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EVOLUTION OF VOID SHAPE ANISOTROPY IN DEFORMED BCC STEELS

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Abstract

Microstructural analysis to support the development of material models provides valuable information to design complex forming operations. Damage models such as e.g. by Gurson consider spherical voids only. However, investigations of bcc steels by scanning electron microscopy reveal that voids exhibit an ellipsoidal shape with progressing deformation. The material's weakening in the Gurson model is taken into account by the void volume fraction. Therefore, a three-dimensional characterization of the void shape offers important data for modelling. Thus, information on the anisotropy of the process of void evolution and accordingly, about the anisotropy of the deformation process is provided. Application of the information regarding the void shape anisotropy within the Gurson model is discussed.

Introduction

All stages of plastic deformation have a different physical-mechanical nature, thus it is required to describe the structure for the corresponding associated models. Usually it is assumed that the formation and evolution of voids in the field of structural defects and inhomogeneity is connected to a substantial development of plastic deformation [1]. In the initial state only a small number of nano- and microvoids are present in steel sheets. Subsequent growth of the voids depends on the size of the local stress and the intensity of the plastic deformation. In the case, where the local stresses in the metal are too small for an intensive growth of voids, the substantial development of plastic deformations can result in the formation of secondary voids. The rate of secondary formation of voids depends on the concentration of the precipitations in the metal, the microstructure of the material, the size of the phase boundaries and the intensity of the development of plastic deformation [2].

For the description of the mechanical material behavior of ductile damage micro-mechanical models can be applied, which are based on the well-known criterion of plastic flow of porous metal of Gurson-Twergaard-Needleman [3, 4]. The physical motivation is given due to void distortion and void interaction with material rotation under shear. Taking into account the experimentally determined critical size of micromechanical damage parameters the initiation of cracks was investigated at the example of compact samples. Therefore the assumed crack position was determined by numerical calculations of thin samples. This model can be used to predict crack initiation.

The relationship of stresses and deformations is determined by Hooke's law and the law of plastic flow which describes the correlation between stresses and the resulting deformation strain for the plastic state taking into account the condition of plastic flow in accordance with the criterion of von Mises. Additional attention is given to the reduction of the cross-section as a result of the formation of damage within the Gurson Twergard model by considering an equivalent void volume concentration. The size of the equivalent void volume fraction f^* is calculated according to Eq. 1:

$$f^* = \begin{cases} f, & f \leq f_c, \\ f_c + \dfrac{f_u^* - f_c}{f_f - f_c}(f - f_c), & f > f_c. \end{cases} \tag{1}$$

Here, f denotes the void volume fraction, f_c and f_f denote the critical void volume fraction at incipient coalescence and the void volume fraction at final fracture; f_u^* is defined as the ultimate value of f^* at which the stress carrying capacity vanishes macroscopically as was proposed by Tvergaard and Needleman [4].

Research of the anisotropy of damage and the corresponding void formation can be helpful for a further development of the model.

Experiments and Analytical Methods

For the investigation of damage, that is nano- and microvoids, it is necessary to apply methods which do not influence or modify the near-surface microstructure which formed during the prior plastic deformation. It is intended to ablate a certain layer of the material uniformly. This can be realized by ion slope cutting. Thus, a removal of a metallic layer without damaging the microstructural elements of the material can be achieved by using accelerated argon ions. The thickness of the layer removed is determined by the duration of the ion processing, the voltage at the cathode, the incident angle and the speed of rotation of the sample in the ion slope cutting processing. Different removal depths due to differently oriented grains enable to investigate the particularities of the damage development e.g. at grain boundaries. Here, the void formation and development are investigated as a consequence of plastic deformation in the dual-phase ferritic-martensitic steel DP600. Statistically data of the damage is acquired by taking multiple images: pictures were taken at five locations, lying 50 µm apart. At each location 5 times 5 pictures were taken at a magnification of 5000. In total 125 pictures were analyzed (which complies to the area of 0.5 mm²). The chemical composition of the steel is given in Table 1. For the investigation flat tensile specimens were deformed in a universal testing machine Zwick 100 with optical strain measurement according to the standard DIN EN ISO 6892-1. After deformation, cutting, mechanical grinding and polishing the specimens were subsequently treated by ion slope cutting using an ion-polishing system of the type Met Etch (Gatan Co). The microscopic examination was performed with an in-lens detector in a scanning electron microscope (SEM) of the type Zeiss Supra VP55.

