ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 11 N° 4 2015
pp. 330-336

IMPLEMENTATION OF COMPUTER AIDED TOOL FOR NON-DESTRUCTIVE X-RAY MEASUREMENT OF MOISTURE CONTENT DISTRIBUTION IN WOOD

José Miguel COUCEIRO
Luleå University of Technology, TVM
Div. of Wood Science and Engineering
Address: LTU Skellefteå, SE-93187 Skellefteå – Sweden
E-mail: jose.couceiro@ltu.se

Diego ELUSTONDO
Luleå University of Technology, TVM
Div. of Wood Science and Engineering
Address: LTU Skellefteå, SE-93187 Skellefteå – Sweden
E-mail: diego.elustondo@ltu.se

Abstract
This paper reports recent attempts for implementing non-destructive measuring of moisture content in wood based on computed tomography technology. The study focus on an image analysis method that has been already proposed and validated in the literature, but it has not been tested for measuring low moisture content variations below fibre saturation point. The computed tomography method was tested against the oven-dry method. The results show that it is possible to apply this technology to measure low levels of moisture content based on a regression model, where the root mean square error of the model was 1,4 percentage points of moisture content. The method can still be improved because the density differences between samples are relatively small in relation to the experimental error and the computed tomography precision.

Key words: *CT-scanner; image analysis; moisture content; wood drying.*

INTRODUCTION

A commonly used method for measuring wood moisture content (MC) is the oven-dry (OD) method, which compares the weight of a wood sample at a given MC and after drying it to 0% MC. The recommended procedure for applying the OD method is defined by the European standard EN 13183-1. It recommends cutting wood samples of at least 20mm thick in the direction of the grain and drying them at 103±2ºC until the weight does not change more than 0.1% in a period of 2 hours (Welling 2010). The OD method is usually regarded as the "real" wood MC, but it cannot be used for measuring MC on the same wood area more than once during drying.

An alternative is to use electric meters. These types of meters calculate the MC of the wood by measuring the electric conductivity between two metallic electrodes that are inserted into the wood. This allows measuring MC during drying many times on the same wood area, but MC meters based on electric conductivity are affected by species and temperature (James 1988), and they are not reliable for MC above fibre saturation point (FSP) and below approximately 7% (Forsen et al. 2000). In general, the precision of electric conductivity meters are between ±1,5% and ±2,5% (Milota et al. 1990).

A more precise method for measuring wood MC during drying has been proposed and implemented at Luleå University of Technology. The system comprises of a Siemens medical Computed Tomography scanner (CT-scanner) "SOMATOM Emotion" and a laboratory size drying kiln with a cylindrical drying chamber made of aluminium that was specifically designed to fit within the CT-scanner field of view (Fig. 1). The aluminium permits the X-ray radiation to penetrate throughout the drying chamber, thus making it possible to measure the internal density distribution of the wood during drying.

Measuring wood´s MC through the CT-scanner technique is done by following a method that works analogously to the OD method. It works by comparing the raw data of two CT-images taken from the same area of wood before and after oven-drying. The wood is first CT-scanned to obtain CT-images of a certain area of wood at a particular point in time. The same area of wood is CT-scanned again after oven-drying and it is used as reference to calculate MC. It was demonstrated that the pixel values in the CT-images of wood specimens are linearly related to the density of the material (Lindgren 1991).

Fig. 1.
CT−scanner and specially designed dry kiln in the facilities of Luleå University of Technology
Image: Kersti Bergkvist

During the drying process, however, wood shrinks if MC reach values below fibre saturation point, and it is well known that wood is an anisotropic material that does not shrink evenly in all directions (Dinwoodie 2002). Shrinkage is expected to be higher in the tangential than in the radial direction of the wood with respect to the annual rings. Even in the same direction shrinkage can be uneven if there are other features present such as knots, asymmetries in density distribution, and reaction wood. As a result, a drying sample will also suffer deformation.

To apply the method described in this paper, the CT-images at a certain MC and after OD must fit each other perfectly if they are superimposed. One of the images must be corrected in shape, and this process in turn modifies the numeric value of the pixels in the image. The method needs to operate those values to correct such modification so that the final MC calculation is accurate. This sort of compensation is still an issue that has not been completely solved.

The deformation in the images can be reversed by an image analysis process known as registration. The registration process "un-warps" one of the images (on our case the image of the OD sample) so that it fits the other image (the image of the sample at a given MC, before oven-drying). Since wood is an anisotropic material it is not possible to use the same shrinkage coefficient for all pixels, and this is a key problem that is still unsolved: how to calculate the correct shrinkage coefficient for each pixel.

