THE EFFECT OF SURFACE ROUGHNESS ON THE PERFORMANCE OF FINISHES. PART 1. ROUGHNESS CHARACTERIZATION AND STAIN PERFORMANCE

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ABSTRACT

In this study, the relationship between the morphological structure of the outside wood layer expressed as surface roughness, and the performance of coatings was analyzed. The surface roughness of five roughness categories (processed by planing, sanding, and bandsawing) on three wood substrates (vertical- and flat-grained western redcedar and flat-grained southern yellow pine) was determined by stylus tracer measurements. Several surface parameters were calculated to characterize the five roughness grades. Surface sanding proved to be an advantageous processing step prior to paint application. Sanded surfaces needed a relatively low quantity of paint for coverage and showed best paint performances even on low-grade wood.

Wood structures exposed outdoors need protection against the influence of sunlight and rain. Protection can be achieved with a combination of building design and efficient coating. One basic requirement for sufficient and long-lasting paint performance is good adhesion of the coating product on the wood surface. The ability of a wood surface to accept and hold a paint coating is determined by the natural characteristics of the wood species and the manufacturing processes used (3). Natural factors (anatomical, physical, and chemical properties) vary considerably, not only between different species, but even within the same species and tree. Their influence on paint performance can only be predicted with a high range of variation and this influence is considered to some extent in grading and selecting procedures.

But surface texture is not only determined by the inherent morphological structure of wood. According to a surface-texture system proposed by Marian et al. (13), anatomic structure causes a first-degree texture (e.g., tracheid or vessel diameter and cell wall thickness). A second-degree texture results from the machining method itself (e.g., tooth marks from a saw and waves formed by a machine planer). Third-degree texture results from variation within the machining method (e.g., vibrations, misalignment, and dull tools).

There are two surface roughness textures commonly used for wood siding materials – smooth surface (planed) and roughsawn. In exposure studies, the two surface textures produce different performance results with finish systems. Penetrating stains and preservative treatments gave better results on roughsawn and flat-grained lumber (2,6,12) or rough-textured plywood (5). This was a result of the substantially higher spreading rates generally achievable on rough substrates. Transparent finishes and white film-forming alkyd paints were superior on smooth, edge-grained substrates, because a more uniform film thickness could be established, resulting in better moisture protection (3,12). Film-forming all-acrylic latex paints showed good performance and durability on both smooth and roughsawn wood (23).

However, the mechanisms responsible for these characteristics are not yet fully understood. Surface texture was not characterized in any of these studies. In addition, no information could be found to indicate what roughness grades are best for optimum durability and how finish performance may vary on different roughness surfaces. This is contrary to the situation in wood adhesion science – an area with similar and compa-

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rable problems of paint application and performance, where much more attention is given to surface preparation and its characterization prior to bonding (1,4,14,17).

The purpose of our investigation was to determine how the roughness of wood surfaces affects the overall performance of different coatings (16). This paper presents the results of surface characterization (roughness measurement and interpretation of roughness and roughness standards) and the performance of stained samples in accelerated weathering. Subsequent papers will discuss the relation of roughness and paint adhesion and the performance of painted and stained samples exposed outdoors.

MATERIALS AND METHODS

FINISHING SUBSTRATES

The wood species used were vertical- and flat-grained western redcedar *(Thuja plicata)* (WRC) and flat-grained southern yellow pine *(Pinus spp.)* (SYP). The WRC was obtained directly from a local lumberyard, where it was available in a beveled form resulting from diagonal longitudinal bandsaw cutting of the planed boards in the sawmill, Thus, each board has a rough and a smooth (planed) surface. The SYP was purchased several years ago and had been stored since then in the laboratory. Its surface was originally planed.

TABLE 1. — Surface categories analyzed.

Category	Surface condition	Species[a]
1	Smooth as received (factory planed)	WRC
	Replaned[b]	SYP
2	Sanded	WRC, SYP
3[c]	Rough as received (factory rough)	WRC
4	Re-roughened with bandsaw (blade with normal set)	WRC, SYP
5	Re-roughened with bandsaw (blade with high set)	WRC, SYP

[a] WRC = western redcedar; SYP = southern yellow pine.
[b] SYP boards were replaned in the carpenter shop to eliminate impurities due to the long storage time.
[c] SYP siding was not available in roughsawn quality.

