Usability of Wood as a Direct Printing Medium

KIMMO HÄMÄLÄINEN AND TIMO KÄRKI
Lappeenranta University of Technology, Department of Mechanical Engineering

Hämäläinen, K. and Kärki, T. 2012. Usability of Wood as a Direct Printing Medium. *Baltic Forestry* 18(2): 316–326.

Abstract

Versatility in the appearance of wood and added value to interior decoration markets could be achieved by printing grain patterns of different species or images directly onto wood. The problem is how to transfer a high quality image or print sustainably onto wood, which is porous, heterogeneous, dimensionally unstable, non-white and rough.

The surface properties of wood affect its printability. Optimal adhesion is essential for print quality, as too high ink absorbance can cause spreading and too low ink absorbance pale prints. Different printing techniques have different requirements on materials and production. Non-impact printing techniques provide the best basis for wood printing. Direct printing on wood has potential to provide efficiency to production.

Inkjet printing on wood with different mechanical or chemical surface treatments, and wood plastic composite material gave good results that encourage further studies on the subject. Sanding the wood surface perpendicular to the grain gave the best overall printing quality. Spreading parallel to the grain could not be avoided totally, except in cases where the wood was treated hydrophobic, when in turn the adhesion of ink was not sufficient. The grain pattern of the underlying wood stayed clearly visible in the printed images.

Key words: wood veneer, WPC, adhesion, printing, ink

Introduction

Every piece of wood has a unique and dignified appearance, and wood is accepted as material in many interior decoration, furniture and musical instrument solutions.

There is a large variety of wood species with different characteristic grain patterns, color, density and other features that create the whole look of wood, and some species are considered more distinguished than others. Often the most highly appreciated wood species are either expensive or of tropical origin. Competition in the interior decoration markets requires versatility in appearance and cost efficiency, which have traditionally been achieved by using different wood species with different qualities. There are also products that create versatility by printing technology. Today the printed interior decoration materials consist of core, printed laminating paper, and overlay. Of these types of solutions, the core material is often a substitute for solid wood.

Versatility in the appearance of wood and added value could be achieved by printing grain patterns of different species or images directly onto wood. Printing directly onto wood also shortens the production time and obviates the printing paper handling, which could bring significant cost efficiency to production and challenge the existing solutions based on laminating papers.

The problem when planning to implement wood printing into durable applications is basically how to transfer a high quality image or print sustainably onto wood, which is porous, heterogeneous, dimensionally unstable, non-white and rough.

In wood printing, the rules of any wood surface treatment can be applied, and ink can be seen as an adhesive, such as glue or paint. According to Koponen (1988), there are some requirements for a durable coating, such as sufficient adhesion, and sufficient cohesion in the adhesive liquid; the coat must be able to follow the natural dimension changes of wood after curing, and the coat should have durability against aging during the service life of the end product. Also the wood surface must be wetted by the adhesive. From the point of view of printing, it must be noted that too high absorption causes the ink to spread, which further leads to blurry images. In paper printing it is commonly known that high quality prints are produced on coated paper (Kipphan 2001).

At the moment no unifying theory to explain all the mechanisms in adhesion exists, therefore adhesion must be explained by several different theories, e.g. the mechanical interlocking theory, electronic or electrostatic theory, thermodynamic adsorption or wetting theory, diffusion theory, chemical (covalent) bonding theory, and theory of weak boundary layers and interphases. It must be noted that these mechanisms are not self-excluding, and several of them may occur simultaneously, depending on the situation (Gardner 2005).

Mechanical interlocking, where the adhesive penetrates into the wood and locks itself with the wood

fibers as it cures (Koponen 1988), is seen as the primary phenomenon or mechanism to bond the adhesive into wood and other porous materials (U.S. Department of Agriculture 2007). This is acknowledged also by Koponen (ibid.), as he divides the adhesion theories into two categories: mechanical and specific theories, and points out that the adhesion is a result of both of these affecting together and claims that of the whole adhesion, 10 % is due to mechanical interlocking. Mechanical interlocking theory has also been accepted by Gardner (2005).

As wood is porous material, it is possible for molecules small enough to penetrate into it by diffusion. The diffusion coefficient rises until the water saturation point of wood is reached, after which the diffusion coefficient gets the value of 0. Also the anisotropic structure of wood shows as a different diffusion coefficient whether it is measured parallel, tangential or perpendicular to the grain. The parallel diffusion coefficient can be up to 10 times higher than the other directions. (Koponen 1989)

The thermodynamic adsorption or wetting theory is vastly accepted to explain the adhesion on solid surfaces (Borch et al. 2001). Thermodynamics considers the prerequisite for actualized adhesion to be that the adhesive forces are stronger than the cohesive forces of the adhesive (NDT Resource Center 2009).

Surface energy is an adhesive force, which becomes from the forces that hold the molecules of a substance or material together. In order to create adhesion, these forces have to overcome the forces that hold together the molecules in the adhesives (PRA 2009). Wetting and spreading can be decreased by processes that reduce the free surface energy of the solids sufficiently (Borch et al. 2001). Surface treated wood, for example, has lower surface energy than untreated wood, and therefore it is more difficult for example for water to adhere into treated wood. The surface of untreated wood consists of a mixture of molecules that consist of carbon hydrogen and oxygen, and therefore there are a lot of polar groups like OH or hydroxyl groups that react with adhesives (PRA 2009).

Cohesion forces exist on the molecular level, and they are the forces after which the molecules and atoms group, eventually forming bodies. Cohesion attracts the molecules to each other, and the distance between the molecules depends on the dimension of the molecules, which is proportional to the size of the molecules. Liquids have two coordinates of free space for the free motion of molecules, while solids have none (Prebeg 2002).

Surface tension is the phenomenon that embodies the cohesion forces that effect on the surface of liquids. This is because the molecules on the surface are not surrounded by other molecules in every dimension, as the molecules inside the liquid substance. Therefore they cohere more to the other surface molecules, creating a layer or a film with stronger bonding than with the molecules inside the liquid. The strength of the surface tension of liquid is proportional to the amount of polar groups in it. Water, for example, has high surface tension because it has a lot of OH or hydroxyl groups in it. Alcohols have lower surface tension because they have less OH groups. The surface tension in water causes it to form drops on solid hydrophobic surfaces. The lower the surface tension in the adhesive, the easier it forms a sufficient film on solid surfaces. (PRA 2009)

Surface tension can be quantified by the forces acting in the interphase of liquid and air. Units that define surface tension are dynes per centimeter [dyne/cm] and newtons per meter [N/m]; 1 dyne/cm = 1 mN/m. The units are the same as for surface energy (PRA 2009). The surface tension of water is 72, that of alcohols is 20 – 22, and of solvents 20 – 30 dyne/cm (SensaDyne 2009). Inkjet inks have a surface tension of 34 – 40 dyne/cm (MrInkjet 2009).

