Fatigue damage cumulation in brass under variable loading

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Abstract
In the paper there was presented the course of fatigue damage cumulation in specimens made of CuZn37 brass. During the analysis the course of damage cumulation there were used parameters of hysteresis loop and microstructure changes for different levels of fatigue damage, that were registered during the tests. Basing on the analysis of three hysteresis loop parameters (stress amplitude $\sigma_a$, plastic strain amplitude $\varepsilon_{ap}$ and plastic strain energy $W_{pl}$) it has been found that during variable loading the smallest changes are observed for the energy $W_{pl}$. Microscopic analysis of brass specimens after various fatigue levels showed that fatigue damage cumulation is also visible in changes taking place both within grains and at their boundaries. These changes include the presence of failures at boundaries of grains and slide banding systems inside of them, which are typical for plastic strain of the material.

Keywords: Damage cumulation, Cyclic properties, Fatigue damages

1. Introduction

Variable loadings of construction units generate, in the material of which they are made, specific changes and fatigue phenomena. If these loadings are big enough they may locally cause the plastic strains in such a unit. During fatigue life calculations of the construction units containing locally areas of the plastic – elastic strains there are used material data defined in the low-cycle fatigue area \cite{1}. Experimental conditions in this fatigue area are defined i.e. in the standards \cite{2, 3}. The characteristic feature of the low-cycle fatigue area is forming, in every cycle of variable loading, of hysteresis loop (Fig. 1).

Characteristic loop parameters i.e. are: total strain amplitude $\varepsilon_{ac}$, plastic strain amplitude $\varepsilon_{ap}$, stress amplitude $\sigma_a$ and ranges of the mentioned parameters, that is: $\Delta \varepsilon_{ac}$, $\Delta \varepsilon_{ap}$, $\Delta \sigma_a$ (Fig. 1). The area enclosed by the loop is the yardstic of the energy dissipated in the material during one loading cycle. This energy is also called as the plastic strain energy $\Delta W_{pl}$. Analysis of the mentioned parameters in the function of the loading cycles number enables the description of changes of the cyclic properties of the material and also the course of the damage cumulation.

The changes of the properties as the result of the variable loadings (cyclic hardening or softening) belong to extraordinary processes that accompany the low- cycle fatigue of metals. At the present moment there is a number of cyclic hardening or softening hypotheses. Some of these hypotheses are in connection with hypotheses elaborated for the static loading or they directly result from them \cite{4, 5}.

The aim of the paper is the analysis of the course changes of the basic hysteresis loop parameters under fatigue loading. The additional aim is the microscopic structure analysis.
the use of so called relative life $n/N$, where $n$ is the current number of loading cycles and $N$ is the number of cycles until fatigue failure. After realization of the defined number of $n$ cycles for a given loading level the test was stopped and specimens underwent a detailed microscopic examination. Specimens were given this examination in the following situations:
1) after static tensile test,
2) after 100 cycles of variable loading ($\sigma_0 = 86.4 \text{ MPa}$),
3) after 50 000 cycles of variable loading ($\sigma_0 = 86.4 \text{ MPa}$),
4) after 200 866 cycles of variable loading ($\sigma_0 = 86.4 \text{ MPa}$)-failure of the specimen.

Fig. 2. Specimen used in fatigue tests: a) smooth, b) with a notch

In Table 2 there were shown loading diagrams of specimens 1-4 and the ranges of observations.

Table 2.
The range of the microscopic observations

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Scheme of loading</th>
<th>Description of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\sigma$ Crack</td>
<td>Crack and surface of a specimen</td>
</tr>
<tr>
<td>2</td>
<td>$\sigma_n$ Without crack</td>
<td>Surface of a specimen</td>
</tr>
</tbody>
</table>

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Specimens destined for microscopic examinations were specially treated. Their side surfaces in the notch zone were grinded and then polished. After static and fatigue tests there were performed observations of specimen surfaces with the use of light metallographic microscope and scanning electron microscope (SEM).