The surface roughness categories (RC) listed in **Table 1** were defined in relation to the machining processes done to the surface of the wood samples. Sanding was done with a Solem double-belt sander, using only one belt and a 50-grit sandpaper. All samples were processed with the same feed rate; belt pressure was regulated automatically by a hydraulic device.

RCs 4 and 5 **(Table 1)** were processed with a horizontal bandsaw (Wood-Mizer LT 30). This type of saw allowed roughening the samples with a constant feed rate and minimized uncontrolled grooves in the surface profile, which were frequently found using manual feed. RC 4 was sawn with a bandsaw with minimal tooth set (approximately 0.04 mm) and a distance between two teeth of 19 mm (3/4 in.). The bandsaw used to produce RC 5 had a distance between two teeth of 22.3 mm (7/8 in.) and a manually adjusted higher set (approximately 0.06 mm). Both the bandsaw speed and feeding rate were maintained constant for the two RCs.

ROUGHNESS MEASUREMENT

Roughness measurements of all 366 specimens prepared for finishing were done with a commercial instrument (Perthometer S6P, drive unit PRK of Feinprüf GmbH, 37008 Göttingen/Germany). This stylus tracing device was developed for quality control on work pieces with relatively smooth surfaces, such as metals and plastics. It was necessary to adjust the measurement range to scan the rough surfaces in our study by elongating the length of the commercial pickup. Before being traced, all specimens were conditioned to 12 percent equilibrium moisture content (EMC) in a climate room at 27°C and 65 percent relative humidity (RH) for at least 1 week. **Table 2** lists the characteristics of the tracing process.

TABLE 2. — Characteristics of stylus tracing.

Tracing direction	Across the grain
Tracing length	56 mm
Tracing speed	0.5 mm/sec.
No. of measured points/trace	8,064
Pickup length	130 mm
Stylus tip radius	ca. 40 µm
Force exerted on surface	130 mN

Because the number of data points measured per tracing unit (144 points/mm) was more than necessary and slowed later calculations, the data sets were compressed by selecting only every sixth value. The remaining raw data gave a detailed reproduction of the total movement of the stylus on the traced surfaces, including the roughness as well as the waviness and form of the surface. The latter two components were excluded from the raw data profile by a 2-step floating average of 100 data points each. The result was a de-trended roughness profile representing 48 mm (reference length) of the tracing length.

Three standardized (DIN 4768/ISO 4287) roughness parameters: average roughness (Ra), average roughness depth (Rz), and maximum roughness depth (Rt); and two derived numbers: peak roughness (Pr) and peak index (Pi) were calculated and compared statistically. Ra is the arithmetic mean of all, and Pr is the arithmetic mean of only the peak and valley points within the reference length. Rz measures maximum vertical distances within the reference length. Pi was used in former studies to evaluate wood-based siding (11). Pr was modified by giving more emphasis to the larger peak and valley points.

FINISHING AND PERFORMANCE RATING

A total of 66 boards (76 by 100 mm) were finished by brush with a linseed oil-based, semitransparent stain (cedar brown), using two methods. First, the specimens of all RCs were coated with the recommended (normal) coverages. The finish applied per panel was weighed and the spreading rates were calculated. Then, duplicates of the rougher samples (RCs 3,4, and 5) were finished trying to apply only the quantity of stain used for the smooth surfaces (reduced coverage). This was achieved by using a 1:1 dilution of stain and mineral spirits to duplicate the amount of stain applied to the smooth surfaces. The resulting spreading rates are listed in **Table 3.**

The specimens were exposed to accelerated weathering in a xenon arc weathering chamber (Atlas Weather-O-Meter), where they received a daily cycle of 20 hours of light and 4 hours of light plus water spray. The upper third section of each specimen was protected from weathering with a stainless steel plate, and served as a reference area. The finish performance (erosion and discoloration) was sated according to

ASTM D 662-92 (erosion rate of semitransparent stain) after 600, 1,200, 1,800, and 2,400 hours of exposure. The degradation modes were rated on a 10 to 1 scale where 10 = original condition and 1 = total failure.

