DUCTILE DAMAGE IDENTIFICATION AND TENSILE NOTCH EFFECT FOR EUROFER97 STEEL

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Received: 21.10.2012
Accepted: 06.03.2013

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Abstract

The effect of stress multiaxiality on void nucleation and growth at ductile fracture was studied for a Eurofer97 steel. To investigate the effect of stress multiaxiality and void’s nucleation and growth, the tensile testing of smooth and notched round bars was performed. The fractography and metallography analysis on broken halves of tensile bars together with the image analysis were carried out. The increasing stress multiaxiality in the bars lowers the strain at fracture. The ductile damage of the steel consists from the nucleation of the voids by decohesion mechanisms, their gradual growth and finishes by rapid void coalescence. The increasing stress multiaxiality causes larger growth of voids together with observed restriction of void’s nucleation.

Keywords: Eurofer97, notched tensile bars, voids, nucleation and growth

1 Introduction

There is certain trend of miniaturization of test specimens, e.g. monitoring of industrial structural component, the need of local mechanical properties evaluation, e.g. weld join [1], or need of extraction of mechanical properties from small volumes of the material [2-4]. The size and geometry effects make interpretation of the test results measured on sub-sized specimens difficult in comparison with standard specimens. Important task is therefore separation of fracture behaviour of the material from size and geometry effects. The local approach and micro-mechanical modelling offer attractive possibility [5]. Ductile fracture of engineering alloys consists from stages of nucleation of micro-voids and/or their growth and subsequently from their coalescence to the macroscopic crack. One of the most using model for ductile fracture is the Gurson-Tvergaard-Needleman (GTN) model [6, 7], which requires identification of several micro-mechanical parameters describing void’s behaviour during the whole damage process. Also the material stress-strain relation at various levels of the stress multiaxiality is usually necessary for purses of modelling. In this study, the ductile fracture at various levels of stress triaxiality is investigated by testing smooth and notched round tensile bars. The tested specimens are further analysed to describe damage of the material by micro-void mechanism and to quantify it.

2 Experimental

The tested material was Eurofer97 steel developed for structural applications relating to future fusion/fission power generation [8]. This progressive alloy has chemical composition...
9Cr-1W(V-Ta) with very low impurity content. Its structure consists of tempered martensite with fine precipitates. The precipitates of the steel are formed by population of larger carbides type of M23C6 and by population of smaller precipitates type of MX [9, 10]. The microstructural parameters of the steel in the form of the plate of thickness 25 mm (heat nr. 993393) were obtained. The specimens were prepared by standard metallographic way and the microstructure was revealed etching by Villela-Bain. The specimens were then observed in scanning electron microscope (JSM 6460, Jeol). The microstructure micrographs were obtained at magnification 5000 and processed by image analysis according to the process described below. The obtained microstructural parameters of the steel are in Table 1.

Table 1 Microstructural parameters of the Eurofer97 steel

<table>
<thead>
<tr>
<th>Volume fraction of precipitates, ( f_p ) [-]</th>
<th>Mean diameter of precipitates [( \mu m )]</th>
<th>Mean size of Prior Austenite Grain [( \mu m )]</th>
<th>Areal Particle density ( (N_A)_p \times 10^{10} ) [m(^{-2})]</th>
<th>Volume Particle density ( (N_V)_p \times 10^{10} ) [m(^{-3})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.041</td>
<td>0.21</td>
<td>25.00</td>
<td>118.8</td>
<td>284.9</td>
</tr>
</tbody>
</table>

For tensile testing the smooth and notched round bars were manufactured from the same piece of material in longitudinal direction of the plate. Two pieces of specimens per geometry were prepared. The smooth tensile specimens and specimens with notch radii 3 mm and 1 mm were prepared to have the same initial diameter 4 mm and gauge length 20 mm. The specimens were tested quasistatically by the speed 1 mm/min at room temperature (Zwick Z50). During the tests axial displacement of specimens was monitored by the external extensometer, the actual diameter was monitored optically by digital camera in regular intervals. Metallographic examinations of the tested specimens were performed on their longitudinal sections located on the central axis mainly beneath the fracture surfaces. One specimen per tested geometry was evaluated. To produce equivalent surfaces, the metallographic preparation scheme was devised consisting from standard metallographic grinding on sand papers and polishing using micro-paste and final mechanical-chemical polishing with OPS suspension (Struers). The specimens were studied using SEM at different magnifications. The quantitative void measurements were obtained from areas beneath the fracture surfaces in the centre of the specimens on eight micrographs at magnification 500. The presented characteristics were obtained from images processed by image analysis (software ImageJ2x [12]) as the particle area projected. Typical standard deviation of the measurements was 15%.