Table 1. Constituent elements of the investigated steel in wt % determined by GDOES

Steel	C	Mn	Cu	Ni	Cr	Mo	Al	S	Si	Fe
DP600	0.10	1.4	-	max. 1.0			0.02-0.06	0.008	0.15	bal.

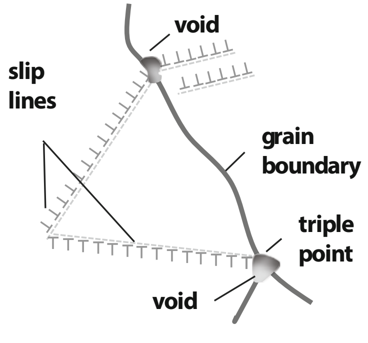
Results and Discussion

It can be observed that an anisotropic development of voids takes place. Furthermore, the changing of the modulus of elasticity is anisotropically as well. Anisotropy of the damage development is taken into account by applying the Gurson-based Gologanu-Model which considers an elliptical void shape though not the change in the elastic modulus [5]:

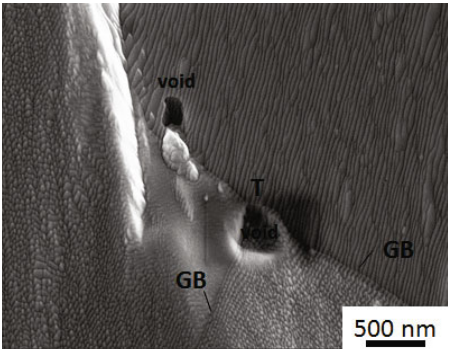
$$S_i = \log a_i/a_z \qquad (2)$$

with S_i: Gologanu "shape parameter"; a_i: major semi axis along the 0_z direction, a_z: minor semi axis along the 0_x and 0_y directions.

Determination of individual voids includes newly-formed voids, coalescing ones and growing ones. By applying the preparation technique based on ion slope cutting micro and nano voids can be prepared with a high quality [6]. Thus, a detailed three dimensional investigation of voids formed by plastic deformation can be achieved in comparison to established approaches to observe void formation, coalescence and growth on micrometric scale [7]. The shape and size of damage during plastic deformation is determined by the nature and the mechanisms of dislocation slip. The damage development depends on which structural elements are involved in the damage process during plastic deformation. An important role for the damage anisotropy plays the character of dislocation slip inside grains as well as the interaction of moving dislocations with each other and with grain boundaries (Fig. 1a). Frequently, the formation of voids occurs at the boundaries or in the vicinity of grain boundaries thus e.g., large wedge-shaped voids are formed at triple points (Fig. 1b).



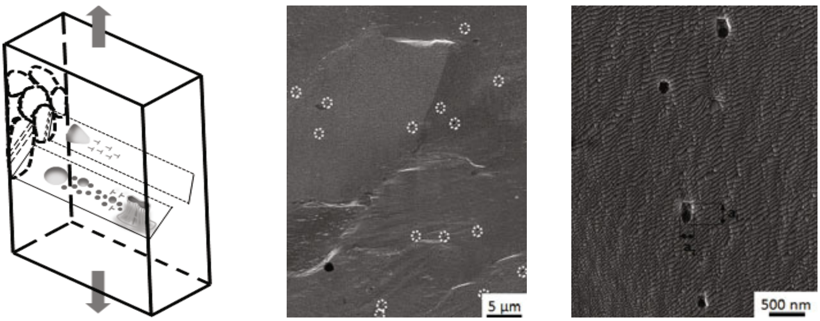
a)



b)

Fig. 1. Damage due to interacting dislocation slip and damage at a triple point, ε = 0.12; a) scheme of interaction between dislocations and elements of the microstructure; b) void formation at grain boundaries (GB) and triple points (T) after plastic deformation.

