ANALYSIS AND EXPLORATION OF CT-DATA USING APPLICATION SPECIFIC MULTI-DIMENSIONAL TRANSFER FUNCTIONS

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Abstract

In this paper an analysis chain is presented, that builds on an interactive, visualisation-driven approach for the examination of the object under investigation. In this way, the domain expert can easily adopt the procedure to changing conditions of the analysis task or the acquisition and reconstruction of the CT-data investigated.

A visualisation-driven approach offers the advantage that the expert user can control which features to include in the analysis. To implement such a procedure multi-dimensional transfer functions were chosen for the exploration step. New application specific multi-dimensional transfer functions are applied to efficiently analyse and quantify specific features in a given sample volume.

In two application scenarios the novel workflow using the analysis chain is shown. The first scenario deals with the orientations of fibres in Steel Fibre Reinforced Sprayed Concrete (SFRSpC). The orientations of the steel fibres and their distribution, depending on the concrete's application direction, are analysed and quantified. This is a crucial step in assessing the material's behaviour under mechanical stress, which is still in its infancy and therefore an important topic to building industry.

The second application scenario is the designation of the microstructure of ductile cast irons with respect to the contained graphite. This corresponds to the requirements of the ISO standard 945-1, which deals with 2D metallographic samples. We illustrate how the necessary analysis steps can be conducted efficiently using the analysis chain for 3D volumes.

Overall, we show that a visual approach with custom transfer functions in specific application domains offers significant benefits and has the potential of greatly improving and optimizing the workflows of domain scientists and engineers.

1. Introduction

The rapidly increasing use of x-ray computed tomography (CT) in non-destructive testing (NDT) for numerous technical applications has increased the need for specific analysis of CT-data. Based on two specific application scenarios a new concept for a visualisation-driven approach for the analysis of a given CT data set with respect to certain properties is introduced.

Today the most widely used approach for the visualization of volume-data is "Direct Volume Rendering" (DVR) which uses the whole volume for image generation [1]. A quadruple of (r, g, b, α) is assigned to each position in the volume, where α corresponds to the opacity and r, g, b give the color of one voxel. One-dimensional transfer functions where color and opacity are assigned on the basis of the local density value (grey value) are the most widely used transfer functions. With this approach all positions in a volume with the same density are represented in the same way and material boundaries such as pores or inclusions cannot be addressed directly.

This leads to the standard approach of feature detection which is usually performed via some type of segmentation, which most commonly builds on region-growing and filtering operations such as morphological operators. Segmentation results in one or several static segmentation masks, which can be visualized as part of the 3D volume and also form the basis of quantification. The segmentation cannot be modified without re-computation. This decouples the detection of features from visualization and prevents working in a fully interactive manner. Most of all, it hampers interactive exploration of the volume without knowing what features are contained in the volume beforehand. Whenever the segmentation results for specified parameters are not satisfactory, the user has to modify the parameters and the entire segmentation has to be computed all over again. This is often time-consuming and tedious. Unlike this standard approach we propose a visualization-driven method for feature detection allowing features in the volume to be explored interactively without re-computing the segmentation [2].

2. Visualisation-Driven Concept

The basis for the application-specific approaches in this paper is a pipeline for interactive exploration and quantification of industrial CT data [2]. This pipeline employs an interactive, visualization-driven approach for feature detection, exploration, and quantification. This is made possible by pre-computing a family of feature segmentations over parameter domains instead of fixed parameter settings (Fig. 1, left). It is based on seeded region growing that is computed in multiple passes, where the main region growing parameter such as the density variance allowed in a region is successively increased from pass to pass. The resulting features and their changes are tracked and stored in compact form in an additional feature volume and feature size curves (Fig. 1, middle).
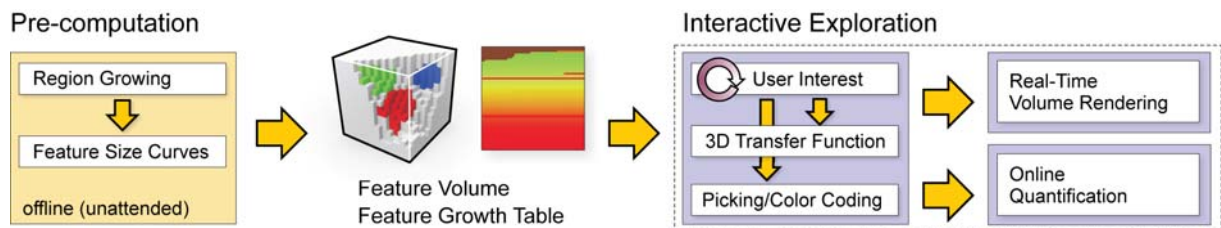

Fig. 1: Overview of the system-pipeline. The unattended pre-computation stage computes and stores all data needed for the subsequent interactive exploration stage.

