AlVis - An Aluminium-Foam Visualization and Investigation Tool

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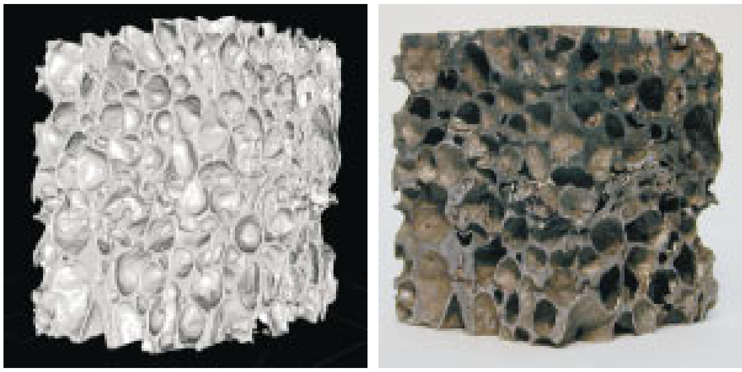

Fig. 1. Comparison of visualization (left hand side) and reality

Abstract. In recent years there has been an increased interest in metal foams in the field of material science. The stress absorbing potential is one of the most interesting properties for the application of aluminium foam (e.g. car manufacturing). Material scientists need to investigate the structure of metal foams in order to optimize their deformation behavior. An interactive tool for the investigation is presented in this work. Real-time surface rendering, automatic parameter determination, and display of local and global foam properties enable the user to understand the complex structure of the metal foam.

Keywords: aluminum foam investigation, surface extraction

1 Introduction

In recent years there has been a continuous increase in interest for metallic foams. Foams based on aluminium provide a number of advantages over solid materials: low specific weight, high specific rigidity, high energy-absorbing potential, reduced conductibility of sound and heat, non-combustibility, and the ability to be recycled. Metallic foams can be compacted at a relatively constant stress level which qualifies them for energy absorption applications (e.g. car manufacturing). Their mechanical behaviour is influenced by imperfections caused by the foaming process. Spatial variations in the foam cell-size distribution[1] and imperfect cell wall geometries are studied as examples for such imperfections. Small samples (about $2 \times 2 \times 2$cm) are deformed in a repetitive way. Pressure is applied to the sample in one direction, until cells start deforming and the sample loses some small amount of length in this direction. Then the deformation characteristics of the sample is investigated. This procedure is repeated until all the cells are entirely collapsed and the sample is completely compacted. In order to aid these investigations, a tool is needed, which allows the non-destructive investigation of samples during the single steps of the deformation procedure. The next section discusses the demands material scientist expect such a tool to meet.

2 Requirements for the investigation of aluminium foam

The demands for the investigation of aluminium foam risen by material science experts are manifold. Due to the repetitive nature of the investigation of deformation results, the foam sample must not be destroyed for the investigation. Thus, cutting techniques cannot be employed. The approach presented in this work utilizes a non-immersive way of gathering information about the local properties of the foam sample: The sample is scanned with the usage of a computer tomograph (CT) modality. Whereas medical CT modalities are limited in terms of scanning resolution (due to the radiation harm for the patient), industrial CT scanners feature resolutions of about 0.04mm.

The visualization of the scanned volumetric data sets shows the requirements of classical volume visualization problems as well as special demands:

- **Interactivity**: As the investigation procedure includes zooming in on different cells of interest, an interactive visualization approach is crucial. The manipulation of the viewpoint (movement of the camera) as well as manipulations of the data set (cutting planes, etc.) should be possible with interactive frame rates.
- **Accuracy**: As the relation of cell size to wall thickness is of interest to the investigation, high accuracy has to be ensured. The visualization should represent the the structure and topology of the real sample as accurately as possible (with respect to the limitations of the scanning procedure).
- **Measurements**: Tools for investigating the size of cell features have to be provided.

