Exterior Wood Coatings

Mojgan Nejad and Paul Cooper

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/67170

Abstract

In addition to aesthetic appeal, coatings are designed to protect the wood from weathering degradation in outdoor conditions. This chapter gives an overview of the effects of the main coating components, coating properties, wood properties and treatments on coated wood performance in service. Understanding how different type of resins, pigments, solvents, and other major additives affect coating performance on wood, helps coating formulators to develop more durable coatings. It is beneficial for both wood scientists and coating chemists to learn which properties of coatings have the highest impact on predicting their service lives when exposed to weathering. For instance, measuring glass transition temperature (Tg) defines the degree of flexibility of a coating. Since wood swells and shrinks due to moisture uptake and subsequent drying, flexibility of a coating plays a critical role in defining its durability on wood in exterior conditions. Similarly, learning how preservative treatment or a new modification technique changes the surface properties of wood will help coating formulators to adjust properties of coatings in way that would have better adhesion and performance on that specific modified wood. Also, the effects of these factors in increasing service life of exterior wood coatings are discussed.

Keywords: exterior, wood coating, weathering, treatment, performance and durability

1. Introduction

The performance of coatings in exterior applications depends on many factors such as wood species and their physical properties, coating types and properties, application procedures, and exposure conditions. In North America, cedar (*Thuja* species), spruce (*Picea* sp.), pine (*Pinus* sp.) and fir (Abies sp.) are the most commonly used wood species in exterior building constructions. Among these, cedar has very low density, and it is known as a naturally durable wood species. The fungicidal effect comes from extractives that exist in heartwood of cedar, which provide protection against decay fungi and insect. Cedar boards are available for decking, fencing and siding, but they cost more than other softwoods (spruce, pine and fir that are generally called SPF). SPF lumber is usually treated with either preservative chemicals or modified by high temperature if intended for outdoor or contact ground applications. More detail on effects of different treatments on changing the surface properties of wood is discussed later in the chapter.

In addition to deterioration caused by decay fungi and insects, wood-exposed outdoors go through some physical and chemical changes known as weathering. Weathering degradation mainly affects the surface of the wood, except when the checks that form on the wood surface expand deeper into the boards. Weathering is caused by exposure to UV and visible radiation, moisture (rain, snow and dew) and wind. UV and visible radiation degrade wood components, especially lignin, causing the surface to turn grey and fibres to loosen and be abraded or removed by insects such as wasps for their nests. Precipitation contributes to leaching of wood extractives and their migration to the wood surface where they initially darken the wood but eventually contribute to greying of the surface as they leach out. Changes in moisture content cause swelling and shrinking leading to stresses and checking of the surface. Repeated freezing and thawing of liquid water in the wood cells result in additional stresses in the wood. Wind and wind-driven particles scour the wood surface contributing to uneven wear in the earlywood and latewood. Some also consider the staining and surface deterioration by mould, soft rot and decay fungi on the wood surface as a biological component of weathering.

Application of surface coatings on wood is one of the best ways to reduce weathering degradation. However, depending on the severity of exposure and coatings' type and properties, refinishing is needed every few years. For instance, solid colour stains and paints have much longer service life than transparent or clear formulations. This is due to the fact that clear or transparent formulations do not have pigments to absorb the UV rays; thus, the UV can pass through the clear coating layer and cause oxidation of lignin. Lignin degradation in one of main reasons for wood colour change and contributes to increased water uptake and defibrillation of cellulose fibres from the wood surface. Thus, if we can find a good way to prevent lignin degradation, for instance by having high pigment concentration or other UV absorbers, then the coating will last longer. The main drawback of high pigment is that it will hide the beauty of the wood grain.

Formulating coatings for wood, as a biological material with huge variability, is not an easy task, especially when the coatings film has to have excellent weather resistance and provide exceptional protection for wood against weathering factors. Exterior wood coatings have very complex formulations and are categorized in different ways, for example, based on the carrying media, that is, water based versus solvent based, on the amount of pigment that is added to the formulation, that is, solid, semi-transp`arent and transparent coatings, and based on whether they form a film (film forming) or are penetrating stains. Most coating formulations are made of the following main components: (1) resin or binder, (2) solvent which could be organic solvent or water, (3) pigments (transparent coatings either do not have any pigment or only contain nanopigments) and (4) other additives. Additives as the name implies are chemicals that are added in very small quantities but play significant roles in defining properties and performance of the coatings on wood products.

http://dx.doi.org/10.5772/67170

Effects of wood properties, wood treatment, weathering and coating properties, and how all of these can affect coating performance are discussed in more detail in the chapter. We hope that by the end of this chapter, readers will have a better understanding of factors affecting coating performance in exterior applications and how we can improve the durability and service life of coatings.

2. Weathering of wood

Weathering is mainly a surface phenomenon and the grey layer of weathered wood is only about 125-μm thick [1]; however, checking and cracking of the wood may occur if wood is left uncoated for an extended period of time. In general, weathering is a combination of degradation by solar radiation (ultra violet, visible light and infrared), moisture changes (rain, dew, humidity and snow), oxidation and temperature effects (heat and freezing). Among these factors, UV degradation and moisture effects are the most influential factors on performance of coated wood.

The majority of light (80–95%) is absorbed by lignin in wood [2]. Lignin absorbs light between 200 and 400 nm with a strong absorption peak at 280 nm [1]. Photo-oxidation of lignin will cause the formation of phenolic radicals, which turn quickly to ortho and para quinonoids chromophoric groups [1]. Formation of these yellow to brownish compounds causes the initial dark brown colour of wood during weathering. Further exposure of wood surfaces to rain leaches out degraded lignin from the surface and leaves cellulose fibre exposed, a phenomenon known as "roughening". The loss of a hydrophobic compound (lignin) from the wood surface not only loosens the fibres but also reduces the water repellency of the wood.

In addition to the effects of moisture on swelling and shrinking of the wood discussed above, moisture also helps the radicals formed during UV exposure to diffuse deeper into the wood. Although the UV light can only penetrate up to 75 μm in the wood [3], the thickness of the brown layer beneath the grey wood has been reported to be up to 2500 μm [1]. Visible light has higher penetration (200 μm) than UV but does not have sufficient energy (70 kcal/mol) to initiate radical formation or cleave chemical bonds [1]. Thus, this brown discoloration of wood is not caused by visible light confirming that the radicals formed at the surface are transferred inside the wood by water.

