

Critical Void Volume Fraction f_c at Void Coalescence for S235JR Steel at Low Initial Stress Triaxiality

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Abstract. The paper is concerned with the nucleation, growth and coalescence of microdefects in the form of voids in S235JR steel. The material is known to be one of the basic steel grades commonly used in the construction industry. The theory and methods of damage mechanics were applied to determine and describe the failure mechanisms that occur when the material undergoes deformation. Until now, engineers have generally employed the Gurson-Tvergaard-Needleman model. This material model based on damage mechanics is well suited to define and analyze failure processes taking place in the microstructure of S235JR steel. It is particularly important to determine the critical void volume fraction f_c , which is one of the basic parameters of the Gurson-Tvergaard-Needleman material model. As the critical void volume fraction f_c refers to the failure stage, it is determined from the data collected for the void coalescence phase. A case of multi-axial stresses is considered taking into account the effects of spatial stress state. In this study, the parameter of stress triaxiality η was used to describe the failure phenomena. Cylindrical tensile specimens with a circumferential notch were analysed to obtain low values of initial stress triaxiality ($\eta = 0.556$ of the range) in order to determine the critical void volume fraction f_c . It is essential to emphasize how unique the method applied is and how different it is from the other more common methods involving parameter calibration, i.e. curve-fitting methods. The critical void volume fraction f_c at void coalescence was established through digital image analysis of surfaces of S235JR steel, which involved studying real, physical results obtained directly from the material tested.

1. Introduction

Nucleation and growth of defects in the material microstructure are the main causes which initiate the failure process. Due to their relative high stiffness, micro-defects form cavities, denoted as voids, during the material deformation process. The voids evolution determines the mechanisms of material damage. This problem is very complex due to a lot of phenomena and factors, including distributions of voids in the microstructure at the initiation phase, void nucleation, anisotropy of the shape and spacing of the inclusions, changes of void shapes during the material deformation, interactions between voids and the evolution of secondary voids near coalescence. These processes are modelled basing on different concepts of damage mechanics. The main problem is a high level of complexity of particular material models, which limit the possibility of their practical applications.

One of the key step which affect the material failure phenomena is the void coalescence, shown schematically in figure 1. Voids nucleated at inclusions and precipitations grow due to deformations of the material matrix. With a significant effect of localized plastic strains, the voids link together,



creating the cavities. Due to considerable size of such void formation, this process leads finally to the material fracture.

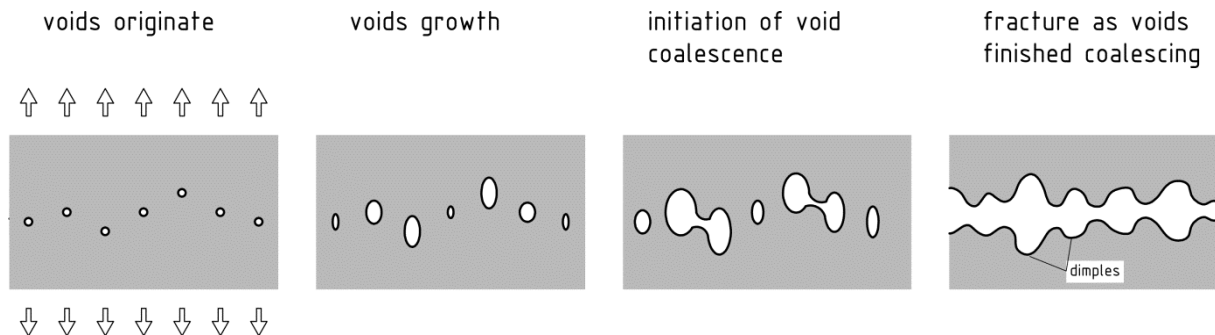


Figure 1. Scheme of the void coalescence

The knowledge about damage mechanisms taking place in the material microstructure is very important, from scientific as well as practical point of view. By using several damage models now it is possible to model the failure processes and perform numerical analysis. There are a lot of engineering computer programs that allow to simulate the material failure and structure collapse. Basic problem is connected with material constants necessary for application of material models based on the damage mechanics. There is a lack of constants for many structural materials, including structural steels used in engineering.