The pre-computation has to be performed only once for a given data set and forms the basis of interactively exploring all contained features. When the pre-computed data is available, it can be explored interactively for features of interest in the exploration stage (Fig. 1, right). Originally, feature exploration builds on the specification of a 3D transfer function (TF) in the *(density, feature_size, time)* domain. For the presented application scenarios we transferred the *feature_size* parameter to the specific parameter spaces, like the orientation of the fibres or the roundness of particles (Fig. 2) [3]. TF specification is not only the means by which the

user determines the visualization, but also how features are selected to be quantified. During exploration, the current feature classification is displayed using real-time volume rendering (see e.g., Fig. 7b, Fig. 9b).

From the feature classification specified by the user during the interactive exploration phase, the quantification stage automatically computes statistical measures such as feature count, volume, and surface area for features that have been selected in the exploration stage. Additional, new visualization capabilities are invented to support quantification of the two applications outlined above (Fig. 2, right). That is, quantification is performed in a visualization-driven manner, where everything that is selected for feature visualization is included in the quantification. Performing quantification only for the feature classes found to be of interest during exploration, empowers the domain expert to interactively control the final result. Both feature exploration and quantification can be performed as often as desired without requiring additional pre-computation.
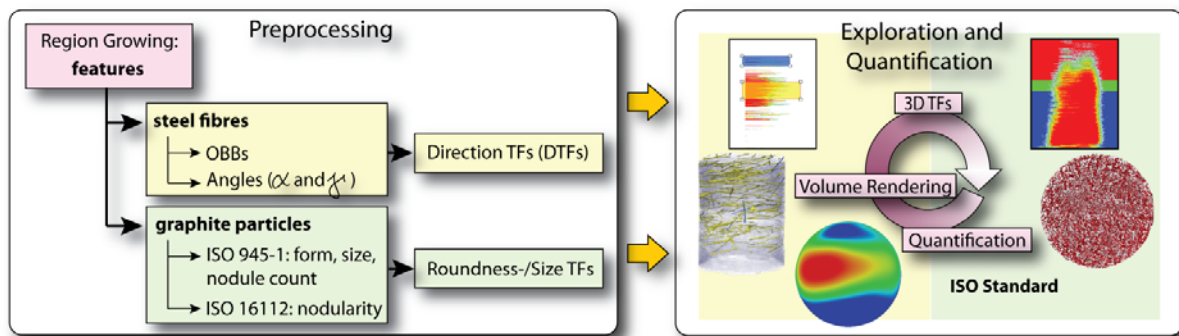

Fig. 2: The pipeline modified for the two application scenarios. During the automatic pre-computation phase, the specific calculations required for the two applications are performed (left). The TFs for the exploration phase are also generated. The user explores the features using the TFs in the specific parameter domains and controls the selection in the volume rendering view, the appropriate visualizations and quantification results.

3. Steel Fibre Reinforced Sprayed Concrete

Steel fibre reinforced sprayed concrete (SFRSpC) is a composite material that is widely used for various applications in geotechnics. It combines the high compressive strength of the sprayed concrete with strength after cracking through the addition of the steel fibres. That means that the material is brittle until a crack starts and subsequently maintains ductility through the steel fibres. Ideally, the steel fibres represent a continuous reinforcement if the fibres are distributed randomly and homogenously.

SFRSpC is used, when a quick application of a shell is needed as it is the case in geotechnics, where walls or rocks have to be secured avoiding the use of steel rod mats. In comparison to sprayed concrete the SFRSpC can endure higher displacements of the rock due to the quasi-ductility of the material. Furthermore, the characteristics of the SFRSpC increase the safety for the workers at the site, as cracks can be seen long before the failure of the material [4].

