A Visual Approach to Efficient Analysis and Quantification of Ductile Iron and Reinforced Sprayed Concrete

Category: Application

In recent years, the introduction and rapidly increasing use of 3D computed tomography in non-destructive testing (NDT) applications has opened up many powerful possibilities for analyzing and testing industrial parts such as cast metal without destroying them. However, many important tasks in this area such as designating the microstructure of ductile cast irons are still routinely carried out using a (destructive) metallographic approach and subsequent manual visual analysis. That is, the metal under inspection is examined by sequentially removing layers via grinding or etching, and taking microscopic photographs. Due to the complexity of the observed structures, in current practice the classification of important properties such as the form of graphite particles that are crucial for ductility is performed by human visual analysis and manual comparison with reference images. This process could be simplified tremendously by using computed tomography (CT) and powerful visual tools. However, currently there is a clear lack in visualization solutions that provide sufficient flexibility for exploration and inspection, as well as ultimately quantification, to do so. Moreover, the use of CT in non-destructive testing is increasingly employed for non-metallic or compound materials. For example in the analysis of different types of concrete, which probably is the most widely used non-natural material worldwide. The inspection of concrete by CT is becoming more widespread, but the subsequent analyses are very time-consuming and in current practice still involve a considerable amount of manual work due to insufficient tools.

In this paper, we describe novel, visual workflows that are customized for applications in non-destructive testing which are of high relevance for NDT practitioners. The presented approaches have been developed jointly with expert users from this domain, both from a more practical engineering and testing perspective, as well as a view relating to materials research. The first application scenario that we describe is the analysis of Steel Fibre Reinforced Sprayed Concrete (SFRSpC), which is of very high importance in the building industry. We are concerned with the examination and analysis of the enclosed steel fibres regarding their orientations and distribution with respect to the application direction in which the concrete has been sprayed. SFRSpC is a relatively new material that is used in various applications in geotechnics. However, although the distribution of fibre directions could strongly influence the mechanical properties of the material, they have not been properly explored yet. Instead, a continuous distribution was assumed. A preferred orientation of the fibres, however, can result from the application process of the concrete, which could significantly alter its mechanical behavior. Our specific example is concerned with the examination of this form of sprayed concrete in tunnel linings. In a previous study of our domain expert collaborators, drill core samples have been taken and scanned using 3D CT. Then, each single steel fibre was measured individually, which required a significant amount of tedious work. Additionally, different tools were required in order to compute and visualize statistical results. In con-

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Abstract—This paper describes advanced volume visualization and quantification for applications in non-destructive testing (NDT), which results in novel and highly effective interactive workflows for NDT practitioners. We employ a visual approach to explore and quantify the features of interest, based on transfer functions in the parameter spaces of concrete application scenarios. Examples are the orientations of fibres or the roundness of particles. The applicability and effectiveness of our approach is illustrated using two concrete scenarios of high practical relevance. First, we discuss the analysis of Steel Fibre Reinforced Sprayed Concrete (SFRSpC). We investigate the orientations of the enclosed steel fibres and their distribution, depending on the concrete’s application direction. This is a crucial step in assessing the material’s behavior under mechanical stress, which is still in its infancy and therefore a hot topic in the 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 carried out much more efficiently using our system 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.

Index Terms—Non-Destructive Testing, Multi-Dimensional Transfer Functions, Direction Visualization, Volume Rendering.

1 INTRODUCTION

In this paper, we describe novel, visual workflows that are customized for applications in non-destructive testing which are of high relevance for NDT practitioners. The presented approaches have been developed jointly with expert users from this domain, both from a more practical engineering and testing perspective, as well as a view relating to materials research. The first application scenario that we describe is the analysis of Steel Fibre Reinforced Sprayed Concrete (SFRSpC), which is of very high importance in the building industry. We are concerned with the examination and analysis of the enclosed steel fibres regarding their orientations and distribution with respect to the application direction in which the concrete has been sprayed. SFRSpC is a relatively new material that is used in various applications in geotechnics. However, although the distribution of fibre directions could strongly influence the mechanical properties of the material, they have not been properly explored yet. Instead, a continuous distribution was assumed. A preferred orientation of the fibres, however, can result from the application process of the concrete, which could significantly alter its mechanical behavior. Our specific example is concerned with the examination of this form of sprayed concrete in tunnel linings. In a previous study of our domain expert collaborators, drill core samples have been taken and scanned using 3D CT. Then, each single steel fibre was measured individually, which required a significant amount of tedious work. Additionally, different tools were required in order to compute and visualize statistical results. In con-

