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Influence of Material Ductility on Fatigue Life under Multiaxial Proportional and Non-Proportional Normal and Shear Stresses

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Abstract. Current experiences show that a non-proportional loading of ductile materials such as wrought steels, wrought aluminium or magnesium alloys, not welded or welded, causes a significant fatigue life reduction under an out-of-phase shear strain or shear stress superimposed on a normal strain or normal stress compared with proportional in-phase loading. However, when ductility, here characterised by tensile elongation, is reduced by a heat treatment or by another manufacturing technology such as casting or sintering, the afore-mentioned life reduction is compensated or even inversed, i. e. longer fatigue life results compared with proportional loading. Some actual results, determined with additive manufactured titanium, suggest that microstructural features such as manufacturing-dependent internal defects like microporosities should be considered in addition to the ductility level. This complex life behaviour under non-proportional loading cannot always be estimated. Therefore, in experimental proofs of multiaxial loaded parts, especially safety-critical components or structures, with real or service-like signals, emphasis must be placed on retaining non-proportionalities between loads and stresses/strains, respectively.

1 Introduction

Generally, local strains and stresses of a structure arise from external loads and determine the fatigue life. The behaviour of the structure or of its individual components depends, for a given material, not only on the relation between the external loads and local strains/stresses but also on the correlation between the multiaxial components of the local stress/strain tensors, especially with reference to their proportionality [1]. In this context how a non-proportionality between normal and shear components of a strain/stress tensor

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may affect fatigue life is of considerable importance, especially when, for a given component, materials are changed for technical, cost or marketing reasons. An often neglected aspect in evaluating local stress/strain states is the fact that some materials react with a decrease of fatigue life, some remain neutral and some show a fatigue life increase.

Therefore, in experimental proofs of multiaxial loaded parts, Fig. 1 [2] with real or service-like signals, emphasis is put on retaining time-dependent phase-shifts between loads and stresses/strains, respectively [3, 4]. However, in simplified, so-called damage-equivalent proof tests with constant amplitudes, the phase correlation between multiaxial components is often ignored. To what extent life is controlled by material ductility, here characterised by the property of tensile elongation, is the major subject of this paper.

The paper will not present hypotheses for accounting for different material behaviour, but will display the contrasting diversity of material behaviour in the case of non-proportional loadings, by examples of commonly used metallic materials for industrial applications: wrought and welded steels, sintered steels, cast iron, welded and cast aluminium and magnesium as well as additive manufactured titanium. The compiled results are determined using un-notched specimens submitted to deformation control or with notched component-like specimens and welded joints under load control, where the local normal and shear strains are deformation controlled [5]. As in the presented investigations with un-notched specimens under load control the local stresses remain elastic, the local values can be considered as being deformation controlled.

The possibly ductility-related differences in the multiaxial fatigue behaviour are displayed. The paper aims at sensitizing non-expert design and testing as well as aiding software engineers to be aware of the different material responses especially under multiaxial non-proportional loadings.

