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Process characterization for molding of paper bottles using computed tomography and structure tensor analysis

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Abstract

Packaging products find their significance in almost all classes of consumer goods and products. The use of plastic and metal based packaging for beverages is highly dominant. However, there is a constant urge for development of eco-friendly packaging alternatives. The article focuses on characterizing an inflatable core assisted paper bottle molding process with respect to the obtained fiber distribution in the bottle. Distribution of paper fibers affect product characteristics such as thickness and mechanical strength of the bottle. Assessment of fiber orientation using structure tensor analysis is therefore performed. The results confirmed non-uniform fiber compaction in the paper bottle. This gives rise to non-conformities such as non-uniform thickness distribution. The approach discussed in the work can be utilized as a Non Destructive Testing technique to evaluate the quality of paper bottles.

Keywords: Paper bottle, Fiber orientation, Molded paper products, Structure tensor analysis, Molding process

1 Introduction

Packaging industry is a growing and highly competitive market. In last two decades, plastics and metals have captivated the packaging field. Packaging products in general can be divided into three classes: Primary, Secondary and Tertiary packaging. **Primary packaging** also known by the name of consumer packaging, is a material that forms the first layer of packaging. In this case, the product is in direct contact with the content. Typical examples include, carton boxes, egg trays etc. **Secondary packaging** or transport packaging is the packaging that forms the outer covering of primary packaging. Several primary packaging can be grouped together inside a secondary packaging. Corrugated board box is a common example of this category. **Tertiary packaging** refers to the packaging products used for bulk material handling or warehouse storage such as stretch films and pallets.

Over the years, development in the paper industry has led to development of more bio-based products, satisfying consumer demands [1]. The use of paper as a packaging product is well known in modern times. These products are good alternative to their plastic counterparts because of the challenge in degradation imposed by plastic products. Paper packaging products in some cases can be recycled to extract cellulose fibers which can be used again. In other cases, where it is not possible to recycle the paper products, they can be disposed by methods less harmful to the environment compared to plastics. They are cheap, efficient and versatile mode of transporting and protecting wide variety of items. They are also light-weight and customizable as per product requirements [2]. Some of the common packaging items include: container-board, paperboard, paper bags and shipping sacks.

Beverage industry is highly dominated by plastic, metal and glass based packaging products. Due to constant thrive for sustainable alternatives, eco-friendly products such as tetra-pak[®] have emerged. However significant research is undergoing on development of molded paper products for carbonated beverages [3],[4]. Molded paper products can broadly be classified into Thick wall, Transfer molded, Thermoformed and Processed [5]. Transfer molded products are typically used for electronic packaging, fruit trays and egg cartons. One such product is the Green Fiber Bottle (GFB). The GFB is intended to be an environmentally sustainable alternative to the existing glass and plastic beer bottles [3]. A quality evaluation of such bottles was recently reported by Saxena et al.[6]. The authors pointed out an occurrence of non-conformities in the bottle production due to inflatable core assisted molding process. This requires to develop robust methods and approaches for evaluation and assessment of the paper bottle molding process.

The work carried out in this article focuses on evaluating the molding process at micro-level for production of paper bottles. Fiber orientation in different sections of the paper bottle is analyzed using structure tensor analysis. The results obtained are correlated with the manufacturing process and discussed in this study. For the study, two bottle specimens are produced with two inflatable cores made of silicone but differing in material composition. As the paper bottle is axi-symmetric, an evaluation on



3cm X 2cm strip from bottle is performed. The specimens are obtained from neck, body and bottom with curvatures. In total 6 samples are evaluated (3 each from bottle produced from two different core materials). The samples are scanned and the data-set is post-processed to visualize fiber orientation and thickness. The thickness of the paper in each of the section gives an estimate of fiber compaction. The results obtained are correlated with the manufacturing process and discussed in this study.

2 Manufacturing process

The manufacturing process for molding of paper bottles is based on the patent obtained by Søllner [7] in 2016. This is also the most recent available method for molding paper bottles as seen from the literature survey. The process is used as a benchmark in the current work and investigated further. The molding setup described in this section is available at the production facility of ecoXpac A/S, Denmark. The manufacturing method is a two stage process; the forming (or the shaping process) and the drying process. The pulp used for manufacturing bottles can be prepared in-house or can be bought from an external supplier.

