LOCAL FRACTURE BEHAVIOUR AND CRACK TIP DEFORMATION IN METAL FOAMS

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ABSTRACT

The renewed interest in metal foams, which has been induced by the transport industry in the last few years, leads to a need of detailed information about mechanical properties of this new material class. The aim of this study is to provide information on fracture toughness and fracture processes of ductile metal foams. Investigations were carried out on ALPORAS and ALULIGHT aluminium foams with different specimen sizes and different relative densities. Standard fracture mechanic tests were performed. The fracture toughness values are in the range of 0,1 to 1,5 $MPa \cdot m^{1/2}$ for K_Q and 0,1 to 1,0 kN/m for $J_{0,2}$, mainly depending on the relative density. In-situ tests in the scanning electron microscope and in the optical stereomicroscope were performed also to observe the crack growth processes and determine the local deformation in the cell walls in front of the crack tip. The crack follows apparently the weakest path through the foam structure and is accompanied by building of crack bridges and by initiating of secondary cracks in front of the crack tip, so the crack resistance can decrease with increasing crack propagation. The tensile deformation of the foam structure is very localized in few cells and is further concentrated to the weakest part of the cell walls.

INTRODUCTION

Structural efficiency and cost requirements have erated renewed interest in cellular solids. Successful design of this new class of materials requires an understanding of their response to load. Comprehensive work has been done on characteristics of compression deformation and energy absorbing behaviour of metal foams [1-3]. Work on tension and fracture properties of these foams are rather limited. But for efficient design of load bearing structural elements their mechanical properties in tension are also very important. The aim of this paper is to provide some information on typical fracture toughness values of aluminium foams with different densities, crack growth behaviour and the identification of damaging processes in the foam structure upon crack propagation. This leads not only to an understanding of the fracture toughness of metal foams, it can be used also to describe tensile performance and fatigue properties of these cellular solids.

For that reason standard fracture mechanic tests were performed to obtain fracture toughness values depending on parameters like relative density of the foam, cell structure and specimen size. These investigations were accompanied by in-situ tests in the scanning electron microscope (SEM) and in the optical stereomicroscope to observe crack initiation and mechanisms of crack growth. Additional to these investigations local deformation measurements were carried out to identify damage and fracture processes in the foam structure.

EXPERIMENTAL PROCEDURE

Specimen preparation

For our investigations we used two closed-cell aluminium foams, an ALULIGHT foam (AlSiMg0.6 alloy) and an ALPORAS foam (AlCa1.5Ti1.5 alloy) with different densities, ranged from 0.25 g/cm^3 to 0.5 g/cm^3. CT-specimens with sizes of W=50 mm, B=25 mm, a_0/W=0,45 to W=290 mm, B=30 mm, a_0/W=0,45 were cut out of the foam plates with a diamond wire saw to avoid deformation of the cells. All specimens had an open surface. The surface of specimens, which were used for the in-situ tests were, carefully mechanical polished. The starter notches were preliminary machined with electro-discharging or with a diamond wire saw, which gave a notch radius of approx. 0,3 mm. Then for some of the specimens the notch tip radius was reduced to 30 µm with a special razor blade polishing technique [4]. Since this gave indistinguishable results in the fracture tests compared to fatigue pre-cracked specimens, which is also reported by other authors [5], all fracture tests were performed with such prepared specimens. An example of a CT-specimen, which was set up for the fracture tests is shown in Fig. 1.

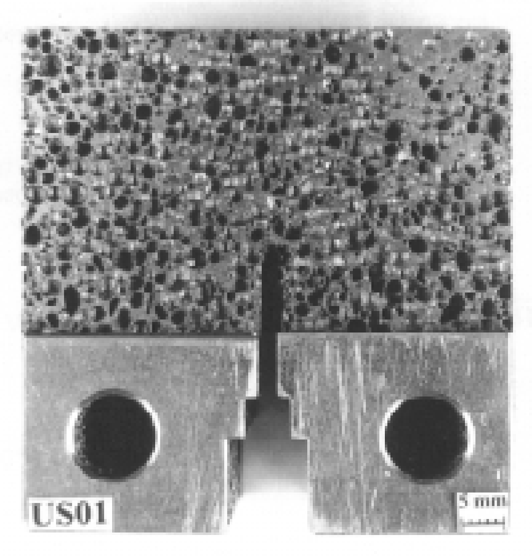

Figure 1: Example of a CT-specimen, which was used for the fracture tests.