Research has been made in the recent years for trying to solve this problem, and some of the developed methods have shown very good results. Watanabe et al. (2012) proposed to use a Digital Image Correlation software (Pan et al. 2009) that was first developed for research about the shrinkage in dental composite materials during the curing process (Chiang et al. 2010). Hansson and Fjellner (2013) had a different approach. They calculated the shrinkage coefficient through the technique of polygon clipping, which uses displacement information to calculate shape changes in the images.

According to what is found in the literature, these methods have not been tested for low MC. Measuring wood samples with low MC through CT-scanner techniques might be misleading because the density differences between samples are relatively small in relation to the experimental error. Therefore, this paper presents the first experimental attempts to measure MC profiles at lower MC by using the non-destructive CT-scanner technology available at Luleå University of Technology. The results show that it is possible to apply this technology for measuring low MC values, but further refinement in the image processing is needed, as well as possible re-calibration of the CT-scanner operation parameters.

OBJECTIVES

The purpose of this study was to apply the method proposed by Watanabe et al. (2012) to measure wood internal MC profiles with the CT-scanner available at Luleå University of Technology in

Skellefteå, and compare the results with MC gradients measured through the OD method. The study focused specifically in low MC levels.

METHOD, MATERIALS AND EQUIPMENT

CT-scanner technology

A fourth generation Siemens medical CT-scanner "SOMATOM Emotion" is used at Luleå University of Technology for non-destructive measurement of wood internal density. The basic principle behind the CT-scanner technology is that monochromatic X-ray radiation flowing through a material attenuates by following Lambert-Beer´s law (Hendee and Russell Ritenour, 2002); where μ is the attenuation coefficient, I_0 is the incident X-ray intensity, **I** is the intensity of the X-ray after it passed the material, and **z** is the thickness of the material:

$$I = I_0 \, e^{(-\mu z)} \tag{1}$$

If the X-ray passes through a homogenous material, then the previous equation can be used to determine the attenuation coefficient, which is a function of both the material’s density and atomic number (Jacobs et al. 1992). If on the contrary the material is not uniform, then the exponent in Lambert-Beer´s equation becomes the summation of many μz (Hendee and Ritenour 2002). This makes impossible to deduce the density of the material based on a single source of X-ray radiation.

The CT-scanner technology has solved the problem by rotating the X-ray source around the material so that the X-ray attenuation is measured from many different angles. By making many attenuation measurements in the same plane but at different angles it is possible to calculate a distribution of attenuation coefficients over a cross sectional area. This is then transformed into a grey-scale image representing CT numbers. For the case of wood, Lindgren (1991) showed that the CT-scanner numbers are linearly related to the density. By using a previous generation of CT-scanner, Lindgren et al. (1992) found that the accuracy of the measured density was between ±2 and 6kg/m^3, but more recent work with a fourth generation of CT-scanner suggested a higher accuracy (Hansson and Fjellner 2013).

Watanabe method

CT-images are no more than a matrix of pixels, where each pixel value is translated into a grey scale. Images can be calibrated by using air as a reference for 0kg/m^3 and water for 1000kg/m^3, so that a density value for each pixel can be calculated by assuming a linear relationship between these two points (Lindgren 1991). If the same piece of wood is CT-scanned before and after OD, then the same point in the sample would have a density D_u at *u*% MC and a density D_0 at 0% MC. If no shrinkage and deformation occurred during drying, then the MC for each pixel can be calculated through the following equation:

$$MC = \frac{D_u - D_0}{D_0} \cdot 100 \tag{2}$$

For this method to work at the pixel level the images must fit each other perfectly after they are superimposed. As explained above, this requires compensating pixel values in the images for shrinkage and deformation. In the Watanabe method the MC calculation comprises two image processing steps: image registration and shrinkage compensation. The geometrical deformation of the sample during drying is first corrected through an image processing method called elastic registration. In elastic registration an algorithm interprets one of the images (source) as a deformed version of the other (target), and then applies an elastic deformation (considering the elastic fields as B-spline functions) to fit the source image into the shape of the target. This algorithm is implemented in *ImageJ* software through a plug-in called *bUnwarpJ*, and is set to use the image measured at u% MC as the target image and the image measured at 0% MC as the source image. The result is the un-warped version of the image at 0% MC (registered source image) fitting the shape of the image at u% MC.