The thermodynamic adsorption or wetting of any solid surface can be explained or indicated by the concept of the contact angle (U.S. Department of Agriculture 2007). When the contact angle between a drop of liquid and the solid surface is higher than 90°, the drop is hydrophobic, and when it is lower than 90°, the drop is hydrophilic (Viluksela et al. 2007). However, contact angle measurements on wood surfaces are difficult to perform because of the roughness, porosity, and absorbing and swelling properties of wood surfaces. Often the measured contact angle is an average contact angle of multiple measurements (Minford 1991).

Other theories of adhesion include the attraction forces on the molecular level that affect both the adhesives and wood, and the theory of weak boundary layers. There are three main attraction forces, which are also known as van der Waal's forces or dispersion forces, including firstly dipole-dipole forces or negatively and positively charged polar molecules that have strong attraction to other polar molecules. Secondly, they include London forces that consist of the weaker attraction forces that non-polar molecules have to each other. Thirdly, there is the hydrogen bonding force, which is an important attraction force affecting through hydroxyl (OH) groups, which are also present in wood hemicelluloses and cellulose (U.S. Department of Agriculture 2007). Attraction forces can also act negatively, as it is known that aqueous or other polar liquids do not wet non-polar surfaces such as polyethylene (Conners and Banerjee 1995).

The hydrogen bond is considered the most notable bonding force in many wood modification methods. It is formed between the hydrogen atom and other atoms through electrostatic interaction. The hydrogen atom has one electron which it donates to electronegatively charged atoms, creating a bond between the two atoms. (Desiraju and Steiner 2001)

Covalent bonds are formed when atoms of nonmetals interact and share electrons, forming molecules and thus making very strong bonds (U.S. Department of Agriculture 2007). However, a covalent bond between wood and adhesives has not yet been demonstrated (Gardner 2005).

Bond energy is defined as the bond length where the molecules are at the most stable stage. It can also be defined as the energy that is required to separate two atom molecules into individual atoms. When more electrons are shared between atoms, the stronger the bond energy, the stronger the bond becomes. Also growing differences between the electronegativity and orbital overlap of the atom have the same kind of influence on bond strength. (Olmsted and Williams 1997)

Electrostatic forces consist of dispersion forces and forces of permanent dipoles. This can be confirmed by detecting electric discharges when an adhesive is peeled from a substrate. (Petrie 2007)

Table 1. Bond energy in different adhesive forces. (The Adhesive and Sealant Council Inc. 2009)

	Bond length (nm)	Bond energy (kJ/mol)
Chemical bonds:		
Covalent	0.1 - 0.2	150 - 950
Metallic	0.3 - 0.5	100 - 400
Ionic	0.2 - 0.3	400 - 800
Intermolecular interactions:		
Van der Waal forces	0.4 - 0.5	2 - 15
Hydrogen bonds	0.2	20 - 30

The weak boundary layer theory suggests that when a failure in adhesion occurs, it is due to cohesive failure of the weak boundary layer. Petrie (2007) claims that a true adhesion failure happens rarely, and that cohesive failure often occurs so near the interface that it seems that the adhesion fails in the interface. Weak boundary layers may develop before or during applying adhesives, while setting or curing the adhesive, and during the service-life of the joint. A common factor that may develop a weak boundary layer is atmospheric moisture (ibid.). Weak boundary layers on wood are related to variations on the wood surface. They can be either chemical or mechanical by nature. Chemical weak boundary layers occur through the movement of wood extractives to the surface. Some of these extractives, like fats, waxes, resin acids or sterols are related to hydrophobic properties on the wood surface, while others, like sugars, phenols, tannins and proteins are related to the hydrophilic properties of wood. Mechanical weak boundary layers result from damaged surfaces, oxidation or degradation by light (Rowell 2005).

There are two principal methods to approach the adhesion problems in printing industry: firstly, efforts to decrease the surface tension of adhesives or inks, and secondly, efforts to increase the surface energy of solids. (Argent 2008)

The surface tension of water-based inks can be lowered by adding solvents, such as alcohols to the mix (Argent 2008). Green (1999) has tested the influence of solvents on surface tension by mixing methanol to water, and found that in a mixture with 49 % of methanol, the surface tension is 35 dyne/cm Argent (2008) presents that mixing ethanol to water decreases the surface tension of the mix from 72 dyne/cm to 47 dyne/cm with a 10 % ethanol content, and to 33 dyne/cm with a 25 % ethanol content. Ethanol has the surface tension of 22 dyne/cm.

The adhesion improving techniques on solids can be categorized into mechanical: abrasion etc., chemical: primer or solvent treatment etc., and energetic: corona, flame, laser or plasma treatment methods (Petrie 2007). The solutions aim at oxidizing a solid surface by UV-radiation, plasma and corona treatment, flame treatment, or acid treatment (PRA 2009). In the wood industry, a simple sanding process is widely used to increase the surface energy of wood (U.S. Department of Agriculture 2007). The polarity of non-polar solid surfaces, such as polyethylene films, can be altered by acid or alcohol treatment, which improves the adhesion of polar substances. Acids are thought to affect the pH of surfaces (Conners and Banerjee 1995).

Printing techniques can be divided into two main principles: mechanical and digital prints. Mechanical prints are based on plate-using methods where the printed subject is transferred from a plate or a roll, called master, to the printed surface through pressing. Digital prints use a non-impact technique where the printed surface does not have a physical contact with the printing heads. The clear advantage of digital printing techniques is the possibility to change the printing image flexibly so that sequential prints may have individual information. (Viluksela et al. 2007)

Inkjet printing is a form of digital printing where the ink is led to the printed surface in drops guided by the image signal. The multiple drops of ink eventually form the subject on the print. The printer heads may produce some 75,000 drops per second. There are two separate methods in inkjet printing, according to

the formation of the drop stream: the continuous stream method and the drop-on-demand method (DOD). In the continuous stream method the stream of drops is by name continuous and the drops that are not intended to fall on the print are guided into collectors. The separation between the drops is done by electrical charge conducted in the drops (Viluksela et al. 2007). In the drop-on-demand method, the drops are only sprayed when the printer heads are directly over the spot. This can be done by heat or electrostatic or piezoelectric force (ibid.).

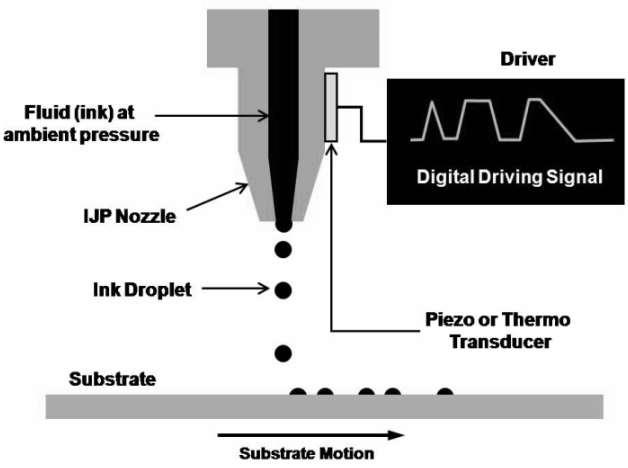


Figure 1. Principle of DOD inkjet printing (SPIE 2009)

The printing inks consist of three main components: pigments (soot, minerals, salts), adhesives (oils, alkyds, resins) and solvents (hydrocarbons, esters, ketones, alcohols, water). Pigments create contrast, adhesives bind the pigments onto the printed surfaces, and solvents affect on viscosity (Viluksela et al. 2007).

