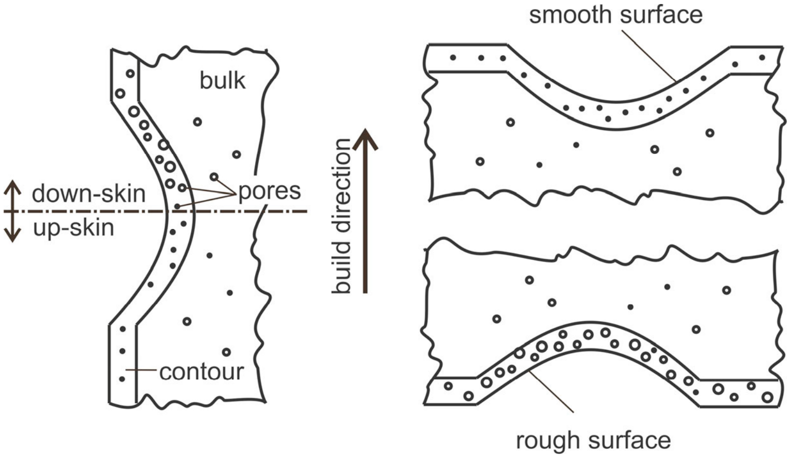

Fig. 1: Microstructure of an additively manufactured notch detail (schematically)

Depending on the exposure strategy, two types of microstructure can be distinguished. The first one represents the bulk and the second one the contour material. Furthermore, an influence of up- and down-skin is visible, which is characterised by the presence of an increased porosity for the down-skin region. With respect to the microstructure, it is not possible to define an infinitesimally small material volume, representing all the different microstructural morphologies. On the other hand, up to now, it is not possible to predict the position and size of every pore, but, based on experience, the region, where pores occur, is assessable.

Another impact factor on the fatigue is the surface. In order to achieve a smooth surface, an additional set of scanning parameters is used for the lightening of the contour. By this expedient, the resulting surface roughness is quite low, as long as no support structures are required to achieve the geometry. If support structures are required, this influences the contour material even after the structures have been removed, because they change the mass distribution and therefore the local cooling conditions.

Finally, the main disadvantage of the local strain concepts is the transferability from the material properties derived with sound material to the component-related material behaviour, which is characterised by imperfections such as pores and technical surfaces. In order to close this gap within numerical fatigue approach transfer concepts, accounting for property gradients, size effects etc. are used to manipulate the stress-strain and the strain-life curve. Keeping the heterogeneous microstructures of additively manufactured components in mind, structure elements, which are correlated to the exposure strategy, can be defined, Fig. 2. Therefore, three different orders are used

- First order: Structure elements of the first order describe the sound material behaviour. So far, they can be assumed as being equivalent to the conventional cyclic material properties.
- Second order: Structure elements of the second order consider the influences of pores and surface roughness
- Third order: Beside pores and surface roughness, the structure elements of the third order contain the interaction between different microstructures, possibly caused by different scanning strategies. Therefore, they are suitable for the consideration of the different microstructures of contour and core material.

Testing additively manufactured specimens means investigating the representative structure element's behaviour of the third scale.

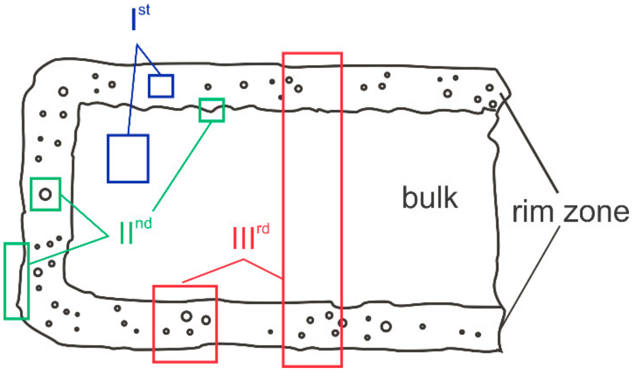

Figure 2: Definition of representative structure elements (schematically)