In addition to discoloration and defibrillation, exterior woods develop extensive cracking, checking and mould or mildew growth on the surface. The mildew growth that usually appears as black spots on the wood or coating surfaces are different from decay fungi in that they consume nonstructural components such as sugars and starches and do not degrade the major components of wood (cellulose, hemicelluloses and lignin). The mildew can be removed with a dilute solution of sodium hypochlorite. Most wood coating formulations contain mildewcides. Checking of the wood is much more difficult to prevent. When wood adsorbs moisture, it swells, and as it dries, it shrinks; when the stresses exceed the elasticity and strength of the wood [4], small cracks will develop which later expand to checks if wood remains exposed to outdoor conditions. Evans et al. [5] reported that samples that were exposed to UV-rays had higher surface checking than those that were protected by filter. The study showed that direct exposure to UV increases the surface checking as a result of lignin degradation.

3. Factors affecting performance of exterior coatings on wood

3.1. Effects of wood properties

Variability in wood contributes to its aesthetic appeal when compared with other building materials like cement, steel or plastic. However, this variability creates many challenges for coating chemists. Wood properties not only differ significantly among different wood species and especially between hardwoods and softwoods, they also vary within the same board [6]. Most hardwoods have relatively higher density than softwoods and have coarser grain because of the relatively large vessels or pores. Within the same board, there is a significant variation in the density and permeability of the wood depending on the latewood to earlywood ratio and the relative amounts of sapwood, outer heartwood, and pith-associated heartwood or juvenile wood. For example, latewood of southern pine is almost three times as dense as the earlywood [7]; thus, the wider the latewood bands, the higher the density of the section of the board (**Figure 1**). In general, coatings perform better on low-density wood such as cedar and redwood than on higher density woods like Douglas fir and southern pine [8] because low-density woods have lower shrinking and swelling than high-density wood [9]. Swelling happens as a result of water adsorption in the cell walls of wood, which continues only until wood reaches its fibre saturation point at about 30% moisture content (dry mass basis) [10]. The thicker cell walls of latewood hold more moisture in a given volume and so swell or shrink more than thinner earlywood cell walls. This creates stresses in a coating which explains why coatings start to fail in the latewood and then failure progresses into earlywood [11, 12]. In flat-sawn lumber where the tangential surface is exposed on the face of the board, wood has wider latewood and earlywood bands exposed than on quarter-sawn lumber. Thus, coatings show higher durability performance when applied on the radial faces of quarter-sawn boards [9].

Figure 1. Image of flat-grained southern yellow pine wood showing distinctive wide earlywood and latewood sections.

Moisture content of wood is another important property that affects coating performance on wood. Wood swells when it absorbs moisture and shrinks when it dries; these dimensional changes are more pronounced in latewood than in earlywood. Shrinking and swelling of

http://dx.doi.org/10.5772/67170

the wood constantly cause stresses in the coating film. The moisture content of green wood can be more than 150% (dry wood basis), but above the fibre saturation point (FSP ≈ 30%), wood does not absorb any more water in its cell walls and is in its fully swollen or green condition and dimensionally stable [10]. Applying coatings on wet wood may cause early failure of the coating because of initial adhesion issues, shrinking of wood underneath, and migration of moisture out of the surface as wood dries. This is especially problematic for film-forming low-permeability paints. If a coating is applied to wood under these moisture conditions, it must have good water vapour permeability [13] to allow the absorbed water to escape without causing coatings to blister. If the water stays in wood, it will create suitable conditions for growth of decay fungi inside the wood. In service, wood adsorbs or desorbs moisture in response to ambient relative humidity conditions, and eventually, it reaches its equilibrium moisture content (usually around 12–15% MC). It is recommended to apply a coating when wood reaches moisture content close to its average equilibrium moisture content in service [14].

In some wood species, natural extractives negatively affect coating appearance and performance. Extractive bleeding is caused by migration of water-soluble extractives or thermally induced movement of water-insoluble resin or pitch to the surface of the coating. Resin (from wood) usually leaves a yellow stain which is sticky to touch. Pitch (a mixture of rosin and turpentine) problems are mostly associated with pine, spruce and fir [15]. Proper kiln drying of the wood to evaporate the turpentine and set the resin, application of a sealant such as shellac to knots or resin pockets and cleaning of the wood surface with turpentine before application of the coating have been reported to resolve or minimize these issues [12].

For exterior applications, coatings have better adhesion to rough sawn woods [15] than to planed or sanded wood. This is probably due to the fact that rough surfaces have more anchoring sites for mechanical interlocking, thus improving adhesion of the coating to the wood. It is important to remember that there should not be any saw dust remaining on the wood surface either after sanding or planing, because then the coating will adhere to the saw dust not the wood. The surface of the wood after sanding can be easily cleaned using a damp cloth to remove extra saw dust from the surface and leave the pores open for possible coating penetration.

3.2. Effects of wood treatments

Unlike weathering, decay fungi and insects can completely deteriorate wood and cause serious structural damage. To prevent or delay deterioration of the wood, most wood products should be protected from decay fungi and insects if intended for exterior applications [16]. These protections can be divided into two categories: chemical and thermal treatments. In chemical treatments, either preservative chemicals (classed as pesticides) are impregnated into the wood, or different chemicals are used to modify the wood to make it less susceptible to biodegradation. Preservative formulations usually include fungicide(s) and insecticide(s), which are added to the wood by using high pressure and vacuum applications [16]. The degree of treatment depends on the formulation, preservative loading and treatability of different wood species. In a three-year natural weathering study, we observed that overall preservative treatment-enhanced coating performance [17]. All the tested coatings had better general performance on all preservative treated wood than they did on untreated southern pine samples. After 3 years of natural exposure, coatings had less surface erosion and peeling on preservative-treated wood than they had on untreated wood as shown in **Figure 2**.

