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ANALYSING CLEAT ANGLES IN COAL SEAMS USING IMAGE ANALYSIS TECHNIQUES ON ARTIFICIAL DRILLING CUTTINGS AND PREPARED COAL BLOCKS

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(10 figures, 2 tables)

ABSTRACT. For coal seams, considered as gas reservoirs, the orientation of the major cleat directions are dominating the flow direction and control the Darcy permeability. Information on the intra-cleat angles is obtained from coal fragments, which simulate drill cuttings. The methodology here below describes the use of image analysis techniques to determine from cuttings the intra-cleat angle and the angles between the cleats and bedding. The analysis is based on the phenomenon that cleats and bedding planes form the weakest bounds in a coal bed. Up to two thousand fragments, of three French coal samples, are analysed to characterize a cleat angle distribution for each coal. After the extraction of the (sub-) spherical fragments, shape factors are calculated for the fragments left behind. These shape factors act as a second filter, which remove grains with no rectangular or parallel like shape. The relationships between measured spatial properties are summarized into frequency histograms, which give a picture of the most abundant face angles in the accepted fragments. The resulting histograms are compared with 3D cleat angle reconstructions of the same coal samples, obtained from CT-scans. These scans are analyzed on their fracture patterns in three orthogonal directions. Here the results are from macro-cleat spacings with a larger cleat distance than obtained from the fragments.

Keywords: Coal, Cuttings, Image Analysis, Cleat, Angle Distribution, CT-scan.

1. Introduction

If coal seams are considered as gas reservoirs for methane production and CO_2 storage, one requires an evaluation of the flow characteristics near the injection/production wells and, when possible, infer from these the flow behaviour through the coal seam. Transport of gases and water through coal seams takes place mainly along the macro-cleat system, which acts as the major flow path. The cleat distance in this system varies from centimetre to decimetre scale. Within this macro-system, micro-cleats partly follow this structure. For another part, it follows the matrix structure of the coal, which is defined by the maceral and mineral content. In coal, the two major directions of the macro- system have to be considered, namely the rather continuous face cleats and the discontinuous butt cleats (Pattison et al., 1996). In order to predict the flow capacity and direction, a thorough study of the cleat properties, such as cleat spacing, cleat apertures and cleat angles are of great importance. These flow characteristics are needed as input in coal reservoir models, such as explained by Bossie-Codreanu et al. (2003). As described in many papers (de Haan, 1999; Bertheux, 2000; Wolf et al., 1999) the dominant flow direction is related to the existing cleat system. This structural feature is the main property controlling the Darcy permeability.

Information on the cleat stress patterns is normally provided from the regional geology, appraisal drillings and sometimes from coalmines. Hence, investigations are normally carried out on samples obtained from the following sources, taking into consideration their advantages and disadvantages:

- From Outcrops: easily accessible but the coal often is seriously weathered.
- From Core plugs: difficult to obtain, expensive, the pore quality hard to assess, due to breaking and grinding.
- From Mines: if present and accessible. Large fresh samples, not too much damaged, are probably the most representative.

Up to now, cuttings from drillings did not play an important role in this evaluation. The use of these small fragments (< 2 cm), to define the major cleat orientations in the appraisal phase, is based on a concept of Steidl (1997). In regular coalfields, the angle between both cleat systems and the bedding very often creates a more or less rectangular to parallelogram like shape of the fragments. These often-occurring shapes were considered to provide in two dimensions a good representation of the angle between two faces. In his study, the face angles of single grains were characterized by low-resolution image analysis. In this particular study the improvement on fragment recognition from cutting samples is based on an increased scale related pixel resolution and the development of a rotation program (Bertheux, 2000). Improvement of pixel resolution enhances the determination of fragment faces; the rotation program is able to improve the face orientation determination.

In addition, the introduction of cleat characterization, by the use of CT-scan images, gives another option to visualize the macro-cleat spacing and cleat orientation. With the use of micro-CT scanning techniques, Van Geet et al. (2001) were able to perform 3D-fracture analysis on 8 mm size Campine Basin coal samples. The aperture distribution of a micro-cleat system of an unstressed coal matrix was measured and compared with microscopy results. For this sample, a voxel size of about 22 μm was achieved. In our study CT scans of the three French coal blocks have been created with medical computer tomography. The blocks, about 30 to 50 cm in size, are analysed in terms of the cleat angle distribution of the macro-cleat system. A major part of the previously mentioned image analysis techniques, as applied on the cuttings, is also used to determine the cleat angle characteristics. The results of both methods, which were obtained at different scales, using different pixel resolutions, are compared.