The **forming process** is a shaping process, and does not require any heat. Free water is removed only by mechanical action of vacuum suction. The forming mold is a split cavity mold. Two halves of the mold are clamped together to form a hollow cavity (as shown in figure 1a). The mold when closed, reproduces a negative geometry of the intended bottle. The mold is drilled with holes sufficiently large enough to remove water. A wired mesh is stuck to the inner part of mold. The dimension of the mesh is as such that it allows water to pass through but it doesn't allow the paper fibers to go out, thereby forming the shape.

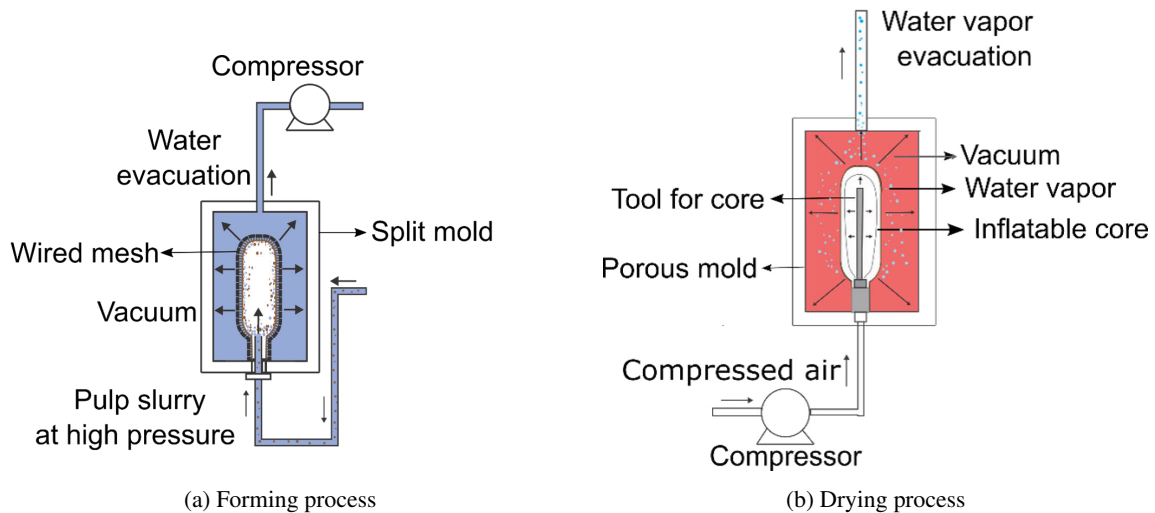


Figure 1: The paper bottle molding process

Pulp is injected into the forming mold with the help of a pump. Once the pulp is pumped in, it experiences a vacuum suction radially outwards. Pressure differential is created across the walls of the tool using vacuum suction. This process continues for a short span of time, to ease the formation of bottle shape. After the desired amount of pulp has been injected, injection stops and with the assistance from the vacuum suction, the free water is drained out from the pulp. The vacuum is then turned off and the mold is opened up to remove the wet geometry. The wet bottle is then transferred to a drying mold for the drying process with the help of a rotating table.

The **drying process** helps in removal of all the bound water that is absorbed by the paper fibers. The drying mold is also a combination of two half molds aligned similar to the forming mold (shown in figure 1b). The mold is made of porous material, unlike the forming tool. This is because, the wired mesh is unable to generate the desired surface finish and is replicated onto the bottle surface upon drying. The porous mold is preheated to the temperature required above the level for water evaporation. As the wet paper comes in contact with the hot tool, the drying process starts.

An inflatable core made of silicone material is then inserted in the cavity to press the formed bottle and release the bound water content. Vacuum suction is applied, which drives the bound water outside the drying mold to obtain a finished bottle. The core serves three purposes: (a) Compaction of wet fibers (b) Avoiding shrinkage of paper during the drying process and (c) Removal of the water absorbed by fibers by pressing. Pressure differential is created across the walls of the drying tool using vacuum suction. This facilitates the flow of water outwards during the process. Once the drying process is completed the mold opens up and the dried paper bottle is obtained. For this study, the bottles are produced using two different silicone materials. The

exact material composition is not disclosed due to a proprietary agreement with industrial partners. They are thus referred to as Silicone A and Silicone B in subsequent sections. The core has been identified as a critical element in the molding process and it's significance in achieving the good quality paper bottles has been cited in the literature [4] [6] [8].