STATISTICAL EVALUATION

A two-way analysis of variance was carried out on all data to determine whether surface roughness (RC or selected roughness parameter) significantly influenced the experimental data (spreading rate and paint performance). Differences between the means of independent variables were tested for significance using Tukey's Studentized Range Test. Significant differences were recorded at the 5 percent probability level. All statistical calculations were performed with the SAS software package (19).

RESULTS AND DISCUSSION

ROUGHNESS EVALUATION

Stylus tracing was a suitable method for roughness determination. Although mainly used for polished and smooth surfaces, the commercial device was able to measure the coarse substrates after some mechanical modifications. This is consistent with recent studies where the value of stylus tracing systems for wood surface measurements was shown (9, 18). The five calculated roughness parameters selected were compared statistically in a correlation analysis, manifesting a high correlation between all parameters **(Table 4).** The highest and most homogeneous coefficients were found for Ra, representing the arithmetic mean of the absolute values of the profile deviation. Because its calculation is standardized and the parameter is used in other studies for roughness characterization (8, 15), Ra was selected in our study to quantify surface roughness.

TABLE 3. — Spreading rates and evaluation of erosion and discoloration after accelerated weathering (mean values of three replicates).[a]

Samples	Spreading rate	Erosion after (hr.)				Discoloration after (hr.)			
		600	1,200	1,800	2,400	600	1,200	1,800	2,400
	(ft.^{4}/gal)								
SYP, RC 1, SR 1	442	8.7	5.0	4.0	3.3	7.7	4.0	4.0	3.3
SYP, RC 2, SR 1	268	9.0	6.7	5.7	5.0	8.3	5.7	5.7	5.0
SYP, RC 4, SR 1	220	9.3	7.3	5.3	4.0	8.3	6.3	5.3	4.0
SYP, RC 5, SR 1	158	9.0	7.7	5.7	5.0	8.7	6.7	5.7	5.0
SYP, RC 4, SR 2	453	5.3	3.7	2.0	1.0	5.3	3.7	2.0	4.0
SYP, RC 5, SR 2	355	6.0	5.0	3.0	2.0	6.0	5.0	3.0	4.0
WRC-F, RC 1, SR 1	430	5.3	3.7	3.0	2.0	6.0	5.0	3.0	2.0
WRC-F, RC 2, SR 1	371	9.7	8.7	7.0	6.3	9.3	8.7	6.7	6.0
WRC-F, RC 3, SR 1	219	9.0	7.3	6.3	5.7	9.0	7.3	6.3	5.7
WRC-F, RC 4, SR 1	207	9.7	7.0	6.0	4.7	9.7	7.0	5.0	4.7
WRC-F, RC 5, SR 1	155	9.0	6.3	5.3	4.3	8.3	6.3	5.3	4.3
WRC-F, RC 3, SR 2	464	4.3	3.0	2.0	1.0	4.3	3.0	1.0	2.0
WRC-F, RC 4, SR 2	446	4.7	3.0	2.0	2.0	4.7	3.0	1.0	1.0
WRC-F, RC 5, SR 2	396	3.3	2.0	2.0	2.0	3.3	2.0	1.0	1.0
WRC-V, RC 1, SR 1	437	9.7	7.0	6.0	5.0	9.0	6.3	5.3	5.0
WRC-V, RC 2, SR 1	376	9.7	8.7	7.0	7.0	8.7	8.0	7.0	7.0
WRC-V, RC 3, SR 1	200	9.0	7.0	6.0	5.0	7.7	7.0	5.3	5.0
WRC-V, RC 4, SR 1	193	9.0	7.0	6.0	5.7	8.0	7.0	6.0	5.7
WRC-V, RC 5, SR 1	177	8.0	6.0	5.0	5.0	8.0	6.0	5.0	5.0
WRC-V, RC 3, SR 2	462	4.7	2.3	1.7	1.0	4.7	2.3	1.0	1.0
WRC-V, RC 4, SR 2	449	4.7	3.0	2.0	1.0	4.7	3.0	2.0	1.0
WRC-V, RC 5, SR 2	418	4.3	2.7	2.0	1.0	4.3	2.0	1.0	1.0

[a] RC = roughness category; SR 1 = normal spreading rate; and SR 2 = reduced spreading rate.