Viscosity is an important feature or concept for adhesives and inks. It indicates the flow properties of fluids and is a measure of resistance in liquids. Viscosity has an effect on sharpness by spreading control (Viluksela et al. 2007). Viscosity does not actually affect the capability of any adhesives to fill cavities but it has an effect on the time that the filling takes (NDT Resource Center 2009). The unit for viscosity is pascal second (Pa.s) or centi Poise (cP). 1 cP equals 1 mPa.s (Kipphan 2001).

The drying phase is also important for the result of the printing in the printing process. It can be divided into two phases, curing and actual drying. In curing the viscosity in the ink grows because of the nature of the ink or the evaporation of solvents. As the ink dries, the adhesives form a film which eventually affects by sticking the ink onto the printed surface. (Viluksela et al. 2007)

The conventional inkjet systems cannot put out ink that is too viscous (above 10 cP). It is also difficult to produce high speed printing of good quality with inkjet systems if the inks are too fluid or runny. Therefore there is interest towards systems that could jet high viscosity inks in order to prevent ink spreading. The solutions require integrated heating systems for printers, to decrease the viscosity temporarily. Higher viscosity would also improve printing on porous materials, such as wood. The viscosity of standard inkjet inks is 3 – 5 cP (Cox 2008), whereas water in the room temperature is 1 cP (University of Waterloo 2009).

Printing quality can be measured with different measured quantities or by visual evaluation, which is a subjective method and therefore questionable for quality analysis. However, visual evaluation can be well employed in detecting defects caused by the printing process itself. These include alignment inaccuracy, spotting or other possible defects. Visual evaluation of printing quality is done by comparing samples to a selected specimen that is agreed to have sufficient quality. Measuring the printing quality is a more precise method for quality analysis. By measuring, the prints can be set to meet selected measuring values and standards. The measured values are different measures for color, resolution and gloss. (Viluksela et al. 2007)

Spectrophotometer is used for color measuring by measuring the wavelength of colours. The measurement gives information of the precise colours of the produced prints. The results are often compared to values given in the CIELab color system (Viluksela et al. 2007), which is a three-dimensional system for defining colour shades, where L (luminance), a (red-green scale) and b (blue-yellow scale) are the dimensions in the system (CIELab 2006).

The darkness of a printed surface is measured by density, which is a quantity that indicates the thickness of the printed layer and its ability to absorb and transmit or reflect light. Density is defined as follows:

$$D = lg\ lo/l$$

where lo = intensity of the incident light beam; l = intensity of the reflected light beam. (Viluksela et al. 2007)

As density is a logarithmic value, it means that at value 0 all the light is reflected, at value 1 10 % is reflected, and at value 2 only 1 % is reflected (Räty 2009). Density can be measured with densitometers. They analyze the light transmitted or reflected from the printed surface. The typical value for density in newsprint is 1.10, whereas in better quality printing the density increases closer to value 2. It is possible to analyze the density of different colors by filtering the

light with complementary color filters. Densitometers can be used for defining the ability of the printing system to replicate the original colour, hue or tint (Viluksela et al. 2007).

Gloss is as an important feature of transmitting quality in printed images, as it is claimed to have as much psychological impact on a consumer as colors on products (GlossMeters 2006). High gloss is often associated with high print quality (Kipphan 2001). Paints and coatings industries, furniture industries and printing industries use primarily 60° angle geometry measurements to control gloss (ibid.).

In printing, the difference to color hues is produced by screening or rasterizing (also halftoning), which is done by breaking the image into small dots and changing the amount of dot covering in the image. The measures of screening are lines per cm (l/cm) or lines per inch (LPI), which indicate the distance of the lines to each other. The screen of newsprint is typically 40 l/cm, that of magazines 54 – 60 l/cm, and of art graphic books 70 – 80 l/cm. Modern printing has an integrated raster image processor (RIP) that creates the screen. (Viluksela et al. 2007)

The capability to produce sharp images is important for high quality. Sharpness is defined by the boundaries or edges of different tones or hues. The shorter the shift from one tone to another, the sharper the image. Sharpness can be measured from the print by the rise distance or the distance that is needed for the full tone shifting in the tone boundary. (Imatest LLC 2009)

Resolution is also a measure that describes the sharpness of the image. It is presented as dots per inch (dpi) or pixels, and describes how many drops there are compared to the surface area (Viluksela et al. 2007). The higher the number of dots or lines compared to the surface area, the sharper the image. However, the porosity and roughness of the printed surface increase the dot gain, which leads to printing results that are darker than intended. Higher quality papers, such as coated or art graphic papers allow a screen that has more density. The dot gain affects most in middle tones or hues. In newsprint the dot gain is 25 – 30 % with 40 % tone, and in offset printing on coated paper the dot gain is correspondingly 15 %. Contrast or the difference between light and dark tones is also an element of sharpness. It is normally attempted to be maximized in printing (Viluksela et al. 2007).

The surface roughness of wood has some effect on the results of surface treatments, and especially on the eventual smoothness of the treatment. Different surface machining methods result as different amounts of roughness on wood surfaces. For instance planning leaves a more rugged surface than sanding. Also the softer earlywood in softwood species tend to behave better than latewood when machined. This causes the early and the late wood to be on a slightly different level to each other. (Koponen 1988)

Producing white color into prints on wood surfaces can not be done by conventional printing equipment using just a CMYK (Cyan, Magenta, Yellow, Black) color combination. White has to be brought into the wood by preliminary white coating or by using overlaying white ink. White inks can be produced of titanium dioxide (TiO2) or calcium carbonate ($CaCO_3$) (Viluksela et al. 2007). Printing with white inks requires special inbuilt features from the machinery. Titanium oxide or other mineral-based inks need to be stirred constantly, so that they do not settle. At the same time, shaking is not recommendable, and so the stirring must be done carefully (SignIndustry.com 2009). Settling occurs due to the mineral consistence of white inks that is liable to sedimentation, which further on leads to diluting of the color (Mimaki Europe B. V. 2007).