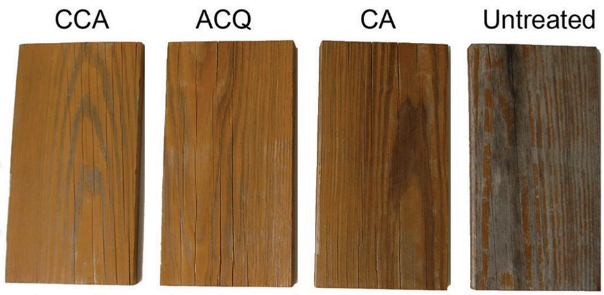

Figure 2. Image of treated and untreated southern pine samples coated with an alkyd-acrylic water-based coating after 3 years of natural weathering in Toronto, Canada.

Up until 2005, many decks and fences were treated with waterborne-chromated copper arsenate (CCA) formulation, but due to concern about leaching of arsenic and chromium from CCA-treated wood, the preservative industry voluntarily shifted to other copper-based or organic preservatives. In North America, waterborne alkaline copper quaternary ammonium compound (ACQ), copper azole (CA) and micronized copper are dominant formulations in the residential market now. Although oil-based preservative formulations such as pentachol-orophenol (PCP) and creosote are used in several industrial products, coatings are mainly applied to above ground-treated wood products such as fences, decks and siding that are treated with water-based formulations.

CCA was the main formulation for treating woods for about 50 years almost from 1953 when CCA was first standardized by AWPA, until the voluntary phase out from residential application in 2005 [18]. During this time, many exterior coatings were formulated and tested on CCA. Coatings have been reported to generally perform better on CCA-treated woods than untreated woods [17, 19]. We observed that CCA-treated wood had much better water repellence performance compared to ACQ and CA [17]. **Figure 3** shows the moisture content changes of the different coated treated woods during 3 years of natural weathering. As can be seen, the alkaline Cu-based preservative-treated wood (ACQ and CA) had higher water uptake than even untreated wood [17]. This is a good example of why coating chemists should understand how different treatments change the properties of the wood. Many coatings that were formulated for exterior applications before 2005 were tested on CCA-treated wood [17]. They did not show the same level of performance on the replacement alkaline Cu-based preservative-treated wood during 3 years of exposure to natural weathering in Toronto, Canada [17]. Thus, with any new formulation or changes in wood treatments, coating industries should consider modifying their formulations based on how the treatment has changed the surface properties of the wood. In this case, in order for coatings to have high durability, they should have higher water repellence performance than those formulated previously for residential decking and fences that were designed for CCA. Both CCA and alkaline Cu-based preservatives provide some degree of UV protection by modifying lignin [20] and reducing the colour change of coated-treated wood in comparison with untreated wood [17], but they have completely different performance when it came to water repellency.

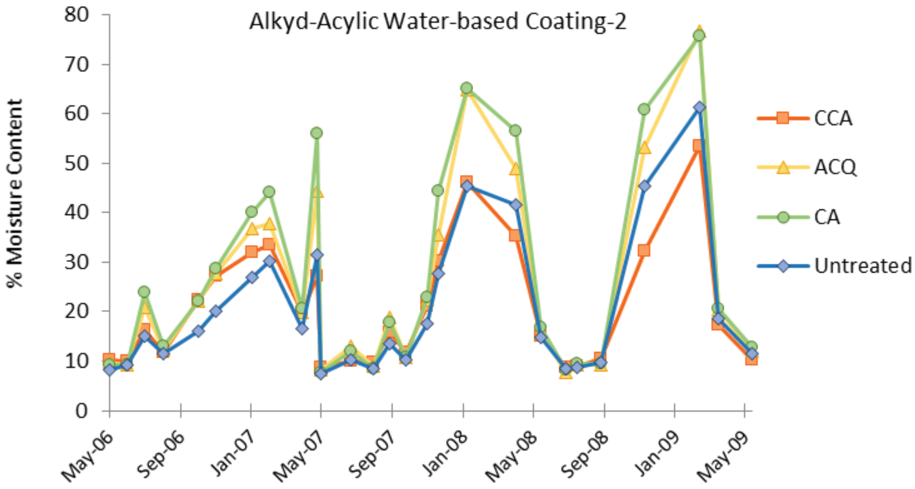

Figure 3. The average percent moisture content changes of coated-treated southern pine samples during 3 years of natural weathering in Toronto, Canada.

Another issue associated with preservative-treated wood is possible leaching of preservative components from wood in service [21–23]. We also studied effect of coatings in reducing leaching of heavy metals (As, Cr and Cu) and found that application of one coat of semitransparent stain could effectively reduce the leaching of these preservative components on average by 60% [24]. One of the most interesting points was that Cu leaches at a really high rate on uncoated wood during the first 6 months of exposure. We observed that even when the coatings start failing and eroding from the wood surface, the rate of Cu leaching from coated wood never reached to the same level as of uncoated samples (**Figure 4**). Further in-depth analysis of samples showed that application of coating during early stage of exterior exposure help fixation of copper in wood, by protecting it from the initial high rate of leaching until it could react more completely with the wood.

Multivariate analysis of data obtained during 3 years of natural weathering of performance of coatings on different kinds of treated wood showed that preservative treatments (CCA, ACQ and CA) had a greater effect than any other coating properties such as resin type, base (water-based or solvent-based), flexibility or film thickness on coating performance on wood [25].

Another modification method used at the commercial scale is protecting wood by changing the surface chemistry of wood by acetylation. Acetylation reduces the hydrophilicity of the wood, thus its equilibrium moisture uptake to a level that would not be favourable for decay fungi [26]. In this approach, acetic anhydride treatment will replace hydrogen in hydroxyl functional groups of mainly hemicelluloses in wood with acetyl groups (CH_3CO–) [27]. Acetylation of wood is associated with weight gain of treated wood of about 30–40% [26]. Acetylated wood has been reported to protect the wood when the percent weight gain is more 20% after treatment [28]. This higher dimensional stability of acetylated wood automatically reduces stresses applied to the coating's film, resulting in overall better coating performance. However, coated-acetylated wood was reported to have significant surface mildew growth on the finished surface after 3 years of natural weathering which probably impaired the effectiveness of the coatings [29]. Acetylation of wood was shown to improve colour stability of wood by preventing lignin degradation when modified woods were exposed to UV radiation [27, 30, 31].