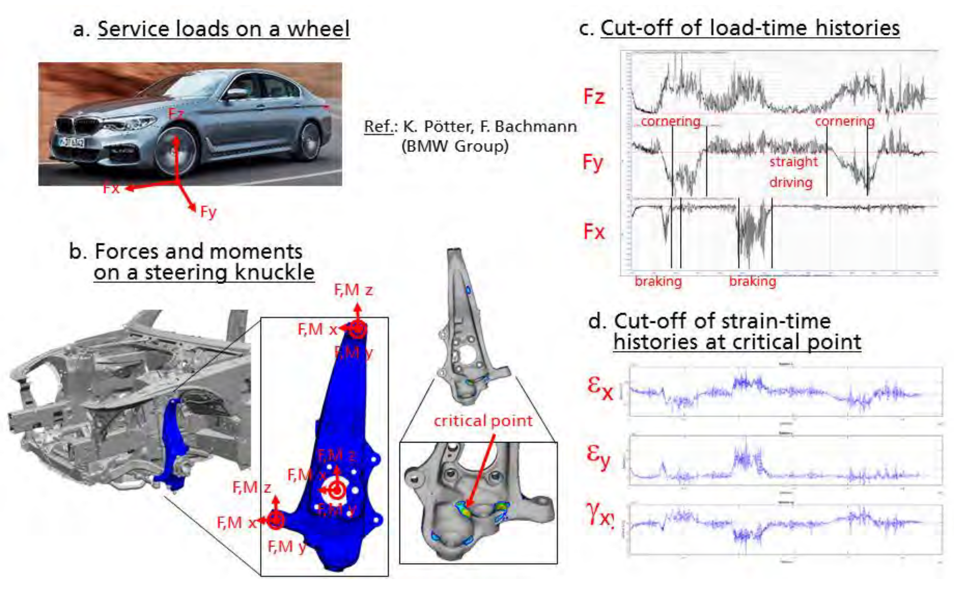

Fig. 1. Example for a multiaxial loading of a car and resulting strains on a steering knuckle under different driving conditions

2 Methods for presenting multiaxial fatigue results

The information on the life response of a material under multiaxial strains/stresses is included in data obtained under multiaxial deformation- or load-controlled fatigue tests with un-notched or notched samples. As there are different possibilities for presenting these data, this aspect will be initially discussed.

Often multiaxial fatigue results are presented by using conventional hypotheses such as von Mises or principal (normal) stress. However, the example with a sintered steel [6] shows, how the application of a strength hypothesis, here von Mises or the principal stress, may lead to a misunderstanding: When presenting the data just on the basis of the applied loads (or load related nominal or local stresses), the out-of- phase torsion prolongs fatigue life, Fig. 2. However, the presentation of the results using the mentioned strength hypotheses, Fig. 3, leads to an opposing conclusion and so to a misinterpretation.

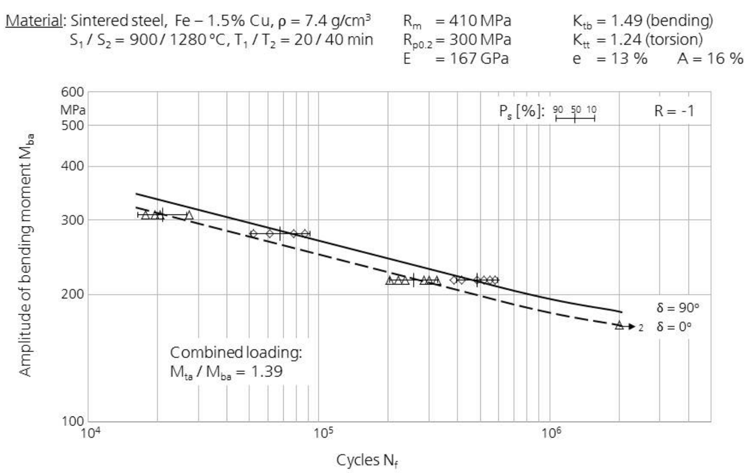

Fig. 2. SN-lines for combined in- and out-of-phase plane bending and torsion of component-like notched samples of a sintered steel (e = 13%)