There is growing interest among printing industries to include white inks into inkjet printers in order to produce high quality printing on non-white surfaces, such as wood or cardboard. Abandoning the use and handling of intermediates and printing directly onto end material reduce the total production costs significantly (SignIndustry.com 2009). Zünd is a Swiss company providing a flatbed inkjet printer with white ink printing on different materials, including wood up to 40 mm thick (Zünd 2009). Mimaki Engineering co. Ltd has developed a solvent-based white ink for inkjet printing which allows printing white and CMYK colours simultaneously (Mimaki Europe B. V. 2007).

Materials and methods

Samples of birch (*Betula pendula*) veneers and wood plastic composite (WPC) materials containing spruce (*Picea abies*), polypropylene and maleic anhydride polypropylene (MAPP) were prepared to 1.5 mm thickness. Also high quality Epson Premium Luster Photo Paper, coated with polyethylene, was used as reference material in the testing. The birch veneers were cut roughly to A4 paper size, except for samples in batch A, which were 100 × 300 mm. The dimensions of the WPC samples were 120 × 300 mm. The cutting was done with a Casati 3050 hydraulic cutter. In total, 14 batches with different surface characteristics were included in the printing tests.

The samples of batch A were cut from planed birch planks that were stored dry for at least one month. The planning was done with a MP6-230S planning machine, made by Holytek Industrial Woodworking Machine Corp., and then processed into 1.5 mm thickness.

Table 2. Samples

Batch	Material	Surface	Number of samples
A	Birch veneer	planed	20
B	Birch veneer	sanded	20
C	Birch veneer	thermo-mechanically densificated	20
D	Birch veneer	sanded and waxed	20
E	Birch veneer	sanded perpendicular to the grain	20
F	Birch veneer	sanded, silicon sprayed	20
G	Birch veneer	sanded, waxed, alcohol wiped	20
H	WPC 20 % PP	virgin	9
I	WPC 30 % PP	virgin	10
J	WPC 40 % PP	virgin	5
K	WPC 20 % PP	sanded	10
L	WPC 30 % PP	sanded	10
M	WPC 40 % PP	sanded	5
N	Printing paper		8

The samples were lathed and then stored in dry atmosphere for at least one month. Batches B, D, F and G were sanded parallel to the grain, and batch E was sanded perpendicular to the grain. The sanding was done with an NV RRR 13 wide belt sanding machine made by CB s.r.l., with 180-grit sanding paper.

The samples of batch C were thermo-mechanically densified in an open system. The temperature in the process was 110 °C. The pressure was first raised to 1.7 N/mm^2 for four minutes, then raised to 4 N/ mm^2 for four minutes, and then lowered to 1 N/ mm^2 for three minutes. After the densification, the thickness of the samples had changed from 1.6 mm to 1.2 mm. The samples were cooled before printing. During the compressing, three samples of the total 20 were wetted in hydraulic oil and they were thereby rejected.

The samples of batches D and G were sanded, and then treated from one side with the OsmoColor transparent clear wax of Osmo Holz und Color GmbH & co. KG. The waxing was performed once, after which the samples were left to open-dry overnight. Batch G was wiped with ethanol before printing.

The waxed samples were measured for weight before and after the waxing with an electrical scale. The average change in weight was increased in sample batch D by some 2.2 % or 1.35 g. In sample batch G the results were 3.6 % or 2.2 g increase in weight. Therefore it can be calculated that the amount of wax/ m^2 was approximately 21.7 g in batch D and 36.2 g in batch G. The standard deviation of the measured weight increase is less than 22 %, meaning that it is moderately high.

The samples of batch F were sanded, and then sprayed on both sides with Kivisil Primer of Tikkurila Oy, which contains polydimethylsiloxane, isooctyltrimethoxysilane, acetic acid and methanol. The used substance is a concentrate and it was diluted with water according to the manufacturer's directions. Two spraying treatments were done, first with a 1/19 silicon content and second with a 1/9 silicon content. After the first spraying, the samples were stacked and left in a press overnight, because they showed intense curving. The second spraying was done the next day, after which the samples were left to open-dry for two days. Both sides of the samples were sprayed, because this was found to decrease the curving of the samples.

The silicon-treated samples were measured for weight with an electrical scale before and after the spraying. The average change in weight was increased by some 1.3 % or 2.4 g. The amount of diluted silicon/ m^2 on one side was therefore approximately 19 g.

The samples of wood plastic composite in batches H, I, J, K, L, and M were made by direct extrusion with a double conical screw -type extrusion machine CE 7.2 FE, made by Hans Weber Maschinenfabrik Gmbh. The samples were produced into some 20 mm thick profiles, then cut and sanded into 1.5 mm thickness. Batches H, I and J were sanded from one side only, so that a virgin WPC surface could be printed. Batches K, L and M were sanded on both sides.

The gravimetric material composition of the WPC samples was in batches H and K 20 % PP, 77 % Spruce and 3 % MAPP; in batches I and L 30 % PP, 67 % Spruce and 3 % MAPP; and in J and M 40 % PP, 57 % Spruce and 3 % MAPP.

The printing was done with an Epson Stylus Pro 4450 Inkjet printer, with inks that were factory-set by the printer manufacturer: Epson Ultra Chrome – Matte Black, Cyan, Magenta, and Yellow. The printer has a resolution of 1440 × 720 dpi (dot per inch) and it utilizes piezoelectric drop-on-demand technology. The drop size is 3.5 picoliter. The printed test image was

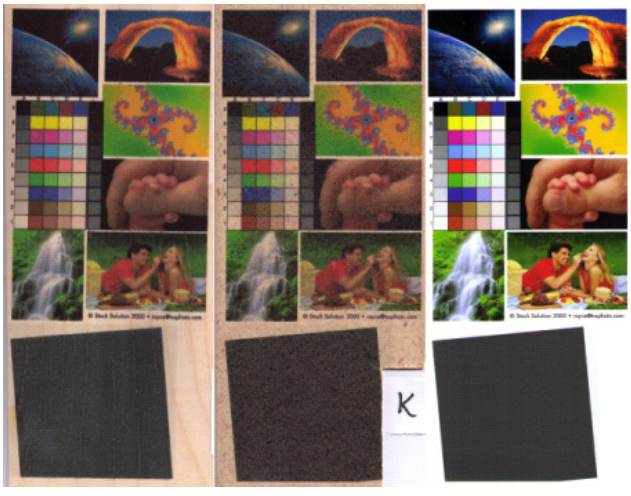


Figure 2. The printed test images (E left, K middle, N right)

printed via the Picture Window Pro 5.0 program. Due to the unevenness or curviness of some of the veneers, some samples were left unprinted.

Results

Visual evaluation of the printing quality was done by concentrating on possible errors in printing and also by evaluating ink spreading in the samples and comparing them with reference prints. Spreading can be easily detected by observing the faces and expressions of the persons in the printed image. Also the borders of the image blocks reveal spreading easily.

Table 3. Visual grading. Scale: excellent, good, satisfactory, fair, and poor.