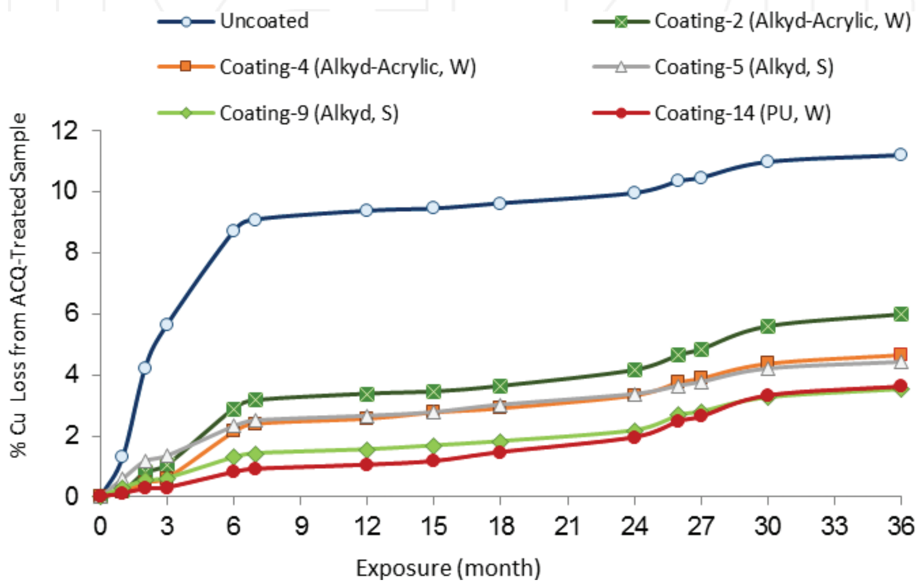

Figure 4. Effect of semi-transparent stain coatings on copper leaching reduction from ACQ-treated wood samples during 3 years of natural weathering exposure in Toronto, Canada (W = water based, S = solvent based).

Thermal modification is another treatment method, which has growing market acceptance, especially in Europe. In thermal treatment, wood is heated at about 200°C under oxygen-free environment for a few hours (3–7 h) using either steam or hot oil as media for continuous heat transfer [32]. Thermally modified wood, like acetylated wood, has improved dimensional stability due to lower water uptake as a result of decrease in available hydroxyl functional groups in hemicelluloses. Protection provided by thermal treatment is not as effective as preservative treatment; therefore, the thermally modified wood is not recommended for ground contact applications [33]. Since during thermal modification wood is only subjected to high temperature and no chemicals are used, thermally modified wood is considered as a more environmentally friendly product than preservative-treated wood. It also has the advantage of complete treatment of the wood, even in species that cannot be penetrated effectively by preservatives or acetylation chemicals. The most important benefit of the thermal modification

http://dx.doi.org/10.5772/67170

process is the improved dimensional stability of the wood [26, 33, 34]. The chemical changes that occur during heat treatment such as reduced hydroxyl content and higher degree of cellulose crystallinity [35] increase the hydrophobicity of wood, thereby improving the water repellence performance of coated heat-treated wood [36].

3.3. Effects of coating components

Formulation of coatings is very complex, and we can only cover a few major components and their potential interaction effects with wood in this chapter. Coatings are generally made of four main components: (1) resins or binders, (2) pigments, (3) solvents and (4) other additives. Different coating formulations may not have all these four main components. For instance, powder coatings do not have any solvents, but they are mostly used for metals which can be electrically charged. Also, clear and transparent coatings usually do not have any pigments in their formulations. For exterior wood applications, we are mainly dealing with water-based and solvent-based coatings, UV-curable coatings are becoming more popular for interior wood flooring but not yet for exterior applications. Most coatings for exterior woods are applied at the site, except for some siding products, window frames and doors which are factory primed (mostly white) and occasionally finish coated.

3.3.1. Resins

In any coating formulation, the main component is the resin (or "binder"). Resin governs to a large extent the major properties of the coating [37]. Exterior wood coatings are largely made with alkyd, acrylic or polyurethane resins. Recently, combinations of two binders that are called hybrid or core-shell systems are also used in wood coating formulations like alkyd-acrylic, acrylic-urethane, and alkyd-urethane.

Alkyd resins, which are modified-natural polyester resins, are one of the first synthetic resins used in surface coatings and are the most commonly used binders in exterior wood coating formulations. Alkyd is derived from polyols (glycerol), fatty acid oil (linseed oil or vegetable oil), and dibasic acid (phthalic anhydride) [38]. Alkyd-based coatings have generally poorer outdoor durability than acrylics and polyurethanes but have fewer film defects and lower costs [37]. Alkyd coatings are cured through an oxidation process [39], and sometimes it takes months to cure in outdoor exposure. This slow curing will affect the initial water repellence performance of an alkyd-based coating, but it improves over time as the resin cures [17]. Alkyd resins have very low molecular weights and therefore have potential to penetrate into wood cell walls when they are formulated at low viscosity range that can penetrate the wood surface.

Acrylic resins are prepared by chain-growth polymerization of various (meth) acrylic monomers [37]. They have excellent exterior durability [37] and are especially known for their superior UV resistance and resistance to yellowing [40]. Acrylics have high molecular weight (usually 75,000 or higher) which would result in higher film strength [37, 41]. But resins with such a high-average molecular weight cannot penetrate into wood cell walls. The largest polymeric compound that is reported to penetrate into wood cell wall is polyethylene glycol of 20,000 [42].

Polyurethanes (PU) are made of a polyol (R-OH) and isocyanate (R-NCO) forming urethane or carbamate linkages (>NH–CO–O<) through a condensation polymerization reaction [37]. Polyurethanes have high chemical resistance and are well known for their superior abrasion resistance [37]. They are mostly used as topcoats for flooring, cabinets and automotive applications [37]. Polyurethane resins generally have low molecular weights which would enable them to penetrate into wood cell walls. Free isocyanate of PU resins can easily form chemical bonds with hydroxyl groups in the wood. In addition, coatings made with aliphatic diisocyanates with hindered amine have exceptional exterior durability [37]. There are both solvent-based and water-based formulations of all three resins (alkyd, acrylic and PU) in the market.