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[1] The field of computer graphics often refers to the term *cell* as a sub-cubiod of a volume data set with eight data values at its corners. In the field of metal foam research the term cell refers to the air filled bubbles within the solid material. In the presented work the term cell is used in the later meaning.

- **Shape criteria**: Different metrics for the description of cell characteristics are needed.
- **Statistical evaluations**: Besides the investigation of local cell properties, also information about global foam sample properties and the entirety of cells is desirable. Visual aids for the user to distinguish between regions of the foam sample with different characteristics should be provided.

Existing commercial as well as academic visualization systems cannot be employed for the investigation task. Due to the high spatial resolution of the CT scanners, data sets of enormous size are generated. Existing systems are not capable of rendering these data sets in real-time. Furthermore the display of special properties of foam cells as required by the cooperating material scientists (like shape and size criteria) is not supported by existing systems.

The approaches employed in AlVis to deal with these requirements are described in the following sections.

3 Interactive Rendering

In order to meet the requirements of interactive rendering, a surface shaded display approach is used. Modern hardware graphics accelerators are capable of rendering large amounts of polygons in real-time frame rates. The OpenGL [5] graphics library is employed to generate the visualization.

The segmentation of the volume data set into a surface representation is done with the aid of an isosurface extraction approach. The well known *Marching Cubes* [2] method is utilized. To overcome the drawbacks of ambiguity artifacts [3, 6] an approach by Montani [4] is used.

Three problems have to be overcome with the usage of isosurface extraction: First, a suitable threshold for the surface generation has to be defined. In order to allow the display of foam cell properties, individual cells are identified. Then a way of dealing with the huge number of generated triangles has to be found.

3.1 Threshold definition

The aluminium/air boundary in the sample is represented by a highly wrinkled convoluted surface due to the high frequency nature of the data. Isosurfaces as used in medical visualization applications are usually smoother. For the presented application the specification of an appropriate threshold is crucial in order to meet the accuracy requirements of the investigation procedure. The threshold has to be chosen in a way such that the volume of the foam sample is preserved. Errors in threshold definition have a cubical influence to the volume of foam cells. A rough approximation of a cell is a sphere. A small change in threshold changes the radius of the sphere. This change has a cubical influence on the volume of the sphere. The appropriate threshold for the extraction of the aluminium/air boundary is dependent on the type of modality and external influences. For these reasons, the utilized threshold has to be adaptively derived for every sample to be investigated.

The following procedure yields the optimal threshold:

- The real sample is weighted using high precision scales. Let W_{S} be the weight of the sample.
- The specific weight of aluminium is known: W_{Al} is 2.7kg/dm^3 (2.7g/cm^3)
- The volume of aluminium in the sample resolves to $V_{\text{Al}} = \frac{W_{\text{S}}}{W_{\text{Al}}}$
- The volume of the sample cuboid can be calculated using the measured dimensions of the sample: $V_{\text{S}} = x_{\text{S}} * y_{\text{S}} * z_{\text{S}}$
- The ratio R of aluminium to air in the sample resolves to:

  $$R = \frac{V_{\text{Al}}}{V_{\text{S}}}$$

- Given the histogram of the volume data set $H = \{h_0, \ldots, h_{\text{max}}\}, h_x = |\{v|\text{value}(v) = x\}|$, R_t is calculated as

  $$R_t = \frac{\sum_{i=t}^{\text{max}} h_i * i}{\sum_{i=0}^{\text{max}} h_i * i}$$

  R_t describes the ratio of aluminium to air in case t is selected as threshold. Selecting the threshold t so that $R_t \leq R \leq R_{t-1}$ guarantees that the apparent volume in the computed sample closely corresponds to the real world sample. This is very important as the lacunarity (size and distribution of foam cells) is crucial for judging structural characteristics.

Visual comparisons and spatial relation measurements on the real sample as well as in the geometry representation of the visualized sample have affirmed the validity of the derived threshold (see Figure 1).