The second step is calculating a shrinkage coefficient for each pixel. Shrinkage compensation is based on the technique of Digital Image Correlation (DIC) implemented with aid of the MOIRE software. After performing the DIC process, the software calculates the strains ε_x and ε_y in respectively the x and y directions of the image and export the results for each pixel. The shrinkage coefficient S_h is then calculated through the following equation (Watanabe et al. 2012):

$$S_h = 1 - (1 + \varepsilon_x)(1 + \varepsilon_y) \tag{3}$$

Finally, S_h is used to compensate D_0 for shrinkage in Eq.2 (Watanabe et al. 2012):

$$MC = \left(\frac{D_u}{D_0 (1 - S_h)} - 1 \right) \cdot 100 \tag{4}$$

Experimental data

Six 125mm by 30mm Norway spruce samples were collected from the green sorting station at a local sawmill and transported to the laboratory. The samples were cut into 60 to 100cm long sections, end sealed with heat resistant silicon glue, and dried in the laboratory kiln to MC levels between 7,13% and 19,67%, as determined after drying through the OD method. The drying schedules were designed trying to produce a high MC gradient between the centre and the surfaces of the boards. The dried samples were then CT-scanned for measuring density profiles over a cross sectional area located in a knot free section of the boards. The scan was performed with the CT-scanner parameters set to 110kV, 120mAs, 0.8s scan time, and 10mm slice thickness.

After CT-scanning, three adjacent slabs were cut from the scanned area of the pieces according to the procedure illustrated in Fig. 2. The slab in the centre was oven dried and then CT-scanned again for using as reference image at 0% MC. The other two adjacent slabs were used for measuring MC gradients through the OD method as described in Esping (1998) (Fig.3): First two small blocks (numbered 1 and 7) are cut from the right and left ends of the wood slices, and then the remaining section of the slices is cut into 5 parallel layers from top to bottom (numbered 2 to 6). In the case of this study, the MC profile was estimated as the average of the two adjacent slices cut around each CT-scanned area.

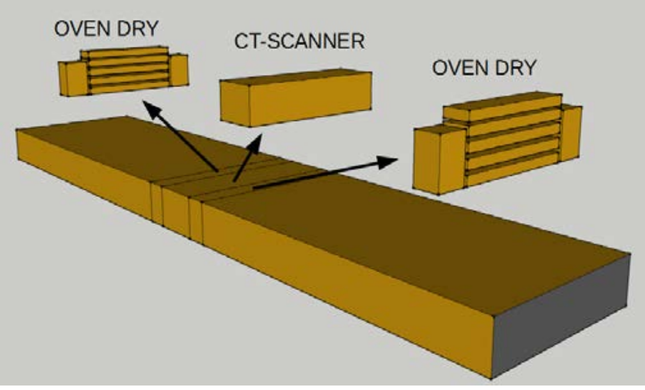

Fig. 2.
Sketch of the sample preparation for MC measurements through OD method and CT-scanning

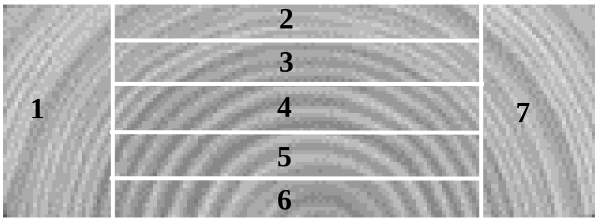

Fig. 3.
Schematic diagram of the procedure for MC gradient measurement

RESULTS AND DISCUSSION

The results are summarized in Fig. 4. The figure shows the results for the MC calculations of six samples, each divided in seven different sections as explained above (Fig. 3). Each of these sections is considered as an individual observation, and the MC data calculated through the CT-scanner method are compared with the corresponding OD values. The linear regression model between the CT-scanner method and the OD values is shown in Fig. 4 as well. The regression model shows that the MC values obtained through the CT-method tend to be higher than the values obtained through the OD method. The ratio between OD and CT-scanner MC was approximately 0,77, with a R^2 of 0,93. In actual MC percentage points this also shows that this error is higher for higher levels of MC. Nevertheless further statistic calculations show that the model fits with a root mean square error (RMSE) of 1,396 percentage points of the MC value.