3.3.2. Pigments

Pigments are important components of the exterior coatings, providing colour, opacity and UV protection. Inorganic pigments are the most universal pigments used in the formulation of exterior wood coatings. Iron oxide (red, yellow, brown and black) is frequently used in wood stains, whereas titanium dioxide (TiO_2) is used for white or other light coloured paints. TiO_2 has excellent hiding power, but it is relatively expensive compared to other white pigments. In most pigmented formulations, extenders and fillers are added to formulations; these commonly include calcium carbonate ($CaCO_3$) or talc (magnesium silicate, $H_2Mg_3(SiO_3)$). $CaCO_3$ has much lower hiding power than TiO_2, but it is more affordable. In transparent coatings, nanopigments are also used to protect the wood from UV degradation and/or improve coating scratch resistance (by using Al_2O_3) while not blocking the beauty of the wood grain [43, 44].

3.3.3. Solvents

Except for powder coatings and high solid formulations, about 30–50% of most coatings is comprised of solvents. Solvents can be either organic liquids or water. The most commonly used organic solvents in wood coating formulations are mineral spirits, methyl ethyl ketone, butanol, propyl alcohol, ethyl acetate, acetone, toluene and xylene [4]. Solvents are added for various purposes such as dissolving the resin and adjusting viscosity to a range that helps the application of coating either by brush or spray. In every coating formulation, a mixture of different solvents is used to optimize the required properties such as improving spray application and reducing the drying time. To meet environmental regulations for reduced amounts of volatile organic compounds (VOC) in coatings, water-based formulations were developed. Water-based formulations are formulated either with very low amounts of organic solvents or none with zero VOC.

3.3.4. Additives

As their names implies, additives are substances that are added to the coating in very small quantities to impart specific properties. Additives can be divided into various groups such as wetting and dispersing agents, defoamers, flattening agents, rheology modifiers, light stabilizers, dries, accelerators, and biocides [38, 45]. In water-based formulations, low evaporation

http://dx.doi.org/10.5772/67170

rate of water compared with organic solvents, especially aromatic solvents, is a major challenge. To reduce drying time and ensure a defect-free dry film, co-solvents, coalescing agents or driers (mostly for alkyd resin) are used in the formulations [40]. Getting into detail of coating formulation and additives is beyond the scope of this chapter. However, it should be noted that even small amounts of additives can significantly change properties of coatings. For instance, we observed that addition of 0.1% a surfactant and wetting agent significantly reduced the surface tension of a water-based PU resin from 44 to 29 mN/m, minimized initial foam formation and left almost no bubbles in the clear wood coating's film [46]. Mildewcides, surfactants, defoamers, UV-stabilizers, wetting and dispersing agents are very common additives used in water-based wood coating formulations.

4. Influence of coating characteristics

4.1. Coating types

Wood coatings are divided into two major categories known as film forming and non-film forming or penetrating stains. Film-forming coatings for wood are mainly paints or varnishes (lacquers). The term paint is used for film-forming coatings that are highly pigmented and mask the substrate underneath completely. Paints are commonly used for wooden windows, doors and siding. They usually have the highest durability performance on wood, due to the fact that they contain a high concentration of pigments which protects the wood surface from UV degradation [47]. Varnishes and lacquers are clear film-forming formulations that are not designed for exterior application. Williams et al. [12] showed that clear varnishes will crack and peel from wood surfaces in less than 2 years.

Stains are capable of penetrating into the wood and were generally considered to not form any film layer on the surface. However, depending on the resin type and viscosity, different stains may also form a film layer on the surface of the wood [9]. **Figure 5** shows scanning electron microscope photos of cross sections of southern pine samples coated with two different semi-transparent penetrating stains with different viscosities. The coating with higher viscosity has much greater film thickness than the one with lower viscosity, and although these two formulations are designated as stains, they both form a film layer. Stains are divided in three different categories: transparent, semi-transparent, and solid colour stains. Transparent or clear stains either do not contain any pigment or contain nanopigments. Because clear stains do not have any pigment they need other types of UV stabilizer or blocker to be able to protect the wood from UV degradation. Wood coated with transparent or clear stains will usually turn to grey at the same rate as uncoated wood samples. As the wood below the coating degrades, the film will crack and then slowly peel from the surface. On the other hand, semi-transparent stains have some degree of pigment to protect the wood from UV-degradation while not too much to hide the beauty of wood grain. Solid colour stains were defined as penetrating formulations which usually provide the highest degree of protection by completely blocking the harmful effect of UV, yet they still do not form a thick film layer like paints; therefore, they are less likely to crack or peel from wood surface the way that varnishes and paints do.

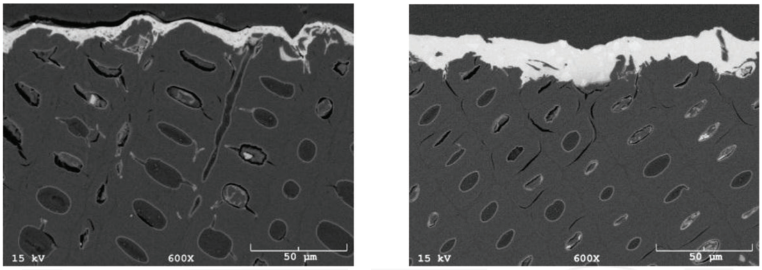

Figure 5. Back scattered electron images of cross-sections of pine samples coated with semi-transparent stains: alkyd-acrylic water-based stain (left) and a PU water-based formulation (right).

4.2. Coating properties

Understanding how different physical, chemical, and thermal properties of coatings affect their performance on woods in exterior conditions will help coating chemists develop more durable coatings. As the discussion of chemical properties of coating needs more in-depth overview of polymer and organic chemistry, this chapter will mostly be focused on the thermal and physical properties of coatings and their correlations with their performance on wood.

Testing wettability (the ability of liquid to spread on the substrate) of a coating is the first step in defining adhesion of a coating to wood or any other substrate. Measuring the contact angle of a droplet of coating on the substrate is used as a measure of wettability of the coating formulation. The lower the contact angle means better wetting and spreading of coating on wood. In general, to have good wetting, coatings should have much lower surface tensions compared to the surface energy of the substrate [48]. Wood has an average surface energy of 44 mN/m [49]. Solvent-based coatings have surface tensions of around 25 mN/m, whereas water-based coatings have on average surface tension of 32 mN/m [25]. Although both are lower than average surface energy of wood, reducing the surface tension of water-based systems will improve their adhesion and performance on wood.