3.2 Foam cell identification

Before the isosurface is extracted, single cells are identified. The volume data set is interpreted as a binary image, separated into voxels having lower or higher values than the threshold derived in the last section. A *two-pass labeling* approach yields the number of distinct foam cells as well as the different sets of voxels contributing to the single cells. Based on this information, the isosurface is extracted on a cell by cell basis. The generated triangles are stored indexed with accordance to the cell they represent. Special care is taken about additional closing triangles at the cut up faces of the foam sample.

3.3 Rendering acceleration

The extraction of the isosurface from the volume data set yields an enormous number of triangles. Even for up to date hardware rendering accelerators, special strategies have to be employed in order to provide real-time frame rates.

Two cases have to be distinguished for rendering: The viewpoint might be inside the boundaries of the foam sample, investigating inner cell structures. It might also be outside the sample, when the user wants to gain an overview of cell size and shape distribution.

The viewpoint will be most of the time during the examination inside the cave-like structure of the foam. As the maximal viewing distance is very restricted, only a small part of the geometry data is visible. A special subdivision scheme is applied for rendering. Similar to the proposals of other authors [1, 7] a regular partitioning of the display geometry is employed. The volume data set is subdivided into sub-cuboids of user defined size. These subregions are called *macrocubes*. The surface portions generated during the marching cubes procedure are stored separately for each macrocube in an optimized OpenGL triangle-strip data-structure. The rendering procedure employs an progressive approach:

- **Interactive phase**: As long as the user moves the viewpoint, the rendering budget is limited by the performance of the used graphics hardware. A limited set of macrocubes within the viewing frustum is determined. This set is rendered front to back, until no more time for this frame is available (see figure 2, left hand side). Thus the maximal amount of information for real time frame rates is rendered.
- **Completion phase**: When the user stops moving the camera, more rendering time can be invested. The OpenGL z-buffer is checked for regions, where no triangles have been rendered possibly due to not yet rendered macrocubes. Using the camera location and direction, the according set of macrocubes is derived, which is rendered front to back, either until the z-buffer is completely covered with triangles or until no more macrocubes inside the viewing frustum are left to render. The later case might emerge, if the user has positioned the camera facing from within an open cell to the outside of the sample.

Un-filled z-buffer regions can only emerge in situations, when the camera faces structures of connected foam cells, which tunnel into the depth of the visualization. This happens rarely during the investigation. Usually just the interactive phase has to be performed.

When the camera is outside the limits of the data set (to gain an overview of the entire foam sample), the macrocubes rendered in the interactive step are those that lie in the three faces of the data set facing the camera.

In addition to the gain of rendering speed, the usage of macrocubes has an additional benefit. When the triangle sets of different macrocubes are colored individually, the size of foam cells can be quickly visually derived by the user. Due to the usage of perspective rendering the perception of depth also gains a lot by the different size of near and far macrocubes (see figure 2, right hand side).

4 Measurements

The size of foam cells is one of the most important properties for the investigating material scientists. The size of cells in relation to the thickness of the surrounding walls is characteristic for the deformation behaviour. In order to allow spatial measurements a metaphor based on the analogy of a rubber band (elastic) has been integrated. Figure 5 (color-plate section) shows the usage of this tool for the determination of the diameter of a very small foam cell. The length of the rubber band being manipulated by the user is displayed in real time.

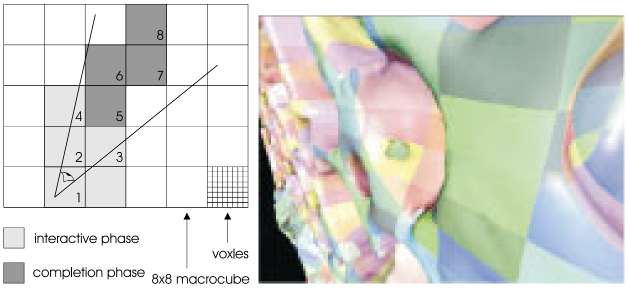

Fig. 2. Left: The rendering subdivision scheme using macrocubes. In the interactive phase, macrocubes 1-4 are rendered. In the completion phase, macrocubes 5-8 are rendered in order to patch an un-filled region. Right: Individually colored macrocubes allow a quick perception of feature size and depth information. The size of one macrocube in this image is $0.32 \times 0.32 \times 0.32$mm.