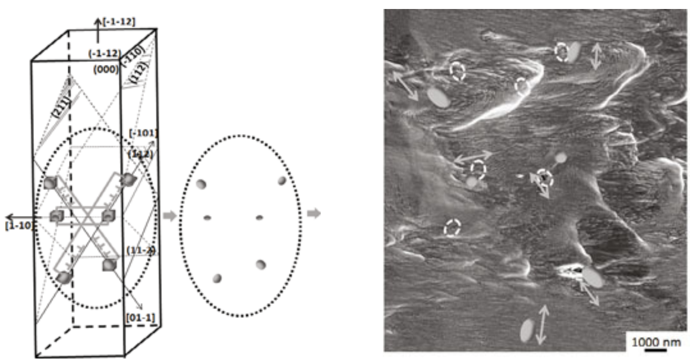
The three dimensional distribution of voids corresponds to a void development due to sliding in closed packed planes (Fig. 2 a, b, c).



a) b) c)

Fig. 2. Relationship of the dislocation structure after deformation with elements of damage in the volume of the material: a) scheme of interaction between the microstructure elements; b) macro level of the damage: void distribution in the sample after plastic deformation, ε = 0.16 (white dotted circles denote voids); c) micro level of the damage: void distribution in the sample after plastic deformation, ε = 0.16

The anisotropy of the three dimensional distribution of damage is determined by the laws of dislocation slip in close-packed planes of the crystal lattice. This can by illustrated by applying a crystal based geometrical scheme to potential damage in the material volume (Fig. 3a) and by comparing the resulting crystallographic space available for void formation with the presence of real damage in some places in the deformed metal (Fig. 3b)



a) b)

Fig. 3. Three-dimensional distribution of voids after plastic deformation, ε = 0.16; development of the cavities due to sliding in the close-packed planes: a) scheme of interaction between the dislocations in closed-packed planes; b) void distribution in the sample after plastic deformation;

the double arrows indicate the direction of a crystallographic allowable displacement of voids produced in a single slip plane, white dotted circles denote voids

Character of dislocations slip and number of involved slip planes is determined by the degree of deformation and defines the shape, size and distribution of voids in the metal volume (Fig. 4a). Thus, when the degree of deformation in bcc steel is less than 0.12, dislocations slip primarily in one close-packed plane {110} is observed, Fig. 4b. Regarding void formation and growth a mechanism of rotation of the matrix material during plastic deformation has to be considered (Fig. 4d and 4c). Figure 4c depicts one possibility of growth and movement of voids by a rotation of the matrix material.

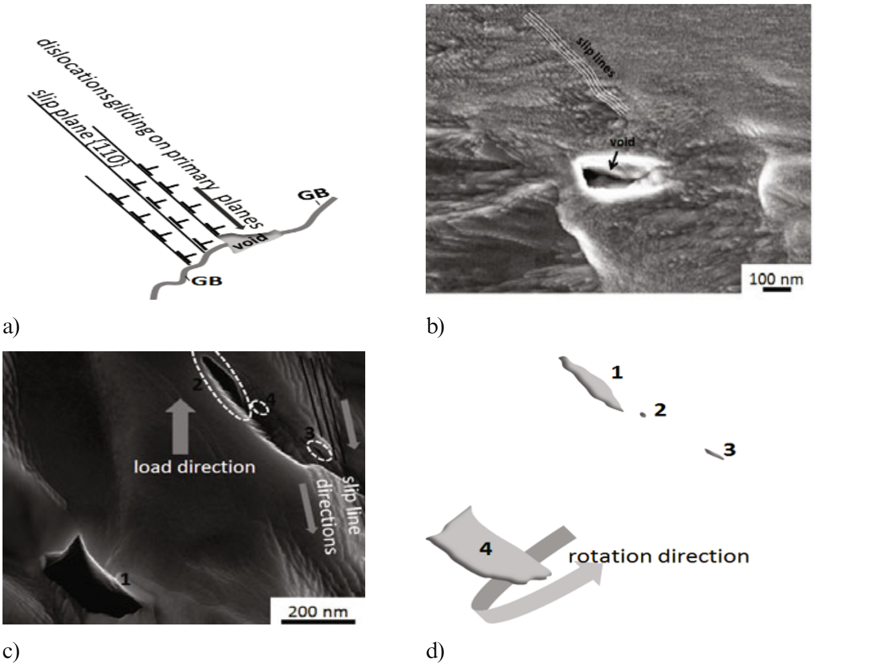
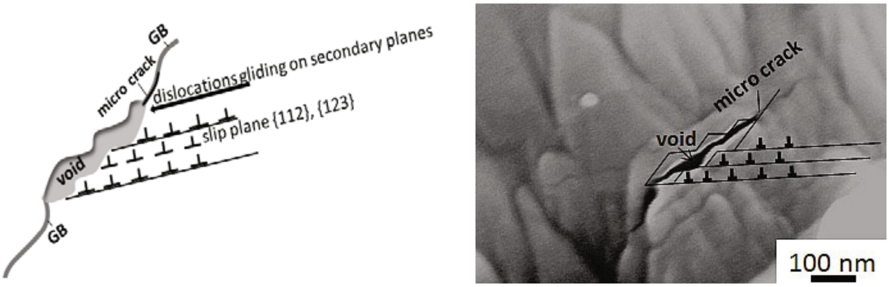


