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CRACK DETECTION AND CLASSIFICATION OF OAK LAMELLAS USING ON-LINE AND ULTRASOUND EXCITED THERMOGRAPHY

Djordje POPOVIC
Jönköping University, School of Engineering
Gjuterigatan 5, SE-551 11 Jönköping, Sweden
Tel: +46 767 634617, E-mail: djordje.popovic@jth.hj.se

Peter MEINLSCHMIDT
Fraunhofer Institute for Wood Research, Wilhelm-Klauditz-Institut WKI
Bienroder Weg 54E, 38108 Braunschweig, Germany
Tel: +49 531 2155 449, E-mail: peter.meinlschmidt@wki.fraunhofer.de

Burkhard PLINKE
Fraunhofer Institute for Wood Research, Wilhelm-Klauditz-Institut WKI
Bienroder Weg 54E, 38108 Braunschweig, Germany
Tel: +49 531 2155 449, E-mail: burkhard.plinke@wki.fraunhofer.de

Jovan DOBIC
Tarkett Eastern Europe, BU WOOD
Industrijska zona 14, 21400 Bačka Palanka, Serbia
Tel: +49 531 3515 87, E-mail: jovan.dobic@tarkett.com

Olle HAGMAN
Luleå University of Technology, Wood Science and Engineering
SE-931 87 SKELLEFTEÅ, Sweden
Tel: +46 910 585310, E-mail: olle.hagman@ltu.se

Abstract

On-line thermography and ultrasound-excited thermography have been evaluated for the detection of cracks in oak lamellae of flooring top layers. Image acquisition accompanied the tests and the objects were identified by post-processing and the evaluation of lamella images. The results were validated by comparing these findings with the actual state of the lamellae in terms of cracks and the classification accuracy of the method was calculated. The classification accuracy of the ultrasound-excited thermography method was three times greater than that of on-line thermography. The main conclusion is that the ultrasound-excited thermography method is the more suitable for the detection of cracks and the classification of lamellae.

Key words: *classification; cracks; image; lamella; thermography.*

INTRODUCTION

Tarkett is a worldwide leader of innovative and sustainable flooring and sports surfaces (Tarkett 2015), and one of the product types which the company offers is an engineered wood floor board. The flooring is a three layer cross-laminated construction, with a surface coating on the top layer, which consists of 3-4mm thick hardwood lamellae. The company strives to deliver flooring with a flawless surface, i.e., no tangible cracks in the top layer. There are four steps along the production line where the presence of cracks is inspected and patched, and the company manages to attain the required surface quality. The future goal of the company is, however, to improve the detection of cracks at the first inspection station, which would result in less patching and cut the costs of quality inspection. Tarkett has estimated possible savings of EUR 100 000 per year for the production of two million square meters of flooring, if there were no need to rework the surface.

The first inspection is at the lamella sorting station. The operation is semi-automated where the inspection is done by human operators while the lamellae are continuously transported on a conveyer. The operators sort the lamellae according to various features such as color, the presence of knots, cracks etc.

Cracks in lamellae are classified according to their acceptability. The rules of acceptability are established according to the result of the quality inspection after the finishing line, and they define limits for crack characteristics such as: a) width, b) angle towards the lamella face, c) length and d) position along the lamella width (Fig. 1).

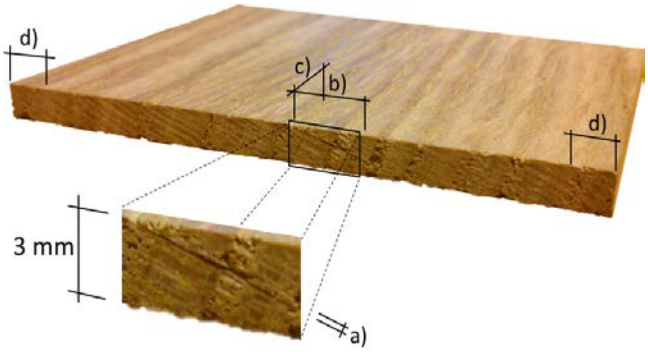

Fig. 1.
Example of an unacceptable crack that is hard to detect by visual inspection. Crack characteristics used in the inspection are: a) width, b) angle towards the lamella face, c) length, and d) position along the lamella width. Most of unacceptable cracks have a crack-opening approximately parallel towards the lamella face

Cracks that are completely filled and covered with a lacquer during finishing are deemed to be acceptable, whereas cracks that are visible after finishing are unacceptable. A main problem during the inspection of lamellae is that thin and short cracks are hard to identify with the naked eye.

