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ORIGINAL

Estimating the spread rate of urea formaldehyde adhesive on birch (*Betula pendula* Roth) veneer using fluorescence

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Abstract In plywood production, human operators find it difficult to precisely monitor the spread rate of adhesive in real-time. In this study, macroscopic fluorescence was used to estimate spread rate (SR) of urea formaldehyde adhesive on birch (*Betula pendula* Roth) veneer. This method could be an option when developing automated real-time SR measurement for plywood or processes. Estimation of SR was shown where adhesive was spread uniformly and also where adhesive was spread as lines. For uniform spreading, average intensity of the fluorescence image predicted the SR of adhesive well, with an R^2 of 0.97 and root mean square error (RMSE) of 13 g m^{-2}. For line-spread adhesive, line average intensity and width were used to estimate SR, and all these features predicted SR well. Furthermore, adhesive penetration into veneer over time could be detected from fluorescence images taken over time.

1 Introduction

Controlling adhesive spread rate in plywood or laminated veneer lumber (LVL) production is important, since it affects not only the final product properties (Marra 1992) but also cost and environmental impact as well. Ideally just enough adhesive will be applied in order to form the bond. Bekhta and Marutzky (2007) and Bekhta et al. (2009) proposed to use compressed veneers as a method for reducing adhesive consumption in plywood production whilst retaining the good properties of the material. Another important reason for controlling adhesive spread rate is the need to reduce formaldehyde emissions. Qiang et al. (2011), for example, showed that when using a soybean meal/melamine urea–formaldehyde adhesive, the amount of formaldehyde emitted was reduced when using a lower adhesive spread rate.

Currently, visual inspection and gravimetric methods are the usual ways of assessing spread rate. Workers can see bare spots when and where they occur and can sometimes see large variations in adhesive spread and whilst useful this method is rather imprecise and made all the harder with clear adhesives like urea formaldehyde (UF). The standard method for quantifying spread rate (SR) is to put a coupon of standard size through the glue spreader and measure its weight gain, however, the SR data obtained in this way can be inaccurate because of differences in the surface chemistry and roughness between the coupon and veneers, differences between the different sides of the spreader and differences in spread rate between the leading and tailing edges of a veneer sheet. In addition, measurement tends to be infrequent because of the labour (i.e. cost) involved.

An automated method for monitoring spread rate would have many potential advantages. By quickly and reliably identifying areas of the veneer where insufficient resin has been applied, or where there are adhesive-free spots, poor bonds and inferior product could be avoided. Lower average adhesive application rates and hence cost savings would be possible for several reasons. Firstly, such a system would ideally identify when adhesive over-application is occurring, allowing immediate correction. Secondly, automated monitoring would find trends in non-uniform application and provide feedback to operators to tell them

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when operational changes are required to improve uniformity. Finally, excess adhesive could be used as insurance in areas of lower than average application. Because of reduced variability, the target spread rate could potentially be lowered. By automating the quality assurance of spread rate, automated veneer layup should be available to even more mills and in mills with automated layup, line speed could be increased as the need for a spreader operator to monitor spread rate is a limit to line speed.

Such a system could be based on analysing images of veneers as they exit the glue spreader. The images would be instantly analysed by computer and the relevant information (spread rate and variability information) extracted from the image, which would be used to adjust operation conditions. One critical feature of such a system would be that the adhesive must be readily distinguishable from the wood. Fluorescence is useful for this because in fluorescence a material is illuminated at one wavelength and the fluorescing material emits light of a different wavelength. A camera with the appropriate filter to block the illumination and record the emitted light can then easily identify only the fluorescent material. This approach has been widely used to investigate adhesive penetration at wood bond lines (e.g. Gollob 1989; Johnson and Kamke 1992; Sernek et al. 1999; Frihart 2004; Gavrilović-Grmuša et al. 2008; Modzel et al. 2011).

In this study, fluorescent dye was added to clear UF adhesive. Under the right conditions, the intensity of light emitted increases with the film thickness, which provides a measure of spread rate.