3.1 Background

The mechanical properties of SFRSpC are a well studied problem. Although the orientation and the distribution play a major role for these properties, it is difficult to evaluate these two critical parameters for SFRSpC. In a first attempt samples shall be checked for preferred orientations of the fibres. That would lead to a reduced ductility in directions with fewer

fibres than these special textured orientations. Therefore the goal is to identify prevailing characteristic orientations of the fibres in dependence of the application direction. Thus detecting a preferred texture of the wires with respect to the application direction.

Current guidelines for SFRSpC as the standard EN 14488-7 or EFNARC European Specification for Sprayed Concrete 1996 only estimate the total number of fibres in a sample of fresh or hardened concrete respectively. The given guidelines have no method to examine the orientation of the fibres.

The directions of the fibres are converted into two angles α and γ respectively. α is the angle between the x-axis of the coordinate system and the projection of the fibre in question in the xy-plane. γ is the angle between the z-axis of the coordinate system and the fibre in question (Fig. 3). To have a well defined orientation of all fibres it is necessary to only give the directions in one half of the Cartesian room or in one half of a sphere. A classification over α and γ respectively shows if some orientations are preferred.
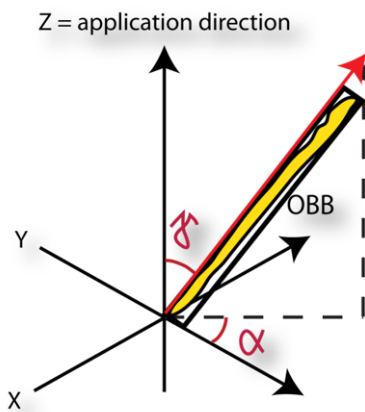

Fig. 3: Schematic representation of the features direction as the longest axis of the OBB (black rectangle) enclosing the fibre in question (yellow). The angles α and γ are the parameters that give the direction.

Fig. 4: One of the drill core samples of a tunnel lining used for the investigations.

The samples used were core samples of a sprayed concrete shell of a tunnel wall (Fig. 4). When drilling the cores the axis of the cylindrical sample was aligned with the surface normal of the inner tunnel wall. This direction can be assumed to be the direction in which the sprayed concrete has been applied. X- and y-axis are adopted from the CT-model's coordinate system.

For the SFRSpC samples it has to be assured that the resolution of the CT-model is good enough to identify the steel fibres, that have a high x-ray absorption compared to the concrete matrix. In that way a single fibre is detected as one feature and to prohibit the detection of fibre fragments that would cause the orientation tensor to be altered.

3.2 Data Acquisition and Manual Analysis

The samples were scanned on an x|argos CT of Phoenix|x-ray Systems and Services at the Austrian Foundry Research Institute. This tomograph uses a 320 kV x-ray tube. The x-ray images were recorded using a 5566 pixel line detector with 12 bit dynamic range. For the reconstruction a modified Feldkamp algorithm for the filtered backprojection as implemented

by the system supplier was used. The samples at hand were scanned at a voxel size of $(259 \ \mu m)^3$ per voxel.

For two samples a comparative manual analysis and quantification was conducted [5]. Therefore the CT data of the samples were used to sequentially process each steel fibre to evaluate the parameters needed. The data was used for statistical analysis and interpretation as well as for visualisation of the directions. The overall process in that manual approach took about 50 h for one sample. This was the driving force to apply a new visualisation-based approach.

3.3 Computation, Exploration, Analysis and Quantification

In the pre-processing phase the region growing step segments the features (steel fibres). For each feature an object oriented bounding box (OBB) is calculated using principal component analysis (PCA) [6]. PCA yields the three eigenvectors of the feature. Therefore the OBB approximates the arbitrary orientation of a fibre in 3D space, where the largest eigenvalue corresponds to the principal axis of the fibre. This direction is used for the calculation of the orientation properties α and γ as described above. Both angles are defined in an interval [0°, 180°], which covers all directions possible.