Standard fracture tests

All tests were carried out on a displacement controlled universal mechanic testing machine at room temperature. The cross-head speed was 0,2 mm/min. Beside the force and the load line displacement measurement, also the crack extension was monitored by potential drop technique, which was needed for the single specimen J-integral tests. The validity of this method for metal foams was verified by optical observation of the crack extension and a comparison with the result of the potential drop technique. Therefore images from the specimen surface at different load states were taken with a CCD-camera and analysed subsequently. These images were also needed for the local deformation measurements.

All data were processed with a personal computer online. An example for the resulting load versus load line displacement curve including the crack extension curve is shown in Fig. 2 for two different foams. Since no valid K_{IC} values according to ASTM E399 were achieved in most cases, J-integral versus crack extension plots were calculated following ASTM E1152, ASTM E813 standard, and [6]. From these plots the $J_{0,2}$ fracture toughness values can be retrieved.

In-situ experiments

In order to investigate crack initiation and crack propagation in the foam in-situ fracture tests in the scanning electron microscope and in the optical stereomicroscope were performed. Therefore a small in-situ loading device with a cross-head speed of about 0,15 mm/min was used. CT-specimens with a dimension of W=50 mm, B=25 mm and a_0/W=0,45 were fractured with this device. Load and load line displacement were recorded during the test. Images with a resolution up to 4000x3200 pixel were taken from the foam surface at different load states. Images from the SEM contains 1 to 4 cells in front of the crack tip and gives a detailed view of the crack propagation in the cell walls, whereby images from the optical microscope contains several cells and they are needed to identify the overall deformation of the foam structure. Subsequently, the images were analysed to measure crack length, local deformation and to identify the crack path through the structure.

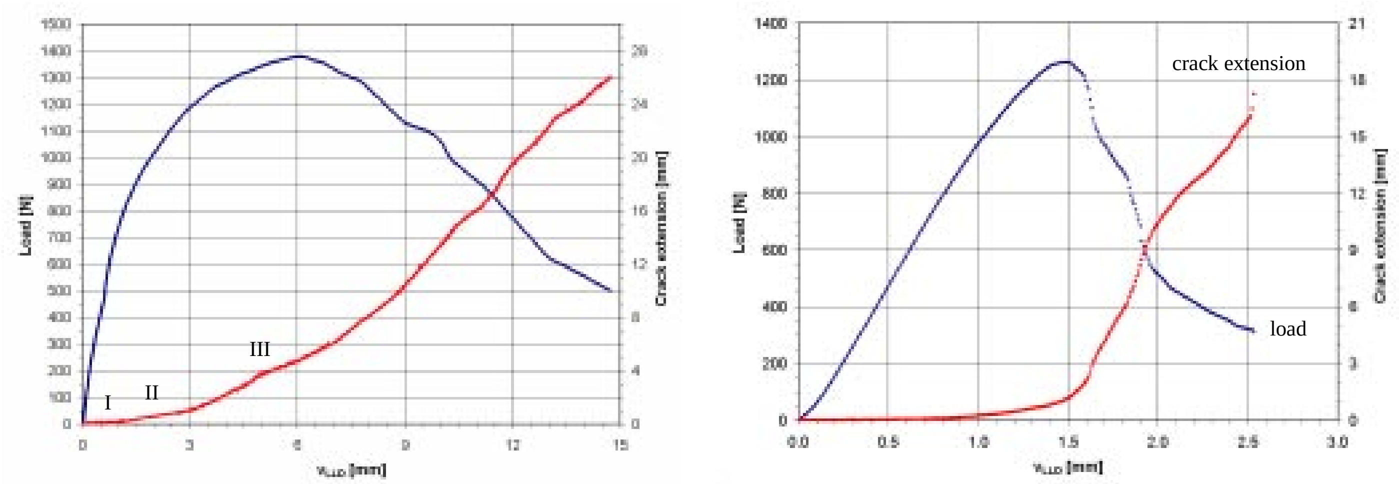

Figure 2: Load versus load line displacement curve and crack extension curve for an ALPORAS foam (W=140 mm, ρ=0,45 g/cm^3) on the left side and for an ALULIGHT foam (W=100 mm, ρ=0,50 g/cm^3) on the right side.