Image analysis is a natural choice for monitoring adhesive spread. It is extremely fast, requires almost no labour or operation cost, and has a proven track record in similar applications. Industrial applications that involve monitoring the thickness and uniformity of a film applied to a surface were reported as early as 1998 (Morris et al. 1998). Earlier, Nozaka et al. (1991) described a method and device for detecting failures in adhesive application and the quantity of adhesive applied, using the degree of luminous emission from a fluorescent substance added to the adhesive. Potential application areas for this method included collators, box-making and book binding machines as well as continuous sheets or sheets of film. Additionally, Mbachu and Congleton (2004) inspected the real-time phenol–formaldehyde adhesive SR of oriented strand board (OSB) by means of NIR spectroscopy. Plinke and Ben-Yacov (2010) differentiated OSB strands with and without UF adhesive using NIR hyper spectral imaging and also estimated UF film thicknesses from planed wood surfaces with the same method.

The aim of the study reported in this paper was to demonstrate that fluorescence based image analysis has the potential to monitor adhesive spread rates on veneer. Fluorescence images were analysed to determine fluorescence intensity as a function of spread rate with uniform spreading and to show the impact of open time on fluorescence. With extruded adhesive lines the aim was to show how intensity and the width of the adhesive line vary at different spread rates.

2 Materials and methods

Fresh silver birch (*Betula pendula* Roth) logs were soaked in water at 40 °C for 48 h and, after debarking, were peeled on a rotary lathe (Model 3HV66; Raute Oyj, Lahti, Finland). The veneers were subsequently dried using a laboratory-scale convective type veneer dryer (Raute Oyj, Lahti, Finland) at 160 °C until bone dry. The nominal thickness of the veneers was 1.5 mm. The dried veneers were conditioned at a relative humidity (RH) of 15 % and temperature of 40 °C until equilibrium was reached, after which they were cut into specimens of $100 \times 100\ mm^2$. The moisture content (MC) of the conditioned veneers was assessed gravimetrically and the average MC was found to be 3.5 %, with a standard deviation of 0.2 %.

The adhesive used was urea formaldehyde (Dynea Prefere 14G014, Hamina, Finland) and the mixing ratio (by weight) provided by the manufacturer was used (resin 61.2 %; hardener 14.3 %; water 24.5 %). Since the UF adhesive itself did not fluoresce enough in the system used in this work, the fluorophore acridine orange (1 % water solution) was added to the adhesive at a rate of 0.08 % by weight. This fluorophore was selected so that the color of the adhesive line would be similar to the color of birch wood itself, as well as working with the filters and lighting using in the system employed (see below). The viscosity of the resin was measured before adhesive spreading and was adjusted by adding water so that it was the same as the manufacturer's recommendation. The viscosity of the adhesive was (Ford Cup 6) 40–45 s between the different adhesive batches.

Adhesive spreading was carried out manually in two ways. The adhesive was spread onto the tight side of the veneer. First, the adhesive was uniformly spread at 50, 100, 120, 150, 180 and 200 g m^{-2} with a glue comb which had 1 mm teeth at 1 mm intervals. This imitates roller spreader, foam spreading and curtain spreading. Three replicates were used at each spread rate. Second, application by extrusion was imitated by spreading the adhesive lines with a syringe at rates of 100, 150 and 200 g m^{-2}. One specimen per spread rate was prepared in this way. Adhesive penetration was investigated at a spread rate of 150 g m^{-2} by taking images at 1 min intervals for 15 min, using three replicate specimens. Between adhesive spreading and imaging there was time between 1 and 2 min. Ten images of approximately 0.9 cm dia. from different areas of each sample were taken.

Fluorescence images were obtained using a Leica DMLAM (Lausanne, Switzerland) light microscope modified by installing a TV zoom lens and removing the objective. A Leica DC300 colour digital camera captured the images and processing was done in the Leica Application Suite software. The specimen was illuminated by a blue LED with wavelength 470 nm. The filter set used in the microscope was the Leica L4, designed for fluorescein isothiocyanate (FITC). The camera settings (exposure time, gain, etc.) were the same within each sample test type.

To estimate the adhesive spread rate from the veneer pieces where spread was uniform, the average intensity of the grey scale fluorescence images was determined. The dependency between average intensity and adhesive spread rate was modelled with regression analysis. From the adhesive lines (simulated extruder), the average adhesive fluorescence intensity was determined by first using a threshold to determine where adhesive was and then measuring the intensity in that area. The width and area of the thresholded region were also quantified. To evaluate adhesive penetration, average intensity was observed over time.