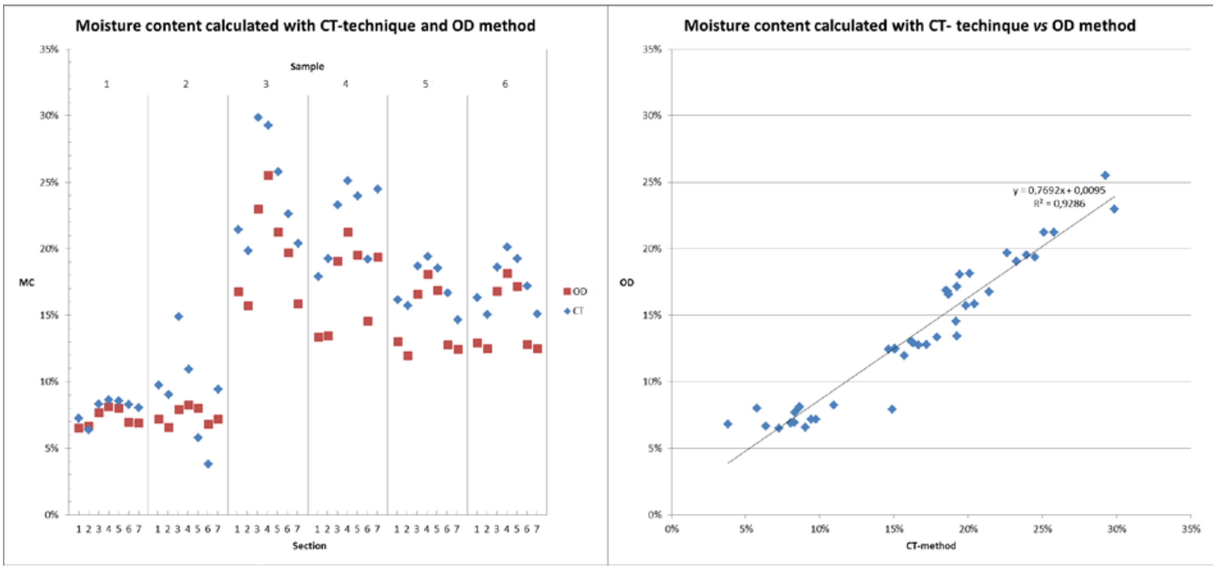

Fig. 4.
Results of MC gradient measurements with the OD method and with the CT-scanner. Left: results for all samples and sections according to the procedure explained in Fig.3. Right: regression model between both methods for all sections in all samples.

For illustration, Fig. 5 shows a comparison between a MC gradient measured with the OD method by cutting the samples in seven sections and the corresponding digital equivalent performed on the CT-scanner image.

One reason for leaving the board external surfaces outside the red rectangles in the CT-images is that the CT-scanner gives inaccurate measurements in regions with strong density gradients (such as the interface between wood and air). By expanding the CT-images in a computer screen, it is possible to see that there is 3 to 5 pixels of blurry transition between the wood surfaces and the air. This also contributes to the overprediction of the MC, as the surface of the boards removed from the images is expected to be dryer than the rest of the wood.

Fig. 5 also shows that distortion of the samples was another problem that led to some wood being let outside the red rectangles in the CT-images, although most of the samples did not deform as much as the one showed in the example. It was found, however, that trying to minimize the amount of material left out during the image processing did not considerably alter the final results.

Distortion patterns also had an effect on the registration step, thus altering all further calculations. For example the left graph in Fig. 4 shows abnormal values for sample number 2 if compared with the other five samples. This is the only sample that had the pith of the tree within the board, which introduced a distortion into the registration step. Removing that sample didn’t improve noticeably the final outcome nevertheless, so it was kept.

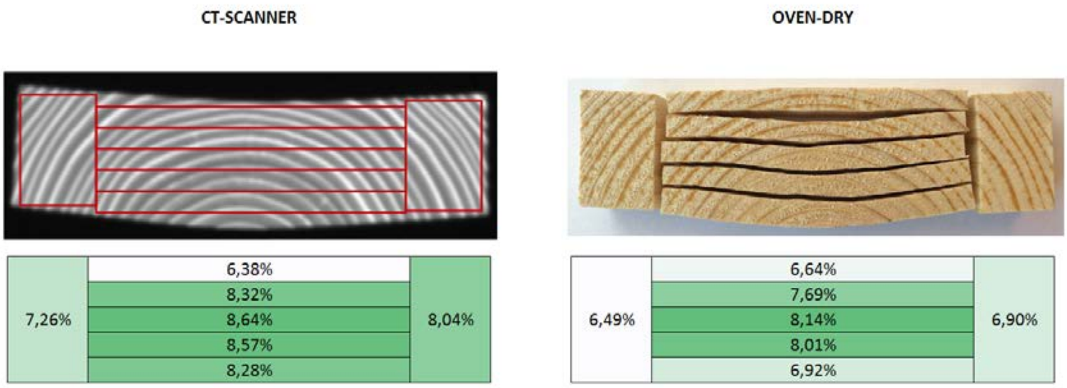

Fig. 5.
Example of MC gradient measurements with the OD method and with the CT-scanner