5 Focused Views

Occlusion problems, which cannot be dealt with using cutting planes, have to be solved with special techniques. In order to extract the important visual information, an approach well established in the field of information visualization is employed: *Focused Views*. Not the entire foam sample is rendered, but only cells which meet certain criteria. Additionally, colors can be used to illustrate criteria characteristics of certain cells. Figure 6 (color-plate section) demonstrates the usage of a simple focused view, where only cells in the inner part of the sample are rendered. This allows the material scientist to gain an overview on the size and shape distribution of cells, which determines the inner stiffness of the aluminium foam. Useful criteria to restrict the rendered information include the size and the shape of single cells. These criteria are discussed in detail in the following sections.

5.1 Cell size

The evaluation of cell size as a focus criterion is straight forward. The number of voxels enclosed by the cell is a feasible approximation to the volume of a cell. The user is free to specify an interval of cell volumes to be rendered. Figure 3 shows the application for small and large cells. It is convenient to allow the specification of the restriction in absolute (e.g. “smaller than 7mm^3”) or relative numbers (e.g. “larger than 80% of the cells”).

5.2 Cell shape

One of the requirements of the investigation of the foam sample was the determination of the shape of the foam cells. The uniformity of cells guarantees an optimal stress absorbance potential. A metric for the judgement of cell topologies is defined. The desirable shape of a foam cell is a sphere. A shape criterion f based on the comparison

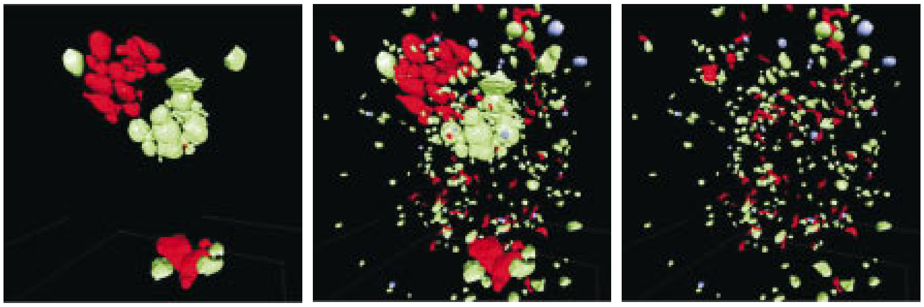

Fig. 3. Focused view based on size of cells (left: largest 10% of all foam cells, right: smallest 20%, middle: both)

of the cell shape to a sphere can be defined as follows: Let B be the set of voxels, which are enclosed by the surface of a certain cell C. $B = \{v_i | v_i \text{ inside cell } C, i = 0 \ldots n-1\}$ Let $\mathbf{M}$ be the center of mass of B:

$$\mathbf{M} = \frac{1}{n} \sum_{i=0}^{n-1} \textbf{location}(v_i)$$

A distance function evaluates the absolute distance of certain voxels to the center of mass:

$$\text{distance}(v_i) = |\textbf{location}(v_i) - \mathbf{M}|$$

The average distance D_{avg} evaluates to:

$$D_{\text{avg}} = \frac{1}{n} \sum_{i=0}^{n-1} \text{distance}(v_i)$$

Two different shape characteristics are of interest to material scientists investigating aluminium foam:

- foam cells closely resembling spheres, only having a small number of high frequency outlying peaks
- foam cells deviating from the shape of a sphere by a lot of minor dents and bumps

