Specimen design for low-cycle fatigue experiments under large strain range

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Abstract

Uniaxial low-cycle fatigue (LCF) test of 08Ch18N10T austenitic steel under large strain range loading conditions is presented and some difficulties connected with this type of experiment are mentioned. Some general facts about LCF and LCF tests are presented. Unsuitability of historically used specimen design is discussed. Loss of stability control of experiment due to buckling effect is described and buckling analysis with inclusion of material plasticity is presented. New specimen design with elliptical longitudinal section is introduced and new sets of material data are presented.

Keywords: Low-Cycle Fatigue, Large Strain Range Experiments , Specimen Design

Introduction

Low-cycle fatigue (LCF) is a part of fatigue phenomenon, where loading implies higher stresses than yield stress in macro-volume point of view (i.e. not locally on crack tip as in high-cycle fatigue (HCF)). Maximum number of cycles to failure for common steel-like materials is usually thousands of cycles or less [1].

Due to large stresses and strains in material, effects like buckling and additional bend can occur. The higher the loading amplitude is, the more obvious are these effects and specimen design must reflect these phenomena.

LCF experiments are usually strain-controlled. Deformation measurement device, for example extensometer attached to a specimen's surface and applied load is feedback controlled by required value of extensometer's displacement. This type of controlling induces strain field in specimen, usually there is required specific value of total strain amplitude in specific point or area.

For 1D tests, bar specimens with smooth working section (hereinafter smooth bar) or specimen with variable longitudinal section (i.e. hourglass specimens) are used. Test are performed on different strain range levels of total strain in working section.

Most of common steel materials, including 08Ch18N10T austenitic steel presented in this paper usually shows initial cyclic hardening followed by saturation of cyclic deformation curve (stress-strain response of every cycle is almost the same). For larger strain amplitudes, slow cyclic hardening (or sometimes softening) can occur for some types of materials. Last stage shows cyclic softening due to degradation of material properties and crack growth up to final failure.

2. Specimen design

1.1. Original specimen design

People usually do not change things that seems to work until it is obvious they are not working anymore. Maybe this was the reason why original specimen design, that has been used for LCF experiments for many years until now, was also applied for the first series of experiments without a suitability analysis.

Ex-post analysis of results shows that original specimens fail outside the working section in radius notch, which is not acceptable mode of failure. Data analysis also shows different history of material hardening than expected. For almost all specimens, there was no material cyclic softening in the final stage typical for ductile materials (see figure 1.). That indicates different type and cause of failure than expected. Finally, data analysis of several specimens shows loss of stability control due to buckling effect. Thanks to all these reasons, it was decided to design new specimen design.

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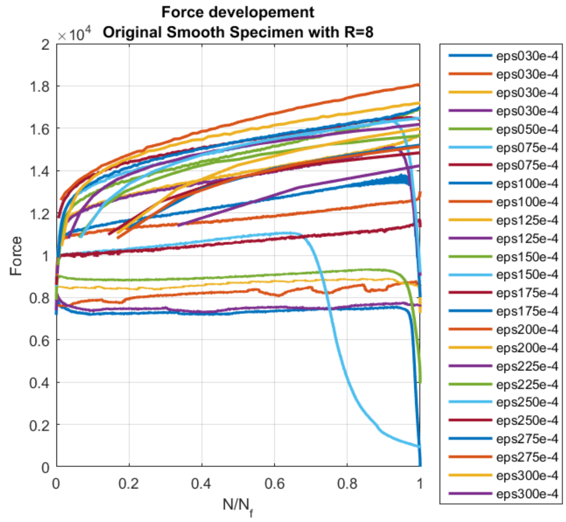

Fig. 1. *Force progress during fatigue life for original smooth bar specimen. See no-cyclic softening in the end of the fatigue life for most of specimens.*

1.2. New specimen design

Two candidates for new specimen design was created, both with variable cross section. This type of geometry localizes deformation into one section (the narrowest one) and also should be more buckling-resistant. First specimen has circular longitudinal section (and is usually called hourglass specimen, see figure 2), second one has elliptical longitudinal section (see figure 3). Both specimens' dimensions are limited by experimental equipment and material cast.