3. Cyclic material behavior

3.1 Low Cycle Fatigue to High Cycle Fatigue

Investigating the cyclic material behaviour in the Low Cycle Fatigue regime up to the High Cycle Fatigue regime requires strain-controlled fatigue tests. In order to describe the cyclic material behaviour, the stress-strain curve, according to Ramberg and Osgood (1943) and the strain-life curve, according to Coffin (1954), Manson (1965), Basquin (1910), and Morrow (1965), are used. Normally, the local stresses and strains, obtained in cyclic tests with polished specimens, are used to describe the material behaviour. In the case of additively manufactured components and specimens, they merely represent structural stresses and structural strains, because of the inhomogeneity of the material.

Due to the short number of cycles to failure in the Low Cycle Fatigue regime, the limited test frequencies are not a relevant criterion for the selection of suitable test systems. Traditionally, the strain-controlled fatigue tests are performed with constant amplitudes, while knowing that the cyclic stress-strain behaviour can be influenced by the load sequence. Hence, different stress-strain behaviour can be observed for constant and variable amplitude loading. Responsible for the different stress-strain behaviours is the slip behaviour of the material. In order to perform an adequate numerical fatigue approach, firstly the actual stress-strain state should be calculated. Keeping in mind that the stress-strain behaviour can depend on the load-time history, a test sequence is required to derive the suitable component-related material behaviour under service loading conditions. In the past, several load-time histories have been introduced, but only the Incremental Step Test by Landgraf et al. (1969) seems to be the best compromise, considering the experimental effort and reproduction of the service loading conditions discussed by Polak et al (1977), Christ (1998), and Wagener (2007).

Fatigue tests with constant amplitude are required to derive the Fatigue Life Curve from the Low Cycle Fatigue regime up to the High Cycle Fatigue regime. This means that, as long as a plastic strain portion can be observed, the derivation of the Fatigue Life Curve takes place with strain-controlled constant amplitude tests. In order to consider the impact of the glide characteristic within a numerical fatigue approach, Incremental Step Tests should be performed and evaluated.

3.2 High Cycle Fatigue to Very High Cycle Fatigue

Fatigue testing in the regimes of High Cycle Fatigue and Very High Cycle Fatigue is very time consuming. Increasing the test frequency is a simple way to reduce the testing time. This procedure is admissible, so long as the resulting fatigue strength is not influenced by the frequency. For the research and the characterisation of the material behaviour in the High Cycle and Very High Cycle Fatigue regimes at a specimen level, this method is approved and the state of the art already exists. A strategy to accelerate fatigue testing has to consider some boundary conditions, such as specimen heating and corrosion effects, as these will influence the resulting fatigue strength and fatigue life. To provide high frequency cyclic testing, the specimen stiffness and the required displacement are two of the most important parameters to be monitored. Therefore, the test frequency of cyclic tests under axial loading is typically higher than under bending or torsional loading.

With respect to service life extension, some key drivers, such as imperfections, e.g. pores, surface roughness, the wish to use the full lightweight design capacity of additively manufactured structures, the knowledge of the fatigue behaviour and the impact of influences on this behaviour, have to be considered.

Above $1 \cdot 10^6$ cycles, the advantage of high frequency testing is noticeable. For this reason, the increase of the testing frequencies to determine the fatigue behaviour in the high cycle and very high cycle fatigue regimes is necessary, in order to achieve:

- Service life extension
- Relevant damage contribution of low amplitudes for the fatigue life assessment

Due to the time consumption, it is usual for fatigue testing to stop the test run at $1 \cdot 10^7$ cycles, even when an indication of damage such as crack initiation is not noticeable. For this reason, Gaßner and Pries (1941) also recommended carrying out fatigue tests at least up to $1 \cdot 10^8$ cycles. To consider this change, Sonsino (2007) suggested reducing the fatigue strength at the knee point of the Wöhler-curve by a factor of 5% for steel or rather 10% for aluminium alloys and welding joints for each decade.