3 Characterization of paper bottles

The characterization is performed on strips of size 3 cm X 2 cm from the bottle. The specimens are obtained from neck, body and bottom with curvatures (shown in figure 2). In total 6 samples were evaluated (3 each from bottle produced from two silicone materials). Measurements are conducted on a 'Zeiss Xradia 410 versa' system available at the 3D Imaging Center at Technical University of Denmark. For the 'Zeiss Xradia 410 versa' system, following process parameters are used: X-ray tube voltage = 40 kV, X-ray tube power = 10 W, Number of projections = 801, Integration time = 7s, Effective pixel size = 308 μm . Reconstruction is done with the commercial software package provided with the system. The reconstruction software is based on FDK algorithm[9] [10]. The scanned specimens are then analyzed for fiber orientation discussed in subsequent sections.

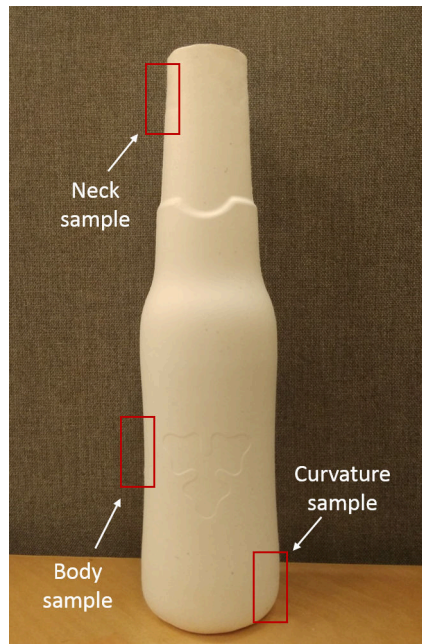


Figure 2: A molded bottle sample showing location of the specimens obtained for the study.

4 Fiber orientation

The orientation distribution of the fibers in paper is estimated using 3D volumetric data. To do so, the authors employed structure tensor analysis. **Structure tensor** is a measure of gradients in several directions in the volume and is given by the matrix shown in equation 1

$$J = \begin{bmatrix} J_{xx} & J_{xy} & J_{xz} \\ J_{xy} & J_{yy} & J_{yz} \\ J_{xz} & J_{yz} & J_{zz} \end{bmatrix} \quad (1)$$

In order to get a measure of orientation from the above defined structure tensor, the eigenvalue problem is solved for J . The main orientation is the eigenvector corresponding to the lowest eigenvalue of J [11] [12]. Using the approach discussed in this section, it is possible to find a main orientation for each of the voxels in a scan. However, the authors are only interested in the orientations from voxels actually contained in fibers. The fiber voxels are separated from the background voxels by a thresholding value. This is not easy to implement due to the low contrast between air and paper in the image data. A common approach for choosing an appropriate threshold value is Otsu's method.[13]. In order to be sure that only voxels in fibers are included in orientation analysis, a conservative threshold which is slightly higher than suggested by Otsu's method is chosen for the analysis. This is a deliberate choice justified by the fact that the intention here is to estimate orientation distribution of the fibers, and the number of observations for estimating such a distribution will still be high. Figure 3 shows estimated orientation distributions for all six samples. The samples obtained from Silicone A are named as 6B = Body sample, 6N = Neck sample and 6C = Curvature sample. Similarly, samples obtained from Silicone B are named as 26B = Body sample, 26N = Neck sample and 26C = Curvature sample. It can be seen that the fibers are mainly oriented in a plane along the z -axis. This indicates that during the molding process the wet fibers align themselves in vertical direction alongside the walls of the mold. This also facilitates good hydrogen bonding between

cellulose fibers facilitating production of a strong bottle sample. Also, the core material, doesn't seem to have any influence in orientation distribution.