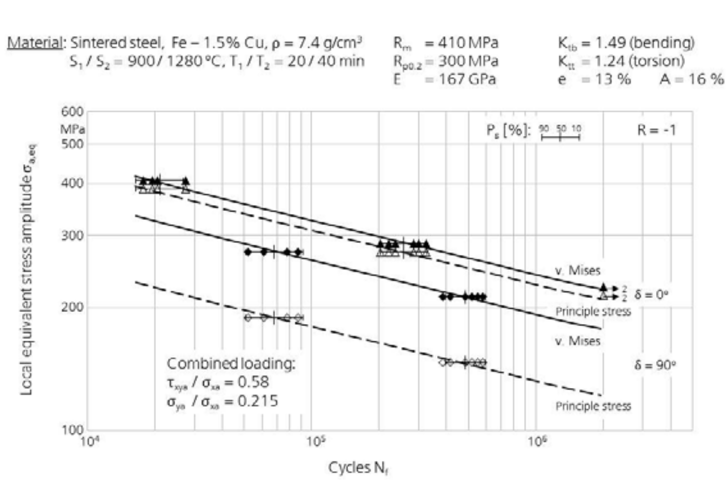

Fig. 3. SN-lines of component-like notched samples of a sintered steel (e = 13%) under combined in- and out-of-phase plane bending and torsion presented by local equivalent stresses

The use of an equivalent value includes all components of the strain/stress tensor, but the applied hypothesis may not be valid for the material and for capturing the influence of a phase shift between normal and shear values on fatigue life. Further, the relationships between the components of the tensor disappear through the calculation of the equivalent value. On contrary, the presentation using only the most dominant component, usually the longitudinal normal strain or stress, does not interpret the results a priori by a hypothesis, but must contain the information regarding the further involved components and their relation to the most dominant one. This mode of presentation, where all occurring strain/stress components are related to applied external loads, allows a direct evaluation of the influence of superimposed shear strains/stresses and of phase shifts on life.

From a practical application point of view, when comparing in-phase and out-of-phase loading, the same applied loads or strains/stresses respectively should be used with no phase shift for in-phase loading and with a phase angle for out-of-phase loading. Therefore, in this paper the displayed examples are free of any hypothetical evaluation; i. e. the results will be presented by using the dominant components of the loads or local stress/strain tensors only, which are the starting values for any evaluation. But the information about the superimposed stress or strain component will be given on the figures. The multiaxial fatigue life outcome will be discussed as a function of the phase shift of the superimposed shear strain or stress versus normal strain or stress, i. e. proportional and non-proportional strain/stress states, and of the ductility of the material.

3 Behaviours of different materials under deformation-controlled combined proportional and non-proportional normal and shear stresses/strains

It is a well-known fact that ductile materials react under non-proportional multiaxial loads or strains/stresses by a significant decrease of fatigue life in the low and medium cycle fatigue domain ($N_f < 10^6$) or along the whole fatigue life line [1]. This behaviour for ductile structural steels under deformation-controlled testing of un-notched specimens is generally observed [1, 7], but also for a notched component-like ductile steel specimens under load-control, Fig. 4, [8] and for seam-welded flange-tubes [1, 9], Fig. 5; for laserbeam-welded ductile steel tube-tube joints same tendencies are determined [10, 11], too. Due to the stress gradients in machined or weld notches local stress/strain states are also deformation-controlled as long as the structural yield-point [12] is not exceeded. In all mentioned cases, the fatigue life decrease, in comparison with the proportional multiaxial loading, occurs by the non-proportional superimposition of torsion at a phase shift of $\delta = 90°$. The materials involved had elongation values of 22 to 25%.

However, for materials of lower ductility a contrasting behaviour is observed. For notched component-like specimens of a cast aluminium alloy for pistons ($e \approx 2\%$) under non-proportional bending and torsion with a phase shift of $\delta = 90°$ a fatigue life increase is determined [1, 13]. This same behaviour is observed for porous sintered steels, Fig. 2 [6], and for cast nodular iron, Fig. 6 [14, 15], too. In both cases because of the local constraints due to pores and graphite nodules, respectively, the elongations were $e \leq 13\%$ despite the ductile matrixes. Also cast aluminium alloys for chassis components with $e = 6\%$ because of coarse grains display a fatigue life increase under non-proportional loading, Fig. 7 [16].