Figure 4 gives a graphical representation of these two cell types. Material scientists want to investigate, if one of these common cell types is responsible for high cell collapsibility during the deformation process. Now two different criteria for the cell can be calculated: the average and the maximal distance of voxels to the center of mass:

$$f_{\text{max}} = \max_{i=0..n-1} |\text{distance}(v_i) - D_{\text{avg}}|$$

$$f_{\text{avg}} = \frac{1}{n} \sum_{i=0}^{n-1} |\text{distance}(v_i) - D_{\text{avg}}|$$

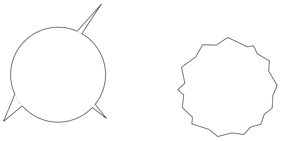

Fig. 4. Cells closely resembling spheres although having single peak-like deformations (left hand side) feature high f_{max} and low f_{avg} values. Cells with a lot of minor dents and bumps (right hand side) vice-versa.

It is convenient to have these absolute f_{max} and f_{avg} criteria scaled to relative values on the basis of all cells in the foam sample. Furthermore the two values can be combined into a weighted sum for the ease of user interaction. The specification of the weights w_{max} and w_{avg} decides which kind of shape anomaly shall be emphasized or ignored when a focused view is applied.

$$f = w_{\text{max}} \frac{f_{\text{max}}}{m_{\text{max}}} + w_{\text{avg}} \frac{f_{\text{avg}}}{m_{\text{avg}}}$$

where m_{max} (respectively m_{avg}) is the maximal value of f_{max} (respectively f_{avg}) for all cells of the sample. Using this approach is is for instance possible for the user to have all cells with an shape criterion f in the best percentile displayed by focusing the view to cells with $f < 0.10$. If cells deviating with single peaks from the shape of a sphere are of interest, w_{max} should be assigned a high value, whereas if w_{avg} is emphasized, cells with a lot of minor deviations are favored.

6 Results

The presented approach was implemented using Microsoft Visual C++ (Developer Studio ver. 6.0), MS Windows NT 4.0. AlVis was tested on an Intel PIII based system (450 MHz, 512 MB RAM, 3DLabs Oxygen GVX1 graphics accelerator). The data set used to generate the results presented in the work featured the characteristics shown in table 1. High resolution images of the results presented in this work are to be found on the WWW:
`http://www.cg.tuwien.ac.at/research/vis/Miscellaneous/alufoam`.
The presented system has been developed in cooperation with a group of material scientists. User studies involving four aluminium foam experts and three different data sets (each with a number of deformed versions) were made. Permanent feedback during the development has assured that the possibilities of the system meet the requirements of the experts. Interactivity has shown to be the most crucial point for daily work. Only the usage of the presented focused views techniques enabled the quick perception of local and global homogeneity properties of the foam structure. As a first research result AlVis has already enabled the material scientists to distinguish different classes of foam cells, which might help to optimize the deformation behaviour of the foam.

size of sample	22.3 × 22.0 × 30.0mm (14.718 cm^3)	relative weight of sample	0.499g/cm^3
weight of sample	7,43 g	fill ratio	18.5%
scanner resolution	0.04 × 0.04 × 0.04mm	value of aluminium	220
data value resolution	8 bit	optimal threshold	35
data set resolution	626 × 626 × 760	# generated triangles	9112628
size of data set	298 MByte	# triangles per voxel	0.04
scanning time	5 hours 37 minutes	# ambiguity cases	11077 (0.04%)
		macrocube size	8 × 8 × 8 voxel
		# identified cells	1150

Table 1. The statistics at the left hand side of the table were known before the investigation. Values at the right hand side were determined by the system.