Local deformation measurements

From the images of the foam surface obtained by the SEM and by the optical microscope local deformation measurements were performed. Thereby images taken at different loads were processed with a special image analysing program [7,8]. This program can detect equal features in two images and calculates the x-y-coordinates of these features (so called homologous points). From the two sets of x-y-coordinates, one for each image, a displacement vector field can be calculated. The derivation in x- and y-direction of this vector field results in a strain field for these two directions (Eqn. 1).

$$\varepsilon_x(x,y) = \frac{\partial u_x(x,y)}{\partial x}, \qquad \varepsilon_y(x,y) = \frac{\partial u_y(x,y)}{\partial y} \tag{1}$$

Where $u_x(x,y)$ and $u_y(x,y)$ represents the displacement in x- and y-direction at a given point (x,y), and $\varepsilon_x(x,y)$ and $\varepsilon_y(x,y)$ represents the strain values. For small deformations (ε smaller than 0,1) these values are in fact strain values. In our investigations the deformations usually did not exceed this criterion. During the deformation the cell walls should not rotate or tilt because this will be interpreted as additional strain in the effected areas. This problem is verified by a 3D reconstruction of the foam surface at different load states that enables a detection and also a correction of such cell wall rotating or tilting. Fig. 3 shows an example of a calculated digital elevation model of a foam surface, which contains a few cells in front of a notch root. The accuracy of this method for strain determination is about ±0,005 (±0,5 %) in absolute strain value. The resulting displacement field contains 30000 to 200000 measurement points depending on the resolution of the used images.

RESULTS

Fracture tests

Only for large (W>100 mm) ALULIGHT foam specimens the condition $F_{max}/F_Q<1,1$ according to ASTM E399 is fulfilled (see Fig. 2). In general no valid K_{IC}-values were obtained. Therefore J-integral tests were performed on the ALPORAS foams. For ALULIGHT foams a comprehensive work on fracture toughness has been done in [9].

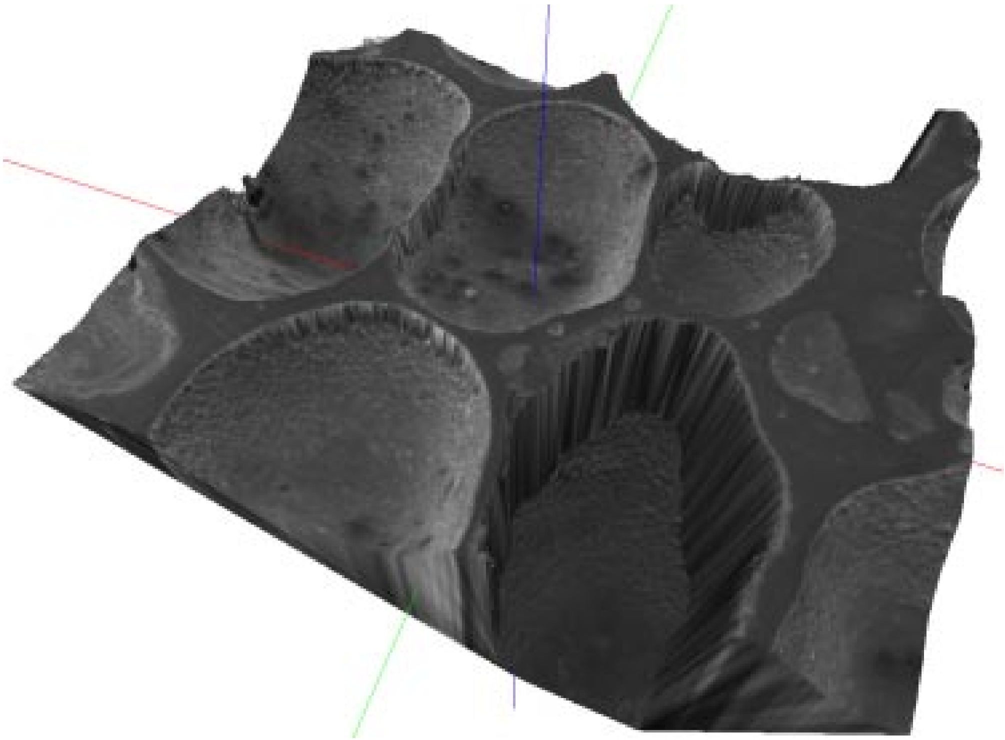

Figure 3: Digital elevation model with about 200000 points of a foam surface in front of the notch root.