The surface tension of water is 72 mN/m, and in water-based coatings, different additives like wetting agents and emulsifiers are added to the formulation to reduce the surface tension of water-based coating to be as close as possible to the surface tension of solvent-based coatings. To ensure the adhesion of a coating to wood, the contact angle test should be performed on late wood areas, because the contact angle of the coating is usually much higher on late wood than early wood [25]. This is another reason why erosion of coatings usually starts first from latewood sections then early wood and is most evident when flat-grained coated wood is exposed to weathering [50].

Another important coating property is glass transition temperature, which is an indicator of polymer flexibility and how it changes as it is heated. Amorphous polymers go through a transition from a glassy state to a flexible state in a temperature range defined as glass transition temperature (Tg). Previous researchers indicated that coatings formulated for exterior wood should penetrate deep into wood and not form any film layer on the top [12, 47].

They reported that film-forming coatings will crack and peel from the surface due to stresses caused by dimensional instability of wood when exposed outside [51]. This is entirely correct when the coating film is not flexible. If the dry coating film has adequate flexibility to tolerate stresses caused by swelling and shrinking of the wood in outdoor conditions, then the coating will be less likely to crack or peel from the surface. The flexibility of a coating film can be measured and defined by its glass transition temperature (Tg). If a coating has Tg lower than the temperature that wood-coated samples will be exposed to during its service life, then it will have high durability and good performance [25, 52]. It should be also noted that the glass transition of the coating may change in service. Podgorski [52] studied the changes in Tg of alkyd coating in natural weathering and reported that the Tg increases initially until it reaches a maximum value when the cross-linking is complete.

One of the basic physical properties of a coating which can be measured easily is viscosity. Viscosity plays a significant role in wood coating performance [25] and is highly correlated to coating film thickness. Lower viscosity coatings penetrate deeper into the wood, whereas higher viscosity coatings tend to form a film-layer on the surface [25]. Nussbaum et al. [53] studied the penetration of solvent-based alkyd versus water-based alkyd coatings and found that coatings with similar viscosities had similar penetration depth into the wood. Furthermore, we observed that higher viscosity coatings which also had higher film thickness and lower Tg (higher flexibility) performed better throughout 3 years of natural weathering of the wood tested in Canada [17].

4.3. Coating performance

Coatings have very complex formulations and their interaction with a biological material like wood makes prediction of their service life and performance much harder [54]. The average service life of exterior wood stains is between 1 and 3 years [55]. Coatings can reduce water uptake, UV-degradation, and checking of wood, which prolongs the service life of wooden structures; however, application of coating every year or two places the wooden products as high-maintenance products when compared to other building materials. Increasing the lifespan of coatings would reduce maintenance, thus encouraging homeowners, architects and contractors to use more wooden products.

There is no doubt that wood properties considerably affect the performance of coatings [6, 14]. The grain characteristics, surface texture, heartwood/sapwood, knots, extractives, moisture content and density are all factors that should be considered when predicting or evaluating the performance of coatings on wood [9, 50, 56].

Treating wood with preservative chemicals such as chromated copper arsenate (CCA) will change the surface property of wood, thus, affecting the coating's life span and durability. Previous studies reported better performance of coating on CCA-treated woods due to presence of chromium [57, 58]. CCA-treated wood has been reported to have lower water uptake and higher colour stability than untreated wood [17] which could be due to presence of chromium oxide in the CCA formulation that can modify the lignin [59]. As pressure treating wood with CCA solution did not change the wettability of the wood [60] while it did improve its water repellency and UV stability, formulating coating for CCA-treated wood was less challenging than any other treated wood.

Alkaline Cu-based preservative solutions such as ACQ and CA and micronized copper formulations that are arsenic and chromium free have now replaced CCA-treated wood in residential markets in North America. Wood treated with alkaline copper quaternary (ACQ) and copper azole (CA) has higher water uptake than even untreated wood [17]. However, they have much lower colour change than untreated wood when exposed to natural weathering [17]. The presence of copper oxide in these formulations has the potential to modify lignin in wood [20, 61]. As lignin is the most susceptible wood component to UV-degradation, modification of lignin in wood could be responsible for improved photo-stability of Cu-based treated wood [1].

Heat treatment is another wood modification technique which is becoming more popular as a green modification method. Heat treatment changes the chemical and physical properties of wood [33], thereby affecting coating performance and its adhesion to the modified wood. Researchers have reported contradictory results for changes in surface energy of thermally modified wood. Some found that heat treatment reduced the surface energy of wood [35, 62], and others reported improvements or no changes after modifications [63, 64]. A few studies also observed reduced adhesion of coating to heat-treated woods in comparison with untreated woods [36, 65]. However, what all researchers agree on is the lower water uptake of heat-treated due to the decrease in wood hygroscopicity after thermal modification [32, 33, 66]. Heat-treated wood has lower water uptake than preservative-treated wood but turns to grey at the same rate of untreated wood [34, 67, 68]. Therefore, coatings that are formulated for heat-treated wood should have higher UV resistance than coatings that were formulated previously for CCA-treated or other preservative-treated woods.

5. Conclusions

The key to designing a coating with better performance on wood is to consider not just the characteristics or interface of the coating and the wood themselves, but to study the interaction among individual wood constituents with the coating components. Close collaboration between wood scientists and coating chemists is the best way to develop new formulations with improved durability. Considering how wood components and surface properties of wood change when exposed to weathering, chemical, or thermal modification will help coating formulators to know where to concentrate research and development efforts. For instance, for heat-treated wood, a coating with higher UV resistance is required, whereas for Cu-based preservative, a coating with higher water repellency is beneficial. Additionally, a closer look at coating properties is critical in predicting the performance of new formulations. Measuring glass transition temperature (Tg) of new coating formulations and monitoring Tg changes during weathering is not a common practice by coating companies. However, this should be a standard practice for those who are formulating coatings for wood. A flexible coating with low Tg can better tolerate stresses caused by the dimensional instability of wood during swelling and shrinking. Thus, such a coating would be more resistant to cracking and peeling compared to a coating with higher Tg and rigid film. In conclusion, to develop exterior wood coatings with prolonged service lives, coating formulators should consider the following parameters: interactions of coating components with wood, coating properties and changes in the surface properties of wood after modification.

http://dx.doi.org/10.5772/67170

Author details

Mojgan Nejad[1]* and Paul Cooper[2]

*Address all correspondence to: Nejad@msu.edu

1 Michigan State University, East Lansing, Michigan, USA

2 University of Toronto, Toronto, Canada

References

[1] Hon, D.N.S. and Shiraishi N., Wood and Cellulosic Chemistry. 2001, New York: Marcel Dekker. 914.

