Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 17 (2014) 772 – 777

www.elsevier.com/locate/procedia

Variety Management in Manufacturing. Proceedings of the 47th CIRP Conference on Manufacturing Systems

Quality Control in the Production Process of SMC Lightweight Material

Alexandra Kraemer[a*], Song Lin[b], Daniel Brabandt[a], Thomas Böhlke[b] , Gisela Lanza[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology, Karlsruhe, Germany*
[b]*Institute of Engineering Mechanics ITM, Karlsruhe Institute of Technology, Karlsruhe, Germany*

* Corresponding author. Tel.: +49 721 44296; fax: +49 721 608-45005. *E-mail address:* alexandra.kraemer@kit.edu

Abstract

The use of sheet molding compounds (SMC) in diverse applications requires different specific material properties for each type of finished parts. These material properties have to be assured by a reliable quality control, which does not only have to be performed for the prefabricated SMC itself but also during the production process of the semi-finished material. This is of high importance because quality fluctuations and defects can already occur during the production of the semi-finished SMC. This results in high scrap rates as well as machine failure and can additionally cause further problems in the following process steps. Hence, an inline quality control can help to establish objective quality criteria for semi-finished SMC and can enable controlled and stable production processes.

Therefore, this paper deals with quality assurance in the production process of semi-finished sheet molding compounds. Air entrapping and fiber distribution are identified as two parameters that influence the quality of the semi-finished product significantly. In addition, the early detection of a pending carrier foil failure can help to establish a stable process. The focus of this paper lies on how various, individually adapted metrology systems can be used for the detection of the respective characteristics and integrated into the production process of the semi-finished SMC. In particular, optical systems, such as area scan cameras and laser stripe sensors as well as thermographic sensors are discussed and possibilities for application-related sensor data evaluation are shown. This helps to reduce the scrap rates of parts and to establish a further automated production process.

Selection and peer-review under responsibility of the International Scientific Committee of "The 47th CIRP Conference on Manufacturing Systems" in the person of the Conference Chair Professor Hoda ElMaraghy"

Keywords: Quality Control; Lightweight; SMC Production

1. Introduction

Individual mobility and transportation is getting more and more important in modern society worldwide. The limited availability of fossil fuel and ecological considerations make a reduction of fuel consumption and hence lower carbon dioxide emission necessary. This development is supported by new regulations of e.g. the European Union and the US, which focus on the reduction of carbon dioxide emissions of OEM car-fleets [1]. One possibility to reduce carbon dioxide emissions is the use of lightweight materials in vehicles. Independent from the drive concept (e.g. fuel, hybrid or electric drive) lightweight materials lead to a reduction of the moving mass and accordingly to lower energy consumption without decrease of passenger safety. One group of lightweight materials is glass fiber reinforced plastics like sheet molding compounds (SMC). SMCs have a wide area of use and show excellent mechanical, chemical and physical properties. These materials thereby offer a good formability in combination with reduced weight. In contrast to other fiber reinforced plastics, SMC offers the advantage that it can be produced at relatively low costs and with high productivity

Selection and peer-review under responsibility of the International Scientific Committee of "The 47th CIRP Conference on Manufacturing Systems" in the person of the Conference Chair Professor Hoda ElMaraghy"
doi:10.1016/j.procir.2014.01.138

because of its short cycle times. This is due to the fact that the press based forming operation is performed separately from the production of the semi-finished material. In addition, SMCs are versatile materials and their application comprises not only multiple exterior and interior parts for the automotive and transportation sector but also components for other applications, such as renewable energy [2].

The use of SMC in such diverse applications requires adapted formulations of the sheet molding compounds with different specific material properties for each type of finished parts. These material properties have to be assured by a reliable quality control, which does not only have to be performed for the prefabricated SMC itself but also during the production process of the semi-finished material. This is necessary because inhomogeneities in the material, quality fluctuations and defects can occur during the production process of the semi-finished SMC. The results are high scrap rates as well as machine failure and can additionally cause further problems in the following process steps.

To counteract this reliable quality assurance has to be integrated in the production process. Therefore, this paper deals with different metrology systems which can be used for identifying and measuring quality critical defects already in the production process of semi-finished sheet molding compounds. Due to the continuous production principle the focus is set on solutions for inline quality control for semi-finished SMC. Based on an analysis of occurring defects at critical process steps the paper will focus on how various, individually adapted metrology systems can be used for the detection of the respective characteristics and integrated into the production process of the semi-finished SMC. In the following, three quality critical influences in the production process are identified. Different measurement metrology systems are be discussed and evaluated according to their potential for inline quality control.