The ALPORAS foams show in the load versus load line displacement curve only a small “linear elastic” regime followed by a large plastic regime (see Fig. 2, left side). After the maximum load a decreasing of the load can be observed whereby the rate of the load drop depends on the density of the foam. In contrast to the region of increasing load in the load-displacement curve, which is very “smooth”, the region of decreasing load shows a certain waviness. The shape of the load versus load line displacement curve doesn’t change significantly with varying the specimen size. Also with the largest CT-specimens (W≈300 mm) it is impossible to obtain valid K_{IC} values. The crack extension curve shows already in a very early stage a significant rise and also a certain waviness at larger crack extensions.

Fig. 4 shows the calculated J vs. Δa curves according to ASTM E1152 standard for ALPORAS foams with two different densities. The shape of these curves differs significantly from those of conventional metals. In the region of small crack extensions where the initial J-values were determined the J vs. Δa curve behaves sometimes very unusual (Fig. 4 is an unusual nice curve). Therefore the calculation of the $J_{0,2}$ values is occasionally problematic and a large scatter of these values can be observed. Maybe the $J_{0,2}$ determination according to the ASTM standards is not useful for ductile metal foams and other evaluation methods should be considered. An other interesting feature of the J vs. Δa curve is the drop of J at larger crack extensions, which is visible in Fig. 4 for foams with lower densities. The determination of $J_{0,2}$ gives values ranging from 0,1 to 1,0 kN/m depending mainly on the density of the foam. For example, the specimens from Fig. 4 deliver $J_{0,2}$ values of 0,63 kN/m for the density of 0,49 g/cm^3 and 0,27 kN/m for the density of 0,25 g/cm^3.

An other way to describe the fracture behavior is to plot crack resistance vs. crack extension (R-curve concept). Fig. 5 shows such K_R vs. Δa plots from the two foams, which are also depicted in Fig. 4. The crack resistance K_R is expressed in terms of the stress intensity K. This is problematic because the stress intensity concept is in this case not valid but the obtained curves show some features that can also be found by other investigation methods. The first stage of the K_R vs. Δa curve shows an increasing crack resistance with increasing crack extension maybe due to building of the crack flanks. In the region of larger crack extensions a significant drop in K_R can be observed, especially in the foams with lower densities. This phenomenon is discussed later.