3 Results and discussion

3.1 Estimation of adhesive spread rate with uniform spreading

Figure 1 shows images taken from veneers with adhesive uniformly spread at rates of 50, 100, 150 and 200 g m^{-2}. As may be clearly observed visually, the intensity increases as the adhesive spread rate increases (i.e. the images become lighter). Figure 2 shows the average intensity from the same veneers as shown in Fig. 1 versus spread rate (plus veneers having spread rates of 120 and 180 g m^{-2}). What may also be observed is that the variability in intensity increases, as seen in the images (Fig. 1) and the error bars in Fig. 2.

Figure 2 clearly shows that average intensity of images is dependent upon the adhesive spread rate, but that even with no adhesive the veneer displays an intensity of some 15 units—the auto-fluorescence of wood (see Fig. 2). A polynomial was fitted to the data in Fig. 2 (Eq. 1), providing a simple model that could be used to quantify

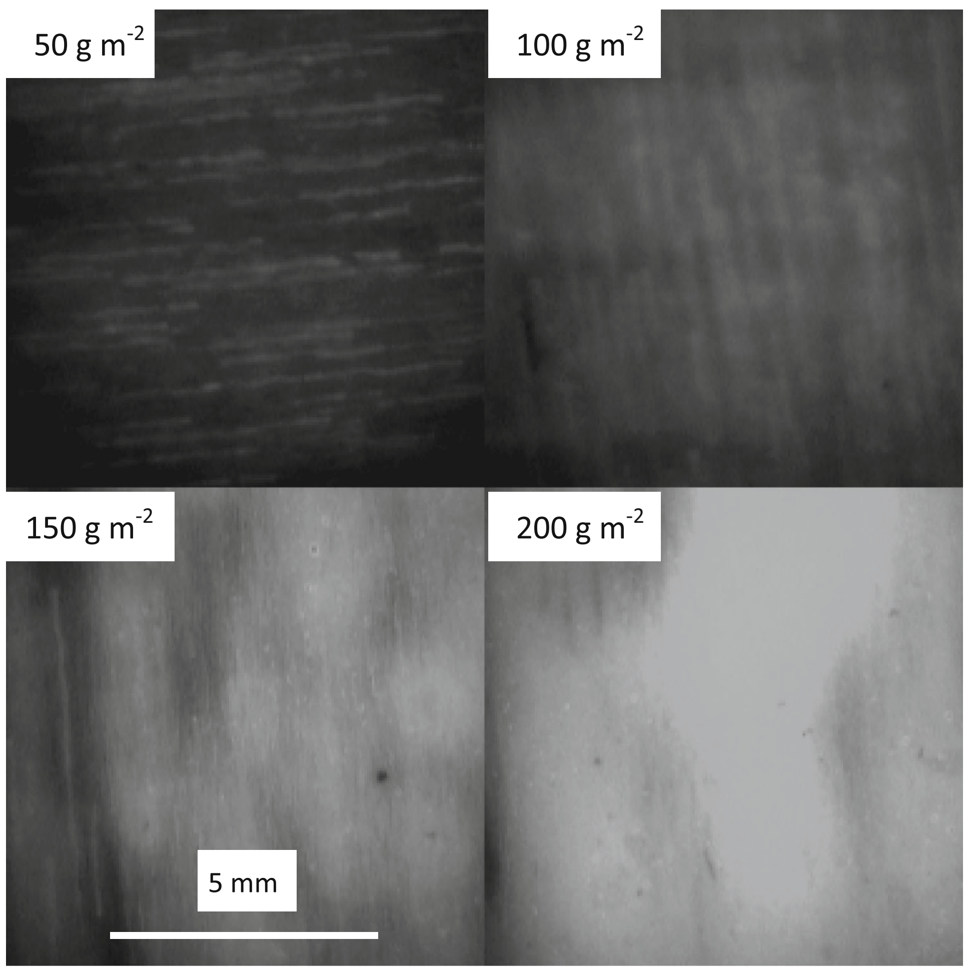

Fig. 1 Fluorescence images of veneers of uniformly spread adhesive at spread rates 50–200 g m^{-2}