Fig. 1. CT-based visualization of drill cores from Steel Fibre Reinforced Sprayed Concrete (SFRSpC) enables inspection and analysis of the distribution of the steel fibres’ directions, which is crucial for the material’s mechanical properties. (a) Frequency of occurrence of directions color-coded in a Direction Sphere Histogram (DSH) (red: highest, blue: lowest); (b) Frontal view; (c) Top-down view.
to parameter ranges such as determining whether the cast iron is ductile. Transfer function presets enable easy classification according to the requirements of the ISO standard. At run-time, the interactive specification of transfer functions that highlight the regions selected by region growing techniques have been integrated into volume visualization systems, expert users can either search the 3D volume for features of interest, which is crucial in our application context. Section 3 review this basic approach and describes extensions demanded by our application scenarios. In our system, the detection of features such as steel fibres or graphite particles is performed using region growing. In region growing techniques, the specification of seed points is crucial. This can be tackled, for example, by evaluating multiple seed points at the same time, or allowing each voxel in the volume to potentially become a seed.

For region growing, we use GPU-based ray-casting with 3D textures and multi-dimensional transfer functions [11]. This allows for real-time rendering combined with considerable flexibility, including efficient memory management for large volumes. Region growing techniques have been integrated into volume visualization systems [8], which can also be used to define two-dimensional transfer functions that highlight the regions selected by region growing. This has also been demonstrated to be very useful in the context of industrial CT data. However, the result is only an approximation and in general cannot reproduce the exact set of voxels of any given feature. In our context, it is crucial that all voxels are included in a feature to enable accurate quantification.

### 3 Volume Exploration for Feature Detection and Quantification

In previous work, a novel method for interactive exploration of industrial CT volumes such as cast metal parts was presented, which helps to bridge the gap between visualization and feature detection as well as quantification. This visualization-driven approach allows features in the volume to be explored interactively without re-computing the segmentation or detection of features. The basis for this is an unattended pre-computation stage that computes a feature volume and additional data structures, which contain the result of feature detection.
tion over parameter domains instead of fixed parameters. The pre-computed feature volume tracks a feature size curve for each voxel over time. Thereby time is identified with the main region growing parameter such as the maximum intensity variance allowed within a region. This pre-computation has to be performed only once for a given data set and forms the basis of interactively exploring all contained features. In contrast to detection of a single type of feature, the user explores all feature classes and decides interactively which classes are of interest, instead of specifying this information beforehand.

The system computes and records the result of region growing for the entire density domain, all different sizes of features, and the entire domain of the most important parameter. In case a specific region growing algorithm is used, this parameter could be the maximum variance, for example. For generality, this parameter is referred to as the time parameter throughout the paper. Together, these three 1D parameters (density, feature-size, time) comprise a 3D domain, which is explored by the user via 3D transfer functions (TFs). In order to make TF specification tractable, a 2.5D metaphor is employed, which still provides the necessary flexibility. This enables a powerful interactive workflow that tightly couples visualization and feature detection. It builds on a multi-pass region growing approach, and allows for a full exploration of the volume with no or almost no beforehand parameter specification. The result of exploration is a classification of all feature classes of interest through transfer functions, which can then immediately be used to quantify only the corresponding features. This implies that the subsequent quantification is visualization-driven as well, i.e., quantification is performed exactly for what the user has chosen to be visualized. This empowers users who are experienced domain experts to decide on their own and make informed decisions for quantification. This is a significant difference to systems currently used in practice, which rely on the result of a given set of parameters.

For the two application scenarios described in this paper, we are using this basic approach of visualization-driven quantification. However, in order to accommodate the specific requirements of these applications, several key aspects and corresponding extensions have to be considered. In the case of sprayed concrete (SFRSpC), the directions of steel fibres must be computed, visualized, and analyzed in particular. For classification and analysis of the graphite microstructure of ductile cast iron, the specific requirements of the corresponding ISO standards must be met.