The fracture surfaces of broken bars were fractographically analysed using SEM.

3 Results and Discussion

The stress-strain curves of tested bars and the load-actual diameter curves in Fig. 1 and Fig. 2, respectively. The overview of the standard characteristics evaluated from tensile tests is in Table 2. With increasing stress triaxiality in the specimen centre, the stress characteristics increase and deformation characteristics decrease. The results were consistent within usually observed experimental scatter for tensile testing [13, 14]. The only noticeable difference is in the final part of fracture for bars with notch radius 3 mm. The very rapid decrease of carrying capacity of specimen is usually observed for notched geometries. That behaviour is apparently connected with the final part of the specimen failure, when cone-cup fracture is developed.
With increasing stress triaxiality in the specimen centre, the stress characteristics increase and deformation characteristics decrease.

The fracture stress ($R_f$) and the fracture strain ($\varepsilon_f$) represent the average values of the characteristics in the specimen at fracture. The fracture strain was determined from initial ($d_0$) and final diameter ($d_f$) of the specimen according to

$$\varepsilon_f = 2\ln\left(\frac{d_0}{d_f}\right)$$

The notch effect increases the stress triaxiality in the specimen centre and lowers the fracture strain, which is the smallest for specimens with notch 1 mm.

**Table 2** The overview of standard characteristics evaluated from tensile tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>$R_f$ [MPa]</th>
<th>Fracture strain $\varepsilon_f$ [-]</th>
<th>Elongation [%]</th>
<th>Reduction area [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth-A3</td>
<td>555</td>
<td>678</td>
<td>316</td>
<td>1.62</td>
<td>25.4</td>
<td>80.2</td>
</tr>
<tr>
<td>Smooth-B3</td>
<td>555</td>
<td>673</td>
<td>315</td>
<td>1.58</td>
<td>25.7</td>
<td>79.4</td>
</tr>
<tr>
<td>Notched R3-A21</td>
<td>867</td>
<td>877</td>
<td>457</td>
<td>1.23</td>
<td>8.6</td>
<td>70.7</td>
</tr>
<tr>
<td>Notched R3-B11</td>
<td>844</td>
<td>855</td>
<td>209</td>
<td>1.24</td>
<td>8.4</td>
<td>71.2</td>
</tr>
<tr>
<td>Notched R1-A11</td>
<td>1047</td>
<td>1047</td>
<td>207</td>
<td>0.96</td>
<td>6.0</td>
<td>61.7</td>
</tr>
<tr>
<td>Notched R1-B21</td>
<td>1074</td>
<td>1074</td>
<td>291</td>
<td>0.87</td>
<td>5.4</td>
<td>58.1</td>
</tr>
</tbody>
</table>

The results of quantitative void measurement beneath fracture surfaces are in **Table 3** and in **Fig. 3**. The quantification showed that the smooth specimen contains on average the biggest amount of voids represented by $(N_A)_p$, which are at the same time the smallest from all three geometries studied. On the other hand, lower plastic deformation together with higher stress triaxiality for notched specimens lowers the amount of nucleated voids and causes their growth. It is within the theory, which assumes that with higher level of plastic deformation of the matrix also smaller particles are sampled by sufficient level of deformation to cause their cracking or interface decohesion particle/matrix [15, 16].

The void volume fraction $f_v$ is for smooth and 3 mm notched specimen nearly identical, what it is in accordance with literature data [17]. On the other hand, the $f_v$ for 1 mm notched specimen is much lower. This deviation is probably caused by the small amount of relatively large voids in this specimen. The voids were preferentially oriented in longitudinal direction towards the fracture surfaces. The aspect ratio of the voids, i.e. length ratio of major axis to minor axis of
fitted ellipse, increases with increasing level of plastic deformation and is the biggest for smooth specimen. For this specimen also the slight coalescence of voids in longitudinal direction was observed. The void’s nucleation mode was observed as decohesion of interface matrix/particle.