7 Conclusions and Future Work

In close cooperation with material scientists a system for the investigation of aluminium foam has been developed. Between iterated steps of deformation CT scans of a foam sample are acquired. Due to the highly complex and wrinkled structure of the aluminium/air boundary, the visualization of these data sets is difficult. As high accuracy is necessary, the threshold value for the employed isosurfacing technique has to be volume preserving. It is derived using the weight and size of the real sample. Due to the structure of the foam, enormous amounts of triangles have to be rendered. A sub-division scheme utilizing macrocubes guarantees real-time frame-rates. In order to aid the investigation task, statistical properties of individual foam cells can be displayed. Focused views enable the user to restrict rendering to cells with certain size and shape criteria. User studies with material science experts proved the usefulness of the integrated tools. As a first research result, certain types of foam cells have been identified, which might influence the deformation behaviour of the aluminium foam.

As future work the system will be extended to handle multiple data sets resulting from the different steps of the deformation analysis. Animating the changes of foam cell size and geometry will yield in deeper insights to the complex relation of foam structure and deformation behaviour.

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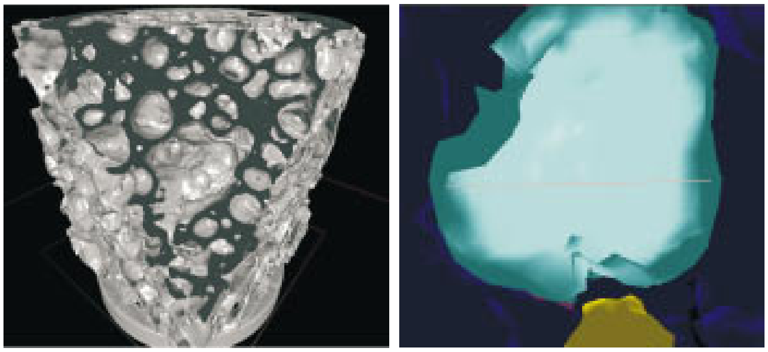

Fig. 5. Left hand side: Sample with cut-away part. Right hand side: Distance measuring metaphor. The current length of the rubber band is 0.6mm.

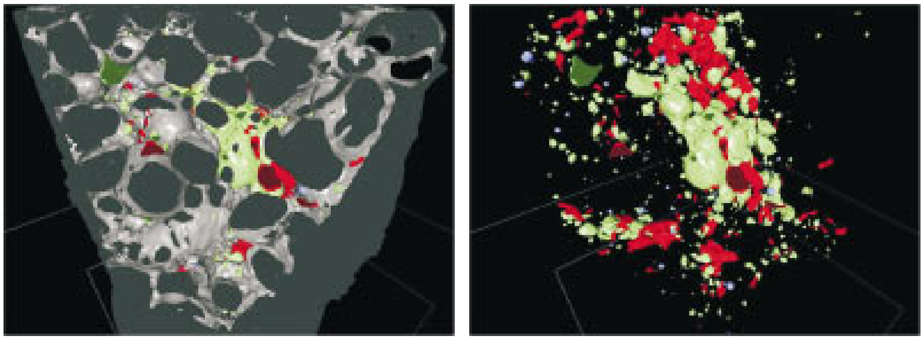

Fig. 6. Application of a cutting plane (left hand side). Focusing (right hand side) renders only cells, which are not cut open by the faces of the sample. Colors indicate the shape factor of cells.

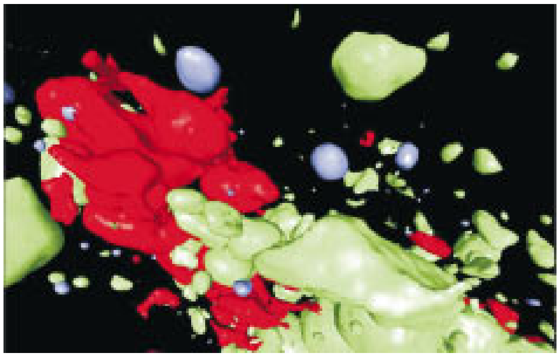

Fig. 7. Focused view based on shape of cells. Blue cells: close to the shape of a sphere, small value of f; green: medium value of f; red: large value of f.