The results are used to calculate 3D histograms of the angles α and γ respectively over feature density and the region growing parameter, that indicate the number of voxels in the features. In these histograms the direction transfer functions (DTF) for the interactive exploration and quantification can be set by the user using widgets that define colour and opacity for a given set of feature voxels (Fig. 5). Another possibility for the visualisation of specific ranges of directions is the use of DTFs in a plot of γ versus α (Fig. 6).
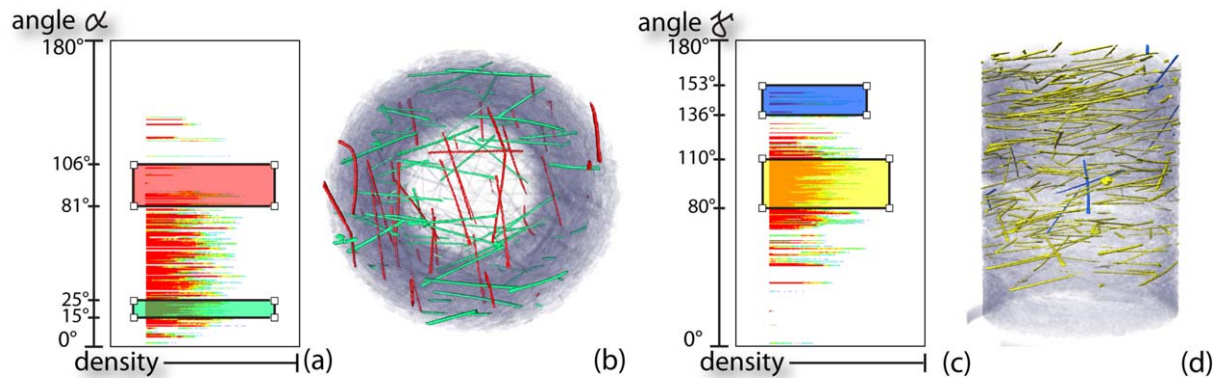

Fig. 5: DTFs for α (a) and γ (d), where the x-axis show the density and the y-axes show the angular distribution of the fibres. The 3D volumeview shows the fibres selected by the widgets in the DTFs for α (b) and γ (d).

The directions of the selected features are represented colour-coded on a direction sphere histogram (DSH) (Fig. 7a). This is a colour-coded visualisation of the distribution and frequency of the directions (α and γ) on a hemi-sphere. In that way preferred directions of the fibres can easily be identified.
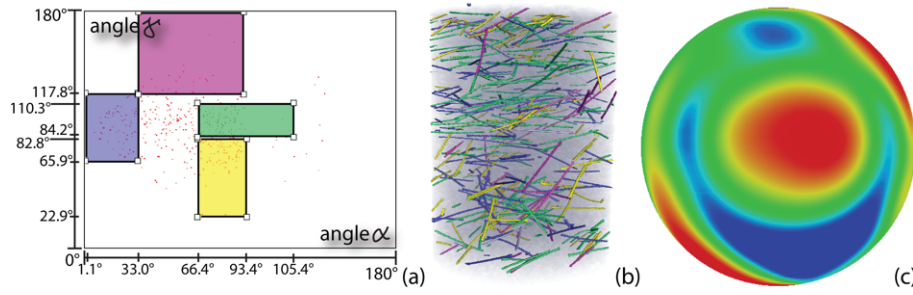
Fig. 6: DTF for γ versus α (a) with the corresponding 3D volume view (b) showing the fibres in the respective colours selected by the DTF widgets.

With these tools – the different DTFs and the DSH – a detailed analysis of a given data set of a SFRSpC sample can be made. Using a DTF with a single widget to cover all features gives an overall examination of the sample, whilst using widgets for different sets of parameters allows a more detailed analysis of the fibres in the sample. The visualisation of the sample and the DSH stays fully interactive all the time and can be viewed from different angles, even when the widgets are changed or moved during exploration.