TABLE 4. — Correlation coefficients between roughness parameters (n = *66, significance level = 5%).*[a]

	Ra	Rz	Rt	Pr	Pi
Ra	- -	- -	- -	- -	- -
Rz	.992	- -	- -	- -	- -
Rt	.981	.989	- -	- -	- -
Pr	.996	.986	.975	- -	- -
Pi	.990	.983	.973	.993	- -

[a] Ra = average roughness; Rz = average roughness depth; Rt = maximum roughness depth; Pr = peak roughness; and Pi = peak index.

In **Figure 1,** Ra mean values and the standard deviation of all 573 profiles scanned in our study (small boards were traced once, larger ones twice) are plotted. The standard deviation was lower for the smooth samples where the sanded surfaces showed a better homogeneity than the planed substrates. Sanding eliminates deviations better because elements found in the anatomic structure (such as resin ducts or earlywood/latewood differences) are more pronounced in the roughness profiles of the knife-planed surfaces, resulting in the higher standard deviations.

The rougher surfaces were characterized by a much higher variability within the individual categories. The Tukey procedure proved that the differences between the means, except for RCs 3 and 4, were significant from each other. Thus, stylus tracing roughness evaluation allowed the characterization and splitting up between the surfaces of four roughness grades: RC 1, RC 2, RCs 3 and 4, and RC 5. Factory processing (RC 3) and the wood Mizer roughening with the normal saw blades in the laboratory (RC 4) both gave similar surface topographies.

The effects of wood species and grain orientation on surface topography in the five RCs are shown in **Figure 2,** where the mean Ra values for the three subsets are depicted (CF = WRC/flat grained, CV = WRC/vertical grained, and PF = SYP/flat grained). To determine the variability within each species group and roughness class, the standard error of the mean was calculated. Connetted bars within the roughness groups mark the means that were not different at the 95 percent significance level. For the planed surfaces (RC 1), all means were significantly different from each other with the highest value for the flatsawn WRC and the lowest roughness for the SYP. The flat-grained WRC was a low-quality grade and the factory planing resulted in uneven and irregular surfaces caused by the poor wood quality and worn or dull knives. Addition-

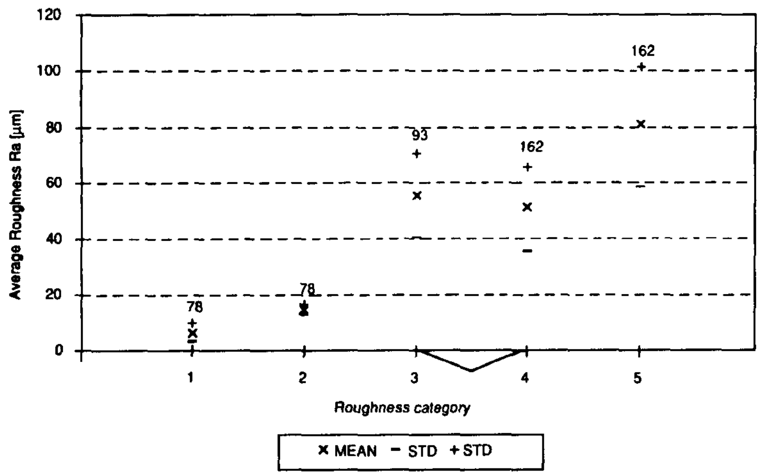

Figure 1. — Mean values and standard deviations of average roughness (Ra) (expressed in micrometers) within the five roughness categories. The numbers quote the sample size. All means, except for roughness categories 3 and 4, were different from each other.