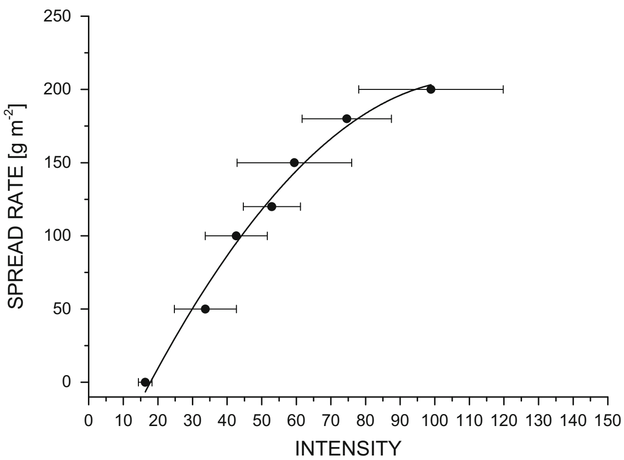

Fig. 2 Adhesive spread rate as a function of intensity average (n = 30 images/spread rate) of images. *Error bars* are ± standard deviation

spread rate from fluorescence intensity in an industrial setting. With this camera and settings, the data follows the form:

$$SR = -0.018I^2 + 4.68I - 80.12 \quad (1)$$

where SR and I are spread rate and intensity, respectively. It is not surprising that the response is nonlinear: in most cases cameras are designed to match the nonlinear response of the human eye. Another possible source of the reduced response could be the 'inner filter' effect, where a significant portion of the illumination or emitted light is absorbed whilst passing through the adhesive film (Lakowicz 1999). In order to avoid the inner filter effect, the adhesive should be clear and the concentration of the dye kept as low as possible to minimize absorption. The key result arising from Fig. 2 is that spread rate can be reliably determined from intensity. For the regression model the R^2 is 0.98 and root mean square error (RMSE) 13.0 g m^{-2}, suggesting that this type of approach has potential. Using the same principle, Morris et al. (1998) were able to accurately measure the thickness of a plastic film from the intensity of fluorescence.

The most probable cause of the increasing variability in fluorescence emission with spread rate is a result of the manual spreading employed to apply the adhesive to the substrate. The adhesive was more difficult to spread uniformly on the veneer sheet at higher spread rates. It was found that the total error from the size of the veneer and total adhesive applied was only 4 g m^{-2} which is quite small.

Wood itself can fluoresce at all wavelengths of visible and ultraviolet light (Donaldson and Bond 2005), so it is necessary to ensure that this fluorescence is much weaker than the adhesive fluorescence. The best image quality was found when exciting at 488 or 568 nm with corresponding long pass emission filters of 530 or 600 nm. Figure 2 shows that the auto-fluorescence of the wood can easily be detected and that even at a spread rate of 50 g m^{-2} the total fluorescence level was approximately twice as great, suggesting that auto-fluorescence need not influence the detection of even low resin spread rates.

3.2 Estimation of extruded spread rate from adhesive line width

Figure 3 shows images from the extruder simulation where adhesive was applied in lines at 100, 150 and 200 g m^{-2}.

On the left are two parallel adhesive lines and on the right are the corresponding threshold images where the adhesive is white and the wood is black. Because the spacing between lines was kept constant, a higher spread rate resulted in more spreading of the adhesive and wider adhesive lines. There is of course some variation in the adhesive line width and spacing due to manual spreading.

Further inspection of Fig. 3 reveals that the edges of the image are consistently darker than the centre which is a sign of non-uniform illumination. Uniform illumination makes image analysis much easier and anyone using imaging to monitor spread rate would have to pay careful attention to lighting conditions. In this study, it caused only minor systematic errors that affect all the images in a similar way, so for this reason it was not corrected.

In uniform adhesive spreading, only image intensity needs to be utilized. However when analysing line images from the simulated extruder, it was found that intensity (Fig. 4) and the adhesive line area (Fig. 5), both changed linearly with spread rate. Again veneer auto-fluorescence is very weak since in the middle of adhesive lines, the veneer is observed to be nearly black (intensity near zero). The good contrast between wood and adhesive makes them easy to distinguish.