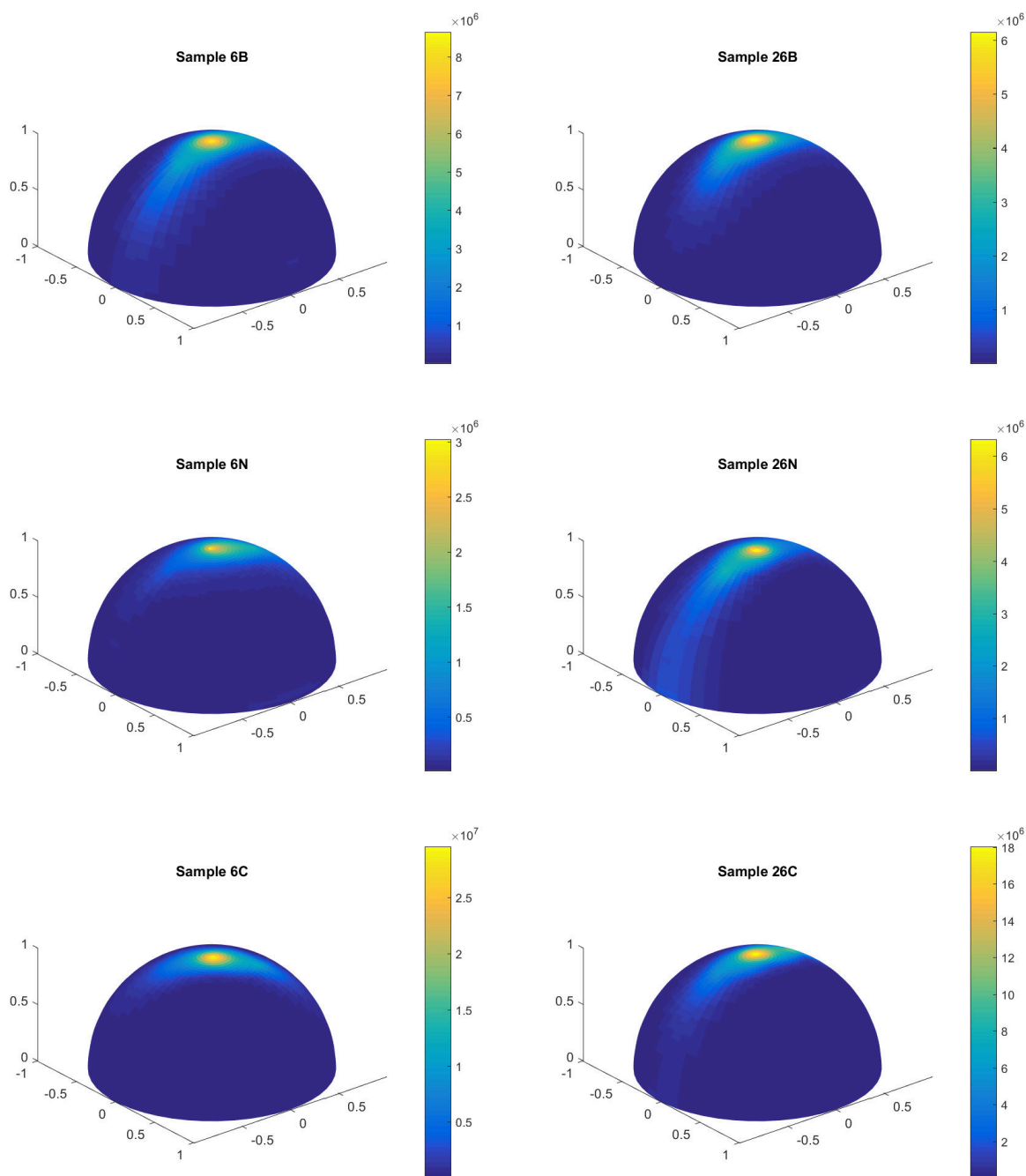


Figure 3: Estimates of orientation distributions for each of the six samples.

In order to illustrate the fiber orientations, a color scale based on the RGB system is employed. The color scheme is illustrated in Figure 4. The plane spanned by the two vectors \vec{u} and \vec{v} is the plane parallel to the paper plane. All voxels with an orientation in this plane are visualized as ranging from red to blue. The voxels with fiber orientations perpendicular to this plane are visualized as green. Figure 5a and 5b show 3D rendering and visualization in the neck specimen, Figure 5c and 5d show 3D rendering and visualization in the body specimen and Figure 5e and 5f show 3D rendering and visualization in the curvature specimen respectively for the bottle produced from Silicone B core material. It can be seen that almost negligible amount of fibers are aligned perpendicular to paper surface. This is indicative of the fact that the fibers are well compressed during the molding process, leaving no fiber coming out of the plane of paper.