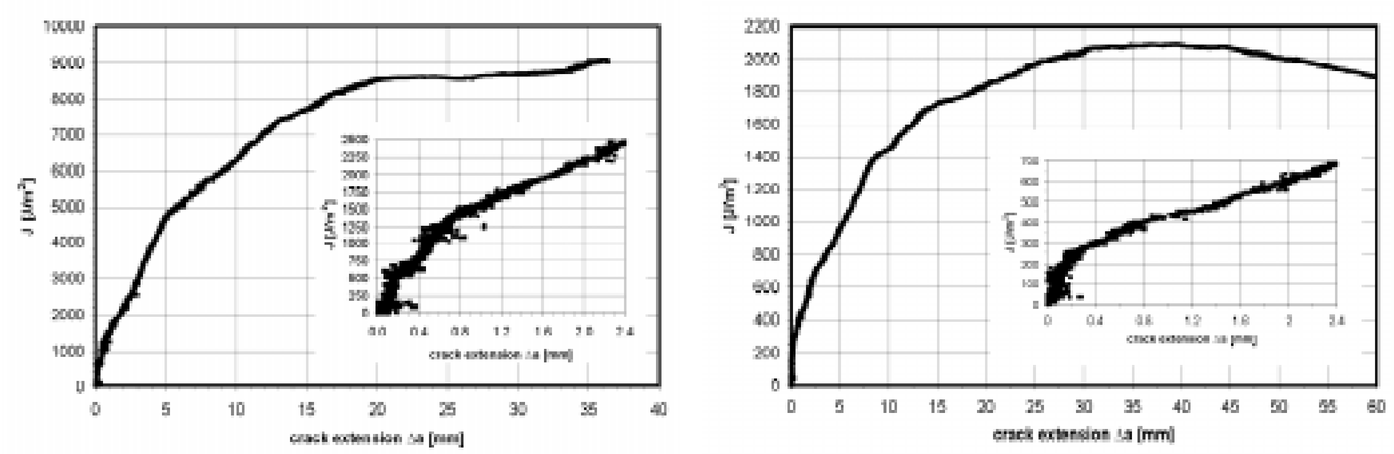

Figure 4: J vs. Δa curves of ALPORAS foam CT-specimens (W=290 mm) with two different densities (0,49 g/cm^3 on the left side and 0,25 g/cm^3 on the right side).

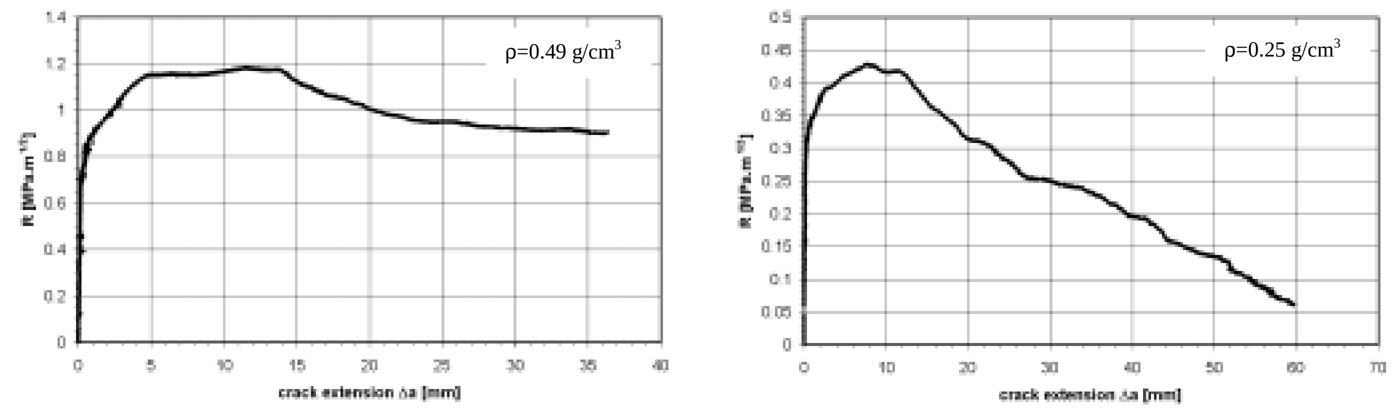

Figure 5: K_R vs. Δa curves of ALPORAS foam CT-specimens (W=290 mm) with two different densities (same specimens as shown in Fig. 4).

In-situ experiments

In order to investigate crack initiation, crack propagation and local deformations in the vicinity of the crack tip in-situ experiments were performed. Fig. 6 shows SEM micrographs from the foam surface (ALPORAS foam, ρ=0,25 g/cm^3) in front of the notch root at different load states. In micrograph (1) one can see the initial cell structure of the investigated area. At approx. 80% of the maximum load crack initiation at the notch root takes place in the ALPORAS foams, which is visible in micrograph (2). In the region of the maximum load the crack is propagated about ¼ of the cell size and some “micro” cracks are formed in the neighborhood of the crack tip, which can be seen in micrograph (3). Micrograph (4) shows the crack in the region of decreasing load. The crack is now propagated nearly through the first cell wall. Several additional cracks are initiated or are grown at this state. Finally, micrograph (5) shows the foam surface in a lower magnification at a later state where the crack is propagated up to several cell sizes. All important features of the cracking process like additional cracks in the vicinity of the crack tip, change of the crack path and crack bridges can be seen.