2. Introduction to the image analysis technology

The previously mentioned methodologies use image analysis techniques to determine cleat angles and angles between the cleat and bedding. During drilling, coal breaks along weakness planes. By creating random fractures in the weak zone, all mentioned fracture types could be a print of the fragment population. Hence, the crushing method used here, grinding broken coal pieces of 10cc between two plates, provides fragments comparable to those created during drilling. The analysis is based on the perception that most of the cleats and the bedding plane are the zones of weakness. It is observed that fragments larger than 400 μm show one or more straight face, which can be related to fractures or bedding.

2.1. Analysis of cuttings

Cuttings show relatively straight boundaries in coal, i.e. the shapes of the fragments after breaking by drilling or grinding. Therefore, often the outline of a coal fragment represents the stress field related to cleat directions. Fragments were scanned at different magnifications to recognize straight faces. Based on image analysis experience, a minimum fragment length of 30 pixels was considered accurate. Up to two thousand fragments of the three French coal samples of different coal rank, were analysed in order to characterize a cleat angle distribution (Wolf et al., 2001; 2002). The fragments analysis is based on the straight face development, their length and relative orientation. In addition, the common spatial properties such as area, length, breadth, aspect ratio and roundness are measured. Only straight faces, with a minimum length in relation to the fragment length, are included in the study. After sorting the measured faces according to descending length, the possible cleat angles per fragment are calculated as the difference in orientation of the longest face and that of the next five faces in length. At most, four face angles per fragment are considered and stored as possible cleat angles. After analysing all fragments, the histograms of the abundant cleat angles show much noise. In this surplus of data, the goal of the analysis, the preferable angle(s), are obscured. This has two causes:

- All fragments are included, even when the shapes are not suitable e.g. too rounded.
- All measured directions are included, also those of random, more or less straight fractures.

In order to address the disadvantages of non-suitable fragment shapes, a geometrical filter has been developed. The (sub-)spherical fragments are rejected from the data. Next, shape factors are calculated for each remaining fragment. These factors are based on area and perimeter (dimensionless). Then they are compared with the shape factor of a parallelogram, with specific fragment features such as length, width and various angles as found. The relationship between these properties can be summarized in frequency histograms, which in turn gives an estimation of the most frequent face angles in the fragments, i.e. the cleat angles and the angles between cleats and the bedding plane.

2.2. Analysis of CT-scan images

In order to assess the relevance of the cleat angle histograms results are compared with a 3D-reconstruction of CT-scans. The CT-images are analyzed on their fracture patterns in three orthogonal planes. Using 3D rendering software in three orthogonal directions, the images were reconstructed. In three coal blocks the determination of open and mineral filled cleats and mineralised layers are distinguished, based on variation in densities. Next, the length and associated relative orientation of each fracture or mineral feature are measured. In addition, the total length per orientation is calculated. Cleat angle distributions are determined using the same procedure as with the coal fragments. Also, graphs of the cleat angle against accumulated cleat lengths are created.

During interpretation and comparison of the results of both analysing methods, important differences between resulting data must be taken into account:

- CT scan images, particularly the reconstructed XZ- and YZ-planes depend on the image reconstruction quality and on the image resolution, in relation to the presence of artefacts. The pixel resolution of the original CT-images is about 700 µm by 700 µm. Due to the interpolation process in the Z-direction and depending on the scan steps, the reconstructed images in the XZ- and YZ-plane do have the same resolution at best. The fracture features shown are running through the entire sample, crossing the different coal laminas. With the pixel definition, images usually preserve relationship between the spatial internal properties within the solid coal at that specific pixel level.
- The method using the crushed coal fragments relies on the assumption that the resultant histogram is representative for the "real" cleat system. It mainly represents detailed macro- *and* meso- cleat system information in all directions at different microscopic magnifications, along with some micro features. (*Note*: *the orientation obtained concerns those cleats making up the Darcy permeability. In numerical models, this is the orientation we are looking for*). Small fragments are scanned at higher magnifications, which results into high-resolution scans. This reduces the pixel size below 100 µm and the fragments represent one or more laminae within the coal sample. The study shows that these fragments, when thoroughly analyzed, can give an estimation of the micro-cleat system at matrix scale and the distribution of cleat angles between the major cleat systems. (*Note: coal is divided in matrix and fracture regions. The matrix part is supposed to contain micro cleats-whereas the fracture region comprises the macro and meso-cleats.*)

The results then can be used in the construction of more realistic network models at various scales. It leads the way to diffusion modelling at micro-scale and permeability values input as parameters in reservoir flow models at macro-scale.