This study is concerned with determination of one of the Gurson-Tvergaard-Needleman (GTN) material model parameters. This model is based on damage mechanics and allows to define and analyse failure processes observed in many kinds of materials. The critical void volume fraction f_c , which is one of the basic GTN parameters, is considered in the study. It is determined for one of the basic structural steel grade, S235JR, commonly used in civil engineering. The critical void volume fraction f_c at void coalescence is established in the case of low initial stress triaxiality. To this end, the digital image method was applied, which involved studying real, physical results obtained directly from the material tested.

2. Critical void volume fraction f_c at void coalescence

History of material models which attempt to describe failure phenomena taking place in the microstructure and link them with the materials response is dated back to the mid-twentieth century [1]. They have been developed until today [2-10], as well as combinations of different methods, eg. [11]. Quite an advanced concept was proposed in 1977 by Gurson [2], who modified original Huber-Mises-Hencky hypothesis. Gurson introduced to the yield potential function the material damage parameter in the form of void volume fraction f [2]. As the effect, he took into consideration the influence of the number of microdefects on the material strength.

Original Gurson material model was modified and developed later during several years. In order to describe the changes in stress state taking place during deformation due to void nucleation and growth, original Gurson yield potential was modified by Tvergaard and Needleman [12, 13]. They redefined void volume fraction parameter according to the following function [13]:

$$f^* = \begin{cases} f & \text{for } f \leq f_c \\ f_c + \frac{1/q_1 - f_c}{f_F - f_c} (f - f_c) & \text{for } f_c < f \end{cases} \quad (1)$$

where: f_c – critical void volume fraction corresponding to the onset of void coalescence, f_F – critical void volume fraction corresponding to the material failure, q_1 – Tvergaard's coefficient.

It allowed to describe the phenomena observed in the material for the range of deformation when the value of f is higher than critical parameter f_c . Critical void volume fraction f_c corresponds to the onset of void coalescence. Together with Tvergaard's coefficient q_1 and critical void volume fraction f_F which corresponds to the material failure, critical void volume fraction f_c affect value of actual void volume fraction f^* , which describes the failure processes taking place in the material. Critical void volume fraction f_c is treated as a material constant, which as criterion parameter determines material rupture.

3. Scope of analysis

The research concerns the experimental determination of the critical void volume fraction f_c at void coalescence for S235JR steel. The case of low initial stress triaxiality η is considered. The investigations include the tensile tests of cylindrical specimens with a circumferential notch, which allowed to obtain low initial value of $\eta = 0.556$. The void coalescence phase was considered during the experiments in order to determine the critical void volume fraction f_c . The material obtained from tensile specimens were used at digital image analysis of surfaces of S235JR steel. The procedure involved studying real, physical results obtained directly from the material tested.

4. Tested material

Due to scientific as well as practical scope of the study, one of the common structural steel, S235JR, used in civil engineering was chosen for analysis. This is a mild, low-carbon steel grade, used for structural elements of building, bridges and others.

Requirements for chemical composition of S235JR steel is described in [14]. According that, the maximum content of elements is: C = 0.14 %, Mn = 0.54 %, Si = 0.17 %, P = 0.016 %, S = 0.026 %, Cu = 0.29 %, Cr = 0.12 %, Ni = 0.12 %, Mo = 0.03 %, V = 0.002 % and N = 0.01 %. For tested steel, large amounts of impurities, i.e. inclusions and second-phase particles, were observed in the microstructure.

Basic mechanical properties of S235JR steel were determined by performing standard tensile tests according to [15]. The specimens in the form of round bars were used. The number of the test was $n = 8$ specimens. The geometric parameters of specimens were: nominal diameter $d = 10$ mm, the gauge length $l_0 = 50$ mm and the initial cross-sectional area $S_0 = 78.5$ mm². Mechanical properties of tested S235JR steel obtained for the significance level of 0.05 are listed in Table 1.

