Strain-amplitude dependent cyclic hardening of 08Ch18N10T austenitic stainless steel

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Abstract. In this paper, cyclic plasticity response of 08Ch10N10T austenitic steel under large strain amplitude loading is presented. Non-Masing behaviour and strain-amplitude dependent cyclic hardening is observed and analysed. Impact on testing and modelling associated with this phenomenon are described.

1 Cyclic plasticity response of 08Ch18N10T austenitic stainless steel

Basic material models of cyclic plasticity assume so called Masing behavior. Illustration of this behavior is in figure 1, where all hysteresis loops are shifted in stress-strain space, so their lower-left points coincide. For every loading amplitude applied, hardening path is the same. Problem is, that construction materials usually do not meet this simplification, as can be seen in figure 2 for 08Ch18N10T austenitic stainless steel.

Figure 1. Example of Masing behavior.

Figure 2. 08Ch18N10T austenitic steel
Non-Masing behavior.
For higher loading amplitudes, the deviation is significant and material model assuming Masing behavior should be used.

The primal cause of non-Masing behavior is material strain-amplitude (also known as strain-range) dependent cyclic hardening. Physical nature of this phenomenon is on the microstructure level of material and resides in different dislocation mechanism activation depending on loading level applied. Electron microscopy of austenitic stainless steel SUS304-HP performed in [1] observed that for larger amplitude loading material slip band density increased and the dislocation structure changed from a planar array for lower load levels to a more cellular-like structure for higher load levels.

As can be seen in figure 3, for lower strain-amplitude loading levels, there is no cyclic hardening. Hysteresis loop saturates after few initial cycles and remains the same up to final softening stage caused by crack growth, which leads to final failure. For higher amplitudes, there is no saturation and material cyclically hardens up to final softening stage. Absolute number of cycles to failure are in table 1.

| $\epsilon_a [%]$ | $N_f$ | $\epsilon_a [%]$ | $N_f$ | $\epsilon_a [%]$ | $N_f$ | $\epsilon_a [%]$ | $N_f$ |
|------------------|-------|------------------|-------|------------------|-------|------------------|-------|
| 0.5              | 16172 | 1                | 2013  | 1.5              | 785   | 3                | 223   |
| 0.75             | 4172  | 1.25             | 1212  | 2.25             | 351   | 4                | 135   |

Table 1. Number of cycles to failure

Figure 3. Force evolution during fatigue life test for various strain-amplitude levels.
Figure 2 illustrates and experimental data analysis proved, that there is a difference in yield stress value and non-linear hardening path between different strain amplitudes. The difference in Yield stress is from about 200MPa in monotonic tensile test [2] up to about 300MPa for $\varepsilon_a = 3\%$. The tendency of increasing yield stress with increasing strain amplitude is supported by performed material hardness test. More on correlation of material hardness and yield stress for austenitic steels can be found for example in [3], but briefly summarized: material hardness increases with increasing yield stress. Hardness test proved increasing material hardness on specimen with variable geometry in axial direction as can be seen in figure 4. Strain amplitude in narrowest part of specimen (distance 0 mm in figure 4) is $\varepsilon_a = 3\%$ and corresponds with highest material hardness measured. As specimen get thicker along the axis (distance > 0 mm in figure 4), strain amplitude gets lower as well as material hardness.

![Figure 4: Material hardness in various points of variable geometry specimen surface.](image)

For the given amplitude level, actual yield stress changes during few initial cycles (see figure 5 for illustration) and then does not change during the fatigue life even for higher strain-amplitude levels (see figure 6). Cyclic hardening is then represented only by different non-linear hardening path for different stage of the fatigue life. Young’s modulus is not affected by cyclic hardening.

2 Impacts on experiment

2.1 Classical experiment scheme issue

This phenomenon brings some complications starting with low cycle fatigue tests. According to [4], for strain amplitudes higher than $\varepsilon_a = 1\%$, specimen with variable longitudinal geometry should be used to prevent undesirable phenomena like loss of stability control etc. Classical scheme of strain-controlled experimental tests looks like this one: deformation is measured by the extensometer, whose tips are
attached to the specimen’s body outside the curved area in the cylindrical part of the specimen. Deformation measured by the extensometer controls the loading of the specimen.

![Figure 5. The first 10 hysteresis loops for $\varepsilon_a = 3\%$ (shifted so their lower-left points coincide).](image)

![Figure 6. Hysteresis loops evolution during fatigue life for $\varepsilon_a = 3\%$ (shifted so their lower-left points coincide).](image)

Problem is, that strain-amplitude dependent cyclic hardening causes significant hardening of higher loaded areas in the narrow parts of the specimen, but lower or no cyclic hardening in the thicker parts of the specimen, where strain amplitudes are lower. This phenomenon along with this classical scheme of experiment control leads to decrease of strain amplitude in the area of interest during the cycles, so experiments are not performed under the constant strain amplitude, strain amplitude is known only approximately and number of cycles to failure is not obtained for constant value of strain amplitude.