3. Equipment

The following equipment has been used:
for the fragment analysis:

- Quantimet 570C image analysis computer and dedicated software (Leica Micro-systems), capable of grabbing and processing 512x512 pixel colour images, 24 bit depth
- Sony DXC-950P video camera for digital colour or grey image acquisition
- Wild M3Z stereo-microscope (Leica Microsystems) with a view field ranging from 10 cm to 100 µm.
- Metzhauser x-y scan stage, 10x10 cm travel, with 0.25 µm steps.
- For both the fragment analysis and CT-scans:
- QWIN image analysis software (Leica Microsystems), version 2.5

for the CT-scans:

- AMIRA 3D visualization and modelling software (TGS Inc., USA)
- General Electric SX/I high speed sequential CT-scanner.

The functional character of the mentioned equipment is explained in the methodology section.

4. Methodology

In figure 1, a flow chart is presented, which describes stepwise the procedure that is used to create cuttings and to quantify their spatial characteristics. The feature results are used to calculate cleat angle distributions. Following the figure 1 scheme, the steps mentioned are discussed in the following sections.

4.1. Fragment production and sample preparation

The fragments are created through the mechanical simulation of drilling crushing. At intervals of 2 to 3 cm, more or less perpendicular to the layering, pieces of coal are

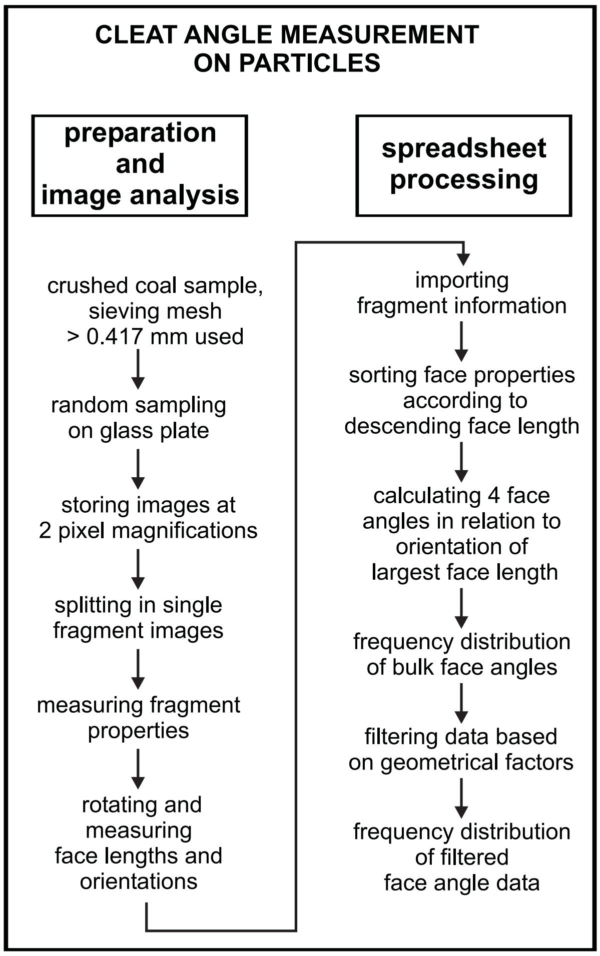


Figure 1. Flow chart of the image analysis procedure to define fracture angles from cuttings.

gathered and broken between two steel blocks, under pressure. The process continues until the sample breaks into pieces with a maximum length of 2 cm. The relevant fragments, showing clear-cut faces, have a minimum size of 0.417 mm. This is done by sieving with mesh 35 (Tyler screen scale) taken as the minimum grain size. To define the minimum number of observations needed for calculating a significant result, two aggregate samples were used. At a certainty level of 5 %, the student-T test confirmed that to guarantee a representative amount of fragments, at least 400 grains are needed to be analysed (Bertheux, 2000). This amount accounts for all fragments, without discrimination of the unsuitable fragments, i.e. well rounded and/or highly spherical fragments. Since those fragments are disregarded after filtering on fragment shape, and large numbers are no problem for automatic processing, a minimum of 2000 fragments per coal sample is chosen.

4.2. View field scanning and separate fragment recognition

Random scoops of coal pieces from the fragment collection are placed free of each other on a glass dish of a computer-controlled stage. The stage, undertaken under a stereomicroscope, is illuminated upwards from below, so that for each fragment a sharp outlined black silhouette is scanned. While inducing an error, this projection is considered as minimal, since the volume of the different fragments is not important. The assumption of Steidl (1997) that the angle between the cleat systems and bedding usually gives a rectangular to parallelogram like shape of the fragments, is adopted in this study. Furthermore, fragments of coal, as described in Pattison and al. (1996) break along well defined planes, which in effect we try to find through the filtering stage. Because of the large difference in lengths of the fragments, two magnifications of the same view field are chosen, in order to get a better accuracy at pixel level (Figure 2). A minimum face length of 30 pixels was considered to be accurate. Hence, the fragments were separated in two