Table 1. Mechanical properties of tested S235JR steel.

	Yield stress $R_{0.2}$ [MPa]	Tensile strength R_m [MPa]	Percentage elongation A_t [%]
Value	318.3	457.4	33.3
Standard deviation	3.73	7.09	2.13

Comparing with standard requirements [14], tested material was characterised by better mechanical properties then it is required.

5. Tensile tests

Tensile tests were the first stage of investigations. In order to take into account the effects of spatial stress state, a case of multi-axial stresses was considered. The spatial stress state was described by using stress triaxiality η parameter, which is defined:

$$\eta = \frac{\sigma_m}{\sigma_e} \quad (2)$$

where: $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$ – hydrostatic stress (with $\sigma_1, \sigma_2, \sigma_3$ being the principal stresses),
 $\sigma_e = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}$ – effective stress according to the Huber-Mises-Hencky.

Experiments were performed with cylindrical tensile specimens with a circumferential notch, as shown in figure 2. The geometric parameters of specimens were: nominal diameter $D = 14$ mm, the notch radius $R = 7.0$ mm. It allowed to obtain very low value of stress triaxiality parameter $\eta = 0.556$. Specimens were subjected to the static tension in a multi-axial stress case.



Figure 2. Geometry of cylindrical tensile specimens with a circumferential notch and view of the tensile test in multi-axial stress case

The main concept of the investigations was determination of the phase of void coalescence. Basing on the results of own research [16-18], the stress-strain curves and the time of rapid void growth was analysed in detail. It was established, that the moment of void coalescence initiation was observed as the stage after exceeding the maximum force during the tensile tests. Basing on these observations, the force criterion was applied for detecting the void coalescence time. According that, the void coalescence was determined when force was about 5 % lower than maximum force recorded during the tensile test. Scheme of that criterion for one of specimens tested is shown in figure 3.

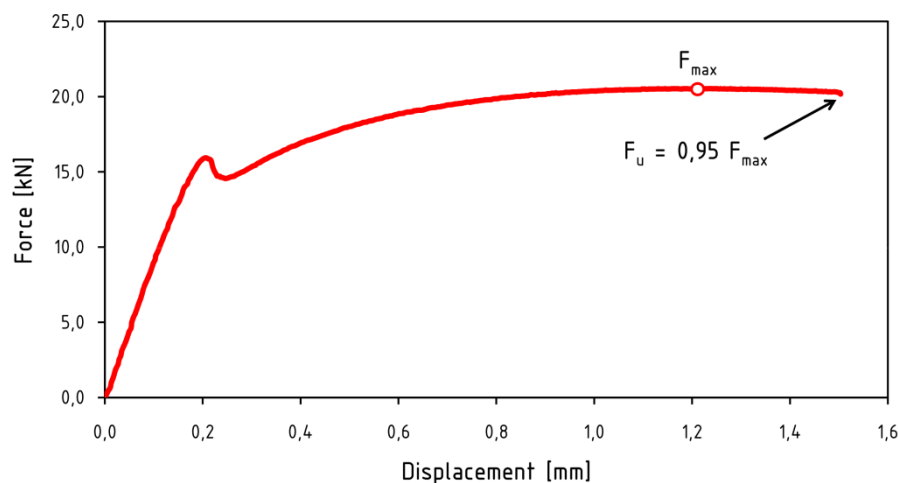


Figure 3. Criterion for determination the time of void coalescence for S235JR steel

Experiments were stopped when above criterion was met. Then specimens were taken out from testing machine and used for further analysis. This way the microstructure of S235JR steel in the void coalescence phase was obtained, and could be used for experimental determination of critical void volume fraction f_c .

6. Methodology for the f_c parameter assessment

Specimens subjected to the loading described above were prepared to microscopic investigations. The area around the notch was cut out (figure 4). The obtained fragment of the specimen was then cut along the longitudinal axis, abraded and polished.