To identify size and shape of the plastic zone and the fracture process zone the in-situ experiments were combined with local deformation measurements. Fig. 7 shows as example the result of these measurements of two different cells. The first cell (upper image in Fig. 7) is located in front of the notch root, whereby the second cell (lower image in Fig. 7) is located in the center of the ligament. The deformation measurements were made between the initial state and the deformation state at crack initiation at the notch root. From deformation analysis of the first cell it is evident that the deformation in front of the notch is very localized. Only a small area of the cell wall is strained up to approx. 20%, whereby the rest of the wall remains nearly undeformed. With further loading the initiated crack will propagate into this high-strained areas. In the second cell, which is far away from the notch root, a certain strain localization can be observed too, but not so extreme as in the first wall in front of the notch root. It is a general feature that the deformation is very localized to some cell walls and there into some parts of the walls.

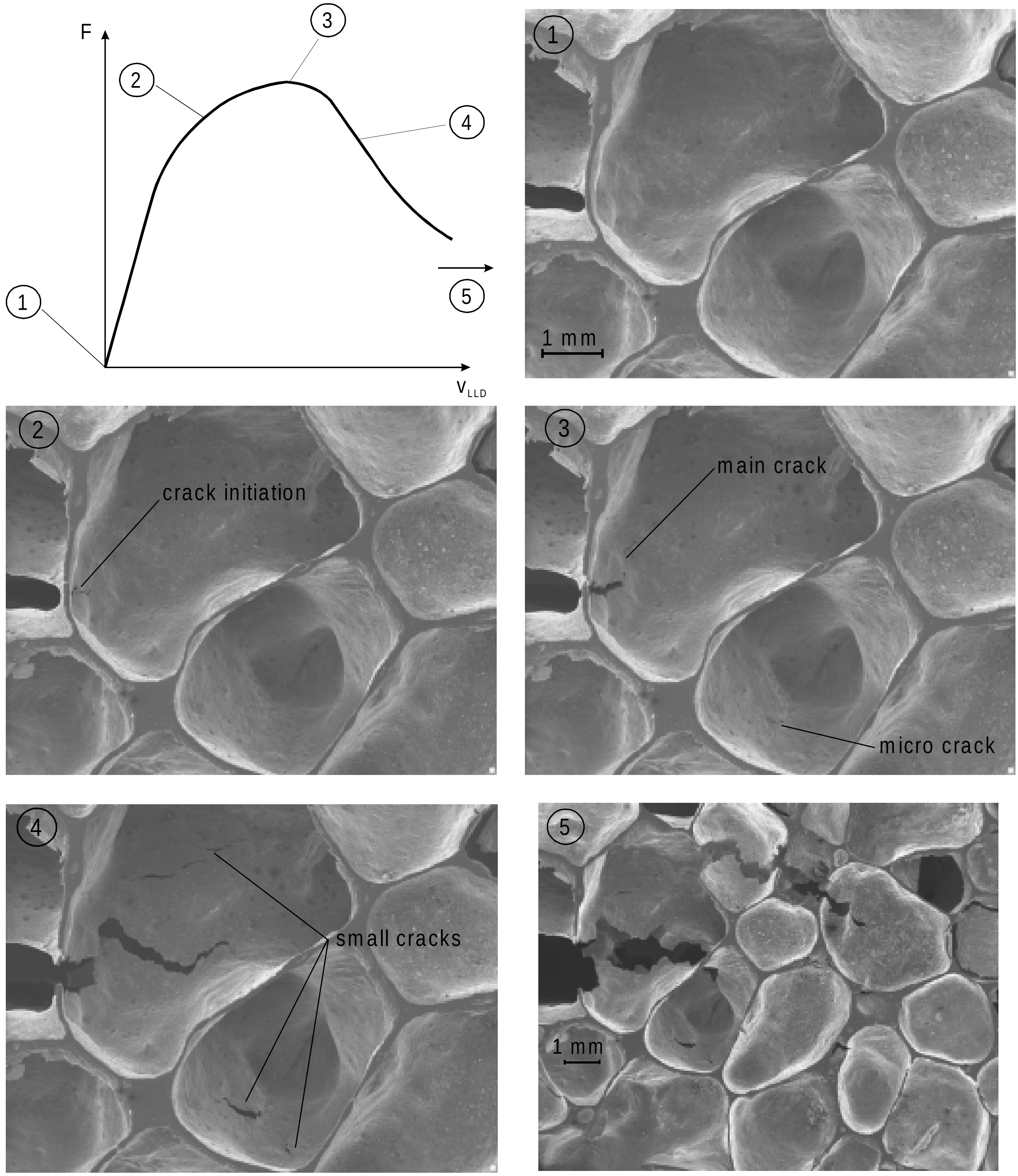

Figure 6: Schematic load vs. load line displacement curve with loads marked from these SEM micrographs were taken. ALPORAS foam, W=50 mm, ρ=0,25 g/cm^3, description see text.

DISCUSSION

A closer look on the load vs. load line displacement curve (Fig. 2) gives some information about the fracture processes: For ALPORAS foams only a small region of linear elastic deformation can be observed. In this stage no crack extension is measured by the potential drop technique (region I in Fig. 2 on the left side). The linear elastic region is followed by a region of plastic deformation. In the first part of this region up to