[2] Feist, W.C. and Hon D.-S., Chemistry of weathering and protection. Advances in Chemistry Series, 1984(207): pp. 401–451.

[3] Hon, D.N. and Ifju G., Measuring penetration of light into wood by detection of photo-induced free radicals. Wood Science, 1978. **11**(2): pp. 118–127.

[4] Schniewind, A., Mechanism of check formation. Forest Products Journal, 1963. **13**(11): pp. 475–480.

[5] Evans, P.D., Urban K., and Chowdhury M.J.A., Surface checking of wood is increased by photodegration caused by ultraviolet and visible light. Wood Science and Technology, 2008. **42**: pp. 251–265.

[6] Forest Products Laboratory, ed. Wood Handbook—Wood as an Engineering Material. 1999, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463.

[7] Kahn, M., Fine Woodworking on Wood and How to Dry it, ed. F.w. working. 1986, United States: Taunton Press. 106.

[8] Feist, W.C., Painting and finishing exterior wood. Journal of Coatings Technology, 1996. **68**(856): pp. 23–26.

[9] Williams, R.S., et al., Wood properties affecting finish service life. Journal of Coatings Technology, 2000. **72**(902): pp. 35–42.

[10] Simpson, W. and TenWolde A., Physical properties and moisture relations of wood. Chapter, 2010. **3**: pp. 1–25.

[11] Van Den Bulcke, J., et al., Adhesion and weathering performance of waterborne coatings applied to different temperate and tropical wood species. Journal of Coatings Technology Research, 2006. **3**(3): pp. 185–191.

[12] Williams, R.S., Knaebe M.T., and Feist W.C., Finishes for Exterior Wood. 1996, Madison, WI, USA: Forest Products Laboratory. 127.

[13] Palanti, S., et al., A simple testing method for the measurement of the water vapour transmission of coated wood longitudinal and tangential to grain direction. Holzforschung, 2001. **55**: p. 7.12.2005.

[14] Williams, R.S., et al., Wood properties affecting finish service life. Journal of Coatings Technology, 2000. **72**(902).

[15] Bonura, T., D. Mall, and S. Williams, Finishing checklist-A guide to achieving optimum coating performance on exterior wood surfaces. Journal of Coatings Technology, 2004.

[16] Lebow, S.T., Wood Preservation, in Wood Handbook—Wood as an Engineering Material, F.P. Laboratory, Editor. 2010, Washington: U.S. Department of Agriculture: p. 28.

[17] Nejad, M. and Cooper, P., Exterior wood coatings. *Part*-1: Performance of semitransparent stains on preservative-treated wood. Journal of Coatings Technology Research, 2011. **8**(4): pp. 449–458.

[18] Freeman, M.H., et al., Past, present, and future of the wood preservation industry. Forest Products Journal, 2003. **53**(10): pp. 8–15.

[19] Feist, W.C. and Ross A.S., Performance and durability of finishes on previously coated CCA-treated wood. Forest Products Journal, 1995. **45**(9): pp. 29–36.

[20] Evans, P.D., Michell A.J., and Schmalzl K.J., Studies of the degradation and protection of wood surfaces. Wood Science and Technology, 1992. **26**(2): pp. 151–163.

[21] Lebow, S., Leaching of wood preservative components and their mobility in the environment: summary of pertinent literature, in General technical report F.P. Laboratory, Editor. 1996: Forest Products Laboratory. p. 36.

[22] Lebow, S., P. Lebow, and D. Foster, Estimating preservative release from treated wood exposed to precipitation. Wood and Fiber Science, 2008. **40**(4): pp. 562–571.

[23] Cooper, P.A. and Ung Y.T., Effect of preservative type and natural weathering on preservative gradients in southern pine lumber. Wood and Fiber Science, 2009. **41**(3): pp. 229–235.

[24] Nejad, M. and Cooper P., Coatings to reduce wood preservative leaching. Environmental Science and Technology, 2010. **44**(16): pp. 6162–6166.

[25] Nejad, M. and Cooper P., Exterior wood coatings. Part-2: Modeling correlation between coating properties and their weathering performance. Journal of Coatings Technology Research, 2011. **8**(4): pp. 459–467.

[26] Rowell, R.M., et al., Understanding decay resistance, dimensional stability and strength changes in heat-treated and acetylated wood. Wood Material Science and Engineering, 2009. **4**(1–2): pp. 14–22.

[27] Hill, C.A.S., Wood Modification: Chemical, Thermal and Other Processes Wiley series in renewable resources. 2006, NJ: John Wiley & Sons, Ltd.

[28] Alfredsen, G., Flæte P.O., and Militz H., Decay resistance of acetic anhydride modified wood: a review. International Wood Products Journal, 2013. **4**(3): pp. 137–143.

[29] Gobakken, L.R. and Westin M., Surface mould growth on five modified wood substrates coated with three different coating systems when exposed outdoors. International Biodeterioration and Biodegradation, 2008. **62**(4): pp. 397–402.

[30] Ohkoshi, M., FTIR-PAS study of light-induced changes in the surface of acetylated or polyethylene glycol-impregnated wood. Wood Science, 2002. **48**(5): pp. 394–401.

[31] Beckers, E.P.J., et al., Performance of finishes on wood that is chemically modified by acetylation. Journal of Coatings Technology, 1998. **70**(878): pp. 59–67.

[32] Wang, J. and P. Cooper. Review on thermal treatments of wood. in CWPA Proceedings. 2003. Halifax, Canada.

[33] Esteves, B.M. and Pereira H.M., Wood modification by heat treatment: A review. BioResources, 2009. **4**(1): pp. 370–404.

[34] Dubey, M.K., Pang S., and Walker J., Color and dimensional stability of oil heat-treated radiata pinewood after accelerated UV weathering. Forest Products Journal, 2010. **60**(5): pp. 453–459.