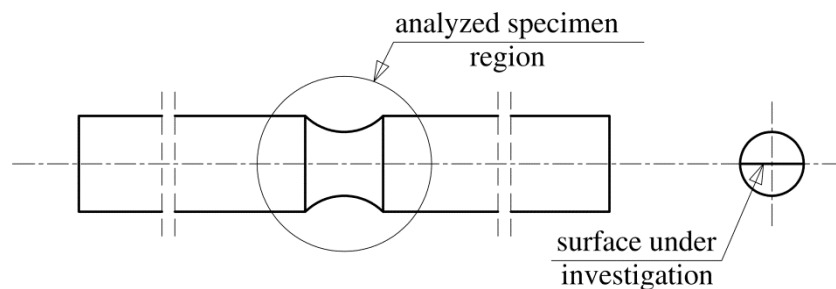


Figure 4. Surface of the notch cross section chosen for microscopic examination

In order to facilitate the implementation of microscopic images the sample was embedded in the resin. The sample used in microscopic investigations is presented in figure 5.



Figure 5. Metallographic specimen used in microscopic investigations

The next stage involved microscopic observations. Scanning electron microscope (SEM) Quanta FEG 250 was used. The photographs were made at the magnification of 1000x. The photographs were divided into three groups, depending on the analysed area (sample axis, area around the notch surface, area between the centre and the edge of the sample – figure 6).

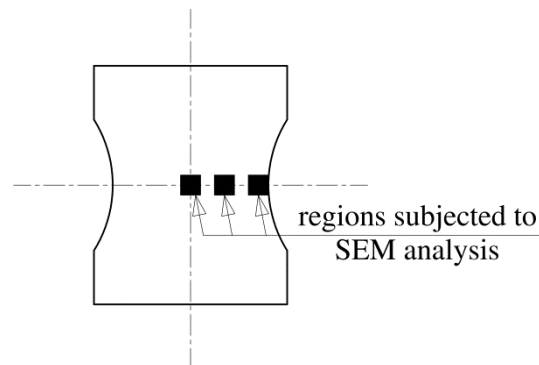


Figure 6. Regions of sample surface under microscopic examination

Figure 7 presents an example of steel microstructure in the area adjacent to the sample edge. Darker areas represent voids and inclusions embedded in the matrix (grey areas). Two merged voids are clearly visible on the right side of the photograph.

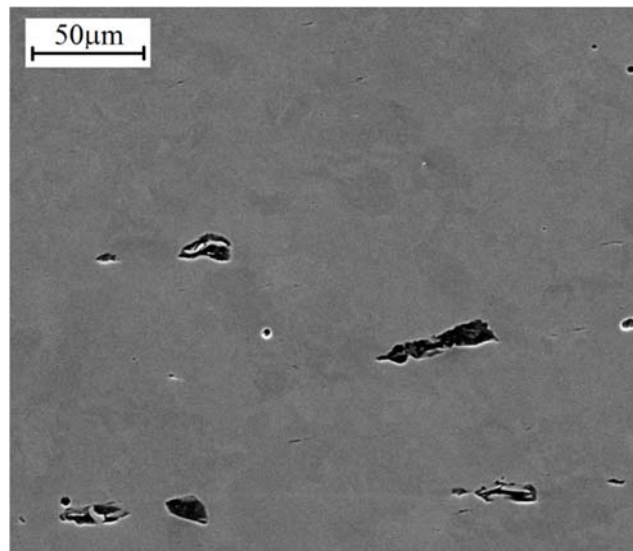


Figure 7. An exemplary microscopic photograph of the sample surface (magnification 1000x)

Assessment of critical void volume fraction f_c required a detailed quantitative image analysis. Basing on the greyscale criterion the image binarization was performed and thus dark areas, representing voids and other discontinuities were deleted. The procedure was performed for 30 photographs. Binary photograph from figure 7 is shown in figure 8.