2.2 Proposed solution

There are two possible ways of performing experiments. The first one is to measure deformation and its evolution during the fatigue life by an optical device (DIC for example) and ex-post evaluation results. The evaluation procedure scheme is following. Manson-Coffin law \cite{5, 6} determines how many cycles to failure $N$ material lasts under plastic strain amplitude $\varepsilon_a^P$ as

$$\varepsilon_a^P = \varepsilon_f'(2N)^c.$$ 

Equation (1) can be modified into form

$$N = 0.5 \cdot \exp \left( \frac{1}{c} \cdot \ln \frac{\varepsilon_a^P}{\varepsilon_f'} \right).$$ 

Palmgren-Miner linear damage hypothesis \cite{7} determines how much damage $D$ cause number of cycles $n_i$ as

$$\sum_i \frac{n_i}{N_i} = D$$ 

where $N_i$ is number of cycles to failure on loading level $i$. Loading level can be represented for example by particular value of strain-amplitude applied. When $D = 1$, material fails. Combining equation (2) into equation (3) results in
where $e_{pa_i}$ is plastic strain amplitude of load level $i$. Final summation of each $D$ from equation (4) during the fatigue test must meet the sum

$$\sum_{i=1}^{N_f} D_i = 1$$

where $e_{pa_i}$ is known in each particular cycle and $N_f$ is number of cycles to failure during the fatigue test. The only unknowns are material parameters $e_f'$ and $c$, which can be determined from applying this procedure to at least two sets of fatigue tests under at least two various load levels. For more than two set of tests, least square method should be used to determine only two unknown parameters.

This procedure can be tricky, because it presupposes validity of the Manson-Coffin law even for large strain amplitude loading and validity of Palmgren-Miner linear damage hypothesis.

The second way is to control the experiment by strain measured directly in selected area, for example by an optical (DIC) device. But there are few complications. First, deformation measured by DIC can be less accurate depending on camera resolution and size of measured area (accuracy of common extensometer is about $\pm 1.5\mu m$ vs about $\pm 8\mu m$ for 4Mpx camera chip and $350mm^2$ measured area). Second, there must be some clear markers in the specimen’s body of which the deformation is determined. But experiments show, that small cracks appear on the specimen’s surface already in the half of the fatigue life, became larger and a new initiate as number of cycles increases, which leads to destruction of markers. This approach can allow holding constant strain amplitude value for certain number of cycles, but certainly does not allow to perform whole fatigue life test up to the final failure. Attaching extensometer tips to the selected area would probably encountered the same problem.

### 3 Material model outline

First attempt to include strain-amplitude dependency into material model was made in [8] by introducing strain memory surface concept, later modified in [9] introducing non-hardening region. These classic models had been modified to include various phenomena like ratcheting or non-proportional loading, one of the most recent modification by [10] is being tested and seems promising. The author’s team has not chosen final form of material model yet, so only brief general outline will follow to remind the main issues.

Generally speaking, there are two basic mechanisms of modeling cyclic plasticity. Isotropic hardening model describes change of the yield surface size (value of yield stress) while kinematic hardening describes shift of the yield surface center point in space of principal stresses (determines non-linear hardening path). Including strain-amplitude dependent material behavior into material model usually needs combination of both mechanisms mentioned above. Using von-Mises yield criterion, the plasticity condition can be described by equation

$$f = \sqrt{\frac{2}{3}(\mathbf{S} - \alpha) : (\mathbf{S} - \alpha) - \sigma_y} = 0$$

where $\mathbf{S}$ is deviatoric part of the stress tensor, $\alpha$ is deviatoric backstress tensor (responsible for kinematic hardening mechanism), $\sigma_y$ is the current yield stress (responsible for isotropic hardening mechanism).

#### 3.1 Isotropic hardening part

As it was mentioned above, material shows increase of yield stress depending on strain amplitude applied, but after few cycles, the yield stress value stays constant for the constant strain amplitude applied (see figures 6 and 7). So in general, actual yield stress $\sigma_y$ from equation (1) must depend on
applied load level function, let’s call it \( L \). This dependency should have fast saturation to the target value, so there is no significant cumulative variable dependency function, let’s call it \( C \).

3.2 Kinematic hardening part

Material hardening on the high amplitude level loading seems to be reflected in non-linear hardening path only as number of cycles increases (see figure 6). So in general, this phenomenon clearly has to be modelled using kinematic hardening mechanism and backstress \( g \) must be function of applied load level \( L \) and cumulative variable \( C \).

So the final plasticity condition equation should be in a form

\[
f = \sqrt{\frac{2}{3} (S - \alpha(L,C)): (S - \alpha(L,C))} - \sigma_y(L) = 0 \tag{2}
\]

Specification of function \( L \) and \( C \) will be the subject of a future article.

4 Conclusion

Cyclic loading response of 08Ch18N10T austenitic stainless steel shows strain-amplitude dependent cyclic hardening and significant non-Masing behaviour. Analysis of cyclic hardening mechanisms shows change of yield stress value dependent on applied load level in first few cycles, but no dependency during the rest of fatigue life. Cyclic hardening is then coupled with change in non-linear hardening part only and should be modelled using kinematic hardening mechanism only. Some consequences of strain-amplitude dependent cyclic hardening on testing are mentioned along with proposed solution. Some impacts on material modelling are reminded.

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