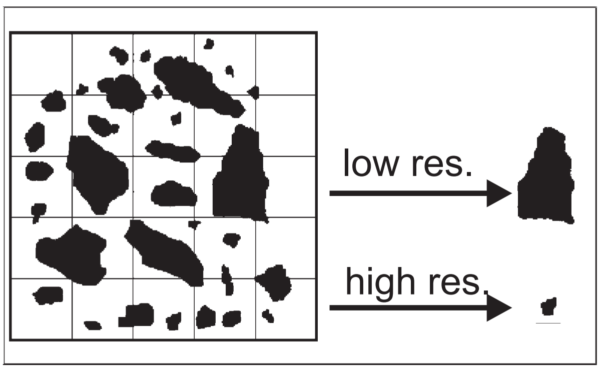


Figure 2. From a fragment aggregate to single fragment images at different resolutions.

area size groups. At a low magnification the calibration values for the field view length and pixel lengths, are respectively 46,3 mm and 90 μm. At this magnification, the total amount of fragments in an image, about 100, is scanned and stored in the Quantimet 570 as a 512 x 512 pixel - 8 bit - grey image. The area size of the grains varies from 1600 mm^2 – 7.5 mm^2. Next, at high magnification, 25 adjacent sub-images are automatically scanned and transferred to the Quantimet in an identical way (Figure 2). Here the field view length and pixel length are respectively 10.8 mm and 21 μm. The grain area varies from 7.5 mm^2 – 0.417 mm^2.

4.3. Fragment feature characterization

In the image analysis program QWIN; a fully automated procedure splits each multi-fragment image in single fragment images. Each fragment gets a one-pixel wide envelope, which acts as an outline. Then the software quantifies for each fragment the area, the perimeter, the fragment face angles, length and width, according to the corresponding calibration values. A second program rotates each fragment in steps of 5° up to a full 180°. In each position the one pixel broad outline of the fragment is analysed on the presence of straight horizontal lines with a minimum length related to the fragment length. This is achieved by an image processing technique called "horizontal erosion". A boundary part that suits the previously mentioned conditions is then extended in both directions as long as its deviation is not more than one pixel, either up or down. Consequently, slightly curved boundaries are also recognized as straight faces. From each selected fragment boundary the total length and relative orientation is stored, according to the rotation angle.

4.4. Data storage, management and definition of angles

After rotating all fragments, the dataset is transferred into spreadsheets. Spatial data of each fragment are stored, including their relative orientations and the lengths of all straight faces. Then face lengths and corresponding orientations are sorted to descending length. The major cleat angles per fragment are calculated as the difference in orientation of the longest face related to the next five length faces. Therefore, at most four face angles per fragment are stored.

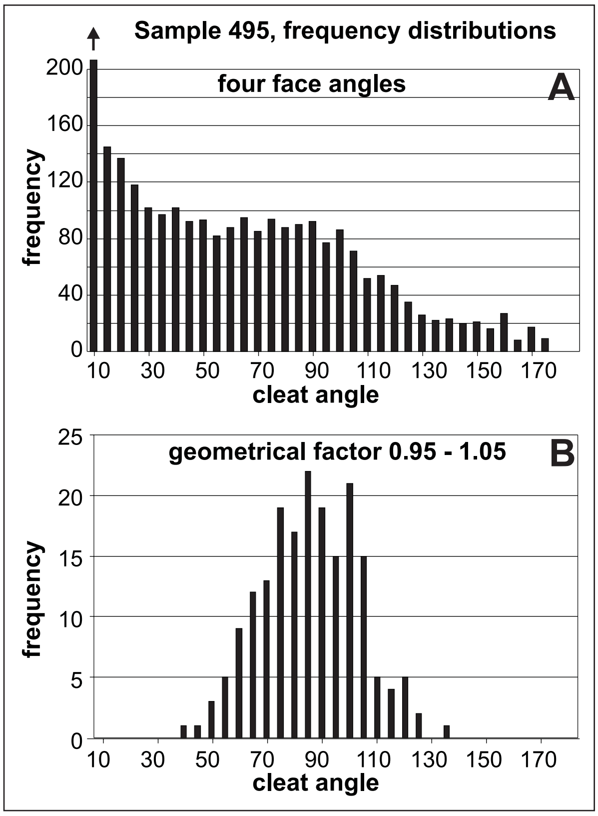
4.5. Fragment discrimination by filtering

Due to the presence of many randomly spread face orientations from fragments with a partly or fully eroded shape (i.e. high roundness), the bulk spreading of the calculated cleat angles gives indistinct data. However, recognizable fracture angles are present in those fragments with a rectangular or poly-faced shape. Hence, a dimensionless filter based on parallelogram features, is introduced (Eq. 1). This filter compares the surface and envelope of a fragment with a defined parallelogram. For each fragment, the fragment area (A_{gr}) is related to its perimeter (P_{gr}). Then the four face angles (α) and associated side lengths (L_{gr},B_{gr}) are used to reconstruct parallelograms. Both dimensionless values, define a geometrical factor, *GF*.