2. SMC Production Process

The production process of SMC consists of four steps: First the thermoset resin is mixed with fillers and additives, such as thickening agent, in a batch mixer. The proportionate dosage and mixture is critical for the later properties of the SMC. Then the resin is continuously applied onto the two moving upper and lower carrier foils by two doctor blades, as depicted in Fig. 1.

In the next step, the reinforcing glass fiber rovings, i.e. bundled fibers with an individual diameter of ca. 14 µm, are chopped from strands by a cutting unit and fall down in a random fashion on the resin, which is transported on the lower foil. The cut fibers usually have a length of 25 mm and 50 mm, respectively. The material then enters the impregnation area, where the upper foil, which is covered with resin as well, is added and calender rolls are used to homogenize and compact the fiber-resin mixture by external pressure. This step is crucial concerning the embedding of the fibers in the matrix (impregnation) and has a significant influence on the air entrapping inside the material [3].

Leaving the impregnation area, the semi-finished mat is rolled up and then transported to a curing area with controlled environmental conditions. During this so-called maturation period the thickening agent helps to further impregnate the fibers [3].

After curing one to three days, the SMC gets its final three-dimensional shape in a hot-pressing process. High temperatures (higher 130°C) and high applied pressures (more than 30 bar) are necessary [3].

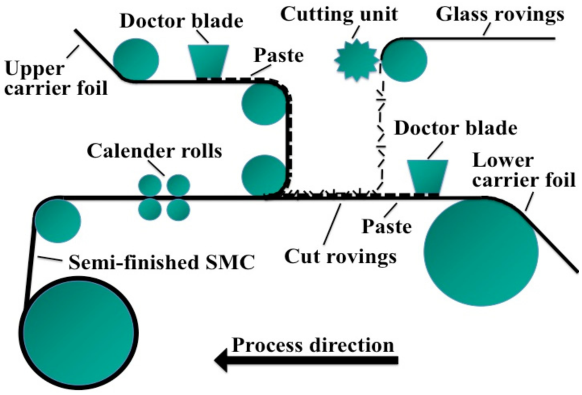

Fig. 1: Production of semi-finished SMC

3. Defects in the Production Process of SMC

On the way to an automated production of SMC one key variable is the quality assurance in the production process of the semi-finished material. Defects, which occur in these process steps, can influence the performance of the later part significantly. One can identify three critical parameters that have to be controlled during the process: fiber distribution, air entrapping and foil tearing. While the first two have a great influence on the quality of the semi-finished material and thus are important for the subsequent process steps, foil tearing can lead to failure of the machine and downtime of the production.

Due to the anisotropic properties of the reinforcing fibers their orientation has a major impact on the mechanical properties of the material, such as strength and stiffness. If the *fiber distribution* shows a preferred orientation the mechanical properties of the semi-finished material and also the final part are anisotropic [3]. This effect is used in long-fiber reinforced polymers. In the case of SMC the material is supposed to show constant mechanical properties independent from the process direction during production. Thus, the quasi-isotropic distribution of the fibers has to be controlled right after their application onto the resin.

Air entrapping during the production of the semi-finished material can lead to failure of the fiber-matrix-structure or surface defects. During impregnation, part of the entrapped air is pressed out of the semi-finished material, but a significant amount stays inside the material. If entrapped gas cannot escape from the material during the subsequent hot pressing process, it can expand inside the material due to the high temperatures. This influences the shape forming and ripples, bubbles and deformations on the part's surface can occur. In addition, the part can be twisted and thus unusable [3, 4, 5]. Hence, it is important to detect the pore volume in an early stage of the production process.

Apart from quality defects inside the material, a stable and continuous production process has to be ensured as well, i.e. machine failure should be avoided. Here, *tearing of the carrier foil* during production has a major impact on the process stability. The tears are not only responsible – due to the low viscosity of the matrix - for defects in the semi-finished material but also can lead to a failure of the foil across the entire width resulting in a stop of the process and contamination of the machine. Thus, in addition to the inline quality assurance of the semi-finished product itself, a process control has to be integrated.