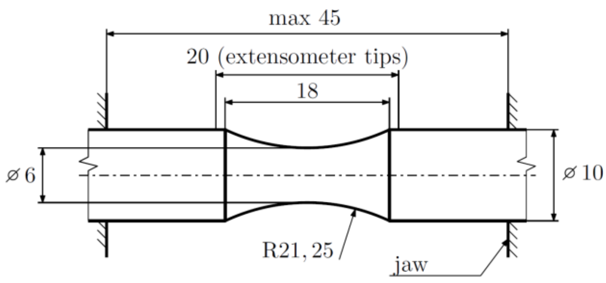

Fig. 2. *Hourglass specimen*

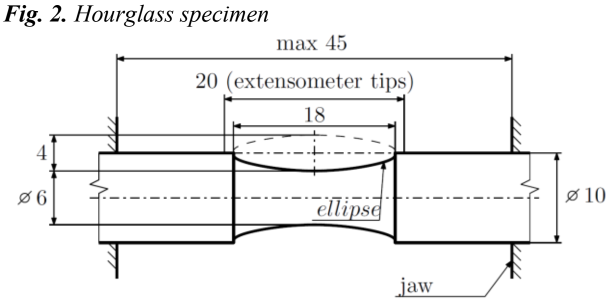

Fig. 3. *Elliptical geometry specimen*

2. Analysis description

Finite element method (FEM) simulation and series of analysis during design phase was done: buckling analysis, strain field analysis and triaxiality factor field analysis.

2.1. Buckling analysis

Buckling analysis should predict lower bound of so-called critical force. It is a force, which can lead to collapse due to buckling effect while applied to a specimen. Buckling analysis included in FEM software Abaqus [2] is unsuitable, because it includes only elastic material or linear estimation of elastoplastic material.

Proposed procedure consists of two steps. First, specimen geometrical imperfection (modelled as the sine shape) as maximum manufacturing tolerance was imported into FEM model as well as maximum allowed axis misalignment (see figure 4). In second step, specimen FEM model (including material non-linear plasticity) is loaded by forced displacement in axial direction. Criterion for determination of a critical force is buckling of specimen by more than 10% from the initial state.

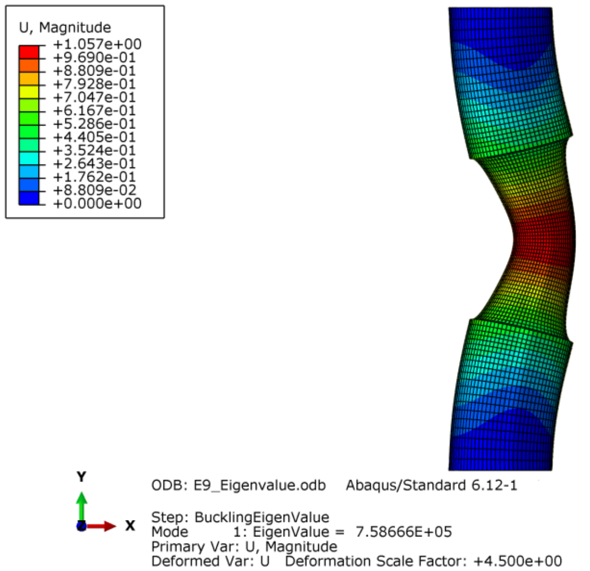

Fig. 4. *Geometrical imperfection (scaled)*

Two variants of plasticity model and two FEM simulations was done to analyze two cases: for first cycle (whether specimen does not buckle in first or first few cycles) and saturated case, after material stiffens due to cyclic hardening.

First material model is approximated from tensile static (monotonous) curve, second is Chaboche-like cyclic plasticity model with non-linear kinematic hardening fitted from saturated hysteresis loop [3].

2.2. Strain field analysis

Unlike smooth bar geometry, specimen with variable longitudinal section has no simple relationship between applied load and deformation of specimen. Strain field analysis finds relationship between displacement of the extensometer attached points and value of total strain amplitude on the surface of specimen in the narrowest point of specimen (point with highest deformation level, where crack usually starts to grow).

FEM simulation on the number of different load levels is performed and total strain amplitude value as a function of extensometer displacement is determined.

2.3. Triaxiality factor analysis

Triaxiality factor (hereinafter triaxiality) is dimensionless parameter defined as

$$TF = \frac{\sigma_{hydro}}{\sigma_{Mises}} \quad (1)$$

where σ_{hydro} is hydrostatic stress and σ_{Mises} is Mises equivalent stress (also known as HMH). It characterises stress field and for example the value of triaxiality for pure tension is $TF = \frac{1}{3}$. The purpose of this type of analysis is to check whether the stress field in analyzed variable geometry of specimen is at least approximately comparable with smooth specimen, so the value of triaxiality in tension is about 1/3. Usually only one load level FEM simulation is sufficient for analyzing the triaxiality field.

3. Analysis results

Results of buckling analysis are in Table 1.