Batch	Grade
A	good; spreading occurs, paler than sanded wood
B	good; spreading occurs
C	satisfactory; more spreading occurs than in sanded wood
D	poor; pale, no spreading, beading occurs
E	good; spreading occurs, deep colors
F	satisfactory; spreading occurs, small cracks on the surface
G	fair; no spreading, beading occurs
H	satisfactory; no spreading, dark, blurry
I	fair; no spreading, dark, blurry
J	poor; no spreading, dark, extremely blurry
K	satisfactory; little spreading, grainy, blurry
L	fair; spreading occurs, grainy, blurry
M	poor; spreading occurs, grainy, blurry

Moisture was measured of the samples before printing with an HM8 – WS1 moisture meter, made by Merlin Technology GMBH. The measuring was performed over a styrofoam support base, following the recommendation of the manufacturer. Each sample was measured once. The moisture content of untreated wood varied to some extent. It was not tested how this affected the printing results.

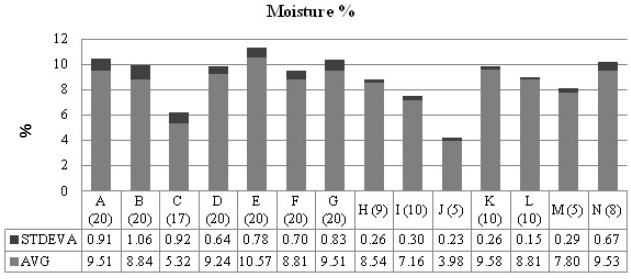


Figure 3. Moisture percentage of the samples before printing, the number of measured samples is presented in parenthesis

Roughness was measured of the samples before printing with a Handysurf E-35B tracer type surface roughness measuring device made by Accretech – Tokyo Seimitsu Co. Ltd. The measuring direction followed the moving direction of the printer head, which was perpendicular to the grain. Each sample was measured 3 times. The results are presented as the arithmetic mean deviation of profile (Ra).

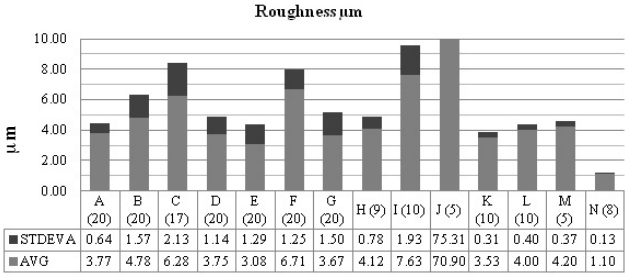
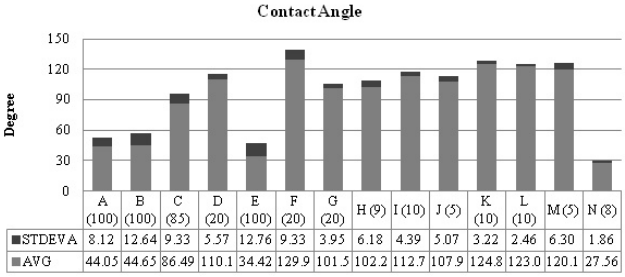


Figure 4. Roughness of the samples (µm), the number of measured samples is presented in parenthesis. The range was set to 160 µm, which was at the highest limits of the machine. In measuring sample batch J, the measuring result went over the limits in 6 measurings of the total 15. These results were marked with the result of 160 µm

Contact angle measurements were done with a KSV Instruments CAM 101 system, which is based on monitoring a drop of water on samples. The behaviour or absorbing of the drop was recorded with a computer- operated camera that was placed in line with the plate that carried the sample. The contact angle was measured from snapshots taken with the camera. Three snapshots of all the drops were taken automatically with 0.5 second intervals.

Sample batches A, B and E were found to be highly hydrophilic and difficult to measure, which is why they were measured by using a time limit of five seconds. In other words, the first snapshot of the set of three was taken after five seconds of releasing the drop. Difficulties were caused by the dynamic nature of the water drop on wood. In the used measuring method the drop should stay static on the surface after release, but the surface on batches A, B, and E was so hydrophilic that it sucked the drops too rapidly. Occasionally the drop remained static but at the same time asymmetric, which indicates a barrier caused by roughness on the surface. In addition to the five-second drops, the measuring of batches A, B and E was also done with one minute drops, which were measured after one minute of the release. Sample batch C was also measured by this method using five-second and one-minute time limits. On the other samples (treated wood, WPC and paper), the water drop remained static, so no time limit was necessary.

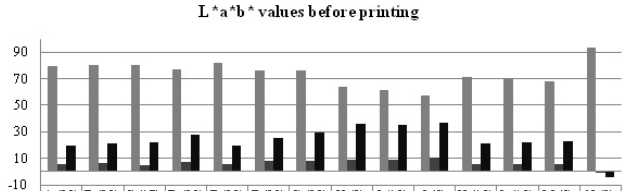
After one minute on sample batches A, B and E, the drop had either been absorbed totally, resulting in a 0° angle, or was very small. On sample batch C all the drops remained unabsorbed after one minute, resulting with an average 65.18° angle (10.79 standard deviation).



	A (100)	B (100)	C (85)	D (20)	E (100)	F (20)	G (20)	H (9)	I (10)	J (5)	K (10)	L (10)	M (5)	N (8)
STDEVA	8.12	12.64	9.33	5.57	12.76	9.33	3.95	6.18	4.39	5.07	3.22	2.46	6.30	1.86
AVG	44.05	44.65	86.49	110.1	34.42	129.9	101.5	102.2	112.7	107.9	124.8	123.0	120.1	27.56

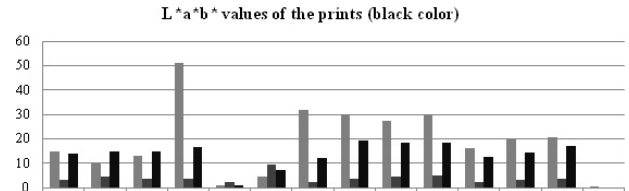
Figure 5. Contact angle of the samples (A, B, C, and E after five seconds of the drop release), the number of measured drops is presented in parenthesis

Colour was measured of the samples before and after printing with a CM-2500d spectrophotometer made by Konica Minolta Sensing Inc. The measuring was done with an 8 mm observation loop, a 10° angle, specular reflectance exluded. The results were received as L*a*b* coordinate values. Each sample was measured three times before printing, five times after printing of the grey patch, and once of the black square A9 (see Figure 2).