[35] Pétrissans, M., et al., Wettability of heat-treated wood. Holzforschung, 2003. **57**(3): pp. 301–307.

[36] Nejad, M., et al., Coating performance on oil-heat treated wood for flooring. Bioresources 2012. **8**(2): pp. 1881–1892.

[37] Zeno W. Wicks Jr., et al., Organic Coatings: Science and Technology. 2007, Hoboken, N.J.: Wiley-Interscience.

[38] Winkelaar, A., Coatings Basics ed. E.C.T. Files. 2010: William Andrew, Hannover, Germany. 140.

[39] Bently, J. and Turner G.P.A., Introduction to Paint Chemistry and Principle of Paint Technology. 1998, London: Chapman and Hall.

[40] Bulian, F. and Graystone J.A., Industrial Wood Coatings-Theory and Practice. 1st ed. 2009, Oxford, UK: Elesvier.

[41] Weldon, D.G., Failure Analysis of Paints and Coatings. 2002: John Wiley & Sons, West Sussex, United Kingdom. 291.

[42] Jeremic, D., Cooper P., and Brodersen P., Penetration of poly(ethylene glycol) into wood cell walls of red pine. Holzforschung, 2007. **61**(3): pp. 272–278.

[43] Landry, V., Riedl B., and Blanchet P., Alumina and zirconia acrylate nanocomposites coatings for wood flooring: Photocalorimetric characterization. Progress in Organic Coatings, 2008. **61**(1): pp. 76–82.

[44] Nejad, M., et al., Studying dispersion quality of nanoparticles into a bio-based coating. Progress in Organic Coatings, 2015. **89**: pp. 246–251.

[45] Heilen, W., Haim J., and Hyatt D., Additives for Waterborne Coatings. 2009: Vincentz Network, Hannover, Germany.

[46] Nejad, M., et al., Waterborne coating: defoamer performance measured by evaluation of coating film appearance. European Coating Journal, 2015. (10): p. 6.

[47] Satas, D. and Tracton A.A., Coatings Technology Handbook. 2001, New York: Marcel Dekker. 902.

[48] Packham, D.E., ed. Handbook of Adhesion. 2nd ed. 2005, John Wiley: Chichester, West Sussex. 639.

[49] Wålinder, M., Wetting Phenomena on Wood: Factors Influencing Meaurements of Wood Wettability in Department of Manufacturing Systems, Wood Technology and Processing. 2000, Sweden: Royal Institue of Technology: KTH.

[50] Feist, W.C., Wood properties and finish durability. Journal of Coatings Technology, 2002. **74**(926): pp. 71–76.

[51] Cassens, D.L. and Feist W.C., Exterior Wood in the South, Selection, Applications, and Finishes, in General Technical Report, F.P. Laboratory, Editor. 1991: Madison, WI: US department of Agriculture. p. 60.

[52] Podgorski, L.. Analysis of the wood coating ageing and prediction of the durability through calorimetric investigations. in COST E 18 Final seminar 6. 2004.

[53] Nussbaum, R.M., Sutcliffe E.J., and Hellgren A.C., Microautoradiographic studies of the penetration of alkyd, alkyd emulsion and linseed oil coatings into wood. Journal of Coatings Technology, 1998. **70**(878): pp. 49–57.

[54] Dickie, R.A., Toward a unified strategy of service life protection. Journal of Coatings Technology, 1992. **64**(809): pp. 61–64.

[55] Knaebe, M., Paint, Stain, Varnish, or Preservative? It's your Choice., in The finish line, fact sheet. 1995, Madison, WI Forest products laboratory.

[56] Jourdain, C., et al., Changing nature of wood products–what does it mean for coatings and finish performance? (Technology Forum: Wood Coatings), 1999. **71**(890): pp. 61–66.

[57] Feist, W. and Williams R.S., Weathering durability of chromium-treated southern pine. Forest Products Journal, 1991. **41**(1): pp. 8–14.

[58] Feist, W. and Ross A.S.. Performance of surface finishes over CCA-treated wood. In 43 rd annual meeting 1989. Madison: Forest Products Reaserch Society.

[59] Michell, A., FTIR spectroscopic studies of the reactions of wood and of lignin model compounds with inorganic agents. Wood Science and Technology, 1992. **27**(1): pp. 69–80.

[60] Ross, A., et al., Finishability of CCA Pressure-Treated Wood, in Miscellaneous Publication, P.a.C. Industry, Editor. 2000, Madison, WI: USDA, Forest Products Laboratory. pp. 44–58.

[61] Grelier, S., Castellan A., and Kamdem D.P., Photoprotection of copper-amine-treated pine. Wood and Fiber Science, 2000. **32**(2): pp. 196–202.

[62] Kocaefe, D., et al., Effect of heat treatment on the wettability of white ash and soft maple by water. Einfluss der Wärmebehandlung auf die Benetzbarkeit von Weißesche und Rot-Ahorn mit Wasser, 2008. **66**(5): pp. 355–361.

[63] Wolkenhauer, A., et al., Plasma treatment of heat treated beech wood–investigation on surface free energy. Holzforschung, 2008. **62**(4): pp. 472–474.

[64] Awoyemi, L., Cooper P., and Ung T., In-treatment cooling during thermal modification of wood in soy oil medium: soy oil uptake, wettability, water uptake and swelling properties. European Journal of Wood and Wood Products, 2009. **67**(4): pp. 465–470.

[65] PetriÄ M., et al., Wettability of waterborne coatings on chemically and thermally modified pine wood. Journal of Coatings Technology Research, 2007. **4**(2): pp. 203–206.

[66] Sailer, M., Rapp A.O., and Leithoff H.. Improved resistance of scots pine and spruce by application of an oil-heat treatment. in The International Research Group on Wood Preservation. 2000. Hawaii, USA: IRG/WP 00-40162.

[67] Nejad, M. and Cooper P., Performance characterization of coatings on treated-wood. 2013, Progress in Color, Colornats and Coatings. pp. 61–65.

[68] Jämsä, S., Ahola P., and Viitaniemi P., Long-term natural weathering of coated ThermoWood. Pigment & Resin Technology, 2000. **29**(2): pp. 68–74.

INTECH