Summing up, the results of this study showed that it is possible to apply the CT-scanner technology for measuring low MC values in small regions of wood, but the methodology can be improved by refining the image processing step and possibly by re-calibrating CT-scanner parameters. Future research should evaluate the following factors, which we believed are the most probable causes of experimental error:

- Inappropriate settings of the CT-scanner parameters
- Errors in the computer processing of the image (it is a time consuming and complex process in which the errors are only evident in the last of several steps)
- Distortion due to pith, compression wood and other features within the sample that might affects the image registration process
- Errors in the calculation of strain in the x and y directions, which are values used to calculate the shrinkage coefficient.

In addition, future research should consider developing a different method for calculation of the shrinkage coefficient and implementing it in the registration process. Such method could be based on an algorithm that has already been proposed by Hansson and Fjellner (2013). These would simplify the image processing as all calculations are performed with the same piece of software.

CONCLUSIONS

The purpose of this study was to evaluate the possibility of measuring the development of wood MC gradients during drying by using non-destructive CT-scanner technology available at Luleå University of Technology, in Skellefteå. The study focused on an image analysis method that has been validated in the literature, but that has not been tested for measuring low MC variations below fibre saturation point. Measuring low MC values with the CT-scanner is still an underdeveloped methodology because the density differences between samples at low MC and OD conditions are relatively small in relation to the experimental error.

The results showed that it is possible to apply this technology for measuring low MC values. In particular, the linear regression model developed through this study can be used to calculate MC from the CT images with a root mean square error of 1,4 percentage points of MC values between 6,49% and 25,49%.

This method has been developed very recently and it has not been studied in depth ever since. Consequently, more research is still needed. This includes possible re-calibration of the CT-scanner operation parameters, as well as exploring and comparing other alternative methods proposed in the literature for image processing.

REFERENCES

Chiang YC, Hickel R, Lin CP, Kunzelmann KH (2010) Shrinkage vector determination of dental composite by µCT images. Composites Science and Technology, 70(6):989-994.

Esping B (1998) Trätorkning: Torkningsfel – åtgärder Volume 2. Trätek, Stockholm.

Dinwoodie JM (2002) Timber: Its Nature and Behaviour, Second Edition. Taylor & Francis group, UK.

Forsen H, Tarvainen V (2000) Accuracy and functionality of hand held wood moisture content meters. Technical Research Center of Finland, Espoo.

Hansson L, Fjellner BA, (2013) Wood shrinkage coefficient and dry weight moisture content estimations from CT-images. PRO LIGNO 9(4):557-561.

Hendee WR, Ritenour ER (2003) Medical Imaging Physics. John Wiley & Sons, New York.

Jacobs P, Sevensa E, Kunnenb M (1995) Principles of computerized X-ray tomography and applications to building materials. The Science of the Total Environment 167:161-170.

James WL (1998) Electric moisture meters for wood. Technical Report FPL-GTR 6, USDA, Madison, Wisconsin.

Lindgren LO (1991) Medical CAT-scanning: X-ray absorption coefficients, CT-numbers and their relation to wood density. Wood Science and Technology 25(5):341-349.

Lindgren O, Davis J, Wells P, Shadbolt P (1992) Non-destructive wood density distribution measurements using computed tomography. Holz als Roh-und Werkstoff 50(7-8):295-299.

Milota MR, Quarles SL (1990) The influence of kiln temperature on the performance of handheld moisture meters. Forest Products Journal 40(11/12):35-38.

Pan B, Qian K, Xie H, Asundi A (2009) Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review. Measurement science and technology, 20(6):062001.

Welling J (2010) Dried Timber - how to specify correctly. European Drying Group (EDG) and COST E53. *Retrieved in March 2015 from www.coste53.net*

Watanabe K, Lazarescu C, Shida S, Avramidis S (2012) A novel method of measuring moisture content distribution in timber during drying using CT scanning and image processing techniques. Drying Technology 30(3):256-262.