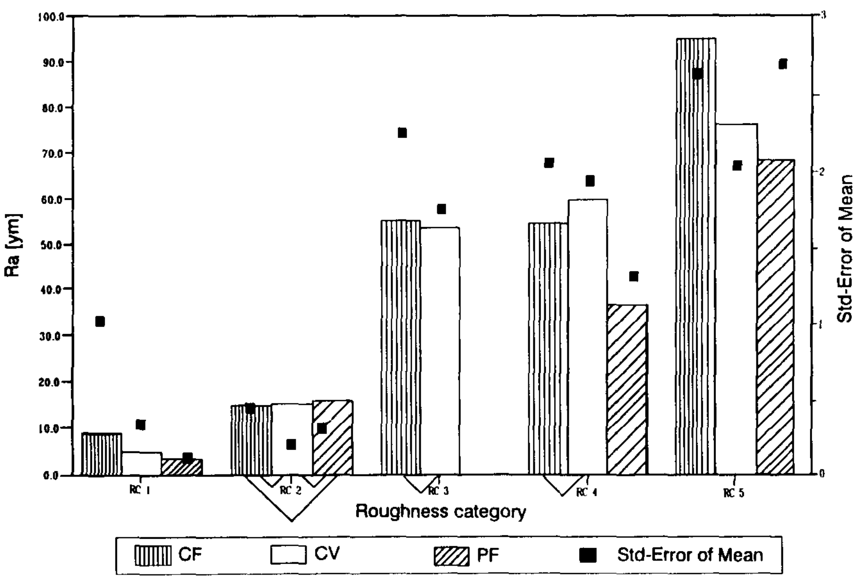

Figure 2. --- Mean values of average roughness (Ra) and the standard error of mean for the species/grain subgroup within the five roughness categories. Bars connected by lines beneath the graph within each roughness group marks mean values not different from each other at a significance level of 5 percent.

ally, the differences in earlywood/latewood density caused higher swelling in the tangentially cut latewood, so that some of the profiles of flatsawn wood looked like densitograms. The fact that the SYP surfaces had the lowest roughness was due to the fresh planing in the laboratory right before roughness was measured.

No significant differences between the substrates were found within the RC 2 and RC 3 and 4 categories (for the WRC specimen). Obviously, sanding as well as factory rough sawing reduced the influences of grain and wood species. Within the WRC group, the lower standard deviation of the vertical grain substrates shows that a homogeneous wood quality results in a more consistent surface quality even after sanding and planing. Compared to WRC, rough SYP showed significantly lower Ra means. It can be assumed that the higher density SYP builds up more resistance against the cutting forces of the bandsaw with normal set (RC 4) and is less compressed, so that the cutting quality is more homogeneous. When the set of the blades is increased, as with the second bandsaw, more fibers are torn off the earlywood tissue, whereas the latewood zones are sheared off, resulting in a high roughness variability of the RC 5-SYP surfaces.

ROUGHNESS AND SPREADING RATE

Ra and spreading rate numbers of the 66 exposure panels subjected to accelerated weathering were compared in a correlation analysis. The results manifest the inverse relationship between surface roughness and spreading rates reported in previous studies (12,23).

An inverse relationship within each of the three clusters presented in **Figure 3** exists between the roughness and the spreading rate with correlation coefficients of r = -0.79 (smooth surfaces, normal application), r = -0.78 (rough surfaces, normal application), and r = -0.42 (rough surfaces. reduced application). The slope of the regression lines depicts that within the samples painted with normal spread, the relationship was stronger for the smoother surfaces compared to the rougher samples.

As was intended by the study design, the reduced spreading rate on the rougher surfaces generated significantly different results from the normal spreading rates on similar rough samples. The spreading rates ranged in the same order as the coverages for the smooth surfaces. The slope of the regression line is nearly the same as for the surfaces painted with normal spread. Tukey groupings based on all data points showed there was no significant influence on spreading rate either by wood species (one exception) and grain orientation.

Figure 3 also allows the visualization of variation within the RCs. It was highest for the sanded specimen with spreading rates between 440 and 250 ft.^{2}/gal. In this group, the SYP specimens needed significantly more paint than the WRC samples, 373 versus 268 ft.^{2}/gal., although no significant differences in the roughness of the two sanded species group had been found **(Fig. 2)**.