3.3 Results

The results of the investigated SFRSpC samples showed a high fibre concentration at γ of about 90° and therefore orthogonal to the application direction as can be seen in the DSH in Fig. 7a as well as in the histogram in Fig. 5c. Such an alignment has proven to contribute to crack resistance in tunnel linings as confirmed in experimental bending tests.
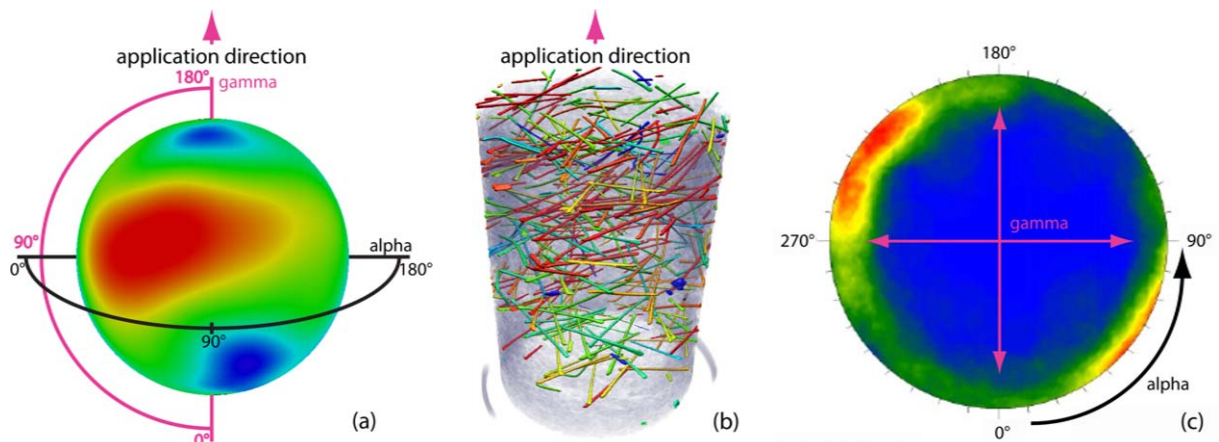

Fig. 7: Visualisation of the results for one SFRSpC sample: (a) DSH showing the frequency of occurrence of directions on a hemisphere, (b) 3D volume view with the steel fibres coloured according to the DSH colour-coding, (c) results of the manual examination on a Schmidt net, giving the lower hemisphere of the directional sphere with α [0°, 360°[applied circumferentially and γ [0°,90°] applied radial with 0° in the centre and 90° at the outer diameter.

An accumulation of fibres can also be seen with α between 10° and 90° and therefore they are not randomly distributed as desirable as can be seen in the DSH in Fig. 7a as well as in the histogram in Fig. 5a. It can be concluded that the application direction has not been the exactly orthogonal to the tunnel lining. That can be attributed to a movement of the nozzle during application.

The evaluation of the system was done using datasets from a manual analysis as described above [5]. The results were exactly the same with the automatic visualisation-driven method presented here (Fig. 7). The results in the DSH (Fig. 7a) of the automatic analysis and the

Schmidt net (Fig. 7c) of the manual evaluation are equivalent. In the Schmidt net the lower directional hemisphere is shown, so that directions that are on the upper half of the DSH are visualised at $\alpha+180°$. One can see that the same accumulation of fibres was detected manually at α between 10° and 90° as well as γ of about 90°.

The work that needed in manual analysis about 50 h of work was accomplished in only about 2 min with the presented tool. Thereby the new tool offers additional possibilities for an efficient real-time exploration of the data-set.

4. Ductile Cast Iron

Ductile Iron, which is also referred to as nodular cast iron or spheroidal graphite cast iron is a family of ferrous alloys with carbon and silicon as main alloying element [7]. The key property of ductile iron is that the majority of the carbon is present as graphite spheres in the ferrous microstructure.

In comparison to other cast irons where the carbon of the alloy is present as forms of graphite for instance in lamellar (flake) shape (grey cast iron) or in compacted (vermicular) shape (compacted graphite iron), ductile iron exhibits higher strength and ductility. Together with a reasonable price for its production this makes it an ideal material for many applications. In 2006 the world production of ductile iron added up to nearly 21.7 million tons [8]. The main share is used in the production of pressure pipes, followed by automotive parts and different parts for mechanical engineering [9].

4.1 Background

To achieve the desired properties of the material its microstructure has to be ensured during production. Ideally the microstructure consists of small, finely dispersed spheres of graphite all over the casting which gives highest strength and ductility as well as high fatigue strength at the same time. Due to different production constraints this can not be achieved in every casting or in every part of the casting. For that reason the examination of the graphite formation is often demanded in quality specifications. To harmonise these examinations the standard ISO 945-1 was established. The classification of the microstructure of graphite in cast irons is based on a comparison by visual examination. In quality specifications for castings minimum requirements concerning graphite form, particle density and maximum particle size are common in the casting industry.

The designation of microstructure in cast irons according to the requirements of the standard ISO 945-1 belongs beside tensile tests or hardness testing, to the most common quantification processes concerning ductile cast iron. Thereby, the cast iron materials are examined under a microscope, whereas the graphite inclusions are classified by its

    (1) form (designated by roman numerals from I to VI),
    (2) distribution (designated by capital letters A to E) and
    (3) size (arabic numerals from 1 to 8).