$$GF = \frac{\dfrac{A_{gr}}{P_{gr}^{\ 2}}}{\dfrac{L_{gr} * B_{gr} * \sin(\alpha)}{(2*(L_{gr}+B_{gr}))^2}} \qquad \text{Eq. 1}$$

With: A_{gr} : fragment area
L_{gr} : fragment length
P_{gr} : fragment perimeter
B_{gr} : fragment width

The actual application of the geometrical filter is applied to the frequency distribution of cleat angles for which the geometrical factor falls within the range from 0.95 to 1.05, indicative of the closeness to a parallelogram shape (Figure 3). Only a limited range of cleat angles fit within this established range and the histogram clearly shows the quantity of preferred angles.



Figures 3 A, B. Comparison of an unfiltered (A) and filtered (B) cleat angle distribution, using a geometrical factor of 0.95 to 1.05.

5. Defining cleat angles using CT scans.

From three different French coal blocks, X ray tomography images were produced at the "Institut Français du Petrole". They were made available as sequential scans in RAW and JPEG format, as 512 x 512, 256 grey levels images. Each pixel in the XY-plane represents an area of 0.7 by 0.7 mm. Open cleats do have the lowest grey level values (near zero) and minerals the highest, evolving to pure white (level 255). The number of slices (Z stacks) varied in each sample and ranged from 330 to 50, with a mutual distance of 1 mm between the slices (Figure 4). Using the 3D modelling and visualization software "AMIRA", the XY-direction is used to render images in the XZ- and YZ-plane (Figure 5). Figure 6 shows the flow chart for the way to obtain cleat angle distributions of CT-scans.

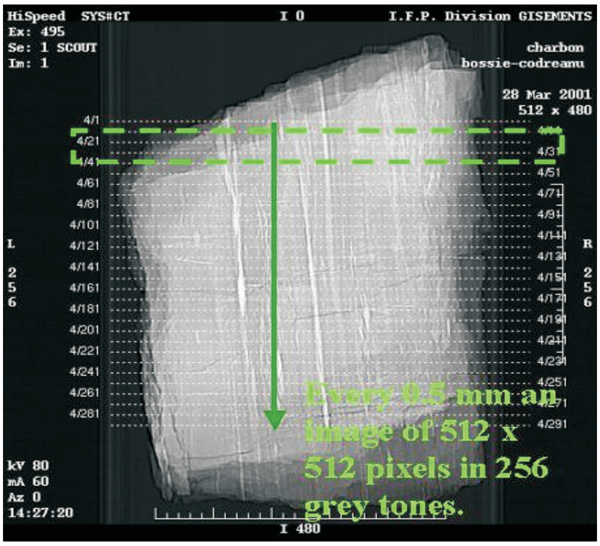


Figure 4. X-ray view on the top of sample 495. The arrow shows the scans according to the Z- direction.

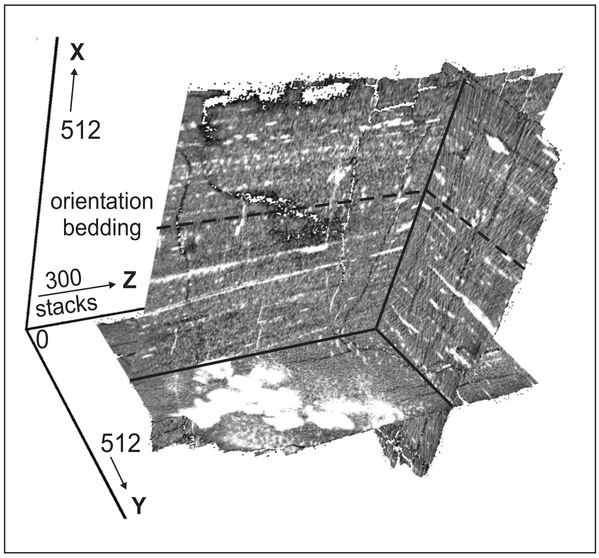


Figure 5. Sample 495, combined XY- (original slice), and the ZX- and ZY - reconstructed sections.