The specific application-triggered technical contributions of this paper are:

- The orientations of the steel fibres in SFRSpC are computed automatically in the pre-computation phase, and visualized interactively in a Direction Sphere Histogram (DSH) that color-codes the frequency of occurrence of directions. This histogram is changed interactively when a different set of fibres is selected via direction transfer functions (below).

- We introduce direction transfer functions (DTFs) for the analysis and visualization of the direction-distribution of the steel fibres in SFRSpC according to the two angles $\alpha$ and $\gamma$, which are specified according to the application direction of the concrete.

- In addition to feature-size, we have integrated the specific properties of feature-diameter and feature-roundness required by the ISO standards for classification of the graphite microstructure of ductile cast iron. These properties can be used in the extended TF domains of (density, feature-diameter, time) and (density, feature-roundness, time), which enables the advantages of the basic approach outlined above to be combined with the requirements of the respective standards.

- Quantification of the microstructure of ductile cast irons with respect to the contained graphite. This is done according to the requirements of the ISO 945-1 and ISO 16112 standards for single 2D slice images as well as for the entire or part of the 3D volume.

4. STEEL FIBRE REINFORCED SPRAYED CONCRETE

Steel fibre reinforced sprayed concrete (SFRSpC) is a composite material used for various applications in geotechnics. It combines the high compressive strength of sprayed concrete with the strength after cracking through the addition of the steel fibres. The material behaves brittle until a crack starts and becomes ductile through the steel fibres afterwards. Ideally the steel fibres represent a continuous reinforcement, if the fibres are randomly and homogenously distributed. For example, SFRSpC is used when a quick application of a shell is needed. This is for example the case, when walls or rocks have to be secured as no steel meshes have to be applied before. 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, as cracks can be seen long before material failure.

4.1 Application Scenario

Although the mechanical properties of SFRSpC are generally a well studied problem, the steel fibres’ orientation and distribution were disregarded in the past. Especially the orientation of the fibres has a great influence on the bearing capacity after the formation of cracks. The aim of this special study, realized at anonymous is a statistical evaluation of the steel fibres’ alignment in SFRSpC applied on a tunnel wall. The goal is to find out whether there is a prevailing characteristic orientation of the fibres that is due to the application direction of the sprayed concrete. Drill core samples are taken from the tunnel lining and are analyzed by means of industrial CT. In the previous, completely manual approach, the CT volume was loaded into a software tool where for each single steel fibre the coordinates of both ends had to be selected manually. Thereby it was important that each steel fibre was processed sequentially, to keep the storage order. Additionally, several formatting steps were required to finally get suitable coordinates for other tools to accomplish the statistical interpretation. This was tedious, time-consuming, and required the use of several different software tools. In contrast, our visualization-driven solution simplifies the steel fibre evaluation significantly, because it automatically computes and visualizes the directions of the fibres, and also provides different possibilities for statistical evaluation.

4.2 Processing Pipeline

The important stages of the processing pipeline are shown in Figure 2. The additional calculations required for this application are described in Section 4.2.2. They are performed in the automatic pre-processing phase, which is the basis of the interactive exploration and quantification process as described in Section 4.2.3.

4.2.1 Data Acquisition

The samples used in this section are core samples of a sprayed concrete shell of a tunnel. When drilling the cores, the axis of the cylindrical...
Fig. 4. The DTFs for $\alpha$ (a) and $\gamma$ (d), where the x axes show the density, and the y axes are the angle distribution of the steel fibres. For this application, it was sufficient to select one representative 2D time step of the 3D TF [7]. The 3D volume view immediately shows the fibres selected by the widgets in the $\alpha$-DTF (b), or the $\gamma$-DTF (e), as well as their distributions in the corresponding Direction Sphere Histogram (DSH), (c) and (f).

sample was aligned with the surface normal of the inner tunnel lining. This direction can be assumed to be the direction along which the sprayed concrete has been applied, which is mapped to the z-direction in our application. The data is acquired from core samples using a microfocus x-ray CT-system scanned on a Phoenix|x-ray v|ome|x c of GI Sensing & Inspection Technologies. For these samples, the resolution has to be high enough to correctly identify the steel fibres, which have a high x-ray absorption compared to the concrete matrix. A single fibre should be detected as one feature, and the detection of fibre fragments should be avoided because these can influence the detected orientations. We have investigated two drill cores in particular, denoted as SFRSpC 1 and SFRSpC 2, respectively. Figures 1 and 4 depict SFRSpC 1, and Figure 3 depicts SFRSpC 2. See also Table 4.