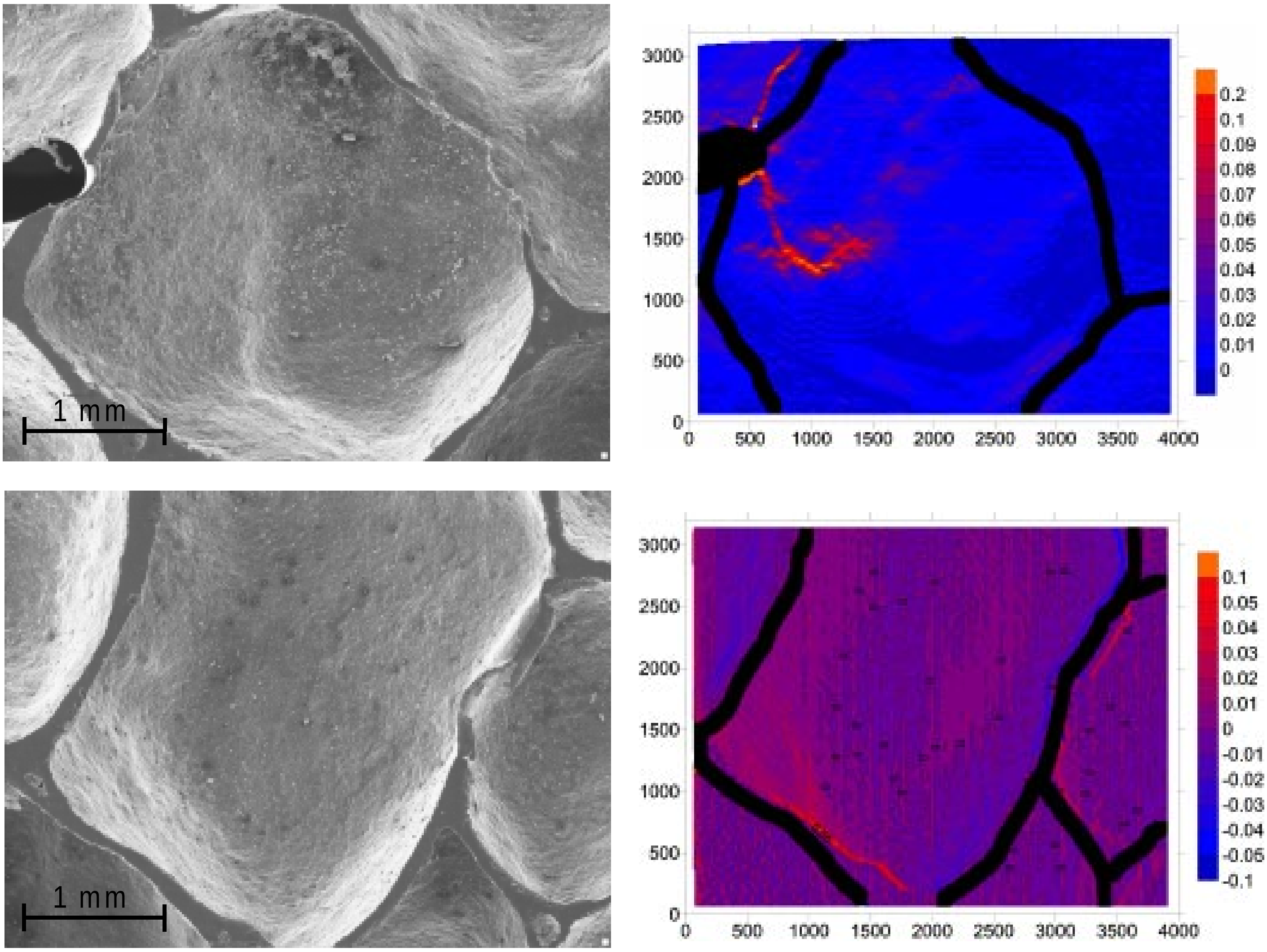

Figure 7: Measured local deformations at crack initiation in the first cell wall in front of the notch root (first row) in loading direction and in a cell in the center of the ligament (second row) perpenticular to the loading direction. 4000 pixels are equivalent to 3.3 mm.

about 80% of the maximum load, F_{max}, a small crack extension is observed (region II in Fig. 2). This crack extension is caused by local plastic deformation and micro cracking of some cell walls. After 80% of F_{max} crack initiation at the notch root takes place and the measured crack extension rate increases (region III in Fig. 2). In the region of decreasing load a certain “waviness” of the load vs. displacement curve is evident. At the state of crack initiation there exists a straight crack front due to the straight notch root. But with crack propagation the crack advances in thinner cell walls, which have a lower crack resistance [10] and the crack front becomes irregular. As result the crack front hits regions in the foam structure that have a larger crack resistance and an additional load is required to advance through this regions. After passing these areas the crack can propagate in regions of lower crack resistance again and a small load drop occurs. These effects explain the “waviness” of the load curve and the J-Δa curve. At crack initiation similar things happen: Due to the different thickness of the cell walls (typically 50 to 200 µm) in front of the notch root these walls have different fracture toughness values. So the crack initiation will not take place in all cell walls simultaneously but will start at the thinner walls. This effect does not yield to a single significant kink in the J-Δa curve in the region of small crack extensions, which is associated with the crack initiation. Two or more of such kinks may be visible that complicates the determination of initial J-values according to the ASTM standards. Maybe a new way for the evaluation of “initial” J-values for ductile metal foams should be found.