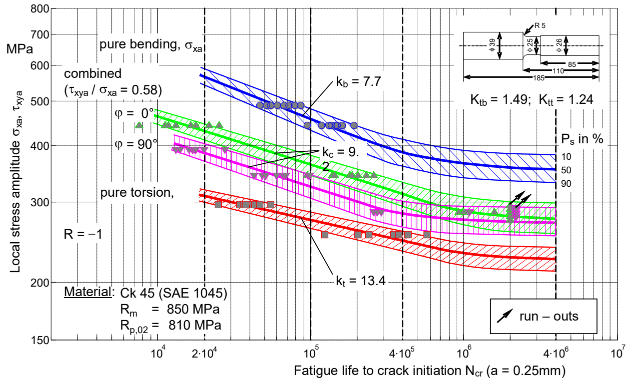

Fig. 4. Fatigue testing results obtained with notched steel specimens (e = 22%) under combined bending and torsion (δ = 0° and 90°) presented by local stresses

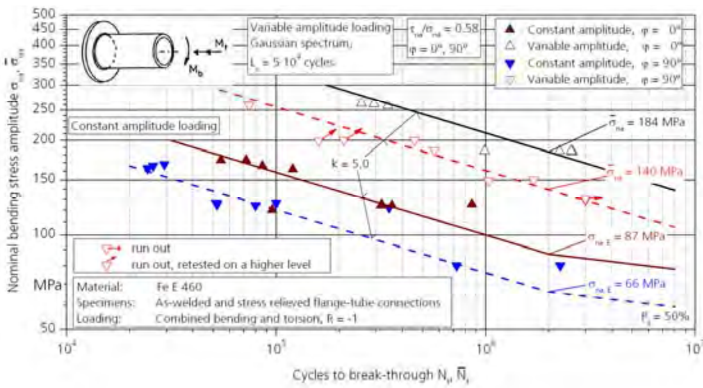

Fig. 5. Fatigue testing results obtained with seam-welded thick (t = 10 mm) steel specimens (e = 25%) under combined bending and torsion (δ = 0° and 90°)

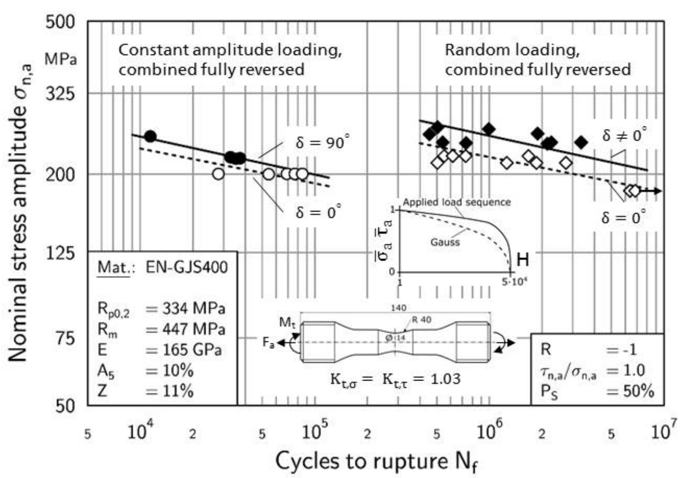

Fig. 6. Woehler- and Gassner-lines for combined axial loading of cast nodular iron (e = 10%)

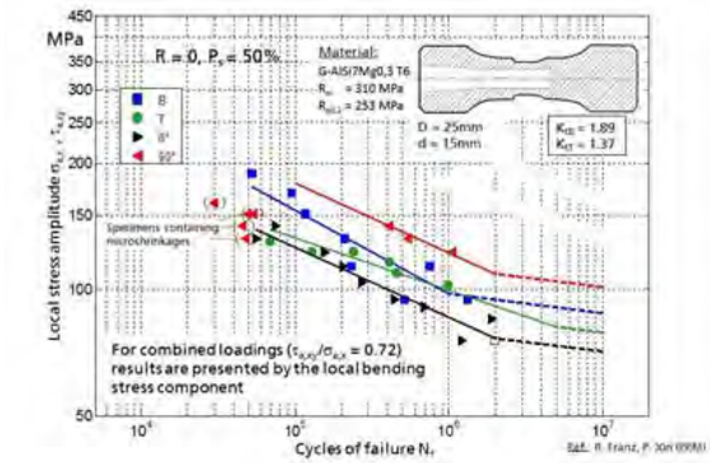

Fig.7. Fatigue behaviour of cast aluminium (e = 6%) under pulsating pure bending, pure torsion and combined bending and torsion