![Fig.3](image)

**Fig.3** Representative micrographs of voids beneath the fracture surface in the specimens, a) smooth, b) notched 3 mm, c) notched 1 mm

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Volume fraction of voids, ( f_v ) [-]</th>
<th>Mean diameter of voids, ( d_v ) [( \mu )m]</th>
<th>Areal Particle density ( (N_A)_p \times 10^{10} ) [m(^{-2})]</th>
<th>Aspect Ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth</td>
<td>0.0044</td>
<td>3.08</td>
<td>1.43</td>
<td>2.20</td>
</tr>
<tr>
<td>Notched R3</td>
<td>0.0043</td>
<td>4.49</td>
<td>0.64</td>
<td>2.00</td>
</tr>
<tr>
<td>Notched R1</td>
<td>0.0028</td>
<td>8.78</td>
<td>0.11</td>
<td>1.86</td>
</tr>
</tbody>
</table>

The only certain fraction of particles in the matrix of the material is subjected to generate the voids [16, 18]. This fraction is usually set as the ratio of volume fraction of voids \( f_v \), to the volume fraction of precipitates \( f_p \), which is for the smooth specimen approximately 10%. For example at identical conditions a fraction of particles in range 15-30% was determined [19]. The examination revealed that voids nucleate just in the neck region in small distance from the fracture surfaces and any voids were observed neither in uniformly deformed part of specimen nor in the screw head of it. The damage process of the steel is driven by the void’s nucleation and their subsequent growth. No marks of significant coalescence process were observed under the fracture surfaces **Fig. 3**, suggesting that the void coalescence was not acted during the substantial part of damage evolution.

![Fig.4](image)

**Fig.4** Macroscopic apperarance of fracture surfaces of specimens, a) smooth, b) notched 3 mm, c) notched 1 mm.

The overview of macroscopic appearance of the fracture surfaces is in **Fig. 4**. The diameter reduction is the largest for smooth specimens. The smooth and 3 mm notched specimens showed substantial amount of axial cracking, i.e. several micro-cracks are visible on the fracture surfaces with the micro-crack planes in direction of the loading specimen axis. Ductile fracture is in
smaller scale composed from two different void populations. The large voids correspond to the largest carbides type of $\text{M}_{23}\text{C}_6$, or oxide particles and inclusions which have usually large size [9, 10, 19]. The large carbides type of $\text{M}_{23}\text{C}_6$ are distributed preferentially on grain boundaries or at interfaces of martensite laths (subgrains) [8, 10]. The small voids are produced by smaller carbides or precipitates type of MX. The largest voids at fracture surface of the smooth specimen are clearly smaller than the large voids of the notched specimens and the notched specimen with radius 1 mm contains the highest amount of large voids at fracture surfaces. The largest particles observed inside the voids had diameter about 4 µm despite void size or specimen geometry. It is thus evident that the final void size is influenced by the stress state and by the final stage of the fracture, when the void coalescence takes place and the void growth is very rapid.

The observation of the fracture surfaces revealed that it contains much higher portion of voids than determined by image analysis from the areas under fracture surface. It could be explained that with increasing amount of plastic deformation, the population of smaller precipitates is sampled causing void growth on them. Because of small distance between small MX precipitates, the coalescence there process is very quick leading to immediate macroscopic crack propagation. Described mechanism can take place in alloys with multi-modal particles distribution [15, 16], which is also the case of studied Eurofer97 steel [9, 10].

Additional investigation was performed to bring into light the cause of axial cracks presented in the smooth and 3 mm notched specimens. The axial cracking is more extensive for smooth specimens than for the notched specimen Fig. 4 and decrease with lowering the fracture strain $\varepsilon_f$ Table 2. The axial cracking was also observed for the similar type of the steel [20]. The longitudinally cut specimens were metallographically prepared and etched in Villela-Bain to reveal microstructure along the loading axis of the specimens. Whereas the orientation of martensite laths (indicated by carbide decorations) in undeformed part of the specimen is randomly distributed in Fig. 5, plastic deformation of the specimen causes alignment of them in axial (loading) direction, Fig. 6. The mechanism of crack initiation is probably connected with shear loading on carbide decorating martensite laths and at certain level of plastic deformation causing decohesion of the interfaces and the crack oriented in axial direction may be able to initiate. The axial cracking is thus connected with certain level of plastic deformation and is more promoted with the increasing extent of plastic deformation.
4 Conclusion
The tensile properties at various levels of stress multiaxiality by testing smooth and notched round bars were determined for the Eurofer97 steel. The increasing stress triaxiality causes lower fracture strains. A quantitative study of void initiation was performed. Voids nucleate preferentially at the largest precipitates by mechanism of decohesion matrix/particle. The increasing stress multiaxiality causes larger growth of voids, which is promoted at the expense of growth nucleation probably as reason of lower deformation level. Obtained quantitative results of void fractions together with the stress-strain behaviour at various levels of the stress triaxiality will be used for calibration of parameters of the GTN model.

References

Acknowledgements
The authors gratefully acknowledge financial support of the projects of the Czech Science Foundation No. GD106/09/H035 and No. GAP108/10/0466 and the project of specific research FSI-J-12-27/1733.