The deformation of the foam structure is very localized into some cells, which can be seen in Fig. 7. The heavy plastic deformed region in front of the crack tip in single cell walls is in the order of 1 mm. But the fracture process or damaging zone is much larger and cover after a certain (relatively small) load the whole ligament. It is evident that the crack propagates through the previous damaged cell walls. So after a certain crack extension the mechanical properties and the crack resistance of the foam in the whole ligament are changed. Due to this localization of the deformation and therefore damaging of the foam the crack resistance can decrease with increasing crack extension. This is maybe an explanation for the drop in the K_R vs. Δa (Fig. 5) and J vs. Δa (Fig. 4) curves. But further investigations are needed to verify this behaviour.

CONCLUSION

Standard fracture test were carried out on ALULIGHT and ALPORAS aluminium foams with different densities and specimen sizes to examine fracture behaviour. Additionally in-situ fracture tests in the scanning electron microscope and the optical stereomicroscope were performed to investigate the local fracture process in the foam structure. For the ALPORAS foams no valid K_{IC} values were obtained, therefore J-integral test were performed. The results for the $J_{0,2}$ values were in the range from 0,1 kN/m to 1,0 kN/m depending mainly on the relative density. But due to the inhomogeneous foam structure the determination of the $J_{0,2}$ values according to the ASTM standards were difficult and a large scatter of the obtained values were observed. The in-situ experiments revealed a very localized deformation in the cell structure that results in a damaging of the foam. This damaging may reduce the crack growth resistance, which can be seen in the K_R vs. Δa and J vs. Δa curves. Further investigations are needed to describe the damaging and the influence on the fracture behaviour.

ACKNOWLEDGEMENTS

The financial support by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung and of the Österreichischen Nationalbankfonds (Project P13231PHY/FWF535) is gratefully acknowledged.

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