One of the means for changing the ductility of a material is through heat treatment, e. g. quenching and tempering with different parameters resulting in different hardnesses. An evaluation of results of deformation controlled tests under combined in- and out-of-phase normal and shear strains with the steel SAE 1050 in different quenched and tempered states [7] shows following, Fig. 8: The material variant with the lowest hardness and highest elongation (ductility) reveals a clear decrease of fatigue life under out-of-phase loading, the material with the medium hardness exhibits a moderate decrease, while the hardest material state remains almost unchanged under the non-proportional loading; the in- and out-of-phase results are overlapping, Fig. 8. Obviously, the change in microstructure from bainite to more martensite and the increased hindrance of dislocations influences the crack initiation mechanisms. The reduction of ductility decreases significantly the fatigue life difference between in- and out-of-phase straining.

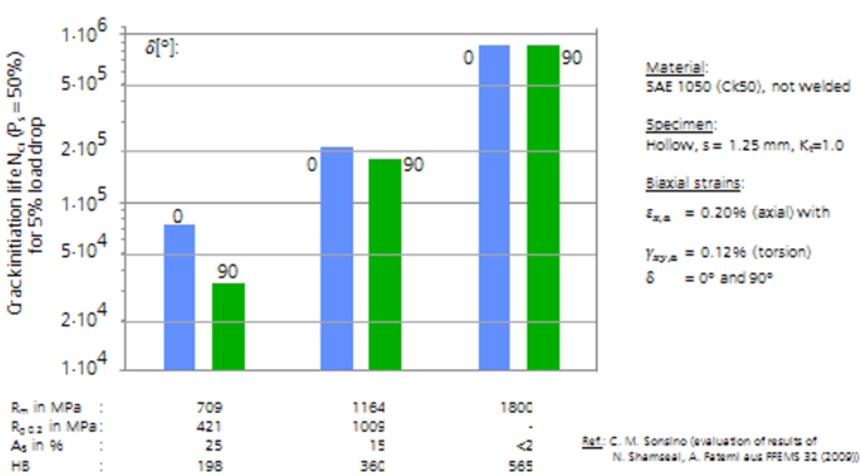

Fig. 8. Influence of material hardness and ductility of a steel on fatigue life by variation of the phase shift between normal and shear strain

While in Fig. 8 at the highest hardness a neutral fatigue behavior under non-proportional loading is still displayed, for laserbeam-welded very high-strength steels with an elongation of e = 12%, a prolongation of fatigue life can be observed, Fig. 9 [17].

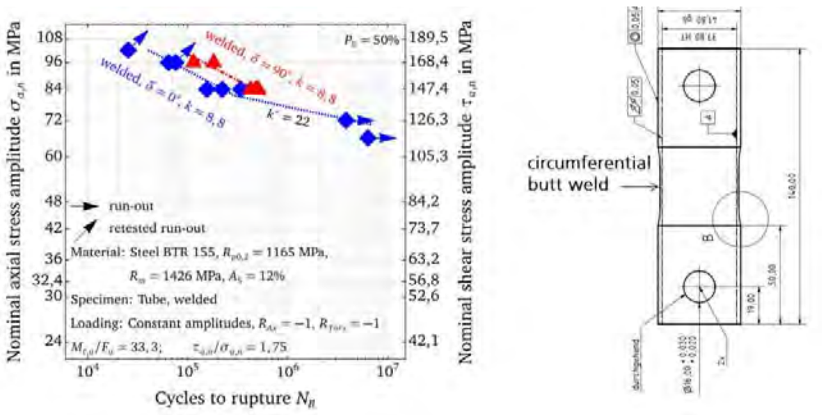

Fig. 9. Fatigue behaviour of a laserbeam-welded thin tube-tube joints of a high-strength steel (e = 12%) under combined axial loading and torsion