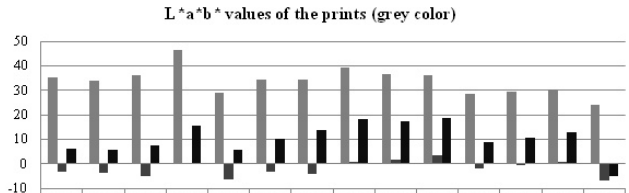
	A (20)	B (20)	C (17)	D (20)	E (20)	F (20)	G (20)	H (9)	I (10)	J (5)	K (10)	L (10)	M (5)	N (8)
L*	79.85	80.6	80.01	77.28	81.82	76.53	76.44	63.98	61.78	57.63	71.52	70.12	68.19	93.57
a*	5.61	6.29	4.77	7.7	5.64	8.12	8.19	9.32	8.93	10.41	5.59	5.61	5.86	-0.07
b*	20.03	20.93	21.92	28.09	19.33	25.21	29.69	36.14	35.08	36.7	21.67	22.08	22.97	-4.3

Figure 6. L*a*b* values of the samples before printing, the number of measured samples is presented in parenthesis



	A (20)	B (15)	C (17)	D (14)	E (20)	F (14)	G (14)	H (9)	I (10)	J (5)	K (10)	L (10)	M (5)	N (8)
L*	14.88	9.90	13.11	51.14	0.76	4.31	32.01	29.83	27.51	30.15	16.29	19.62	20.72	0.09
a*	3.37	4.57	3.50	3.54	2.39	9.43	2.43	3.73	4.37	5.00	2.26	2.97	3.78	0
b*	13.83	14.81	15.03	16.72	1.15	7.25	12.24	19.45	18.28	18.49	12.75	14.45	17.03	0

Figure 7. L*a*b* values of the black printed area on the samples, the number of measured samples is presented in parenthesis

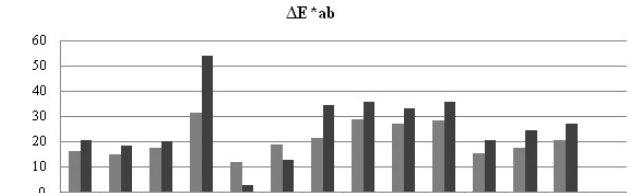


	A (20)	B (15)	C (17)	D (14)	E (20)	F (14)	G (14)	H (9)	I (10)	J (5)	K (10)	L (10)	M (5)	N (8)
L*	35.46	33.98	36.27	46.65	29.02	34.54	34.40	39.28	36.44	36.08	28.47	29.37	30.40	24.18
a*	-3.16	-3.64	-4.89	0.08	-6.48	-3.34	-4.33	0.98	1.67	3.53	-1.91	-0.27	0.92	-6.80
b*	6.10	5.63	7.33	15.70	5.93	10.07	13.72	18.27	17.29	18.61	8.81	10.58	12.70	-5.15

Figure 8. L*a*b* values of the grey printed area on the samples, the number of measured samples is presented in parenthesis. Each sample was measured five times

The difference in hue (ΔE*ab) was calculated of the measured L*a*b* values by using the following function:

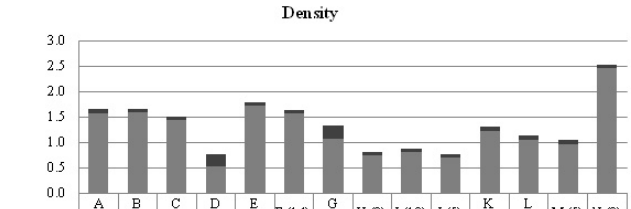
$$\Delta E^*ab = \sqrt{(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2}$$



	A (20)	B (15)	C (17)	D (14)	E (20)	F (14)	G (14)	H (9)	I (10)	J (5)	K (10)	L (10)	M (5)	N (8)
Grey	16.34	14.91	17.48	31.41	12.1	18.74	21.6	28.93	26.94	28.51	15.4	17.8	20.42	0
Black	20.52	18.34	20.19	53.83	2.74	12.63	34.27	35.73	33.24	35.64	20.74	24.48	27.02	0

Figure 9. Difference in hue between the prints, the number of measured samples is presented in parenthesis. Sample batch N was used as the standard

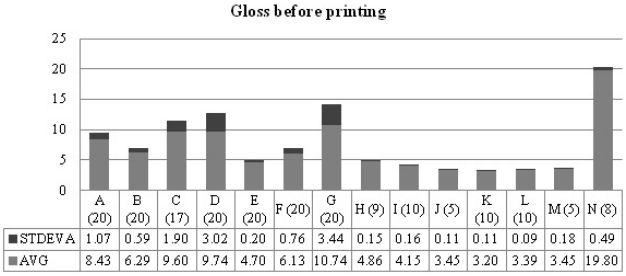
Density was measured of the samples with a SpectroEye spectrophotometer/densitometer made by X-Rite inc. after printing. The measuring was done with a 10° angle and taken from the black square A9 of the test image. Each sample was measured once.



	A (20)	B (15)	C (17)	D (14)	E (20)	F (14)	G (14)	H (9)	I (10)	J (5)	K (10)	L (10)	M (5)	N (8)
STDEVA	0.08	0.06	0.08	0.25	0.05	0.08	0.26	0.08	0.06	0.08	0.08	0.07	0.07	0.06
AVG	1.58	1.59	1.43	0.53	1.73	1.56	1.07	0.74	0.82	0.69	1.22	1.06	0.97	2.46

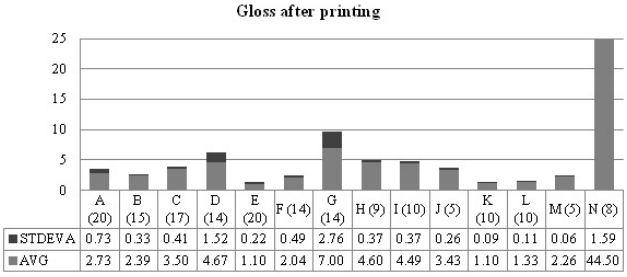
Figure 10. Density of the ink on prints, the number of measured samples is presented in parenthesis

Gloss was measured of the samples before and after printing with a Novo-Gloss Trio gloss meter made by Rhopoint Instruments Ltd. Each sample was measured once with a 60° angle. The measuring that was done after printing was performed of the gray patch at the bottom of the test image (see Figure 2).



	A (20)	B (20)	C (17)	D (20)	E (20)	F (20)	G (20)	H (9)	I (10)	J (5)	K (10)	L (10)	M (5)	N (8)
STDEVA	1.07	0.59	1.90	3.02	0.20	0.76	3.44	0.15	0.16	0.11	0.11	0.09	0.18	0.49
AVG	8.43	6.29	9.60	9.74	4.70	6.13	10.74	4.86	4.15	3.45	3.20	3.39	3.45	19.80

Figure 11. Gloss of the samples before printing, the number of measured samples is presented in parenthesis



	A (20)	B (15)	C (17)	D (14)	E (20)	F (14)	G (14)	H (9)	I (10)	J (5)	K (10)	L (10)	M (5)	N (8)
STDEVA	0.73	0.33	0.41	1.52	0.22	0.49	2.76	0.37	0.37	0.26	0.09	0.11	0.06	1.59
AVG	2.73	2.39	3.50	4.67	1.10	2.04	7.00	4.60	4.49	3.43	1.10	1.33	2.26	44.50

Figure 12. Gloss of the prints, the number of measured samples is presented in parenthesis

Discussion

Visual evaluation was performed on spreading, and it was found that it was not possible to avoid spreading totally, except on the waxed samples (D and G), where in turn the adhesion was not sufficient and the ink beaded on the prints, and in the unsanded WPCs, which in turn had a weak contrast. In all of the untreated wood samples the grain pattern appeared notably as lighter areas on the prints. In the waxed and silicon-sprayed samples it was not as visible. The grain pattern was the most visible in sample E.