4.2.2 Pre-computation

The computations necessary for the direction estimation of the steel fibres are performed during the region growing step in the preprocessing phase. After region growing, for each segmented feature an object oriented bounding box (OBB) is calculated, using principal component analysis (PCA). An OBB is a rectangular bounding box that approximates the arbitrary orientation of an object in 3D space [6]. PCA yields the three eigenvectors for the main axes, where the largest eigenvalue corresponds to the principal axis. The principal axis of the feature’s OBB is used as direction vector in additional orientation calculations, as shown in Figure 3(c). To check the samples for preferred orientations of the contained fibres according to the requirements of the real-world analysis to be performed, we compute two main angles:

- **Alpha ($\alpha$)** is the angle in the xy-plane normal to the concrete’s application direction. It is in the range $[0^\circ, 180^\circ]$, since a half-circle covers all orientations. See Figure 3.

- **Gamma ($\gamma$)** is the angle between the z-axis (the application direction of the sprayed concrete) and the feature direction in 3D. The range for $\gamma$ is $[0^\circ, 180^\circ]$ as well. See Figure 3.

For each angle, a 3D histogram is created, where the distributions are shown along the vertical axis. See Figure 4(a) for one time step in the $\alpha$-histogram and Figure 4(d) for one time step in the $\gamma$-histogram. The angles replace the feature-size described in Section 3. The horizontal axis shows the density distribution, and the third dimension corresponds to the change of the main region growing parameter over time, as also described in Section 3. The color coding indicates the number of features, where red stands for a high and blue for a low occurrence of features at the current position. These histograms are the domains of transfer functions for interactive exploration and quantification described below.

4.2.3 Interactive Exploration and Quantification

For this application, the basic framework described in Section 3 has been extended for the visualization, exploration, and quantification of the steel fibres in SFRSpC. The exploration of the direction distribution of the steel fibres is performed according to their two main angles, via the respective direction transfer function (DTF). Figures 4(a) and (d) depict the distributions of the fibres according to the angles $\alpha$ and $\gamma$ in $[0^\circ, 180^\circ]$. By means of these DTFs, the user can explore the steel fibres according to their angles, using quantification widgets to interactively control the selection. By dragging the widgets with the mouse, their size and position can be adapted to colorize the desired features in the 3D volume view (Figures 4(b) and (e)). Additional values like the degree range, number of features, and the percentage of the volume covered by features selected by the current widget are constantly updated and shown, which provides extra information and aids navigation (Table 1). The 3D volume view allows one to inspect the current selection at any time, and determine if it is satisfactory. Afterwards, the mean and standard deviation of the selected features’ angles are calculated on demand. The frequency distribution of the selected fibres’ directions are color-coded on a direction sphere histogram (DSH). This histogram stores the direction frequency of the selected fibres, which is Gaussian-distributed, at each sphere-vertex. The implementation details are described below. Figure 1(a) shows the DSH for all features in the sample, where red color indicates a high frequency and blue color a low one. Because the two angles $\alpha$ and $\gamma$ are in the range $[0^\circ, 180^\circ]$, it is sufficient to plot the directions on a hemi-sphere. For other applications, this can be switched to an entire sphere. The sphere’s alignment regarding the two angles $\alpha$ and $\gamma$, and the application direction of the sprayed concrete, is demonstrated in Figure 1(a) and Figure 3(a). This alignment is the same for all DSH images shown here. Additionally, the color coding of the DSH can also be used in the 3D volume view, where each fibre is assigned the color according to the frequency of fibres in the same direction (Figure 1(b) and (c)).