The sanding process seems to reveal the best possible individual characteristics of the substrates as they refer to the ability to accept coatings. To a lesser extent, the same is true for the planed surfaces, where the spreading rates for the RC 1 surfaces were grouped between 490 and 390 ft.^{2}/gal. With increasing roughness, the deviation in the spreading rates became smaller. Obviously, anatomic structural elements important for the spreading rate (e.g., cell dimensions and earlywood/latewood distribution in growth rings) are overlapped by roughness effects (e.g., increased surface area caused by valleys, crevices, and upstanding fiber bundles).

ACCELERATED WEATHERING

The results of stain erosion and discoloration evaluation after four 600-hour periods of accelerated weathering are shown in **Table 3.** The numbers represent the averages of three replicates. After 2,400 hours, only small differences between erosion and discoloration were found. In **Figure 4,** the results for vertical grain WRC erosion are graphed as an example to visualize the stain performance during the test on the different RCs.

All boards finished with a reduced spreading rate (SR 2) showed significantly lower ratings in both stain erosion and discoloration as compared to the normally finished boards. The only exception was in the SYP specimens with reduced coverage, where discoloration had increased during the last exposure period and was rated similar to the normally finished boards. The failure in erosion appeared after the first exposure cycle and lasted until **the end** of the test, when most of the stain was eroded completely **(Table 3).**

Within the specimens with a minimum finish spread, no clear influence of the roughness group was visible. This behavior clearly demonstrated that the good performance of stain on roughsawn surfaces seen in previous studies (5-7) is primarily due to the higher quantity of finish spread on the rougher surfaces and not an effect of the increased surface roughness. The rapid erosion indicates that rough wood, if painted insufficiently, might degrade faster because the moisture uptake and retention of roughened surfaces are higher, as are swelling and shrinkage movements in the loosened fibers.

On normally finished wood, the sanded surfaces (RC 2) showed similar (SYP) or better performance than roughsawn specimens. Sanded vertical grain WRC had superior ratings (7.0 for both erosion and discoloration), but the differences in the low-quality flat-grained WRC were surprisingly small (6.3 and 6.0, respectively).

SYP, a species with poorer paint-holding characteristics, was rated 5.0 in both erosion and discoloration for RC 2, which is the same rating as for the RC 5 surfaces. This result is particularly interesting because spreading rates of the sanded boards were 50 to 60 percent higher than those of the bandsawn samples. This indicates it is feasible to reach an equal (SYP) or improved long-term performance (WRC) with less than half of the quantity of stain used on rough wood, which was thought to be the best surface texture until now. Sanding would make stain application more efficient, not only economically (less material use), but also from an ecological standpoint (fewer volatile organic chemical emissions).

The reason for the improved stain performance on sanded boards can be seen in the substrate conditions realized by a slight sanding. A microscopic evaluation of all surface grades showed that the stain uniformly covered the sanded specimens **(Fig. 5).** It has been reported that on a microscopic level, sanding or abrasive planing causes surface and subsurface damage when com-

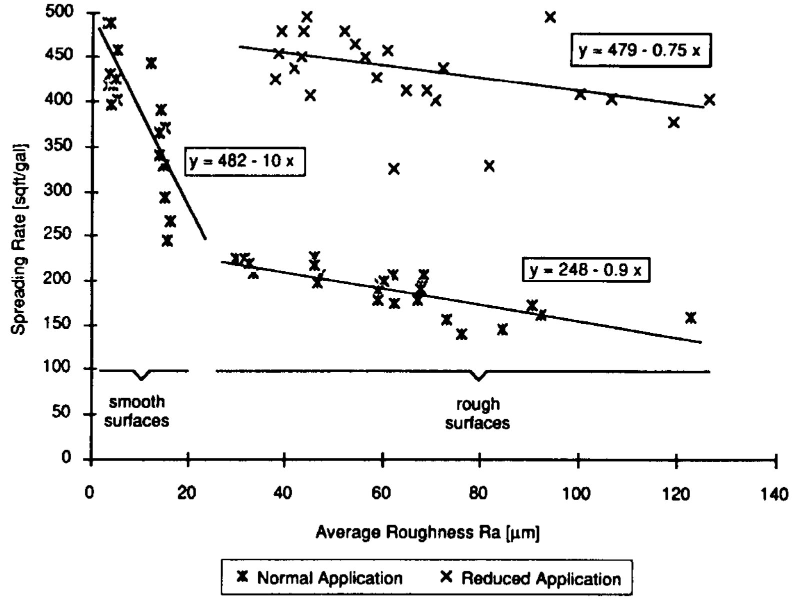

Figure 3. — Spreading rates of stain in relation to surface roughness.