As in the case of uniformly spread adhesive, the deviation increases when spread rate increases. Some of the deviation is most probably due to manual sample preparation. In practise, the values of the geometrical features of the adhesive line would be dependent on the properties of the extruder and the time between extrusion and imaging. There were only three spread rates used in this study but it suggests that any one of the features could predict spread rate quite well. The features correlate well with adhesive spread rate, Pearson correlations between intensity and area being 0.89 and between intensity and line width 0.88 (N = 60 adhesive lines). Furthermore according to a one-way-ANOVA all the features at different spread rates differ from each other with statistical significance ($p = 0.0000$, $\alpha = 0.05$).

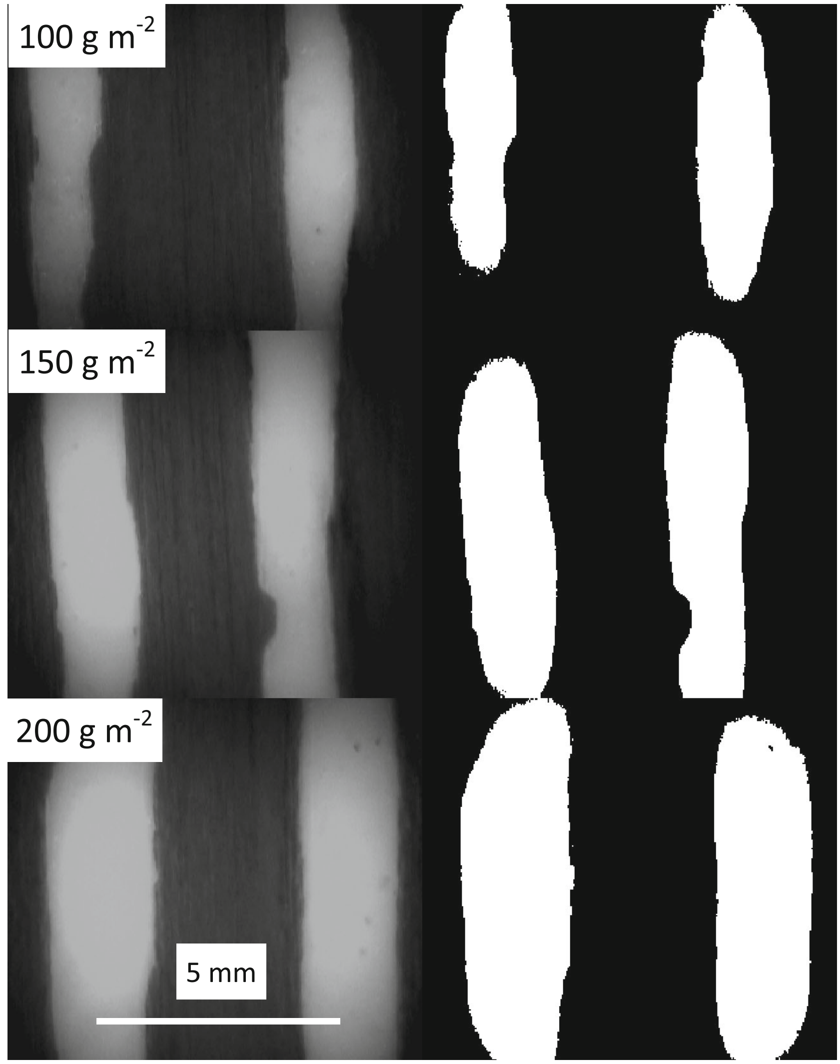

Fig. 3 Fluorescence images of different adhesive spread rates and corresponding binary images

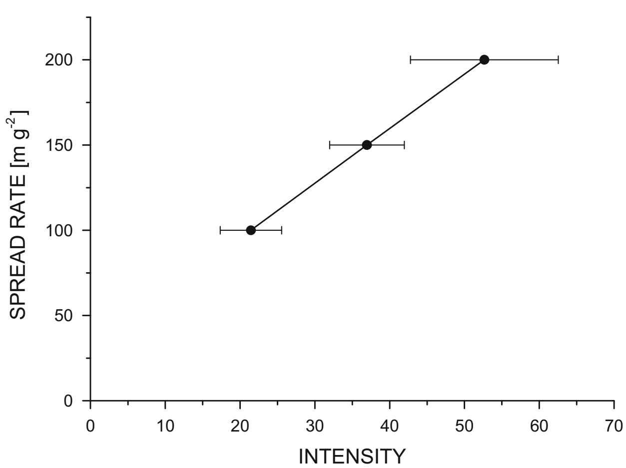

Fig. 4 Adhesive spread rate as a function of average intensity of adhesive lines. *Error bars* are ± standard deviation. (n = 20 images/spread rate)