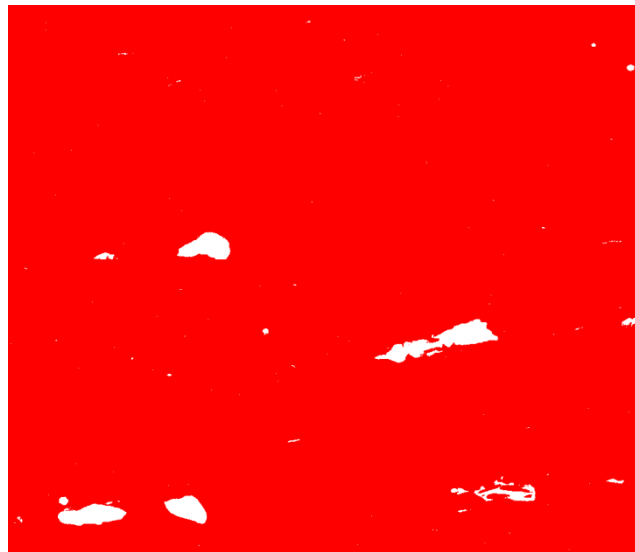


Figure 8. Microscopic photograph of the sample (figure 7) after binarization

The final stage involved calculation of trimmed areas (voids) fraction in the area of the entire image. The obtained value was interpreted as the f_c parameter. It is worth noting that the procedure described above made it possible to calculate superficial, not volume fraction of voids.

7. Results and discussions

The value of f_c obtained in the present study was 1.64%. This is defined as the mean ratio of voids area on the surface microphotograph to the area of the whole analysed surface. The parameter calculated in the present study is noticeably lower than the value of 6% described in the literature [19]. As described in [20] the value of f_c depends on the stress state triaxiality ratio and increases with increasing η . The samples analysed in the present study were subjected to low stress state triaxiality ratio (0.556) and thus f_c is considered to be relatively low.

The final issue was calculation of void volume (not superficial) fraction. A scheme of two spheres was adopted (figure 9) – the smaller sphere represents generalized void embedded in matrix. It was assumed that the relation of small and large sphere cross section areas was equal to superficial fraction calculated for the samples experimentally (1.64%).

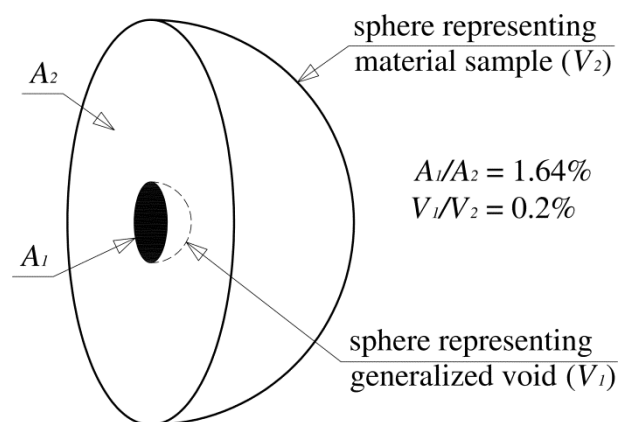


Figure 9. Scheme adopted for void volume fraction assessment

Basing on geometric relationships the ratio of void volume to the volume of the whole material sample was calculated. The void volume fraction obtained using this procedure was 0.2%. As reported in [10] initial void volume fraction f_0 for unloaded S235JR steel was 0.17%, but this value was determined using standard procedure for porosity determination, which is based on calculations of pores area.

8. Conclusions

GTN model is often discussed to be effective in analyses of structural members operating in plastic range, under pre-failure conditions. Lack of the model parameters for typical engineering materials severely limits the possibility of practical application. Typical procedures for GTN parameters assessment involve only numerical analyses and fitting curve procedure. Consideration of actual changes in the structure of the material has received little attention so far.

Research presented in this article is an attempt to assess critical void volume fraction f_c by the experimental procedure, taking into account effect of low stress state triaxiality ratio ($\eta = 0.556$). The final result was $f_c = 1.64\%$, which is considerably lower than typically used in the GTN model [19]. Comparative analysis of f_c and initial porosity f_0 indicates that in the stress range from 0 to the material strength the voids growth is a relatively slight process. Increase in cavities volume shortly before failure is a far more intense process [21].

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