4.2.4 Direction Sphere Histogram (DSH) Computation

For the Direction Sphere Histograms (DSHs) displayed by our system and shown in Figure 1(a), Figure 3(b), and Figure 4(c,f) we use a tessellated sphere as the domain, where each vertex is a histogram bin with a corresponding floating point count that can easily be mapped to a color using a simple 1D color table. The spheres are rendered using OpenGL, where the colors are mapped to vertex colors and interpolation is used within each triangle. For each fibre selected by means of the DTFs, its direction is entered into the DSH by splatting a Gaussian kernel centered at the fibre’s direction onto the sphere. That is, the histogram count of all sphere vertices covered by the (truncated) Gaussian is incremented by a value corresponding to its location with respect to the center of the Gaussian. The integral of the Gaussian kernel is 1, and thus we make sure that we obtain a good trade-off be-

<table>
<thead>
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<th>Angle</th>
<th>Degree</th>
<th>Feature Count</th>
<th>% of Part Vol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>$15^\circ - 25^\circ$</td>
<td>53</td>
<td>0.14</td>
</tr>
<tr>
<td>Fig. 4 (a,b,c)</td>
<td>$81^\circ - 100^\circ$</td>
<td>37</td>
<td>0.08</td>
</tr>
<tr>
<td>Gamma</td>
<td>$80^\circ - 110^\circ$</td>
<td>234</td>
<td>0.60</td>
</tr>
<tr>
<td>Fig. 4 (d,e,f)</td>
<td>$136^\circ - 153^\circ$</td>
<td>9</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 1. Quantification of the steel fibres in SFRSpC 1 selected by the classification widgets shown in Figure 4.


tween accurate counts at any direction, and a distribution over a small neighborhood of directions that results in smooth histograms.

For efficient run-time computation of DSHs, we pre-compute a sampling of the weights of a Gaussian distribution with a user-defined standard deviation $\sigma$ that controls the size of the splt. For the full size of the truncated Gaussian kernel, we use a radius of $4\sigma$. For simple implementation, the function values according to the distance from the center of the Gaussian kernel are stored in a 1D $\text{gauss\_array}$, as shown in Figure 5(a), for use during splatting. During the tessellation of the sphere, the angular distances and number of steps between two successive longitudes or latitudes of the tessellation, respectively, are stored in a $\text{sphere\_distance\_array}$. This enables a fast computation of the area on the sphere that is covered by a Gaussian of a given size.

To calculate the values for the histogram bins, the contributions of the directions of all selected fibre are summed up. According to the previously calculated OBBs, the fibres’ main direction is calculated and the vertices covered by the truncated Gaussian centered at that location are computed. These vertices are then assigned a value according to their distance to the center of the Gaussian (Figure 5(b)). Figure 5(c) shows this procedure for one fibre, whose Gaussian splt covers a certain area in longitude and latitude on the sphere. At each vertex/bin, the contribution of each fibre is summed up. In the last step, the values of the bins are mapped to colors. Figure 5(d) shows the DSH Gaussian distribution of one selected fibre. This technique ensures a fast recalculcation of the sphere colors when the selection of fibres has changed, because only the Gaussian values for the vertices have to be recalculated. This is done by simple look-up operations in the $\text{gauss\_array}$ according to the distance looked up in the $\text{sphere\_distance\_array}$. The whole sphere initialization process must only be recalculated when the $\sigma$-value of the Gaussian distribution changes.

### 4.3 Discussion and Results

Normally, the quantification is needed for all steel fibres in the volume as shown in Figure 1. In this case, the DTFs are mainly used to get a quick overview of the fibres’ occurrences at selected angular ranges of interest to the user by using the classification widgets. For the direction quantification as shown in Figures 1 and 3, a single classification widget was used to mark all steel fibres in the volume, for which it does not make a difference which of the two DTFs is taken. Nevertheless, the user has the possibility to explore and quantify only a selected part of the inclusions interactively, which assists in a fast comprehension of the data. An example of the selective classification is shown in Figure 4. Just a part of the steel fibres are selected by the user employing the quantification widgets, as given in Table 1.