Table 1. *Buckling analysis results*

Specimen geometry	Material model	Max. force during experiment [kN]	Critical force [kN]
hourglass	Static	10	23,6
	saturated	23	30
elliptical	Static	9,5	24
	saturated	22,75	27

Note: difference between force values in static (fist cycle) and saturated simulations: experiments are strain-controlled, so amplitude of force increases as material getting stiffer due to cyclic hardening in first few cycles.

Strain field analysis of elliptical specimen shows slightly non-linear dependency between extensometer displacement and total strain amplitude value (see figure 5) and almost linear dependency for hourglass specimen (see figure 6).

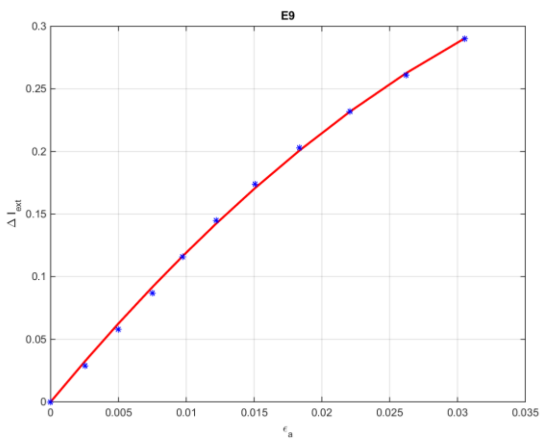

Fig. 5. *Strain amplitude dependency for elliptical geometry*

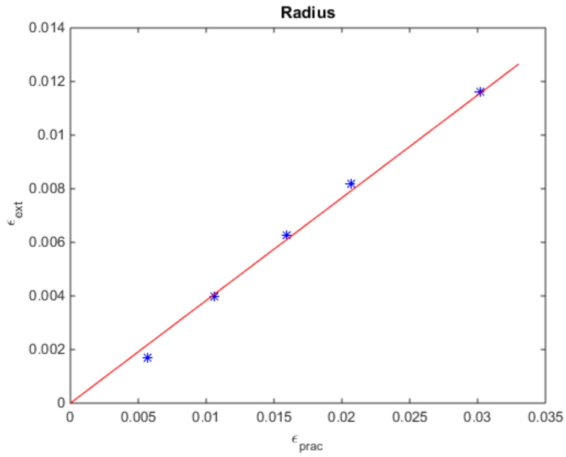

Fig. 6. *Strain amplitude dependency for hourglass geometry*

Triaxiality analysis results are in table 2.

Table 2. *Triaxiality analysis results*

Specimen geometry	Triaxiality in tension
hourglass	0.41
elliptical	0.37

The elliptical geometry specimen has triaxiality parameter little bit closer to smooth bar specimen.

4. Discussion and experimental results

All analysis shows, that both proposed geometries should be suitable for LCF experiments even for large strain range loading. Finally, it was decided to use elliptical geometry, because it passes buckling analysis well and has stress field closer to smooth bar specimen than the hourglass specimen.

Experimental results confirm, that elliptical geometry has no tendency to buckle and force progress during fatigue life is in accordance with expectations (see figure 7.)

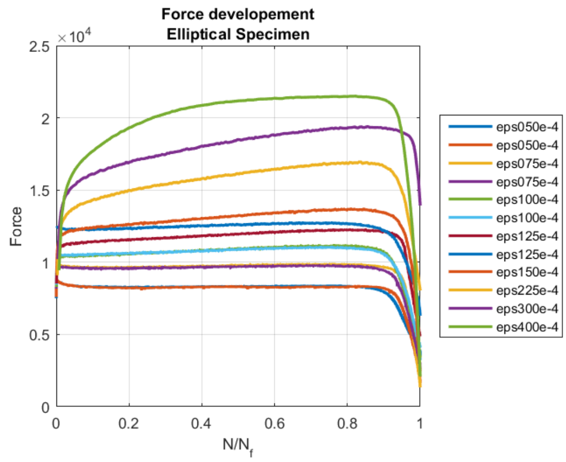

Fig. 7. *Force progress during fatigue life for elliptical geometry specimen*

Conclusion

Unsuitability of historically used smooth bar specimens was briefly analyzed. Two new geometry designs of specimens' candidates were designed. Buckling, strain field and triaxiality analysis was done. Elliptical geometry specimen was chosen because of better triaxiality factor value. Subsequent experiments proved buckling resistance of new elliptical geometry design and force progress during fatigue life in accordance with expectations.

Acknowledgements

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List of symbols

TF	Triaxiality factor (-)
σ_{hydro}	Hydrostatic stress ($N \cdot mm^{-3}$)
σ_{Mises}	Mises equivalent stress ($N \cdot mm^{-3}$)

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