For laserbeam-welded overlapped tube-tube joints of wrought aluminum with e = 17%, a decrease of fatigue life in the medium fatigue range is determined [1, 11], but a neutral behaviour is obtained with seam welded flange-tube joints of aluminum with a lower value e = 13% resulting from coarser grains, Fig. 10 [18]. This seems to be a similar observation to the afore-mentioned behaviour of the heat treated steels as a function of reduced elongation, Fig. 8.

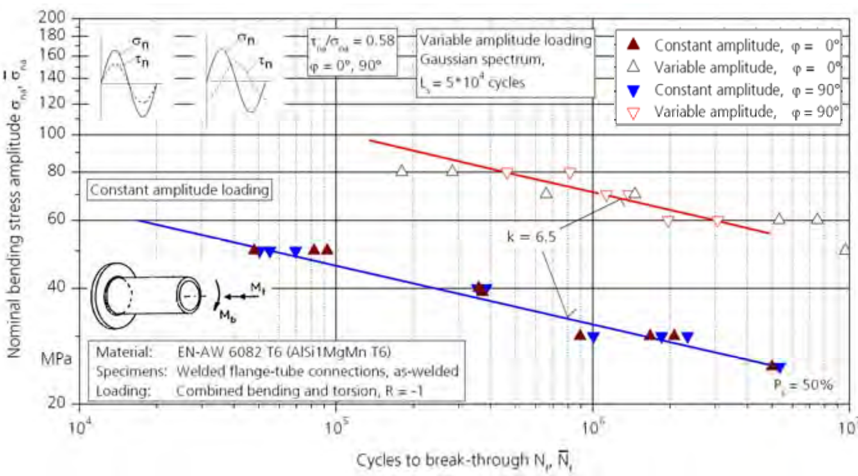

Fig. 10. Fatigue behavior of seam welded wrought aluminum (e = 13%) thick flange-tube joints under combined bending and torsion

Also, magnesium alloys of different microstructures and elongations reveal different reactions when they are submitted to non-proportional loadings [19, 20]. While laserbeam-welded overlapped tubes of wrought magnesium alloys AZ31 and AZ61 with an elongation of e = 14% show a reduction of fatigue life by out-of-phase torque [19], cast magnesium

AZ31 with a reduced elongation of e = 2.5% [1, 20] due to coarser grains reveals the expected prolongation of fatigue life by non-proportional loading.

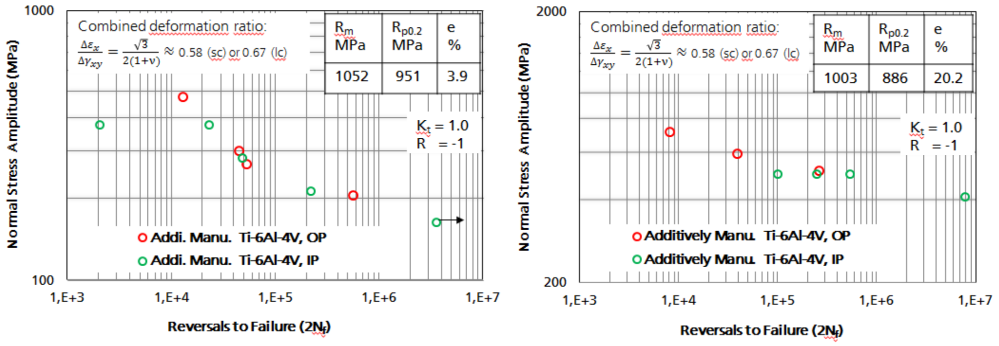

Fig. 11. Multiaxial fatigue of additive manufactured (vertically built) Ti6Al4V, annealed (left) and HIPed (right) under combined axial loading and torsion