All three identified challenges can be detected at different position in the production process and thus require different individually adapted measurement systems (Fig. 2). However, all systems have to fulfill the following criteria:

- Inline integration
- Non-contact method
- High-speed measurement

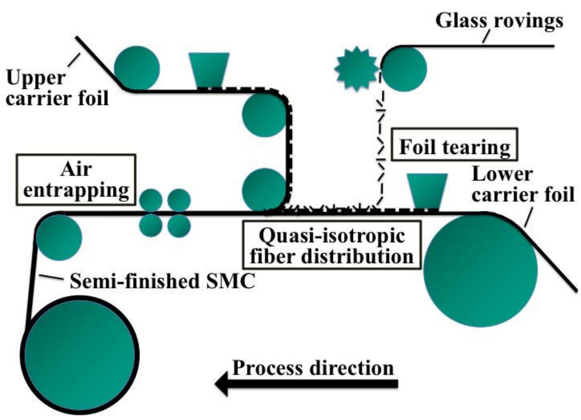

Fig. 2: Quality relevant parameters in the production of semi-finished SMC

Thus, in the following it is concentrated on three different non-contact measurement methods for 2D and 3D inspection. *Lock-in thermography* can be used for inspection of air entrapping inside the material and offers the advantage volume information as well as relatively short image acquisition times. *Laser stripe sensors* provide three-dimensional information about the surface of a structure. In addition, they are suitable for moving parts, because a line scan is used. They are therefore chosen as one method for the detection of wrinkles in the foil. On the other hand, a *camera system* can be a relatively cost effective option, which can also be integrated inline, but is limited to two dimensions.

3.1. Air Entrapping

The challenge for the inspection of air entrapping in the semi-finished material lies in inline-integration of a relatively fast method that can be used to examine the inner structure of the material and makes volume defects visible. Radiographic methods are not suitable, because the integration of ionizing radiation directly in the process would require additional safety measures. In the case of air-coupled ultrasound, the sensor has to be aligned at very short distance from the material's surface. Its very sensitive reactions to changes of the air gap, which are caused by the movement of the material during the process, make inline integration difficult. Thus, lock-in thermography was chosen, which is based on the fact that the heat capacities of air and SMC differ. Infrared cameras allow detecting these differences in temperature of the material. The infrared camera has to be sensitive to small differences in temperature. Scales of about 0,015°K are possible [6]. Two types of heat flow thermography exist: the active and the passive one. In the case of SMC the active approach is used, where the material is heated up by a light source. To be detected, the defects have to be approximately as big as their distance from the surface of the material.

Pre-tests with a stationary thermography setup with flash lamps revealed visible pores (Fig. 3). In addition, the entrapped air between the upper carrier foil and the actual material are visible as well and could cause misinterpretation of the results. Hence, further tests are necessary to establish a distinct and reliable result and to determine the detection limit in pore size. Using a laser line as thermal source, inline-integration can be achieved.

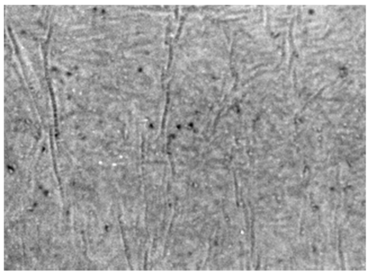

Fig. 3: Thermographic image of semi-finished SMC

3.2. *Fiber Distribution*

In order to examine the quasi-isotropic properties of the fiber distribution and thus of the semi-finished SMC, the inline-acquisition of data is important.

To establish an inline process control, the data acquisition has to take place directly after the fibers are applied onto the resin. Here, a camera system is the system of choice, because for the detection algorithms, 2D information has to be provided. The quality of the generated picture is of great important to ensure a reliable data evaluation. Because of the high process velocities, the parameters must be chosen such that blurring of the image is avoided. Depending on their orientation on the resin the rovings show a width in process direction between 0.1 mm and 0.7 mm. To achieve an unblurred and still acceptable detection of the single rovings, with an average process speed of 6 m/s the shutter speed has to be below 1 ms. Tests were performed to adjust the resolution, illumination and field of view to make an exact and fast image acquisition possible. Due to the reflectivity of the fibers, only diffuse illumination can be used (Fig. 4). In addition, the wavelength of the light can influence the image as well. In our case the tests with blue-LED dome illumination (HPD-400-BL, CCS) in combination with a 5 Megapixel-Camera (BM-500 GE, JAI) showed the most