Whereas the graphite distribution designation is only specified for form I, which does not occur in ductile cast iron and is therefore ignored for our process. For ductile irons the nodule count can be evaluated giving the number of nodules per unit area of the evaluated section surface. The standard ISO 945-1 provides reference images of schematic microstructures of cast iron, as a classification basis. Form, distribution and size of the graphite inclusions

observed at the sample surface, are determined by comparison with the reference images that resemble them most closely. This method permits a quick identification of the graphite form, but is very constrained to the sampling preparation, which means that special attention must be paid to the location, the wall thickness, the distance from the surface and the presence of chills. E.g., depending on the location where the metallographic samples were taken, the results can show a significant deviation. Additionally, the preparation of the sample used is crucial. Careful grinding and polishing of the sample is important, so that the graphite particles appear in their original form, size and distribution, not to cause an unacceptable alteration of the microstructure.

The need for impartial classification and evaluation of the graphite microstructure led to the development of several suggestions to analyse the form of graphite in metallographic sections [10, 11, 12, 13, 14, 15]. These processes are based on different evaluation schemes like image analytical parameters, shape parameters, morphological transformations, and other methods. For compact graphite shapes (Forms III, V and VI of ISO 945-1) the informative annex B of the standard ISO 16112 on compacted graphite cast irons gives a procedure to evaluate the graphite form via the particle's roundness.

To evaluate the 3D shape of the graphite particles metallographic serial sectioning techniques [16] or focused-ion-beam-tomography (FIB) [17] can be used. Both give additional information on the samples microstructure especially on the composition of the matrix that can not be achieved in conventional x-ray tomography. As in both processes the sample is sectioned slice wise (either by FIB or standard metallographic practice), the sample's integrity is lost. Furthermore the process for the data acquisition is quite tedious. The resolution achieved with the FIB-tomography is very high due to the imaging with scanning electron microscopy but the acquired volume is therefore quite small especially in comparison to the size of the graphite particles that are analysed.

The approach via CT-scanning and an interactive visualization-driven exploration of the whole data set can overcome the drawbacks of the conventional, manual approach. In that way a higher number of individual particles are taken into account for the evaluation as well as scattered graphite particle deviations can be found more easily. This method is not suited for the evaluation of the graphite microstructure for whole castings as the resolution of current CT-systems does not allow the analysis of the graphite phase in such samples, but is very effective if a material sample is taken for quality inspection or to analyse other casting defects, where the evolution of the microstructure can give useful information on the processing history of the part at hand.

The data is acquired from materials samples using a microfocus x-ray CT-system. The maximum size of the sample should be in a dimension that the graphite particles can be represented by several voxels in the reconstructed CT-model. The accuracy of the analysis is dependant on the average number of voxels per graphite particle.

4.2 Data Acquisition

The sample used for the current examination was produced out of a thin walled casting out of serial production that had to be checked for its casting quality, one part of which is the evaluation of the graphite microstructure. The piece was scanned on a v|tome|x c of Phoenix|x-ray Systems and Services at the Austrian Foundry Research Institute. This tomograph uses a 240 kV microfocus x-ray tube with a variable focus from 4-200 μm that allows high magnifications and high resolutions. The x-ray images were recorded using a

$(512)^2$ pixel digital flat panel detector with 16 bit dynamic range. For higher spatial resolutions the detector was shifted between the imaging process so that images of 1024x512 pixel could be recorded. The sample at hand was scanned a voxel size of $(4.0 \ \mu m)^3$ per voxel. For reconstruction the same software has been used as described in section 3.2.

4.3 Computation, Exploration, Analysis and Quantification

During the region growing process the additional parameters necessary for the graphite microstructure quantification are calculated. These are according to ISO 945-1 the particle's size, form and nodule count. To evaluate the dominant graphite form in the sample the nodularity is calculated. ISO 16112 defines this parameter for the planar case using the smallest circumscribed circle (Fig. 8). Therefore, for each feature, the smallest enclosing sphere is calculated. The centre voxel of the bounding box is estimated and the sphere radius follows from feature voxel with the largest distance to the centre voxel. The single features are classified according to their roundness, which is defined, analogue to ISO 16112, for the 3-dimensional case as follows:

$$Roundness = \frac{3V_{particle}}{4r_{sphere}^3 \pi} \qquad (1)$$

where $V_{particle}$ is the volume size of the feature, and r_{sphere} is the radius of the enclosing bounding sphere. According to this roundness, the features are classified into three (of the six) different forms, which represent the typical types of graphite particles for this kind of material. The values are taken from ISO 16112, where they are defined for the 2-dimensional case:

- $0.000 \leq$ Roundness < 0.525: vermicular, which denotes the form factor III.
- $0.525 \leq$ Roundness < 0.625: intermediate, which denotes the form factor V.
- $0.625 \leq$ Roundness < 1.000: nodular, which denotes the form factor VI.