For practical evaluation of our system we have made a comparison with the results generated by the completely manual approach performed at anonymous. The result of our system was exactly the same as the manual approach. However, it could be achieved in a fraction of time and provided several additional possibilities for real-time exploration of the data set. The distributions in the $\gamma$-DTF (Figure 4(d)) as well as in the DSH (Figure 1(a)), clearly show that there occurs a high fibre concentration at about $\gamma = 90^\circ$, which is close to a right angle with respect to the concrete’s application direction. Also for the $\alpha$-direction, the DTF (Figure 4(a)) and the DSH (Figure 1(a)) show a preferred orientation between $\alpha = 10^\circ$ and $\alpha = 90^\circ$. Our expert collaborators assume that the application direction in reality was not exactly orthogonal to the tunnel lining, which has lead to the observed orientation according to $\alpha$. As was often tested by using flexural tension tests, the SFRSpC keeps a remaining force after the building of cracks because the steel fibres aligned orthogonal to the crack interact against the bending direction. Due to the observed preferred orientation of the fibres, its effectiveness increases if they lie parallel to the surface, and decreases if they lie parallel to the spraying direction, i.e., normal to the surface.

A direction visualization of the second drill core sample (SFRSpC 2) taken from the same tunnel lining, including more steel fibres, is shown in Figure 3. This analysis emphasizes the observations described above. The guidelines (EFNARC European Specification for Sprayed Concrete 1996) and standards (EN 14488-7) for sprayed concrete, currently only provide the examination of the fibre content in fresh or already hardened probes. In fresh concrete, the fibres must be washed out. In already hardened concrete, the fibres have to be mechanically quarried out of the concrete and cleaned afterwards. Then the number of fibres in the sample can be estimated. With our system, it is now possible to estimate not only the number of fibres, but also their orientation in the sample at hand. Because the fibres’ orientation has a significant impact on the mechanical behavior of SFRSpC, our expert collaborators from the application domain think that in general the quantification of SFRSpC and the analyses of the related properties can be improved tremendously in the future by using such a system, as well as enabling new scientific discoveries in this engineering discipline.

### 5 Ductile Cast Iron

In ductile iron, the majority of the carbon is present as graphite spheres in the microstructure, which exhibits higher strength and ductility than for lamellar shaped graphite particles. The main share of ductile cast iron is used in the production of pressure pipes, followed by automotive parts and different parts for mechanical engineering. To achieve the desired properties of the material, an appropriate microstructure has to be ensured during production. One major influence is the formation of the graphite. 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 even in every part of the casting. For this reason the examination of the graphite formation is often required in quality specifications. To harmonise these examinations the standard ISO 945-1 (ICS: 77.080.10) was established. The classification of the graphite’s microstructure in cast irons is based on a visual comparison. In quality specifications for castings, minimum requirements concerning graphite form, particle density and maximum particle size are common in the casting industry.
The parameters required for graphite microstructure quantification are computed in the pre-computation phase described in Section 3 during region growing. The relevant indications for quantifying the graphite spheres according to the ISO 945-1 standard are their size, form, and roundness. These are measured by means of the smallest sphere enclosing a particle. In the ISO standard, the form of each graphite particle is denoted by the roundness of the particle. The roundness is calculated as a parameter of the dominant form in the microstructure, according to the ISO standard 16112, from the percentages of the different graphite forms in the sample. For each particle, we estimate the smallest enclosing bounding sphere. In this context, the size of a particle is defined as the diameter of its enclosing sphere. Figure 7(d) describes the sizes according to the classes defined in ISO 945-1.

The roundness is estimated in 3D as follows:

\[
Roundness = \frac{3V_{\text{particle}}}{4\pi r^3},
\]

where \(V_{\text{particle}}\) is the volume of the particle, and \(r\) is the radius of the smallest enclosing bounding sphere. The roundness therefore is the ratio between the volume of the particle and the volume of the enclosing sphere. According to this property, the particles are classified as belonging to one of three relevant (of six overall) different forms, representing the typical types of graphite particles for the investigated data:

- **vermicular** (form factor III): \(0.0 \leq Roundness < 0.525\).
- **intermediate** (form factor V): \(0.525 \leq Roundness < 0.625\).
- **nodular** (form factor VI): \(0.625 \leq Roundness < 1.0\).