None of the samples could reach the sharpness of the paper that was used as a reference material. In visual evaluation the sample batch E was evaluated to perform best, mainly because of the good contrast.

The measuring results of roughness indicate that wood is significantly rougher than paper which was the reference material and optimal medium for the used printer. On wood, roughness affects the spreading of the adhesive as the runny ink can spread along the microscopic cavities and channels on the surface. Roughness can be decreased by waxy surface treatments. The large standard deviation on the wood samples verifies the heterogeneous nature of wood material.

Increase in roughness was noted in the silicon sprayed samples (F). This occurred probably because the water in the sprayed solution caused cell bulking and thereby fibre fluffiness on the surface.

The densificated samples were high in roughness, plus 25 % to the sanded samples (B). The higher roughness of the sanded samples (B) compared to the planed samples (A) was probably due to a slight compression and polishing given by the rotating blade cylinder of the machine.

In the WPC material the roughness was the slighter the more wood they contained. The samples that contained only 20 % of plastic and 77 % of wood (H) were among the best performers especially after sanding, which improved the smoothness significantly even with WPC samples that contained less wood. The small standard deviation verifies the homogeneous nature of wood plastic composite materials. The best smoothness was achieved by sanding the wood perpendicular to the grain (E).

The results received in contact angle measuring were influenced by the roughness of the sample surfaces. The roughness caused problems in monitoring the drop and especially the border between the sample and the drop. Slight curviness of the samples caused monitoring problems as well.

In terms of wetting, sanding seemed to be a sufficient pre-treatment for inkjet printed wood. The contact angle was closest to the reference material in samples A, B, and especially E, which were some 20 % more hydrophobic. The drop shape on wood was observed to be significantly more elliptic than on paper. This caused uncontrollable spreading along the grain. The drops on the sample (E) sanded perpendicular to the grain behaved somewhat better. This is because apparently the sanding direction together with the grain orientation creates a mesh on the wood surface, which keeps the drop more symmetric. Also, the perpendicular planning direction opens the wood more efficiently, this leads to better oxidation of the surface.

Samples D and G were measured to be hydrophobic with a contact angle >90°, which resulted in poor printing results, especially with sample D. Sample G behaved slightly better, which indicates that alcohol wiping has a positive effect on the printing results. Sample F was measured to be the most hydrophobic; the printing results indicated, however, that the ink absorption was good in printing. This was probably because of the nanometre size of the sprayed solution combined with picoliter- sized ink drops. In other words, the microlitre -size water drop was not small enough to penetrate the silicon web on the sample, whereas the picolitre size ink drop was.

The WPC materials proved also to be hydrophobic, and the higher contact angle on the sanded WPC samples verifies the claim by Klyosov (2007) that moisture absorption occurs mainly on the top layers of WPC materials.

Colour closest to the reference material was detected in untreated wood. Sample batches A, B, C, and E were only some 15 % darker than paper (N). The WPC samples were the darkest (more than 30 % darker than paper) but sanding improved the lightness with some 9 %. The lightness affects the contrast in prints; the lighter the media is, the better the contrast, or in other words, the better the colour display. All the samples were also significantly more red (positive value in a*) and yellow (positive value in b*), whereas the paper was measured to be only slightly blue (negative value in b*). The yellowish tone was the highest in the chemically treated samples and in the WPC.

The colours measured of the printed samples indicated that the best ability to display colour was in sample E, the measured difference to the reference was 12.1 in the grey, and only 2.74 in the black colour. The WPC material performed the better the more wood it contained. Sample K had a performance comparable to the untreated wood samples. The measurements indicated that the colour display on wood and WPC was better in the middle tones than in the dark tones. In samples E and F the results were the opposite.

In terms of density, samples A, B, E, and F performed the best. Also samples C and K performed well. All the mentioned samples met the density requirements of black ink for newsprints (1.10). The ink thickness was the highest in sample E.

The results of loss measurements indicate that wood is a matte surface. The most matte were the sanded WPCs and wood sample E. Gloss on wood can be increased by waxing and densification. Printing decreased the gloss of the samples and increased the gloss of the reference. Very small increase in gloss was also measured in the printed unsanded WPCs I and J. The highest gloss was measured in sample G.

Conclusions

The natural composition of wood makes its surface heterogeneous and rough compared to traditional printing medias, such as paper. This affects the printing quality by causing difficulties to control the printing quality.

Inkjet technology is very interesting, as it provides a cost-efficient and fast-adapting solution for printing continuously changing information. In the tests of this study, the inkjet technology performed well and gave good results. It would be still interesting to test inks that are more viscous, such as acrylic inks in inkjet printing on wood. Higher viscosity could behave better in terms of spreading.

Maximized efficiency to direct wood printing requires high-speed single-passing system solutions from the technology providers. Also, to create high quality prints on wood, it is necessary to have solutions for white ink printing. Because wood is heterogeneous by nature, it can cause significant problems in repeatability in scaling up the direct wood printing process. It should be further studied whether it would be possible, with sufficient speed, to photograph or scan the intended printed surface just before screening, so that the RIP could react to the natural tone or hue variations on wood and adjust the ink feed as required.

The tests gave information that encourages further study of wood sanded perpendicular to the grain for printing media. The sanding process could be tuned for even better results in inkjet printing. The effect of different moisture contents of wood to the printing quality should also be examined. It would also be interesting to test alcohol wiping, and other methods that increase the surface energy of materials, such as corona or plasma treatment.

Spreading, which was observed in many of the samples, has more relevance when the medium has to be able to display small details. The visible grain pattern under the images is thought to be more a subjective defect. However, if grain patterns of other wood species were printed, the visible grain pattern of the original media would definitely create confusion.

References

Argent, D. 2008. Dyne Levels, Part 1. Paper, Film & Foil Converter. From:[http://pffc-online.com/processmanagement/dyne_levels_part_1_0608/] [retrieved: 28.8.2009]

Borch, J., Mark, R. E., Lyne, M. B. and Habeger, C. C. Jr. 2001. Handbook of Physical Testing of Paper, Vol 2. Marcel Dekker. 560 pp.

CIELab. 2006. What does CIELab Mean. From: [http://www.cielab.com.au/whatiscielab.php] [retrieved: 29.8. 2009]

Conners, T. E. and Banerjee, S. 1995. Surface Analysis of Paper. CRC Press LLC.346pp.