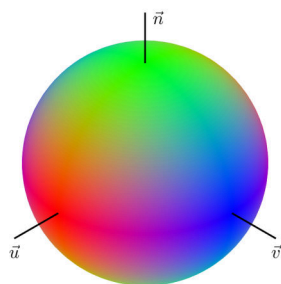


Figure 4: Color scheme for identifying fiber orientations

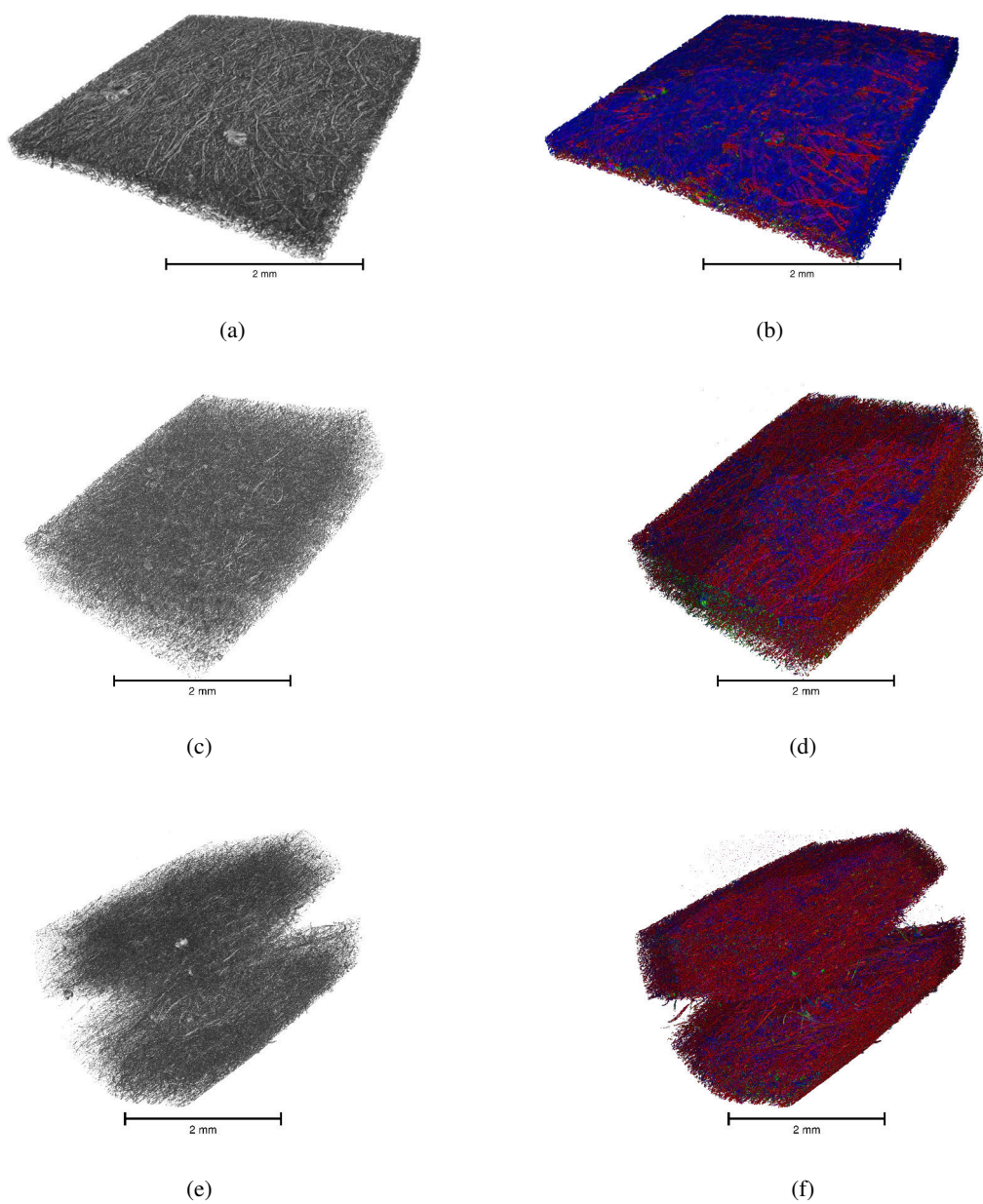


Figure 5: 3D rendering and visualization of fiber orientation in neck specimen (a) and (b), body specimen (c) and (d), curvature specimen (e) and (f) respectively for the bottle produced from Silicone B core material

5 Estimation of thickness

The occurrence of non-conformities due to uneven compaction pressure has been indicated several times in the recent literature [6][8]. To confirm this aspect, thickness of paper in three locations (neck, body and curvature) is measured at three different positions in the volume. For each position along the fiber direction three measurements are performed across the paper resulting in nine measurements for each sample. Figure 6 illustrates shows the thickness measurements carried out in Avizo software for the three different sample types. The measured lines are shown in 'red' color.