Test frequencies should be increased without changing the specimen geometry to provide an effective transferability of test results. In this way, a comparison can be performed with respect to the fatigue results in different testing regimes

3.3 Fatigue Life Curve

Keeping the strategy aim of a continuous Wöhler-curve in mind, optimised test facilities for elastic-plastic and macroscopic elastic stress-strain behaviour is the first step, but is worthless without a method to describe the strain- or stress-life curve. A continuous Wöhler-curve from the Low Cycle Fatigue regime up to the Very High Cycle Fatigue regime should be strain-based, because it is not possible to derive the SN-curve in the Low Cycle Fatigue regime under stress control. On the other hand, in the case of macroscopic elastic material behaviour, there should be no difference between stress- and strain-controlled fatigue test results. The concept of the Fatigue Life Curve according to Wagener and Melz (2017, 2018) fulfills these boundary conditions, as shown in Figure 3. In the case of additively manufactured specimens, the obtained stresses and strains within a fatigue test should be interpreted as structure stresses and structure strains. The combination of strain- and stress-controlled fatigue tests reduces the required experimental test effort and increases the output quality, because, in addition to the fatigue curve, the cyclic stress-strain behaviour can be investigated.

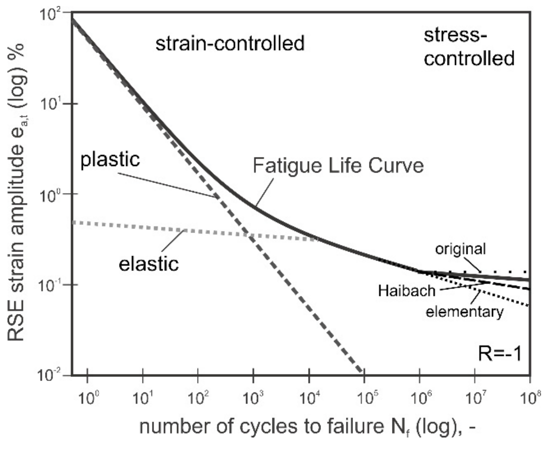

Fig. 3: Fatigue Life Curve in the RSE strain – number of cycles to failure N_f regime

Furthermore, the course of the Fatigue Life Curve in the third regime can be modified according to the Miner-modification as proposed by Wagener (2007) and Wagener & Melz (2017, 2018) in order to consider the damaging influence of the cycles related to the first and second regimes.

4. Numerical support to derive representative structure elements

The usage of stress-controlled fatigue tests reduced the experimental effort to derive the cyclic behaviour. Nevertheless, the required test campaign to consider all local combinations of different microstructures and imperfections is still too large. On the other hand, the definition of RSEs of different orders enables a stepwise numerical support using well-established fatigue approach methods. For example, using fracture mechanics it is possible to calculate the fatigue life of a cube of sound material with one pore. To describe the associated RSE of the second order, instead of the local stress and strain global properties, parameters will be used, such as nominal stress, strain, effective stiffness of the cube, average cube displacement, etc., Figure 4.