Cox, B. 2008. Consistency Is Key. Print Week. From: [http://www.printweek.com/news/840486/Consistency-key] [retrieved: 29.8.2009]

Desiraju, G. D. and Steiner T. 2001. The Weak Hydrogen Bond: in structural chemistry and biology. Oxford, University Press Inc. 507 pp.

Gardner, D. J. 2005. Adhesion Mechanisms of Durable Wood Adhesive Bonds, 13 pp. From:[http://www.entwoodllc. com/PDF/wood%20adhesion%20mechanisms.pdf] [retrieved: 28.8.2009]

GlossMeters. 2006. Gloss Introduction. From: [http://www.glossmeters.com/GlossIntro.html#1] [retrieved: 29.8.2009]

Green, C. 1999. PTN4 Inkjet Paper Testing. 2 p. From: [http://www.paperonweb.com/Articles/PTN4W2.pdf] [retrieved: 28.8.2009]

Imatest LLC. 2009. Image Sharpness. From: [http://www.imatest.com/docs/sharpness.html] [retrieved: 29.8.2009]

Kipphan, H. 2001. Handbook of Print Media. Springer-Verlag Berlin Heidelberg, 1207 pp.

Koponen, H. 1988. Puutuotteiden Pinnoitus [Coating of Wood Products]. Otakustantamo. 127 pp. (in Finnish).

Koponen, H. 1989. Puutuotteiden Liimaus [Gluing of Wood Products]. Otatieto Oy. 142 pp. (in Finnish)

Mimaki Europe B. V. 2007. New SS21 White Solvent Ink for JV33 Series. From:[http://www.mimakieurope.com/new_ss21_white_solvent_ink_for_jv33_series-news,body-en-96.html?p=3-2] [retrieved: 30.8.2009]

Minford, J. D. 1991. Treatise on Adhesion and Adhesives. Marcel Dekker Inc. 528 pp.

MrInkjet. 2009 Technical Report – Water-based Inkjet Inks: A Quick Study. From:[http://www.mrinkjet.com.au/inkreport. htm][retrieved: 28.8.2009]

NDT Resource Center. 2009. Surface Energy. From:[http://www.ndt-ed.org/EducationResources/CommunityCollege/PenetrantTest/PTMaterials/surfaceenergy.htm]/[http://www.ndt-ed.org/EducationResources/CommunityCollege/PenetrantTest/PTMaterials/viscosity.htm] [retrieved: 9.3. 2009]

Olmsted, J. and Williams, G. M. 1997. Chemistry: the molecular science. Wm. C. Brown. 1189 pp.

Petrie, E. M. 2007. Handbook of adhesives and sealants. The McGraw – Hill Companies Inc. 1048 pp.

PRA. 2009. Surface Energy and Contact Angle Measurement on Solids. From:[http://www.pra.org.uk/technical/testing physicalsurfacetension.htm] [retrieved: 12.3.2009]

The Adhesive and Sealant Council Inc. 2009. Wetting.

Prebeg, Z. 2002. Cohesion and Structure of Liquid.. *Journal of Theoretic* 4-5/2002: 4 pp. From: [http://www.journaloftheoretics.com/Articles/4-5/Prebeg.pdf] [retrieved: 10.3.2009]

Rowell, R. M. 2005. Wood Chemistry and Wood Composites. Taylor & Francis Group. 487 pp.

Räty, J. 2009. Skannerit eli kuvanlukijat [Scanners or Image Readers]. From:[http://www.ratol.fi/opensource/pctekniikka/1/Kirjat/skannerit.pdf] [retrieved: 29.8.2009] (in Finnish).

SensaDyne. 2009. Why surface Tension is Important. From: [http://www.sensadyne.com/why.html] [retrieved: 28.8. 2009]

SignIndustry. com. 2009. About White Ink in Black & White. From:[http://www.signindustry.com/flatbed_UV/articles/2006-11-01-JL-DigitalWhiteInk.php3] [retrieved: 30.8. 2009]

SPIE 2009. Novel method for printing high-quality metal wires. From: [http://spie.org/x18497.xml?ArticleID=x18497] [retrieved: 5.10.2009]

U.S. Department of Agriculture. 2007. The Encyclopedia of Wood. Skyhorse Publishing Inc. 496 pp.

Viluksela, P., Ristimäki, S. and Spännäri, T. 2007. Painoviestinnän tekniikka [Technology of Printed Media]. Otavan Kirjapaino Oy. 192 p. (in Finnish).

From:[http://adhesives.org/TrainingEducation/StudentResources/Wetting.aspx*/*[http://adhesives.org/TrainingEducation/StudentResources/AdhesionandCohesion.aspx] [retrieved: 28.8.2009]

University of Waterloo. 2009. The Liquid State. From: [http://www.science.uwaterloo.ca/~cchieh/cact/c123/liquid.html] [retrieved: 29.8.2009]

Zünd. 2009. Zünd UVjet 215-Plus. From:[http://zund.com/media/ broschuren/uvjet_215-plus_en_low.pdf] [retrieved: 30. 8.2009]

Received 25 August 2011
Accepted 30 November 2012

ИСПОЛЬЗОВАНИЕ ДЕРЕВА В КАЧЕСТВЕ ПЕЧАТНОГО НОСИТЕЛЯ

К. Хямялайнен и Т. Кярки

Резюме

Разнообразие внешнего вида древесины и добавленная стоимость на рынке отделочных материалов могут быть достигнуты путем печати разных видов текстуры древесины или изображения непосредственно на деревянной поверхности. Проблема состоит в том, чтобы передать изображение высокого качества (устойчиво распечатать) на деревянную поверхность, которая является пористой, неоднородной, изменяющейся в размерах, не белой и шероховатой.

Свойства деревянной поверхности влияют на её пригодность для печати. Оптимальное адгезия необходима для качественной печати: слишком сильное поглощение красителя вызывает распространение, а слишком низкое поглощение чернил ведет к бледным отпечаткам. Разные технологии печати различаются требованиями, предъявляемыми к материалам и производству. Бесконтактные технологии печати обеспечивают лучшую основу для печати на деревянных поверхностях. Непосредственная печать на деревянных поверхностях имеет большой потенциал по обеспечению эффективности производства.

Струйная печать на деревянных поверхностях обработанных различными механическими или химическими средствами и на поверхности древесно-полимерных композитов показала хорошие результаты, что дает основания для продолжения исследований в данном направлении. Шлифовка деревянной поверхности перпендикулярно зерну приводила к наилучшему качеству печати. Полностью избежать распространения красителя вдоль волокон можно было только в случае гидрофобной обработки поверхности, но адгезия красителя к поверхности, обработанной таким способом, была недостаточной. Рисунок нижележащего зерна древесины ясно виден в печатных изображениях.

Ключевые слова: шпон, древесно-полимерный композит, адгезия, печать, чернила