The nodularity, regarding the three different morphology groups as defined in accordance to ISO 16112, is calculated as follows:

\[
\text{Nod}(\%) = 100 \frac{\sum V_{\text{nodular}} + 0.5 \sum V_{\text{intermediate}}}{\sum V_{\text{nodular}} + \sum V_{\text{intermediate}} + \sum V_{\text{vermicular}}},
\]

where \(\sum V_{\text{nodular}}, \sum V_{\text{intermediate}},\) and \(\sum V_{\text{vermicular}}\) are the number of voxels of all particles with roundness factor nodular, intermediate, and vermicular, respectively. To estimate the nodule count, only the particles of form factor V and VI (see Figure 7(c)) are counted in a reference subset of the whole volume chosen for measuring the nodule count, and \(V_{\text{ef}}\) is the volume of this subset.

To provide an interactive exploration and quantification process, according to the parameters relevant for ISO 945-1 and ISO 16112 described above, we provide two new 3D TFs. Features, i.e., particles are now classified by means of the 3D domain of density, feature-diameter or feature-roundness, and time. Whereas the density- and time parameter stay the same as described in Section 3, the feature-size parameter is exchanged by either the feature’s diameter or roundness factor. The 2D TFs of one selected time step are shown in Figure 7(a) and (d). The number of features is color-coded, where red corresponds to a high and blue to a low occurrence of features at the current position. The backgrounds of the histograms are color-coded according to the graphite’s size or roundness classes, defined by the ISO standards.

### 5.2 Processing Pipeline

#### 5.2.1 Data Acquisition

The sample presented in this section was taken from a thin walled casting from serial production, which had to be checked for its casting quality. The data is acquired from material samples using a microfocus x-ray CT system. The resolution must be chosen high enough to ensure that the graphite particles can be represented by several voxels in the reconstructed CT volume. The accuracy of the analysis is dependent on the average number of voxels per graphite particle.

#### 5.2.2 Pre-computation

The parameters required for graphite microstructure quantification are computed in the pre-computation phase described in Section 3 during region growing. The relevant indications for quantifying the graphite spheres according to the ISO 945-1 standard are their size, form, and roundness. These are measured by means of the smallest sphere enclosing a particle. In the ISO standard, the form of each graphite particle is denoted by the roundness of the particle. The roundness is calculated as a parameter of the dominant form in the microstructure, according to the ISO standard 16112, from the percentages of the different graphite forms in the sample. For each particle, we estimate the smallest enclosing bounding sphere. In this context, the size of a particle is defined as the diameter of its enclosing sphere. Figure 7(d) describes the sizes according to the classes defined in ISO 945-1.

To estimate the form factor for a given graphite particle, we have to calculate its roundness, which is computed in 3D as follows:

\[
Roundness = \frac{3V_{\text{particle}}}{4\pi r^3},
\]

where \(V_{\text{particle}}\) is the volume of the particle, and \(r\) is the radius of the smallest enclosing bounding sphere. The roundness therefore is the ratio between the volume of the particle and the volume of the enclosing sphere. According to this property, the particles are classified as belonging to one of three relevant (of six overall) different forms, representing the typical types of graphite particles for the investigated data:

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\text{Nod}(\%) = 100 \frac{\sum V_{\text{nodular}} + 0.5 \sum V_{\text{intermediate}}}{\sum V_{\text{nodular}} + \sum V_{\text{intermediate}} + \sum V_{\text{vermicular}}},
\]

where \(\sum V_{\text{nodular}}, \sum V_{\text{intermediate}},\) and \(\sum V_{\text{vermicular}}\) are the number of voxels of all particles with roundness factor nodular, intermediate, and vermicular, respectively. To estimate the nodule count, only the particles of form factor V and VI (see Figure 7(c)) are counted in a reference subset of the whole volume chosen for measuring the nodule count, and \(V_{\text{ef}}\) is the volume of this subset.

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Fig. 7. To quantify the graphite microstructure according to the form and size parameters of the ISO 945-1 standard, one appropriate time step of the respective TFs is used: (a) and (d). The color coding according to the three form factors (b) and the eight size-classes (e) is also applied in the 3D volume view. For the nodule count, only the graphite microstructure of forms $V_I$ and $V$ are taken into account (c).

Fig. 8. The same visualization and quantification principle as shown in Figure 7, but for one selected 2D slice, taken from the middle of the volume. Here, the exploration and quantification is based on the same values, but calculated for the 2D case.