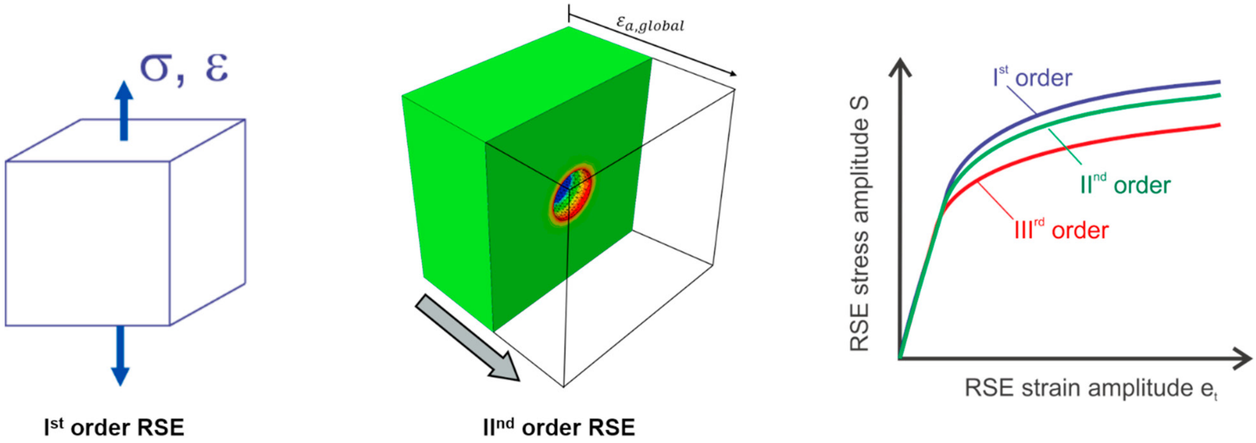

Fig. 4: Comparing RSE of first and second order

Within the design process, the occurrence of pores and imperfections is not known, but based on experience and depending on the exposure strategy, their statistical distribution can be approached. Furthermore, and keeping in mind that every additively manufactured structure will have another distribution of imperfections, it is not possible to derive all required properties experimentally. Sometimes, even within the same build job, the defect population can vary greatly, precluding the investigation of local properties in a consistent framework.

However, as mentioned previously, numerical studies can support the derivation of RSE properties. The impact of different distributions of pores can be studied by simple numerical methods. Due to the fact that only small cubes have to be investigated, sophisticated methods can be applied as long as the results can be described by the global stress, strain and fatigue life, because this information will be used for the RSE properties. Furthermore, the number of required RSEs can be reduced by an approach where the cyclic behaviour depends on measurable values such as density.

6. Conclusion

Representative structure elements can be helpful in describing the material behaviour of additively manufactured components under cyclic loading and, therefore, in enabling the lightweight potential in industrial applications. The combination of well-known and established fatigue and fracture experimental and numerical methods can be used to derive the RSEs of different orders. Furthermore, the numerical effort within the design process is reduced by using statistical distributions instead of the real position and size of imperfections.

References

Basquin, O.H., 1910. The exponential law of endurance tests. Proceeding ASTM, 10, p. 625–630.
Christ, H.-J., 1998. Materialermüdung und Werkstoffmikrostruktur. Frankfurt [Main]: Werkstoff-Informationsgesellschaft.
Coffin, L. F., 1954. A study on the effect of cyclic thermal stresses on a ductile metal. Trans. ASME, 76, p. 931–950.
Gaßner, E., Pries, H., 1941. Zeit- und Dauerfestigkeitsschaubilder für stabartige Bauteile aus Cr-Mo-Stahl, Duraluminium, Hydroaluminium und Elektron. Luftwissen, 8, p. 1–4
Landgraf, W. R., Morrow, J. D., Endo, T., 1969. Determination of the cyclic stress-strain curve, Journal of Materials, 4, p. 176–188.
Manson, S.S., 1965. Fatigue: A complex subject - some simple approximations. Experimental Mechanics, 5, No. 7, p. 45–87.
Morrow, J. D., 1965. Cyclic plastic strain energy and fatigue of metals. ASTM, STP 278, p. 45–87.
Polak, J., Klesnil, M., Lukas, P., 1977. On the Cyclic Stress-strain Evaluation in Low Cycle Fatigue. Materials Science and Engineering, 28, p. 109–117.
Ramberg, W., Osgood, W. R., 1943. Description of stress-strain curves by three parameters. Washington D.C.: National Advisory Committee for Aeronautics.
Sonsino, C. M., 2007. Course of SN-curves especially in the high-cycle fatigue regime with regard to component design and safety, International Journal of Fatigue, 29, No. 12, p. 2246–2258.
Wagener, R., 2007. Zyklisches Werkstoffverhalten bei konstanter und variabler Beanspruchungsamplitude. Dissertation, Institut für maschinelle Anlagentechnik und Betriebsfestigkeit, TU Clausthal, Clausthal-Zellerfeld.
Wagener, R., Melz, T. 2018. Fatigue Life Curve - A continuous Wöhler curve from LCF to VHCF. Materials Testing, 60, No. 10, p. 924–930.
Wagener, R., Melz, T., 2017. Deriving a continuous fatigue life curve from LCF to VHCF. SAE Technical Paper, 2017-01-033