A more sophisticated crack detection method as a complement to the visual inspection is needed to reduce the number of unidentified cracks. Some of the requirements of the crack-inspection method are:

- High accuracy and precision
- Short inspection time (a few seconds or less)
- Non-destructive assessment

Taking these requirements into account, two thermography methods were studied as a means of solving the problem: on-line and ultrasound-excited thermography (UET).

Thermography methods are based on infrared technology and can provide data about the sub-surface structure of a material by observing differences in thermal emission from the surface using infrared cameras to record the data. The emission depends on heat conduction in the material. Depending on the way the heat transfer is generated, thermography methods are divided into passive and active. In active thermography, heat transfer can be initiated by external energy excitation using electromagnetic radiation or ultrasound and is dependent on physical properties of the material such as thermal conductivity and diffusivity, density, moisture content etc. If a defect below the surface has better insulating properties than the rest of the material, the defect acts as a barrier for the heat transfer, so that the emissivity from the surface above the defect is higher (Meinlschmidt, 2005). Variants of the active thermography methods are: pulse, step heating, lock-in and vibro-thermography (Maldaque 2001).

Infrared cameras are devices used for thermal imaging and, like cameras that form images using visible light, have infrared detectors that are sensitive to the infrared part of the thermal radiation, i.e., a range between the visible and microwave radiation of the electromagnetic spectrum (wavelengths 760 nm-1 mm). Results from infrared testing are usually obtained by image processing and analysis. Thermography, infrared technology and image analysis are well described by e.g. Kaplan (1999), Maldaque (2001), Minkina et al. (2009), Gonzales et al. (2010), and Russ (2011).

On-line thermography is a non-contact and non-destructive testing method where the specimen is transported on a conveyor belt while passing beneath a heating source and an infrared camera. The heating source is an infrared lamp that irradiates and heats the surface of the test piece, initiating a heat transfer therein. When the initiated heat transfer reaches a structure with different thermal properties, the emission from the surface of the object is influenced accordingly. The emission is observed with an infrared camera (Meinlschmidt et al. 2006).

Ultrasound-excited thermography (UET) is a variant of vibro-thermography (Maldague 2001). Unlike most thermography methods, the ultrasound-excited thermography is a contact method. A sonotrode is brought into physical contact with a test piece in order to excite the object with a mechanical wave. Heat is generated locally in the cracks and/or other disbonds by friction where a direct conversion of mechanical into thermal energy occurs (Maldague 2001). The initiated heat transfer results in heat emission from the surface of the object. A local increase in temperature is reached within a few milliseconds and is imaged by an infrared camera as a bright IR source on a dark background (Cho et al. 2007).

Thermography has already been applied in wood science and in the wood industry to address different types of problem. Berglind et al. (2003) used pulsed, heating up and lock-in thermography for the purpose of detecting glue deficiency in laminated wood. Sembach et al. (1997) used lock-in thermography to detect air channels beneath the surface of medium density fibreboards and chipboards. Wu et al. (1995) used lock-in thermography to detect different structure of the wood substrate beneath laminated veneer. Meinlschmidt (2005) used on-line thermography to detect defects in wood and wood-based materials. Lukowsky et al. (2008) used ultrasound-excited thermography to detect defects in wood and wood-based materials. Nevertheless, there is no published work using on-line and UET methods to detect cracks in oak lamellae.

OBJECTIVE

The purpose was to study the possibilities of using on-line and ultrasound-excited thermography for the detection of cracks in 3mm thick oak lamellae.

MATERIAL, METHOD, EQUIPMENT

450 oak (Quercus sp.) top layer lamellae were used in this study. The dimensions of the lamellae were 3x67x304mm (TxWxL). Dimension variations were ± 0.1mm in thickness, ± 0.2mm in width, and ±0.5mm in length. These 450 lamellae were divided into three groups as shown in Table 1, by visible assessment.