5.1. Image acquisition, binary recognition and cleat segmentation with orientation

All images are examined with Qwin for open cleats, mineral filled cleats and mineralised layers. Due to the presence of high density minerals, which act as high contrast objects and photon starvation over the length of the coal body, many images show a poor grey level segmentation and by that a relatively low resolution (Figure 7). Van Geet (2001) is also mentioning beam hardening as a disturbing effect on micro samples of coal. This problem was not recognized as a major issue in our samples. Both artefacts were not corrected for during the construction of the raw images. For this reason these artefacts are removed with a "linear open" image processing procedure. This reconstruction algorithm acts as a filter, which keeps continuous elongated individual structures and removes non-continuous small structures. All removed artefacts are scattered diagonal lineament resembling objects. The resulting effect is that open cleats are better distinguished. Finally three binary images were produced from each image; the envelope, open cleats and open cleats with minerals (Figure 8). The cleat images are reduced to lines (skeletonizing) cut on their intersections and measured, based on length and orientation. All cleat orientations are measured relative to an imaginary horizontal line. To open cleats and mineral filled cleats

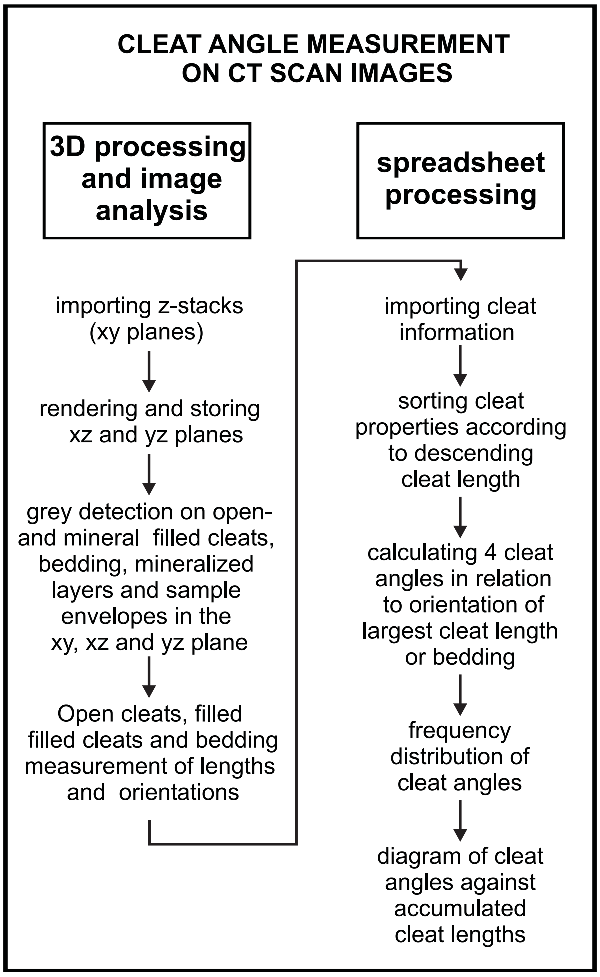


Figure 6. Flow chart of the image analysis procedure to define fracture angles from CT scans.

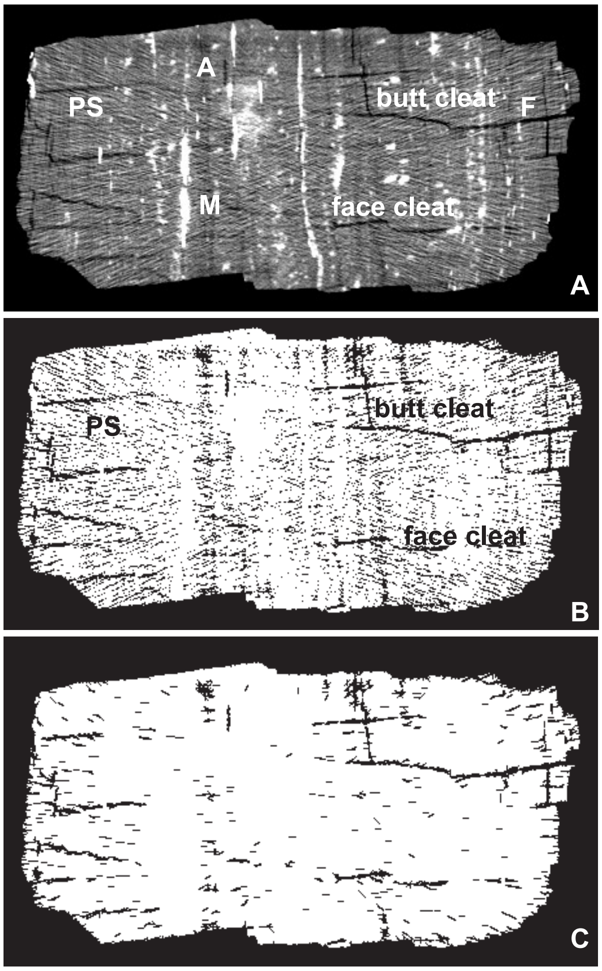


Figure 7. A: CT scan, showing black face- and butt cleats (F), white mineral filling (M), blurred cleats (A), distortion by photon starvation (PS). **7. B**: Initial detection of the open cleats with artefacts. **7. C**: Resulting open cleat system, after "linear open" procedure (no manual editing).