Fig. 4. Void development in the material volume after plastic deformation, ε = 0.12; a) scheme of void formation according to the mechanism of dislocation slip; b) wedge-shaped void in the material volume; c) void coalescence (1), nucleation (2), growth by dislocation slip (3), growth by rotation (4); d) schematic representation of voids forming and growing by matrix rotation

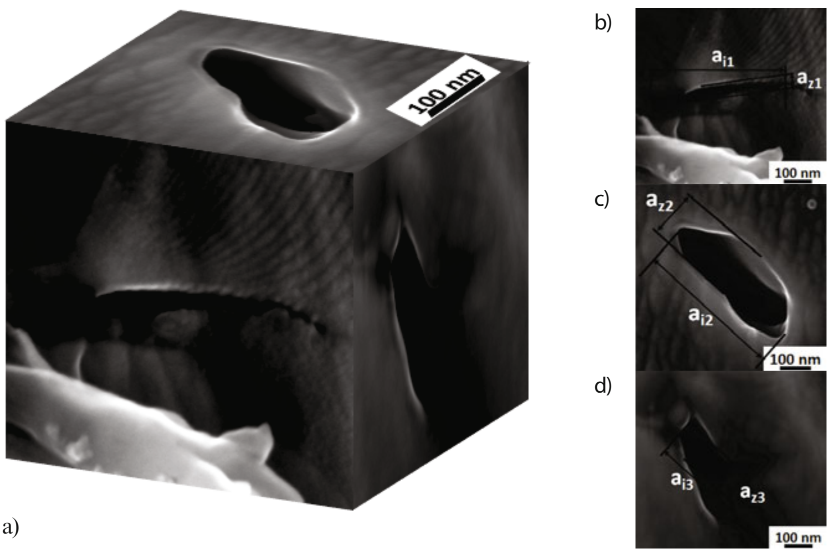
Naturally, the difference in the mechanisms of void development increases the anisotropy of the void distribution in the bulk material. By increasing the degree of deformation to 0.15 or more dislocation slip is observed in the planes {112} and {123} (Fig. 5a), which is in accordance with [8] regarding the development of plastic deformation in bcc steels. In this case, the growth and development of voids has been accompanied by the development of nano-cracks (Fig. 5b), which requires an adjustment in certain values of the void volume fraction.



a) b)

Fig. 5. Damage development in the material volume after plastic deformation, ε = 0.23; a) scheme of void and crack formation according to the mechanism of dislocation slip; b) void and micro crack in the material volume

For a detailed analysis values of the void volume fraction *f* must use estimates of the void sizes and other damage characteristics (e.g. nano- or micro cracks) in all three dimensions (Fig. 6).



a)

Fig. 6. Volume representation of the damage by plastic deformation, ε = 0.23; a) three-dimensional image of damage; b, c, d) representation of the damage in respective planes

For acquiring statistically significant data of damage by 3D images width ((az2+az3)/2 in Fig.6c and 6d), depth ((ai1 + ai2)/2 in Fig.6a and 6b) and height ((az1+ai3)/2 in Fig.6a and 6d) of the voids were analyzed.
Only by using damage parameters for all three dimensions gives correct information about the three-dimensional void volume fraction.

Conclusions

The exact description of the nature and the anisotropy of the damage distribution in the material volume and changes in the shape of voids with increasing degree of plastic deformation allow calculating the void volume fraction regarding an anisotropic distribution of damage. Changes in the shape of voids in all three dimensions at different degrees of plastic deformation can be taken into account. Using the preparation technology of ion slope cutting specimens could be prepared with a high accuracy regarding the parameters of damage.

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