Table 1

Sample overview

Group No.	No. of lamellae	Specification of lamellae according to cracks
1	150	No cracks
2	150	Unacceptable cracks
3	150	Acceptable cracks

The test was carried out at Fraunhofer WKI thermography laboratory. Fig. 2 shows the on-line thermography setup used. The conveyor belt velocity was set to 6m/min. An aluminium shield was mounted on the camera supporting frame in order to prevent radiation from the infrared lamp directly reaching the camera. The distance between the infrared lamps and the infrared camera was 500 mm, since that was the limiting distance below which the aluminium shield could not prevent the direct radiation from influencing the camera. With the given belt conveyor velocity and the horizontal distance between the lamp and camera, the image acquisition took place 5 seconds after the beginning of the irradiation. The vertical distance from the infrared lamp to the surface of the specimen was 120mm. The vertical distance of the infrared camera from the surface of the specimen was 760mm.

Fig. 2.
On-line thermography test setup: a) a "Heraeus mid-wave CARBON twin tube" infrared lamp; b) a belt conveyor; c) an "IRCAM Geminis 327k ML pro" infrared camera; d) a MWIR lens (f/1.5; f = 28mm); e) an "IRCAM compact blackbody" temperature calibration device; f) a "Panasonic Toughbook 31" control unit; g) an infrared camera supporting frame; h) an infrared lamp supporting frame, and i) an aluminium shield

Fig. 3 shows the ultrasound-excited thermography setup. The setup was static and all the specimens were placed in the same position in front of an infrared camera. Exact positioning of the lamella specimens was achieved using a vice with a 125x5mm groove. The specimens had to be firmly positioned because the high intensity mechanical wave tended to shake the test piece if it was not fixed, but this led to a loss of information for the area of the test pieces covered by the vice. The transducer and sonotrode rested on the specimen without any additional pressure, ensuring that a constant pressure was applied throughout the testing. The power generated by the ultrasound wave was 1000W. The image acquisition time was 300 milliseconds after the beginning of excitation. The horizontal distance between the test pieces and the infrared camera lens was 600mm.

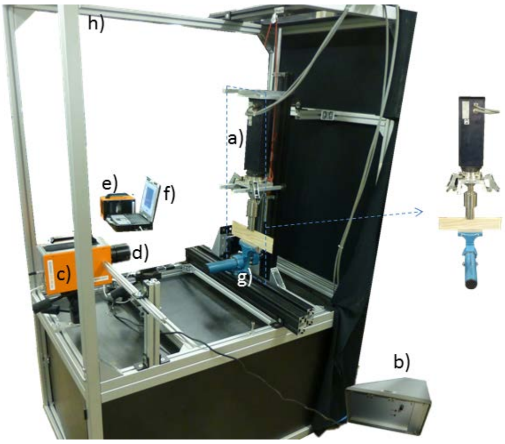

Fig. 3.
Ultrasound-excited thermography experimental setup: a) a "Hielschler ultrasoncs" ultrasound transducer and a sonotrode (1000 W/20kHz); b) an "UIP 1000" ultrasound generator; c) an "IRCAM Geminis 327k ML pro" infrared camera; d) a MWIR Lens (f/1.5; f = 28mm); e) an "IRCAM compact blackbody" temperature calibration device; f) a "Panasonic Toughbook 31" control unit; g) a vice; h) a supporting frame

After the sequences were recorded, a raw data file per each specimen was exported using IRCAM software for both methods. These raw files constituted the input for the image processing and for the evaluation part of the method.

A classifying algorithm for both methods was developed in Matlab 2013b (Mathworks 2015). The parts of the algorithm were: loading and reading the raw files, median filtering, cropping a lamella region of interest (ROI), setting a threshold and multiplying pixels in the constantly bright areas of lamella ROI by zero (mask application). An adaptive threshold approach was applied after cropping a lamella ROI where a threshold was put above of 99% of all data points.