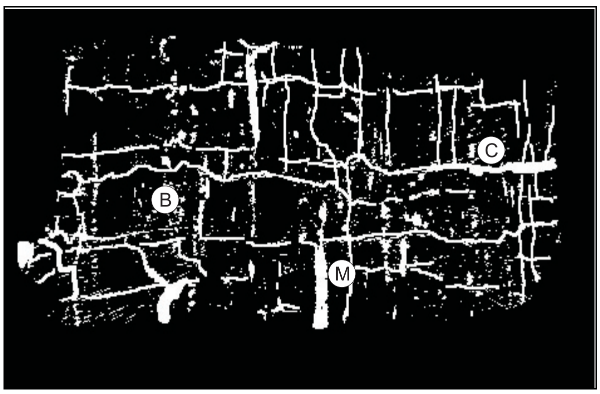


Figure 8. Detected in white, open cleats (C), mineral filled fractures (M) and bedding (B).

are attributed different colours. In this way, it is possible to create a 3D-reconstruction in which the system of open cleats, mineral filled cleats and mineralised layers can be distinguished.

5.2. Data storage, management and definition of angles

The final data are processed in a spreadsheet in the same way as the fragment data. The major angle in each image is taken as the reference for the cleat angles. The geometrical filter described above is not necessary. Additionally all cleat lengths with the same orientation are cumulated and plotted against the cleat angles.

6. Results

Two different sources, coal fragments and CT-scans of coal blocks, are used to identify the geometric attributes of coal cleat systems of three French coals.

6.1. Results of the fragment analysis

The objective of these analyses, meant to recognize the dominant cleat angles and eventually the cleat density in a coal, is possible when a representative amount of cuttings or coal chips is available. Image analysis provides a raw or cumulative data set with a lot of noise, not representative of typical cutting shapes. Therefore, a geometrical filter based on quadrangle values, e.g. squares and parallelograms, is essential for the acceptance of certain fragments. About two thousand fragment images of a sample group give a statistically confident result for the filtered outcomes. These results show that:

- Qwin is able to separate and scan single fragments at different resolutions. The fragments are measured separately on their perimeter and straight faces, including orientation. The relevant fragment size for these experiments is related to its visual recognition and set at a minimum of 0.5 mm.
- The image analysis results provide raw data about all particle faces, including their orientations and face lengths.
- Geometrical filters suppress the noise created by unaccepted grain shapes, i.e. non-angular fragments with a high roundness and high sphericity. After filtering, usually two or three angle concentrations are present. Accumulations around 90° are frequently, but not necessarily present.
- After filtering, the amount of accepted fragments is usually between about 250 and 500.

The samples show that a bi-modal or multi-modal distribution of the angles can be accounted for, based on the filtered outcomes. The following results have been found with a filter factor of 0.95 – 1.05. (Note: an angle cut off from 150° to 30° is incorporated). Table 1 shows the maximum values in cleat angle distributions, present in the different cleat samples. A variation in cleat size, cleat density, and cleat angle frequencies, as a function of maceral content, has not been studied yet.

Sample	Angle max.1	Angle max.2	Angle max.3	Angle max.4
495	85°	100°	75°	
457	85°	100°	70°	55°
446	75°	65°	100°	110°

Table 1. Maximum cleat angles as recognized in the cuttings of three French samples.

6.2. Results on the CT-scans

The objective of these analyses, to recognize the major visible cleat angles and cleat density in a coal, is possible when a representative amount of "stacked" images is available. Image analysis is able to remove noise from the reconstructed scans, but some manual editing on poor quality images is often needed if the optimum threshold values for void, matrix and minerals are overlapping and fading in the image. In general, the macro-cleat system can be interpreted in the original XY-plane and, if the number of stacked images and stepping sizes in the Z-direction are satisfying, the same analysis can be performed in the XZ- and YZ-direction.

- A majority of face and butt cleat related fractures are visible in the reconstructed CT-images. A spatial distinction can be made between open cleats, mineral filled cleats and bedding. The minimum resolution, required for open cleat detection is 0.5 pixel or about 0.35 mm. At lower sizes, the grey-tone values of the matrix and mineral pixels are "incorporating" cleat pixels. They average the grey-tones above their maximum threshold.

Sample	Angle max.1	Angle max.2	Angle max.3	Cleat type
495-XY	90°			empty + filled
495-XZ	90°			empty + filled
495-YZ	90°			empty + filled
495-XYZ	90°			empty + filled
457-XY	70°	40°	130°	empty
446-XY	130°	90°	60°	empty + filled

Table 2. Maximum cleat angles as recognized in the CT-scans of three French samples.