3. Test results

3.1. Static tests

Static test results were presented in the form of static tensile diagrams of the relation stress $\sigma$ - relative strain $\varepsilon$. Stress $\sigma$ values were determined by dividing the momentary loading value of the specimen during the test by its initial cross-section area. An example of the full tensile diagram was shown in Fig. 4a. In Fig. 4b there was shown an initial fragment of this diagram limited to the strains $\varepsilon<2\%$. In Fig 4b there were also drawn strain levels accepted during fatigue tests of the specimen.

3.2. Fatigue tests

During fatigue tests there were observed changes of cyclic properties of tested metal. In order to illustrate the nature of these changes in Fig. 5 there were shown examples of the hysteresis loop registered during the test at the strain level $\varepsilon_{ac}=0,5\%$. Cycles numbers corresponding to the registered hysteresis loops were marked with figures.

3.3. Microscopic examinations

Surface observations of the 1st specimen in the area of intensive plastic strain showed the occurrence of multisystem creeps in grains of $\alpha$ phase (Fig. 6). Strain twins were also visible in some grains. Special arrangement of the creep strands in grains is determined by their boundaries. The arrangement of the creep strands was in agreement with their crystallographic orientation and they had an adequate direction in relation to the direction of the shear stress.
Surface morphology of the 1st specimen next to its crack was shown in Fig. 7. In grains with very high plastic strain there were found twins and permanent creep strands, i.e. in the form of long filaments – cords [7].

Microscopic observations were made also in specimen areas where failure initiation took place. It appeared on the bottom of the notch near the specimen edge. The surface of the crack was orientated at an angle of 90° towards the loading direction and side surface of specimen. In the initiation zone of the fatigue failure there was observed local plastic strain and it was characterized by the presence of the creep strands (Fig. 8).

Basing on the microscopic observations along the straight line, connecting notches on the 2nd specimen, there were found surface irregularities similar to those found on the surface of the 1st specimen in the areas with the small strains.

On the one of surfaces of the 2nd specimen, near the bottom of the notch, there was found singular set of creeping lines. These lines intersected at an angle of 90° (Fig. 9). They were also bended down at an angle of about 45° in the relation to the direction of the shear loading.

There were also made observations of the fatigue cracking area. On the crack surface of the 4th specimen there were found fatigue stripes that were connected with the creep strands in the grain (Fig.10). On the surface of the specimen, near the crack, there were visible, beside the creep strands, the extrusions and protusions. However just below the edge of the crack (in the middle of the picture) on its surface there were found the fatigue stripes.
4. Analysis of test results

Analysis of hysteresis loops presented in Fig. 5 shows that at the strain level $\varepsilon_{ac}=0.5\%$ primary loop parameters such as stress amplitude $\sigma_0$, plastic strain range $\Delta \varepsilon_{pl}$ and plastic strain energy $\Delta W_{pl}$ undergo changes. The shape of the loop and value of its characteristic parameters in the following loading cycles are the proof of brass hardening at this strain level. The momentary values of the loading force and strain registered during the tests at the remaining strain levels were used for calculation of the earlier mentioned hysteresis loop parameters for all strain levels. Their example courses in the function of the loading cycles number were shown in Fig. 11.

![Diagram](image)

<table>
<thead>
<tr>
<th>$\sigma$, MPa</th>
<th>$\varepsilon_{ac}$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>0.5%</td>
</tr>
<tr>
<td>200</td>
<td>0.8%</td>
</tr>
<tr>
<td>180</td>
<td>0.65%</td>
</tr>
<tr>
<td>160</td>
<td>0.5%</td>
</tr>
<tr>
<td>140</td>
<td>0.35%</td>
</tr>
<tr>
<td>120</td>
<td>0.1%</td>
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</tbody>
</table>

![Diagram](image)