5.3 Discussion and Results

The established standard workflow is currently based on determining the classification according to the ISO standards in microscopic 2D slice images such as the one shown in Figure 6(a,b). Due to the significant amount of manual work this entails, all properties are only determined in chosen 2D reference regions, for example the highlighted rectangle in Figure 6(a). This hashuge implications for the accuracy of the obtained results. First, the properties under investigation can change considerably from one region in the volume to another. Second, everything is only determined in 2D cross-sections, i.e., completely independent from the actual 3D shape or volume of the contained particles. Therefore, efforts are underway to move the whole process to 3D and leverage the possibilities provided by 3D CT acquisition. The advantages of extending the quantification to the 3D domain were discussed in Section 5.1. We have compared the results obtained by using our system with manually obtained results in the 2D slice image shown in Figure 6(b). Table 2 gives the quantification results for the evaluated parts shown in Figure 7 and Figure 8. The results for 2D data are comparable considering that differences due to different reference regions used for inspection are to be expected. It was not possible, however, to compare the properties obtained using our system in 3D, since there are no existing reference data. However, as explained above, the results of quantification in 2D and 3D are not directly comparable in general. A manual quantification of the 3D structures in the data to accurately evaluate our system is under progress. Our results show that using the coefficients for form classification defined in ISO 16112 for the 2D case have to be exhaustively reviewed when applying this procedure to a potentially much more accurate 3D application scenario. However, such a review can only be done using a bigger database and is therefore an ongoing process.

Furthermore, graphite inclusions with a diameter less than three voxels must not be included in the analysis to avoid the segmentation of noise. Also shrinkage porosity, which is in most cases much bigger than the graphite particles are not relevant. Therefore, a minimum and maximum feature size can be specified for the region growing process to exclude a priori undesired features from quantification. But this is only an option when the user has a-priori knowledge of the data. However, in our system these undesired features can also easily be removed interactively using transfer functions. Once the feature information has been calculated in the pre-processing step, the user can quantify the sample under investigation at any desired slice position and for the whole 3D volume in real time. This overcomes the problems mentioned in Section 5.1 which occur during the conventional sample preparation. The feature volume is cached and can be quickly reloaded for further quantification.

6 General Discussion

In the case of SFRSpC, our approach is much faster and reduces the required labor time considerably, since the previous method was almost completely manual. The manual quantification process takes hours for obtaining the same results which we have achieved, even when the short pre-processing times shown in Table 4 are considered. For the ductile cast iron, our quantification process generally takes more time than the manual approach if only one 2D slice is prepared, because in...
that case the CT scan takes more time than manual sample preparation. But if more 2D samples are required, it takes an additional 20 minutes per sample. Table 3 compares times of the manual and our automatic approach. Additionally, our system provides many powerful possibilities for real-time exploration that enable domain experts to gain more insight about the material sample at hand. Currently, our system for automatic quantification according to the ISO 945-1 and ISO 16112 standards in 3D is only used for research purposes. It is a first step towards specific quantification tasks in the 3D domain, but further research and refinement has to be performed in the future until the system can be incorporated into the daily quantification process of metallographers. Table 4 gives typical numbers for pre-computation times, memory consumption and volume rendering frame rates for the data sets used in this paper. Performance has been measured on an Intel Core i7 2.95GHz and a GeForce 285 GTX.

7 CONCLUSIONS AND FUTURE WORK

We have presented interactive exploration and quantification of features for two real-world applications of high practical relevance in the building industry. We have demonstrated that our system helps to bridge the gap between visualization, feature detection and quantification, and has the potential of significantly improving the current workflow of NDT practitioners. In the future we would like to integrate further possibilities for interactive measurement, as well as performing further evaluations of correctness of the resulting quantifications. This can be accomplished by further comparisons of manual quantifications, as intended for the 3D case of the graphite microstructure in ductile cast iron. The integration of sub-voxel precision is also an important future goal.

REFERENCES


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Table 2. Comparison of the quantification results from the manual 2D approach using the images (a) and (b) in Figure 6, and the 2D and 3D results of our system, shown in Figure 7 and Figure 8.

Table 3. Time table comparing the conventional manual approach with our automatic method for quantification of ductile cast iron.

Table 4. The data sets from this paper, with typical pre-computation times and typical volume rendering frame rates (viewport 512x512).