The image evaluation was validated by comparing the test results with the visual assessment of photomicrographs of the cracks, their number and positions in the lamella specimens. The comparison led to a classification of the test results in four groups: true positive, false positive, true negative and false negative. It was then possible for both methods to calculate the classification accuracy:

$$A = \frac{\sum True\ positives + \sum True\ negatives}{n} \quad [\%] \qquad (1)$$

where: A is accuracy of the method
n is the sample size
together with the margin of error:

$$m = Z_{\alpha/2} \cdot \sqrt{\frac{A \cdot (1 - A)}{n}} \quad [\%] \qquad (2)$$

where: m is the margin of error
$Z_{\alpha/2}$ is a z-score which at a 95% confidence level equals 1.96

The precision was estimated in order to establish the level of repeatability of the two methods regardless of the classification trueness. The estimation was done using findings from replicate experiments where 15 lamella specimens were chosen from the sample and tested four times each with both methods. The margin of error for the precision estimate was done according to (Eq. 3).

$$m = t_{\alpha/2,(n-1)} \cdot \frac{S}{\sqrt{n}} \quad [\%] \tag{3}$$

where: $t_{\alpha/2,(n-1)}$ is a t-score which at a 95% confidence level and for a sample size of 15 is equal to 2.145
S is the sample standard deviation
n is the sample size of 15

RESULTS AND DISCUSSION

The main results are shown in Table 2, where the on-line and UET thermography method are compared according to their classification accuracy, estimated precision and margins of error. UET thermography is clearly more accurate, although the precision is poorer.

Table 2

Accuracy and precision with margins of error for the two methods

	On-line thermography	UET thermography
Accuracy ± Margin of error [%]	20.89 ± 3.76	60 ± 4.53
Precision ± Margin of error [%]	91.67 ± 0.09	78.33 ± 10.29

More setup parameters must be adjusted for on-line thermography than for UET method and on-line thermography is in that sense more complicated, but less equipment development is needed for it to be implemented at the lamella sorting station. A continuous inspection by on-line thermography is an advantage as the UET method requires fixed positioning of the specimens during inspection. On the other hand in the UET method, beside less parameters that have to be adjusted, a development of setup solution is needed in order to implement it in the factory.

The UET method is simpler with respect to how the energy is brought to the specimen. By applying an ultrasound wave, friction is initiated in the material wherever there is a disbond. In other words, most of the cracks can be excited. The friction area is instantaneously seen by an infrared camera, whereas on-line thermography requires a certain time to detect a crack at a certain depth. Due to the nature of the heat transfer it is possible to extract structural information from the depth of the material, but the penetration depth is time dependent (Berglind 2003). As cracks were found in the specimens at various depths, with the different angles, shapes and sizes, it is obvious that there was no single moment of image acquisition that would result in a successful detection of all types of cracks.

Furthermore, the anatomical structure of oak wood was the biggest obstacle and the reason for the classification of false positives by on-line thermography. At a moisture content below the fibre saturation point the large vessels in the earlywood are filled with air. These vessels extend longitudinally through the lamellae and act as obstacles to heat transfer. Therefore, the heat transfer is retarded when it reaches an earlywood zone in the same way as when it reaches a crack. The heat emission above these areas was higher, leading to image pixels that have relatively high gray-scale values. The algorithm would classify an earlywood vessel as a false positive crack.

The classifying algorithm was based on recognizing the cracks as objects, but not on extracting other information characterising the cracks. For example, a true positive would be assigned to a lamella specimen with many cracks even if the classifying algorithm found only one crack at the correct position.

An ideal inspection method would observe the whole lamella ROI when classifying the observations. In the case of the two methods presented, a trade-off had to be made excluding certain areas within the lamella ROI, in order to reach better results. These areas were bright in almost every image and, in order to exclude them, they were covered with masks of black pixels. Taking into account the sizes, shapes and positions of the masks and the number of cracks found in these areas, the UET has an advantage over the on-line thermography method.

