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Detection of glue deficiency in laminated wood with pulse thermography

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Abstract Adhesion problems sometimes occur during the production of laminated wood products. To minimize such quality problems, there is a need for a nondestructive test that can provide continuous control of the process and the product. This study presents results from measurements performed to evaluate the potential of pulse thermography as a method to detect glue deficiency in laminated wood. Defect depth, defect size, and degree of glue deficiency have been varied. The surface layer was made of merbau (*Intsia bijuga*) and the substrate of Scots pine (*Pinus silvestris*). The results showed that pulse thermography is a promising tool for detecting glue deficiency underneath the thin laminated wood surface layers, mainly because of the short inspection time. Lack of glue with a minimum thermal defect size of 3 was detectable (thermal defect size is defined as the quotient of defect size and defect depth). The penetration depth was 1.0 mm and the highest contrast, 0.62°C, was achieved for one of the largest defects (24 mm) below the thinnest (0.5 mm) surface layer after 1 second. Starved glue joints showed about half the contrast compared to areas with total lack of glue.

Key words Pulse thermography · Laminated wood · Glue line · Adhesive bonding · Delamination

Introduction

Adhesion problems sometimes occur during production of laminated wood products.[1] An explanation might be that the amount of glue is not sufficient or that glue is even missing in some areas. A preferably nondestructive test method that can provide continuous control of the process and the product is needed to solve the quality problems.

Thermography is a noncontact, nondestructive test that uses an infrared (IR) camera to obtain information about the thermal structure underneath the surface of an object to a limited depth. Compared to many other nondestructive test methods, thermography is relatively fast and manages to examine large areas with relatively high speed, thus being potentially well suited for industrial quality inspection purposes.

During thermography testing, heat flow is often produced perpendicular to the potential defect. When a defect is present, the heat flow is disturbed and affects the object surface temperature. An IR camera with sufficient thermal resolution detects such temperature contrast, and the information is thereafter processed using suitable computer software.

The main thermography methods are called pulse,[2,3] heating up, and lock-in[4] thermography. Differences between the thermography methods depend on the type of heating and evaluation methods.

Some thermography research has been performed on glued wood products. Sembach et al.[5] detected 19-mm-wide channels 4–5 mm underneath the surface of medium density fiberboard and chipboard, respectively, using lock-in thermography. Wu and Busse[6] also used lock-in thermography and detected holes with a diameter of 4 mm, differences in wood species of the substrate, and knots in the substrate underneath a 2-mm-thick laminated veneer. Furthermore, Wu et al.[7] detected glue threads under a 1-mm-thick veneer and delaminated areas under a 2-mm-thick veneer as well as under a 1-mm-thick high-pressure laminated film.

Xu et al.[8] used heating up thermography, where 10- to 50-mm-size areas without glue were detected with a contrast up to 0.7°C underneath 1.3- to 3.0-mm-thick surface layers of white seraya. Danesi et al.[9] used cooling down thermography and detected channels in polyvinyl chloride (PVC) at a depth of 1.3–3.0 mm with a maximum contrast of 10°–18°C after 3–5 min, holes in PVC with a diameter of 3–4 mm at a depth of 1.5–2.0 mm, and holes with a diameter of

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Fig. 1. Glue distribution along the test piece (length 155 mm, width 65 mm)

6–8 mm at a depth of 3.0 mm. They also found channels in the wood at a depth of up to 4 mm after 4–5 minutes and, finally, delamination in a plastic coating after 50 s.

Meinlschmidt[10] detected delaminated regions underneath a laminated decorative pressure laminate with both pulse and cooling down thermography. Berglind[11] earlier used pulse, heating up, and lock-in thermography to detect glue deficiency underneath a surface layer thickness of 0.5–4.0 mm of laminated merbau. The penetration depth was 3.0 mm for lock-in thermography and 2.0 mm for heating up thermography. No contrast was obtained for pulse thermography.

The goal of this study was to use more powerful lamps and an IR camera with higher temperature resolution to detect glue deficiency defects with pulse thermography. The defect depth, defect size, and degree of glue deficiency have been varied. Parameters such as resolution capability, penetration depth, and inspection time were studied.

Materials and methods

Test pieces

A test piece consisted of a surface layer glued on a 9.5-mm-thick substrate made of Scots pine (Fig. 1). The surface layer was made of merbau without knots and had a thickness of 0.5, 1.0, 1.5, or 2.0 mm. The grains of the surface layer and the substrate ran parallel to the length of the test piece.