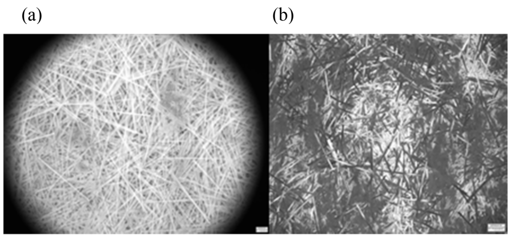

Fig. 4: Fiber Distribution: (a) blue dome illumination, low reflections; (b) red ring illumination, high reflections; courtesy of Stemmer Imaging GmbH (Puchheim, Germany)

promising results.

The evaluation is done with a *matlab*-based image processing algorithm, developed at ITM, Karlsruhe. The planar fiber bundle orientation distribution is determined based on an algorithm, which combines a Laplacian of Gaussian (LoG) image filter with an inverse Buffon transformation [7]. Here, the inverse Buffon transformation represents the planar fiber bundle orientation distribution function by using Fourier series. The results of the algorithm indicate the anisotropy of the planar fiber bundle orientation distribution. An image size of 75 x 75 mm² provides enough information to draw a reliable conclusion of the overall fiber distribution along the width of the SMC mat.

Fig. 5 shows images of two different fiber orientation distributions that were used to test the algorithm. Both images possess a resolution of 500 × 500 pixel².

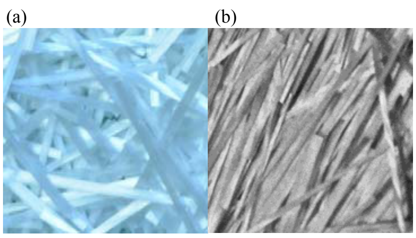

Fig. 5: Two images with different fiber bundle orientation distributions

The LoG results of the both images are given in Fig. 6, in which dark and light gray values give positive and negative responses. Fiber bundle edges manifest themselves as zero-crossing transit. Using the inverse Buffon transformation on the LoG results gives the resulting planar fiber bundle orientation distribution functions, which are shown in Fig. 7. The results indicate that a strong anisotropy can be found in the fiber bundle orientation distribution shown in Fig. 5(b). In this case, the preferred direction is about 115° clock-wisely, which can be also recognized in the LoG result in Fig. 6(b). It should be noticed that the planar fiber bundle orientation distributions in Fig. 7 are obtained based on the 2nd-order Fourier coefficients.

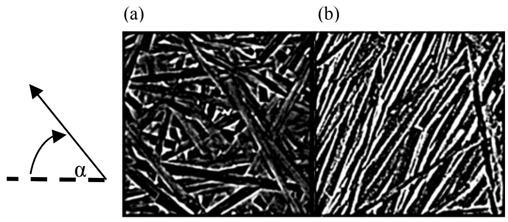

Fig. 6: LoG results of the images in Fig. 5

The next step is now the integration of the measurement setup in the SMC production process. It has to be evaluated at which time intervals the fiber distribution has to be checked during production and if it is necessary to further improve the algorithm to reduce processing time.

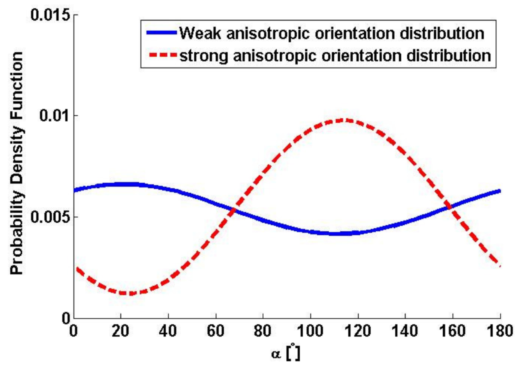

Fig. 7: Results of the planar fiber bundle orientation distribution function

3.3. Carrier Foil

In the production of SMC as semi-finished product one major problem is the risk of torn carrier foil. If for instance lumps of resin or foreign matter get stuck under the doctor blade, internal strain can cause the carrier foil to tear up. The result is a hole in the carrier foil which allows the resin to flow into the machine, consequently requiring a time consuming cleaning process, which leads to down time.