The nodularity in percent is calculated as defined in ISO 16112 according to the volumes of this different morphology groups as follows:

$$Nodularity[\%] = \frac{\sum V_{nodular} + 0.5 \cdot \sum V_{intermediate}}{\sum V_{nodular} + \sum V_{intermediate} + \sum V_{vermicular}} \cdot 100\% \qquad (2)$$

where $\sum V_x$ is the number of voxels of all particles with a roundness class nodular, intermediate or vermicular, respectively.
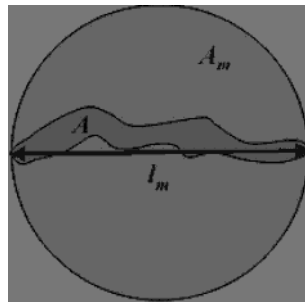

Fig. 8: Schematic representation of the planar evaluation of the roundness according to ISO 16112 as the quotient of particle area A and the area $_{Am}$ of the smallest circumscribed circle.

For this application the 3D histograms are calculated with the parameter's density, the region growing parameter and feature size or feature roundness, respectively. The diameter of the feature's bounding sphere is used as the feature size parameter. For better orientation of the user the background of the histogram is colour-coded for the different roundness classes and size classes as defined in the two corresponding ISO standards.

Transfer functions can be defined using widgets in the parameter domain of interest as explained above to assign colour and opacity. The 3D volume and three orthogonal views are updated in real time, so that the user can fully interactively change his selection. Additional parameters like roundness- and density-range as well as the nodularity of the features selected by the quantification widget are constantly displayed to help guide exploration.

For an overview the particles can be colour-coded according to their roundness classes or size classes given in the ISO standards.

4.4 Results

The results of the analysis of the given sample are shown in Figs. 9 and 10 for the whole volume or just one slice in the middle of the volume respectively. One can see that the classification for different size classes as defined in ISO 945-1 works very well. The use of the roundness classification as defined in ISO 16112 for the planar case proved to be not suited for the 3-dimensional application. In the given sample a lot of particles are classified as vermicular that proved to be not really vermicular particles. The limits for the roundness classification have therefore to be adjusted for 3D. This needs a bigger database and a close review and is therefore an ongoing process.
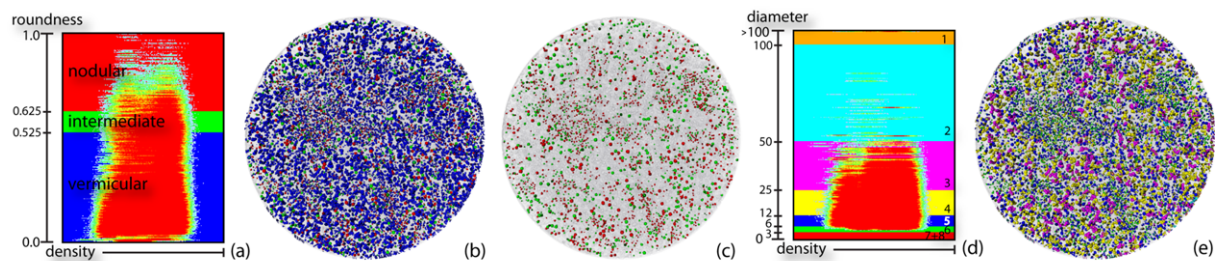

Fig. 9: For quantification of the graphite phase according to form and size parameters, one appropriate region growing parameter is selected interactively for which the corresponding histograms are shown: (a) and (d). Colour-coding according to the three form factors (b) or the eight size classes (e) respectively in the 3D volume view. For nodule count quantification only forms V and VI are taken into account (c).