Last but not least, in Fig. 11 an example is presented, showing that the neutral behavior displayed in Figs. 8 and 10 may also occur at high elongation values for the additive manufactured Ti6Al4V. The increase of the elongation from e = 3.9% for the annealed material up to 20.2% by HIPing, which increases the ductility mainly by the shrinkage of internal defects and porosities, seems not to influence the fatigue behaviour under out-of-phase loading (δ = 90°) [21, 22]. The local constraint by remaining pores at the given ratio between the α- and β-phases of the matrix are probably the main reason for this outcome.

4 Summary, conclusions and outlook

The results compiled here were obtained with un-notched specimens under multiaxial deformation-control and with component-like specimens and welded joints under load-control where the local notch strains and stresses respectively were due to the streress/strain gradients also deformation-controlled. The tests with un-notched specimens under load-control were also regarded as deformation-controlled because the local strains and stresses remained in the elastic domain.

As reported, non-proportional loading of ductile materials such as wrought steels, wrought aluminium or magnesium alloys, not welded or welded, results, under an out-of-phase shear strain or shear stress superimposed on a normal strain or normal stress, in a significant fatigue life reduction compared with proportional in-phase loading. For wrought steels but also for wrought aluminium alloys, this fatigue life reduction can be eliminated by particular heat treatments that render lower ductilities, here characterised by tensile elongation values. For wrought steels as well as for wrought aluminium alloys under reduced elongation values, a neutral (semi-ductile) behaviour may even be observed. However results obtained for additive manufactured and HIPed titanium with significant high ductility contradicts this experience.

In the case of materials such as cast nodular iron and sintered steels which have a ductile matrix, the graphite nodules or pores cause, through internal constraints, an overall low deformability. The consequently reduced ductility leads to a prolongation of fatigue life under non-proportional loading. Also for cast aluminum and magnesium alloys which have low elongation values compared with ductile wrought materials a significant increase of fatigue life is determined under non-proportional loading. The described findings regarding fatigue life decrease, increase or neutral behaviour as a function of ductility are not only valid for combined constant amplitude but also for variable amplitude loadings [1, 9, 15, 16, 20]. However, additive manufactured HIPed titanium alloy displays a neutral behaviour despite its high ductilitiy. For this, beside the microstructure, remaining pores as crack initiation sites with increased constraint may be responsible.

All this information lead to the conclusion that for a variety of materials ductility, a function of microstructure, seems to determine the damage mechanisms: High ductilities render under non-proportional multiaxial loading a reduction in fatigue life, whereas low ductilities generate a prolongation in life and so-called semi-ductilities deliver a neutral effect on life. This underlines the necessity for a proper consideration of non-proportionalities between the components of strain/stress tensors in calculations as well as in experimental proofs.

In past decades, several strength hypotheses have been proposed for assessing the complex proportional and non-proportional material behaviour. Depending on ductility, normal strains or stresses, shear strains or stresses or a combination of these are considered for assessment of the multiaxial fatigue behaviour. By the choice of most damaging strain or stress values, hypotheses indirectly considered the material ductility. But in none of these hypotheses ductility levels have been incorporated explicitly. Therefore, the present state of the art consists of numerical assessments based on different hypotheses and existing experiences, but, especially for safety-parts and structures, e. g. cars, aircrafts, the final experimental verification is performed by full scale tests, under service-like loading conditions [4]. Relevant progress is required in developing hypotheses, which consider explicitly the microstructure-related effect of ductility, i. e. at which elongation value which strains/stresses become relevant, which damage mechanisms result and determine multiaxial fatigue life. For the large variety of applied materials this would be a significant challenge.

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