While on the one side of the doctor blade strain causes the foil to deform, on the other side the foil forms wrinkles because too much material piles up. The wrinkles caused by one single lump spread over the entire width of the foil and can be detected on the part of the carrier foil that is not covered in resin, i.e. in front of the first doctor blade (Fig. 8).

Experiments showed that it takes about 2 - 4 seconds from the first wrinkles until the final failure of the carrier foil. This property is used for the early detection of foil failure. Considering the time needed for an actual shut down of the machine, the automated detection has to be able to detect a pending failure about 1 second before it actually happens.

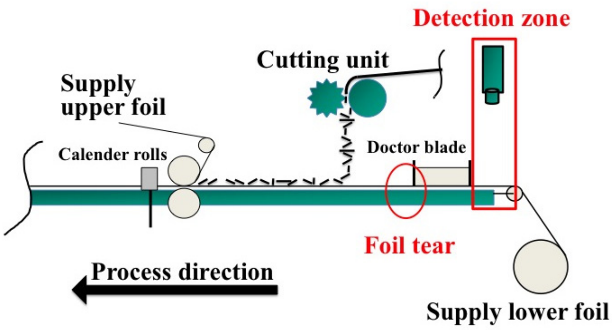

Fig. 8: Detection of foil tearing

A camera system was installed taking continuously pictures of the area in question (Fig. 9). To detect this defect at an early stage the pictures are analyzed with an edge detection algorithm in *Matlab* which renders the detected edges into white pixels in a black and white picture. The algorithm then counts the white pixels and decides based on the percentage of white pixels if the level of wrinkles suggests a pending failure of the carrier foil.

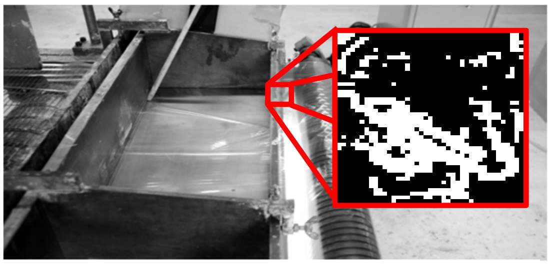

Fig. 9: Photo of the SMC machine. The red area represents the detection area of the camera system and an exemplary b/w-picture after edge detection

The detection algorithm for the edge detection has to be calibrated in a way that it only detects the actual wrinkles, thus a dynamic threshold value has to be defined. This value indicates how thick a detected edge has to be in order to not be considered random noise. If this value is too small, unevenness in the texture of the foil and its background can be misinterpreted as edges leading to a false detection of a pending failure. If the value is chosen too high, the algorithm might detect the foil failure too late in the process or even fail to detect any edges at all.

After testing the setup with 20 different cases of foil failure and five different edge detection algorithms (Sobel, Prewitt, Roberts, Laplace of Gaussian and Canny) the detection of foil failure was achieved within two seconds of the first wrinkles. In Fig. 10 the chart of an exemplary test run using the Sobel operator is visualized. It shows a considerable increase of white pixels in the 42nd frame which indicates the formation of the first wrinkles. The detection algorithm itself only takes 0.002 - 0.2 seconds. A time-critical detection of foil failure is thus possible. The major areas of further investigation are the definition of a proper critical level of detected edges that is considered a pending failure as well as the integration of the camera system in the machine.

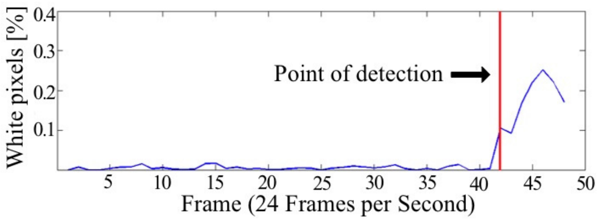

Fig. 10: Percentage of white pixels per frame. The red vertical line indicates the Frame in which the pending failure was detected. The end of the graph marks the actual point of failure.

In comparison to the area scan camera, a laser stripe sensor setup was used. The lasertriangulation principle offers the advantage of a linescan of the foil, which leads to a reduction of the amount of data and the processing time. In addition, the triangulation system also provides height information, such that a detection of the wrinkles is not only made possible by a variation of greyvalues but also offers the advantage of providing information about the shape of the wrinkles. Hence, lump-induced large wrinkles can be easily distinguished from process-inherent small wrinkles.