- Large areas of filled cleats or layering are reduced to strike representing lines, by image processing. Low angle intersections of a thick layer, which create large areas, are discarded by the program.
- Table 2 shows the maximum values in cleat angle distributions, present in the different scanned samples. Due to the poor results in the XZ and YZ plane, the sample numbers 457 and 446 were only useful in the XY-direction.

6.3. Comparison of cutting and CT-scan results

Due to the relatively low resolution, the CT-images provide a restricted amount of cleat directions. The information from the coal is thus more limited, since the blocks represent just a part of the seam. On the contrary, the resulting cleat directions of the scanned cuttings mechanically produced, make up a statistical representative database closer to the real orientation situation occurring over the entire seam, providing the block is reasonably representative. Fragments, ranging from small to large, are generally broken according to zones of weakness. This process extends within the matrix, at maceral scale (micro-scale). Hence, the variability of angles resulting from the cutting is much higher. Comparing both methods of angle analysis one concludes that:

- If sufficient CT-images are present, angles can be measured in different directions and both methods become comparable (Figure 9). This is due to the fact that the increase of the number of images increases the statistical chances of sampling meso- and macro-cleats. The difference between the methods nevertheless still subsists, since cuttings also sample the micro scale domain.
- The angle resolution of cuttings proved, after several test runs, to be higher (5° steps) compared to CT-measurements and its mentioned low pixel resolution (10°). The noise from which CT-images suffer, blurs the cleat orientation distribution. Consequently, the angle-distribution of the cutting analysis is twice as detailed. *Note: for the comparison, the accuracy of the cutting angle-distribution was also reduced to 10°.*
- Figure 10 shows two opposite trends since the outcomes of the CT-scans are not representative. Only nine images of sample 446 in the XY-plane could be used. Hence, images in the XZ- and YZ-plane could not be reconstructed. In addition, large intersections with mineral filled cleats were removed, because they provided a reduced amount of information of the remaining filled and open cleats. One direction, which apparently represents the angle zone of about 50° to 100°, is even fully discarded.

Finally it can be concluded, that if sufficient data are present, either from fragments (about 2000) or high resolution CT-images (more than 30), a reliable angle distribution can be created. His distribution can be used as an input parameter for the cleat orientation in reservoir flow simulations (Bossie Codreanu et al., 2003). While accuracy of the cutting method is higher, both methods can be used for engineering purposes.

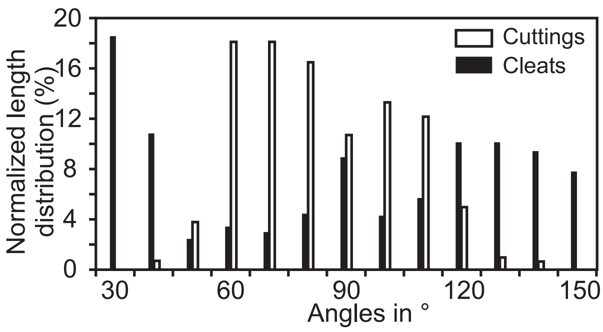


Figure 10. Angle distribution of sample 446 cuttings and the distribution of the open cleats of a limited amount (9) of CT-XY scans. This non-representative number of images results into an unpredictable response.

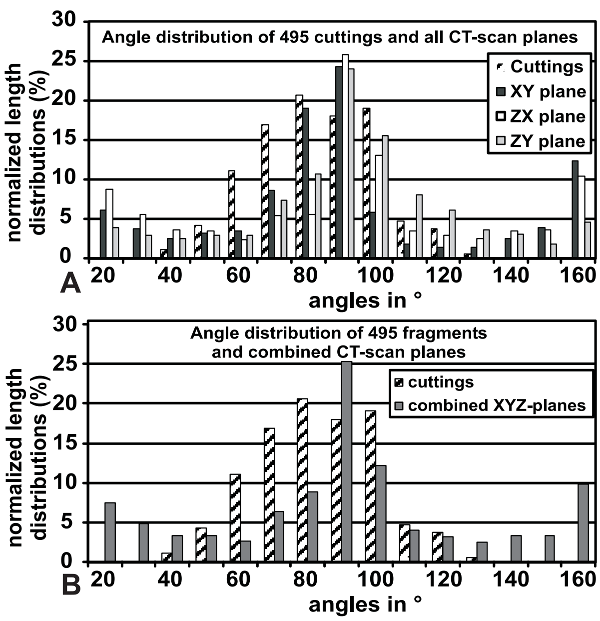


Figure 9 A,B. Comparison of cleat angle results from fragments and CT scans. A: Fragments versus the CT-scan XY- plane and reconstructed ZX- and ZY- planes. B: Fragments versus the combined CT-scan XY, ZX and ZY planes.

7. Acknowledgements

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