<table>
<thead>
<tr>
<th>$\Delta \varepsilon_{ac}$, %</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>0.85</td>
<td>0.65</td>
</tr>
<tr>
<td>0.55</td>
<td>0.5</td>
</tr>
<tr>
<td>0.3</td>
<td>0.35</td>
</tr>
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</table>

![Diagram](image)

<table>
<thead>
<tr>
<th>$\Delta W_{pl}$, MJ/m$^2$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>0.65</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.35</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The course analysis of $\sigma_0$, $\Delta \varepsilon_{pl}$ and $\Delta W_{pl}$ parameters (Fig. 6) shows that cyclic properties of single-phase brass undergo changes at all levels of strain $\varepsilon_{ac}$. For all strain levels cyclic hardening is visible. From the analyzed parameters the least changes in the function of the loading cycles number are observed in the case of the plastic strain energy $\Delta W_{pl}$.

Confirmation of cyclic hardening of brass during variable loading is the mutual position of cyclic and static strain diagrams. Cyclic strain diagram is obtained by description of the hysteresis loop apexes at all strain levels by a suitable equation. The most often applied description in the construction fatigue analysis is the proposal of the equation given by Ramberg-Osgood [6] in the form:

$$E = \left(\frac{\sigma}{\varepsilon_{pl}}\right)^{1/n'}$$

where: $n'$ - exponent of the material cyclic hardening, $K'$ - cyclic life coefficient.

Cyclic strain diagram describing hysteresis loops at all strain levels from the period corresponding to the relative life $n/N = 0.5$ was presented in Fig. 12.

![Diagram](image)

Fig. 12. Hysteresis loops from the half-life period ($n/N = 0.5$) and cyclic strain diagram

In order to illustrate the scale of changes of cyclic properties of brass during variable loading with the use of the equation (1) in Fig. 13 there were shown diagrams of cyclic strain obtained for the hysteresis loops from various periods of $n/N$ life. There was also shown diagram of the static tension. Position of $a$, $b$ and $c$ curves of the cyclic strain above the diagram of the static tension is the proof of proceeding changes of cyclic properties and the process of metal hardening.
Microscopic tests of specimen surfaces after static and fatigue loading showed microstructure features accompanying fatigue cracking and enable showing initiation and development places increasing of the number of cycles of loading.

Basing on the comparison of fatigue and static specimens it was stated that in both cases there appeared the same or similar plastic strain elements.

Dynamic stress activity accompanying static loading caused appearance, next to creep systems, strain twins of the $\alpha$ phase (i.e. in A1 network). During the fatigue process the strain system appeared but in a lower range.

4. Summary

Changeability of the hysteresis loop parameters in the function of the loading cycles number causes that the values of the material data used during fatigue life calculations depend on the life period in which they were determined. It causes the results of fatigue life calculations and also their agreement with tests results is influenced by the life period accepted for determining necessary material data. In consequence the methods of fatigue life calculations based on the assumption of cyclic properties stabilization during variable loadings raise doubts.

The least changes of the plastic strain energy $\Delta W_p$ in the function of loading cycles number are the confirmation of the literature data that this parameter is the least sensitive to the changes of cyclic properties of material. It is caused by the fact that the course of $\Delta W_p$ energy changes takes into account mutual interactions of both stress and strain. Because of that fact it is believed that an energy approach to fatigue process is more complete than strain or stress description.

Microstructure on fatigue specimen surfaces in the notch zone showed its grain structure thanks to creep strands obtained in the grain area. Crystallographic orientation of grains caused that creep strands showed its orientation in relation to creep strands of adjacent grains. Therefore on fatigue grains the relief was observed.

In literature [7] it is stated that plastic strain starts in crystallographic orientation grains according to easy creep direction and next to notches. Therefore grain creep during the fatigue test processed in the same crystallographic systems as during plastic strain.

Plastic strain caused increase of the dislocation density in the $\alpha$ phase during fatigue tests what led to its hardening, and in case of initiation and cracking development those processes appeared with bigger loadings.

Acknowledgements

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References