Interesting findings in the validation step were the different types of cracks that the two methods successfully detected. The on-line thermography method was in general more successful in detecting cracks that had a distinct crack-opening approximately parallel to the lamellae surfaces. The

UET method successfully detected all the cracks where the wood enclosing the crack could vibrate and generate friction energy. In these cases, there was no correlation between the successfulness of detection and the width and angle of the cracks. The on-line thermography method was therefore more successful in the classification of true positives in the group of unacceptable than in the group of acceptable cracks. From the point of view of the production requirements of Tarkett, this is an advantage over the UET method which was almost equally successful in correctly classifying the lamellae from all the groups. The classification accuracy of the on-line thermography was nevertheless much lower than that of the UET method.

It is important to note that the precision results were approximately normally distributed for the UET method, but this was not the case in the on-line thermography method, therefore has to be taken into account when considering the precision margin of error for this method.

The future work might include:

- Multivariate data analysis in terms of principal component analysis (PCA) can be done in order to find the correlation between the classification result and the characteristics of cracks. Besides the general classification, whether a crack is acceptable or unacceptable, characteristics such as the angle, length and width of the cracks can be measured since the microscopic images were obtained for all the cracks present in lamella specimens.
- Another digital image processing approach can be developed in order to improve the accuracy of lamella classification. Gradient information from edge-feature detectors could be combined with information from the adaptive thresholding. Different classifiers could be combined to give a better result.
- Detection of characteristics such as the angle and width of the cracks could provide information about the crack acceptability. The immunity towards acceptable cracks could possibly be improved if this information could be paired with findings from the ultrasound-excited thermography method. The future work might consider the visible light camera images of the lamella foreheads, where the visibility of cracks could be improved by their shadows, initiated with a directed visible light flux at a small angle towards the lamella forehead.

CONCLUSIONS

The main conclusion is that the ultrasound-excited thermography (UET) is the more suitable method for crack detection and the classification of lamella specimens. The drawbacks in the UET method can be improved, but the accuracy of the on-line thermography method cannot be improved due to the anatomical structure of oak wood.

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REFERENCES

Berglind H (2003) Nondestructive detection of glue deficiency in laminated wood using thermography. PhD thesis. Department of Engineering Sciences and Mathematics. Luleå University of Technology.

Berglind H, Dillenz A (2003) Detecting glue deficiency in laminated wood—a thermography method comparison. NDT&E International 36:395–399.

Berglind H, Dillenz A (2003) Detection of glue deficiency in laminated wood with pulse thermography. Journal of Wood Science 49:216-220.

Cho J, Seo Y, Jung S, Kim S, Jung H (2007) Defect detection within a pipe using ultrasound excited thermography. Nuclear Engineering and Technology 37:637-646.

Gonzalez R, Woods R (2010) Digital image processing. Pearson/Prentice Hall, New Jersey.

Kaplan H (1999) Practical applications of infrared thermal sensing and imaging equipment. SPIE Optical Engineering Press, Bellingham.

Lukowsky D, Meinlschmidt P, Grote W (2008) Ultraschallangeregte thermographie an holzverklebungen - Entwicklung einer prüfmethode. Holztechnologie 49:42-47.

Maldague X (2001) Theory and practice of infrared technology for nondestructive testing. Wiley, New York.

Mathworks (2015) Support - Supported and Compatible Compilers - Release 2013b. Online at: http://se.mathworks.com/support/compilers/R2013b/

Meinlschmidt P (2005) Thermographic detection of defects in wood and wood-based materials. Proc. of the 14th international Symposium of non-destructive testing of wood, Hannover, Germany.

Meinlschmidt P, Aderhold J (2006) Thermographic inspection of rotor blades. Fraunhofer-Institute for Wood Research (WKI), Braunschweig, Germany.

Minkina W, Dudzik S (2009) Infrared thermography. Wiley, Chichester.

Russ J (2011) The image processing handbook. CRC Press, Boca Raton.

Sembach J, Wu D, Salerno A, Hora G, Busse G (1997) Non-destructive evaluation of delaminations in laminated wood-based panels by thermographical inspection tools. Proc. of workshop on nondestructive testing of panel products, Llandudno (UK), pp. 41-48.

Tarkett (2015) Company Profile. Online at: http://www.tarkett.com/en/content/company-profile.

Wu D, Busse G (1995) Remote inspection of wood with lock-in-thermography. TAPPI 1995 European plastic laminates symposium. 79(8):119-123.