The comparison of the results with the analysis of a metallographic cross-section is difficult as the properties under investigation change considerably from one region in the volume to another. In the metallographic examination only the planar characteristic of the graphite particles is taken into account, which has to deliver deviations compared to the three-dimensional evaluation. Furthermore the characterisation of the particle's shapes under the microscope has a higher resolution compared to the CT-scan.
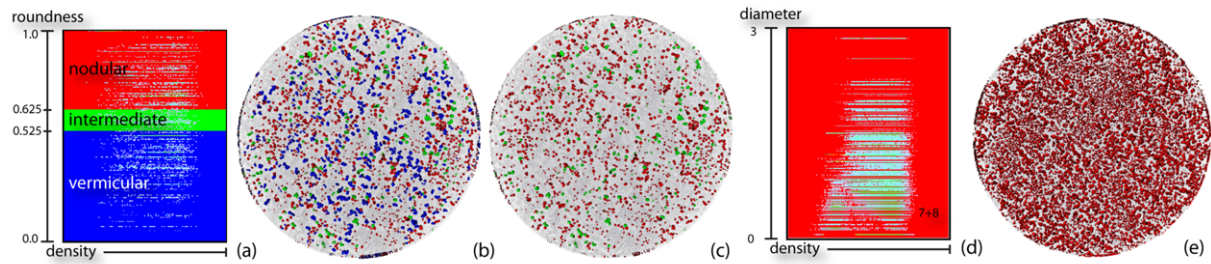
Fig. 10: The same visualisation as in Fig. 8 for a 2D slice in the middle of the sample volume calculated for the 2D case.

A comparison of the results gained with the presented method and with the well established software Volume Graphics Studio MAX 2.0 was conducted (Table 1). The defect detection module of this software was used to segment the graphite particles in the sample. With these results the corresponding parameters size, form, nodularity and nodule count were calculated. They are in good agreement with the new system except for the feature count as small particles were excluded from the segmentation with Volume Graphics Studio MAX.

Table 1:Comparison of the quantification results of the presented system with the standard software VG Studio MAX for the 2D case.

Method	Form	%	Feature Count	Size	Feature Count	% Nodularity	Nodule Count
Automatic, 2D	🟥 🟩 🟦	45,30 15,23 39,47	1485 286 799	7+8	2852	52,91	102 mm^{-3}
Manual, VG St. MAX 2D	🟥 🟩 🟦	46,15 23,08 30,08	n/a n/a n/a	7+8	1553	53,70	97 mm^{-3}

Particles smaller than three voxels in diameter must not be included in the analysis to avoid the segmentation of noise. Furthermore shrinkage porosity which is often bigger than the graphite particles should also be excluded from analysis. Therefore the user has the option to set a lower and upper limit for the feature size in the region growing process, that he can use if he has a priori knowledge of the data-set. Otherwise these exclusions can be set interactively during the exploration of the data using the transfer functions.

5. Conclusions and Outlook

A system for interactive exploration and quantification of CT-data for two application scenarios was presented, that builds on a visualisation-driven approach. Multidimensional transfer functions can be defined in application specific parameter domains that help the expert user to accomplish specific analysis tasks in more detail and/or shorter time.

The use of a CT-scan for examination of the steel fibres in steel fibre reinforced sprayed concrete (SFRSpC) gives the orientation of the reinforcing fibres that were not accessible in a conventional investigation. The use of multidimensional application specific transfer functions in the domain of orientation angles α and γ, density and region growing parameter allows the examination at a fraction of the time used for manual analysis. The visualisation in a direction sphere histogram (DSH) gives additional information on dominant orientations in the sample.

The evaluation of the graphite morphology in ductile iron on the basis of ISO 945-1 and ISO 16112 can give the expert user a valuable analysis of the three-dimensional characteristic of the graphite phase in the sample, that can not be gained by the traditional two-dimensional

analysis as described in the above mentioned standards. The use of multidimensional application specific transfer functions in the domain of size (as diameter of the enclosing sphere), roundness, density and region growing parameter allows for a fast analysis of the data. Comparing the total time for conducting an examination, the conventional way of preparing one metallographic section is faster compared to the CT-acquisition, which gives the full 3D data of the sample. It was shown that the limits for the roundness classification have to be adjusted to the 3D case.

The concept of multidimensional, application specific transfer functions proved to be a powerful tool for the analysis of CT-data improving the workflow of the expert user. Therefore more possibilities for interactive measurements will be integrated, as well as further evaluation of the results will be performed. Also a method for sub-voxel classification shall be developed to further improve quantification accuracy.

Acknowledgements

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