One has to take into account that the laser line projected on the foil partly is reflected on the surface of the foil, but also partly passes the transparent material and is backreflected on the underlying surface. This can lead to a second signal which is received by the detector. Thus, it is crucial to adjust the setup such that the laser line is projected angularly. In this position, the backreflected signal from the surface is not detected.

In Fig. 11 it can be seen that the shape of the foil is visible in the lasertriangulation signal. To visualize the results, here not only one laserline at a time was considered, but the whole area of a wrinkle. The color-coding gives the height information, but it can also be seen that there is no signal for the steep flanks of the wrinkle, because the reflected flank signal is not received by the detector. Thus, in the inline-setup it would be sufficient to detect the signal loss per laser line due to the change in geometry. Here also a threshold value has to be defined. This could be done in combination with the relative height information given by the triangulation sensor. Further steps comprise the establishing of an appropriate threshold value as well as the testing of the detection algorithm especially regarding the processing time.

(a)

(b)

Fig. 11: Lasertriangulation image (a) in comparison with a photographic image (b) of a test specimen made from the carrier foil

4. Conclusion and Outlook

The increasing importance of lightweight material especially in the automotive and transportation sector leads to the need of highly automated production processes. Thus, inline measurement systems are one of the important factors to assure the high quality of the product.

A reliable quality control does not only have to be performed for the prefabricated SMC itself but also during the production process of the semi-finished material, because inhomogeneities in the material, quality fluctuations and defects can occur during the production process of the semi-finished SMC. This results in high scrap rates as well as machine failure and can additionally cause further problems in the following process steps. Air entrapping and fiber distribution are identified as two parameters that influence the quality of the semi-finished product significantly. In addition, the early detection of a pending carrier foil failure can help to establish a stable process.

Based on the results of the measurements an inline integration of the chosen sensor systems for fiber distribution and foil control will be performed. Further reduction of the measurement and processing time is necessary to achieve an early detection and to avoid downtime of the production.

Thermography is a promising technique for inline inspection of air entrapping, but still has its drawbacks due to limited resolution and high process times. In future, more tests are necessary to evaluate its suitability for the inline-integration in a SMC process.

In addition, the relation between the results from air entrapping of the semi-finished material and the air entrapping and impregnation of the semi-finished mats after curing as well as the finished parts has to be further investigated. This information can be related with the material properties and can eventually lead to the definition of suitable quality parameters in the process.

5. Acknowledgements

This research project is funded by the European Union – European Fund for Regional Development and the federal state of Baden-Wuerttemberg. Managing Authority of the operational program RWB-EFRE is the Ministry of Rural Development, Food and Consumer Protection Baden-Wuerttemberg. For more information visit www.rwb-efre.baden-wuerttemberg.de.

We thank Fraunhofer Institute for Chemical Technology ICT (Pfinztal, Germany) for providing the test specimens and Edevis GmbH (Stuttgart, Germany) for performing thermographic measurements.

References

[1] VDMA and Roland Berger Strategy Consultants. E-Mobility – a promising field for the future. Opportunities and challenges for the German engineering industries. Roland Berger Strategy Consultants; 2011.

[2] Orgéas L, Dumont PJ. Sheet Molding Compounds. In: Wiley Encyclopedia of Composites; 2012.

[3] Ehrenstein, GW. Faserverbund-Kunststoffe (Fiber reinforced plastics). Munich: Carl Hanser Verlag; 2006.

[4] AVK – Industrievereinigung Verstärkte Kunststoffe e.V. (Federation of Reinforced Plastics) (Editor). Handbuch Faserverbundkunststoffe (Reinforced Plastics Handbook). 3rd edition. Wiesbaden ; 2010.

[5] Comte E, Merhi D, Michaud V, Månson J.A.E. Void formation and transport during SMC manufacturing: Effect of the glass fiber sizing. In: Polymer Composites. Lausanne; 2006, 289-298.

[6] Sackewitz M. Leitfaden zur Wärmefluss-Thermographie. Zerstörungsfreie Prüfung mit Bildverarbeitung. (Guideline for infrared thermography. Non-destructive testing by image processing). Erlangen: Fraunhofer-Allianz Vision; 2011.

[7] Kanatani, K. Procedures for stereological estimation of structural anisotropy. Int. J. Engineering Science 23 (5), 1985. 587–598.