Glue defects were simulated with bands of different widths (24, 12, 6, and 3 mm), which alternately were covered with glue on both the surface layer and the substrate or only on the substrate, and finally there were bands without glue. Glue on both sides corresponded to the recommended glue spread of 140 g/m^2, whereas one layer of glue had 70 g/m^2.

Surface layers and substrates were glued with urea-formaldehyde glue. Curing took place at room temperature for an hour with a clamping pressure of 0.03 MPa. The wood had a moisture content around 8%. For each surface layer thickness, two series of three replicates was produced. Altogether, 24 test pieces were prepared, 6 for each surface layer thickness.

Experimental setup

The principle of pulse thermography is to apply a short, powerful energy pulse to the examined object to create heat flow perpendicular to a potential defect. The experimental setup is shown in Fig. 2. For each experiment, three test pieces were mounted together in a fixture composed of a heat-insulating material.

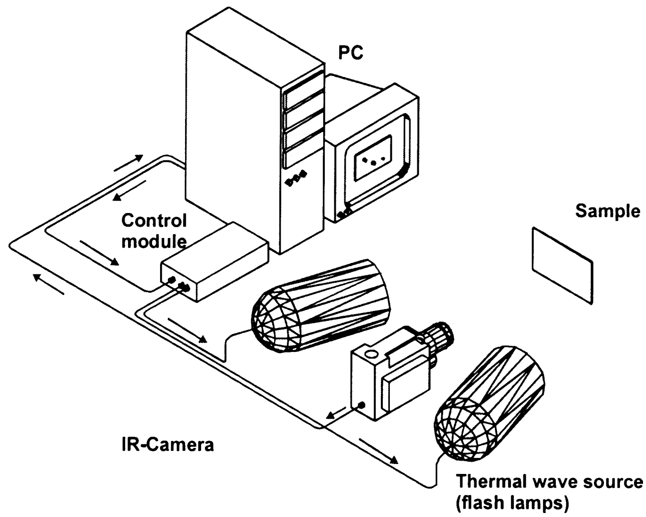

Fig. 2. Experimental setup. *PC*, personal computer; *IR*, infrared

The heat source consisted of four flash lamps, each capable of emitting 2 kJ of light energy. The lamps were placed 0.5 m in front of the test pieces. The IR camera (CEDIP Jade II MWIR) was placed 1.2 m in front of the test pieces. The IR camera detects infrared radiation in the wavelength interval 3–5 μm and has a thermal resolution of 0.02°C.

The IR camera started to sample images shortly before the flash with a frequency of 10–100 Hz depending on the defect depth and with an integration time of 1500 μs (i.e., the time an IR detector collects radiation before each sampling). The scene had a real size of 230 × 170 mm^2; and as images from the IR camera contains 320 × 240 pixels, the spatial resolution of the images was around 1.4 pixels/mm. The gray scale resolution was 14 bits.

Experiments

An experiment was performed on a black body to obtain a spatial illumination distribution reference. To determine resolution capability, penetration depth, and inspection time of the pulse thermography, two experiments with three replicates each were performed for each of the four surface layers thicknesses (0.5, 1.0, 1.5, 2.0 mm).

To determine thermal contrast between correctly glued areas and areas with glue deficiency, the average of the temperatures, T_{ij}, for each of the 194 pixel rows was calculated (Fig. 3a). These average values were plotted on a diagram with the length of the test piece as the x-axis, which resulted in temperature profiles (Fig. 3b). The contrast was then calculated as the temperature difference at a peak caused by a glue defect and the average temperature from neighboring correctly glued areas. To test the repeatability of the contrast determination, one of the experiments was performed three times.

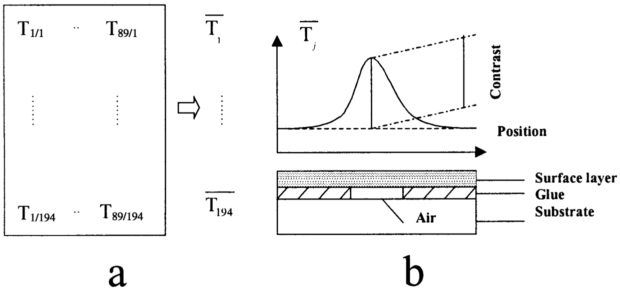

Fig. 3. **a** Test piece with its temperature matrix with 89 × 194 pixels, which were used to calculate an average temperature T_{ij} from each pixel row *j*. **b** Temperature profile above an area with lack of glue and the procedure for determining the contrast between correctly glued areas and areas of glue deficiency