The thickness is found to be varying in three sections and following the same trend for both the core materials. The thickness distribution is reported as (0.262 ± 0.006) mm and (0.723 ± 0.028) mm in neck, (0.548 ± 0.007) mm and (0.634 ± 0.010) mm in body and (1.969 ± 0.014) mm and (1.692 ± 0.070) mm in curvature, of bottle made from Silicone A and Silicone B respectively.

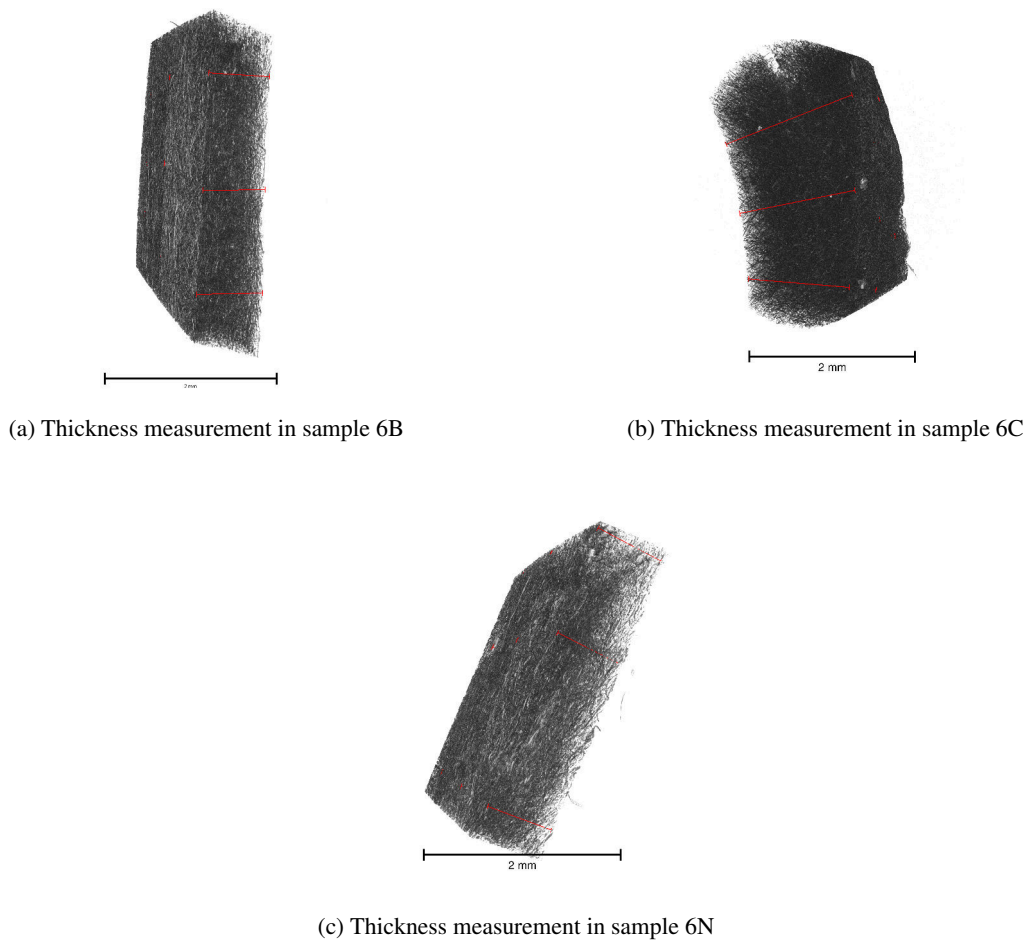


Figure 6: Thickness measurements are performed at nine different spots of each sample across the paper.

6 Conclusions

The work carried out in this paper describes a Non Destructive Testing technique to evaluate quality of paper bottles. A structure tensor analysis based approach has been developed and implemented to identify the fiber orientation in different sections of the paper bottle. The fiber orientation analysis is correlated with process characteristics. The study is run on two set of paper bottles produced from two different core materials. It revealed that fibers are aligned in vertical direction in the plane parallel to the plane of paper. This indicates that during the bottle formation, the wet fibers align alongside the walls of the mold thereby facilitating good hydrogen bonding which imparts good strength to the bottle. Also, almost negligible amount of paper fibers stick out of paper surface conforming the fibers are well compacted in the process. The core material, doesn't seem to have any influence in orientation distribution. However, the thickness evaluation indicates that the fibers are unevenly compacted giving rise to uneven thickness distribution. The core is unable to compact the fibers in the areas of curvature, thereby leading to higher local thickness in that region. This confirms the rise of non-conformities due to core as indicated by previous authors [4][6][8].

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