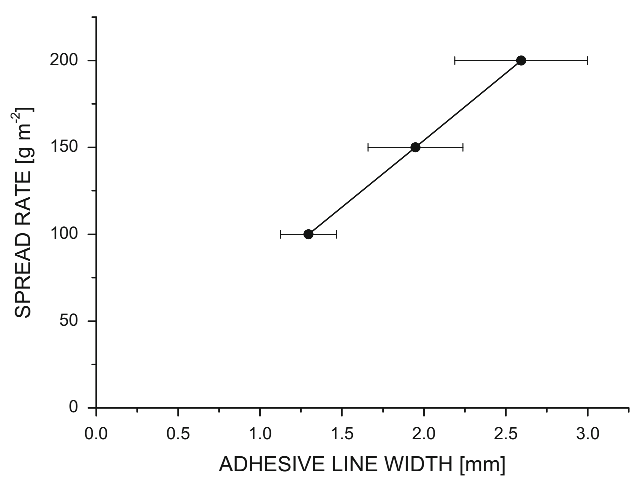

Fig. 5 Adhesive spread rate as a function of average adhesive line width. *Error bars* are ± standard deviation. (n = 20 images/spread rate)

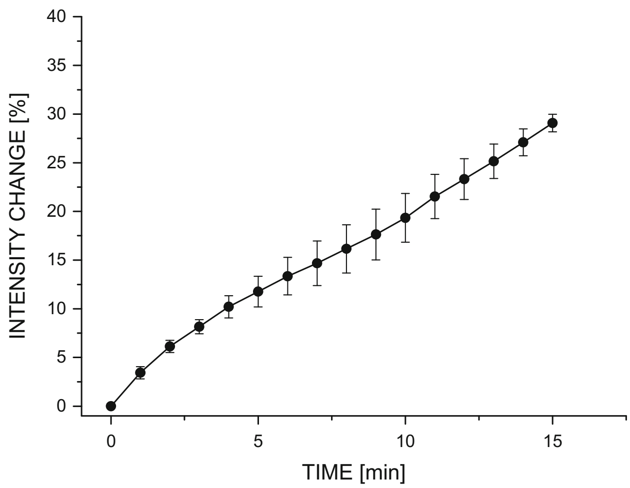

Fig. 6 Image intensity change as percent from original intensity as a function of adhesive open time at spread rate 150 g m^{-2}. *Error bars* are ± standard deviation

3.3 Impact of open time on fluorescence emission

In Fig. 6 the average image intensity is presented as a function of adhesive open time.

Figure 6 shows that there is a relatively linear decrease in fluorescence intensity with time. This is most probably due to the penetration of the adhesive into the veneer over time. If the adhesive flows into the lumens below the wood surface, both illumination and emitted light will be blocked by the wood and so this material will yield lower intensities. Drying and curing of the adhesive could also potentially have an effect on the fluorescence properties.

This method might be utilized in plywood production during process delays. With some experience, it might be possible for the image to indicate when the adhesive has over-penetrated or dried-out enough to compromise the bond. One of the main goals in industry is to accelerate curing in order to reduce production times (Schmidt et al. 2010). With faster curing systems the risk of over-curing before pressing increases.

4 Conclusion

In this study, it has been shown that macroscopic fluorescence imaging has the potential for measuring, on-line, adhesive spread rate and in quality control in plywood or LVL production. With the addition of an appropriate fluorophore to the adhesive, the spread rate can be estimated and the regions that are missing adhesive can be easily detected—even when using transparent UF adhesive. With the relatively unsophisticated system used in this study, even the lowest adhesive spread rate of 50 g m^{-2} was easily distinguishable from the auto-fluorescence of wood.

When adhesive was applied in lines, as in an extruder, adhesive line area/average width and average fluorescence intensity were both found to be dependent on the adhesive spread rate. In addition, the method was able to detect declining fluorescence over time, which could potentially be used as an indication of over-penetration or over-drying.

While fluorescence was used in this study, a standard absorbing dye that contrasts with the wood background could theoretically be used to differentiate wood from adhesive and provide similar information.

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