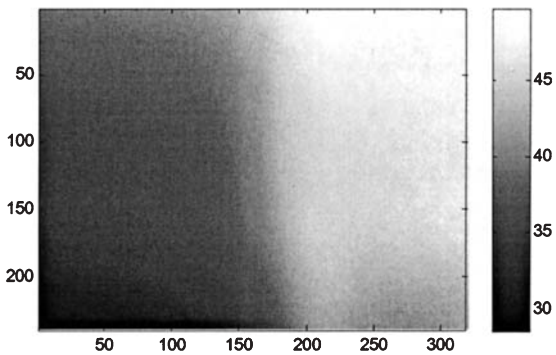

Fig. 4. Infrared image of a black body immediately after a flash

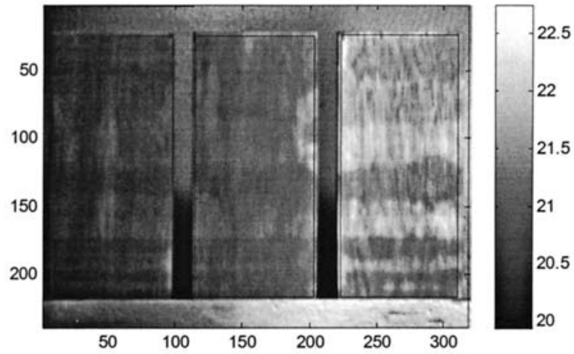

Fig. 5. Infrared image of three test pieces with 0.5-mm-thick surface layers 1 s after the flash. Areas with glue deficiency are bright

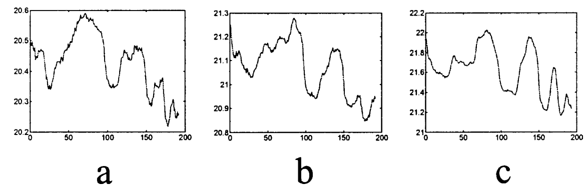

Fig. 6. Signal profiles for the test piece to the left (**a**), in the middle (**b**), and to the right (**c**) in Fig. 5. High values indicate glue deficiency

Results and discussion

Surface temperature

After applying a flash to the test pieces, the temperature increased from room temperature (around 22°C) to more than 50°C within 10 ms according to the shape of the sampled graph. The sensors of the IR camera were saturated for 30 ms at 50°C, which is the saturation temperature at the integration time chosen. The test pieces cooled quickly, reaching 26°–27°C after another 50 ms. The peak surface temperature of the test pieces thus had a duration of 90 ms. The high surface temperature might pose a question about the nondestructive character of the test method and is subject to further study. Because of the difficulty obtaining an even light distribution, the right part of the image showed a higher surface temperature than the left part of the image (Fig. 4).

Over a time interval of 5 s after the peak, a test piece in the middle was 0.4°–1.2°C warmer than a test piece on the left side of the image. A test piece on the right side of the image was 0.7°–2.1°C warmer than a test piece on the left side of the image.

Contrast evaluation

A contrast between areas without glue and surrounding areas developed after application of a flash, reaching its maximum after a couple of seconds. An example of three test pieces with 0.5-mm-thick surface layers is shown 1 s after the flash in (Fig. 5). Signal profiles over the horizontal average gray scale values are plotted against the length of each test piece in Fig. 6. The average temperature is somewhat cooler at the bottom of each test piece, probably owing to evacuation of heat through conduction to the mounting fixture as well as convection. However, all defect sizes were resolved, and the contrast of areas with one layer of glue is about half that of areas without glue. This is best seen for the 24 mm wide defect on the test piece to the right. The more continuous profiles of the other defects might depend on glue spreading during pressing.

The average contrast evolution is shown in Fig. 7 for test pieces with 0.5- and 1.0-mm-thick surface layers and defect sizes of 3–24 mm. No contrast was obtained for either 1.5- or 2.0-mm-thick surface layers.

The maximum average contrast is reached in about 1 s for the 0.5-mm-thick surface layers and varies between 0.04° and 0.34°C depending on the defect size. The highest individual contrast was 0.62°C (Fig. 8). The maximum average contrast is reached in about 4 s for the 1.0-mm-thick surface layers, varying between 0.02° and 0.10°C depending on the defect size. However, the maximum average contrast for test pieces positioned on the right side of the image is more than twice as high as that for those on the left side of the image (Fig. 8), probably due to the uneven illumination distribution (Fig. 4). A higher maximum contrast is thus obtained with increasing defect size and decreasing defect

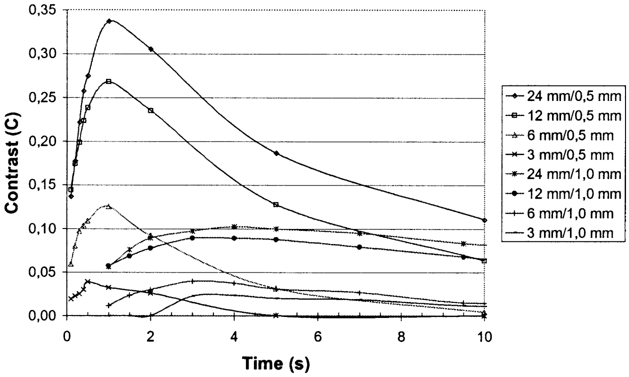

Fig. 7. Average contrast evolution curves for 3- to 24-mm-wide areas without glue underneath 0.5- to 1.0-mm-thick surface layers. Each value is the average of six replicates

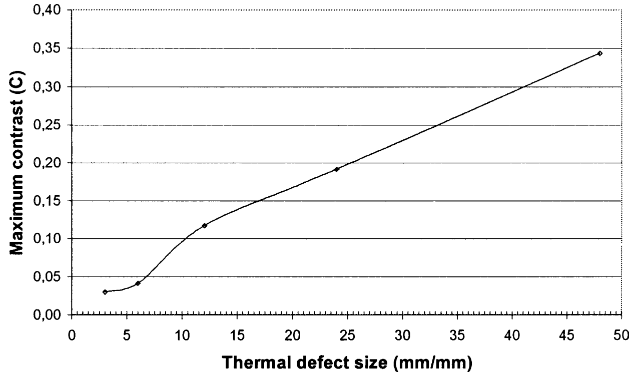

Fig. 9. Maximum average contrast as a function of the thermal defect size (defect size/defect depth). Each contrast value is calculated from 6 or 12 replicates

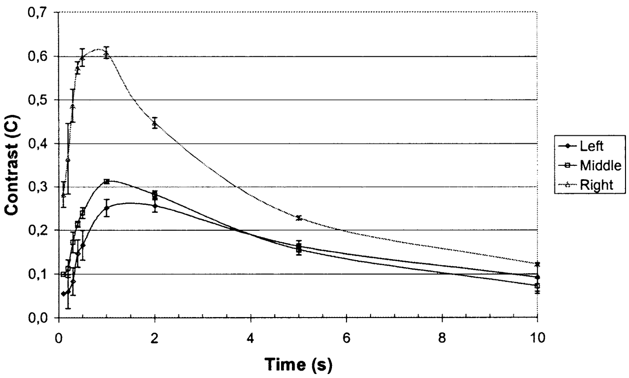

Fig. 8. Contrast evolution curves showing the repeatability of the contrast determination for test piece positions to the left, in the middle, and to the right in Fig. 5. The error bars are based on the standard deviation(s) of the average contrast from the three experiments. The error interval is [−s, +s]

depth. This relation can be expressed in terms of the thermal defect size that is obtained by dividing the defect size by the defect depth.

Figure 9 shows that the maximum average contrast increases linearly with the thermal defect size. The minimum thermal defect size needed to resolve a defect is 3; that is, the defect size must be three times the defect depth to be resolved.

Repeatability

Contrast evolution curves are shown in Fig. 8 for three test piece positions. The error bars express the variation between an experiment repeated three times. Apparently, the contrast determination is quite stable.

Conclusions

With pulse thermography it was possible to detect areas without glue in laminated wood when the temperature resolution was 0.02°C. The average maximum contrast was reached in about 1 s for the 0.5-mm-thick surface layers; it varied from 0.04°C for the 3-mm-wide areas without glue to 0.34°C for the 24-mm-wide areas without glue. The highest individual contrast was 0.62°C. The average maximum contrast was reached in about 4 s for the 1.0 mm thick surface layers, which was the penetration depth of the method; it varied from 0.02°C for the 3-mm-wide areas without glue to 0.10°C for the 24-mm-wide areas without glue.

An area without glue must have a thermal defect size of at least 3 (i.e., a defect size that is at least three times the defect depth) to be resolved. The contrast of areas with one layer of glue was about half that of areas without glue.

The resolution capability combined with the short inspection needed for pulse thermography makes it an interesting possibility for use in industrial applications to detect glue deficiency underneath up to 1-mm-thick laminated surface layers of wood.

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