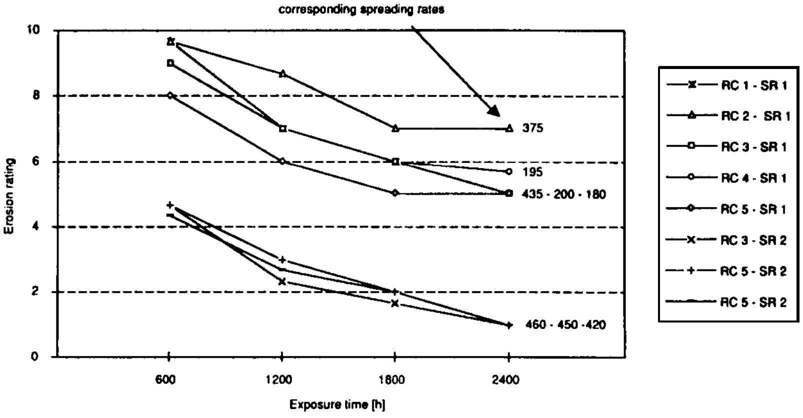

Figure 4. — Erosion rating of vertically grained, stained, western redcedar after four 600-hour periods of accelerated weathering. The numbers identify the correspending spreading rates.

red to knife planing (4,14,21). Surface damage (broken or crushed cell walls) is the reason for a poor bonding quality in shear and adhesion tests. ,

According to our results, this phenomenon proved to be beneficial for finish performance. We assume that the upstanding and lightly crushed earlywood fibers created an increased superficial surface and exerted adsorption forces that prevented the stain from penetrating in deeper wood zones. Further, normal anatomical penetration paths (e.g., wood ray tissue) had been crushed so that an uptake of stain in deeper cell layers was prevented. It is known that sanding alters the cellular structure so that no anatomical roughness (first-degree roughness) is detectable (22). On the other hand, the dense latewood bands were roughened sufficiently so that an increased finish adsorption was possible in these zones, too.

Possibly, the lightly loosened and upstanding cell wall material provided a mechanical reinforcement for the finish layer when covered and immersed by the stain. The finish was concentrated at the sanded surface layer where it nearly forms a uniform film and gives protection against radiation and water This supports earlier results, which reported a complete masking of grain in painted abrasive-planed samples after accelerated weathering when compared to knife-planed samples (10). According to Gaby's study, knife planers or matchers may cause physical surface changes, especially on flatsawn southern pine, which subsequently can affect paint performance, whereas abrasive planers do not compress or burn the surface in the way that may adversely affect paint and stain life,

The reinforcement also appears on the bandsawn surfaces, but the higher roughness allows more penetration in the low-density earlywood cells, which stabilized its weak thin cell walls, but resulted in higher finish uptakes. These low-density earlywood zones became the starting points for the severe failure on planed flatsawn surfaces because the surfaces were not covered and protected sufficiently with finish substance.

It will be interesting to evaluate the boards installed at the exposure site in Madison, Wis., to see if the positive interaction of sanded surface and finish characteristics is limited to the stained samples or if painted boards will show a similar performance. Because of the different viscosities and wetting characteristics of stain and paints, it might be reasonable that another roughness grade may perform better. Conversely, all acrylic paint systems showed the best performance on both roughsawn and scratch-sanded boards after 7 years in outdoor exposure at the USDA Forest Service's test fence (5), so that an equally good behavior might be expected from painted specimens. However, the approach outlined in this study should be replicated in additional studies using other grit sizes and sanding processes to test their influence on finish performance.

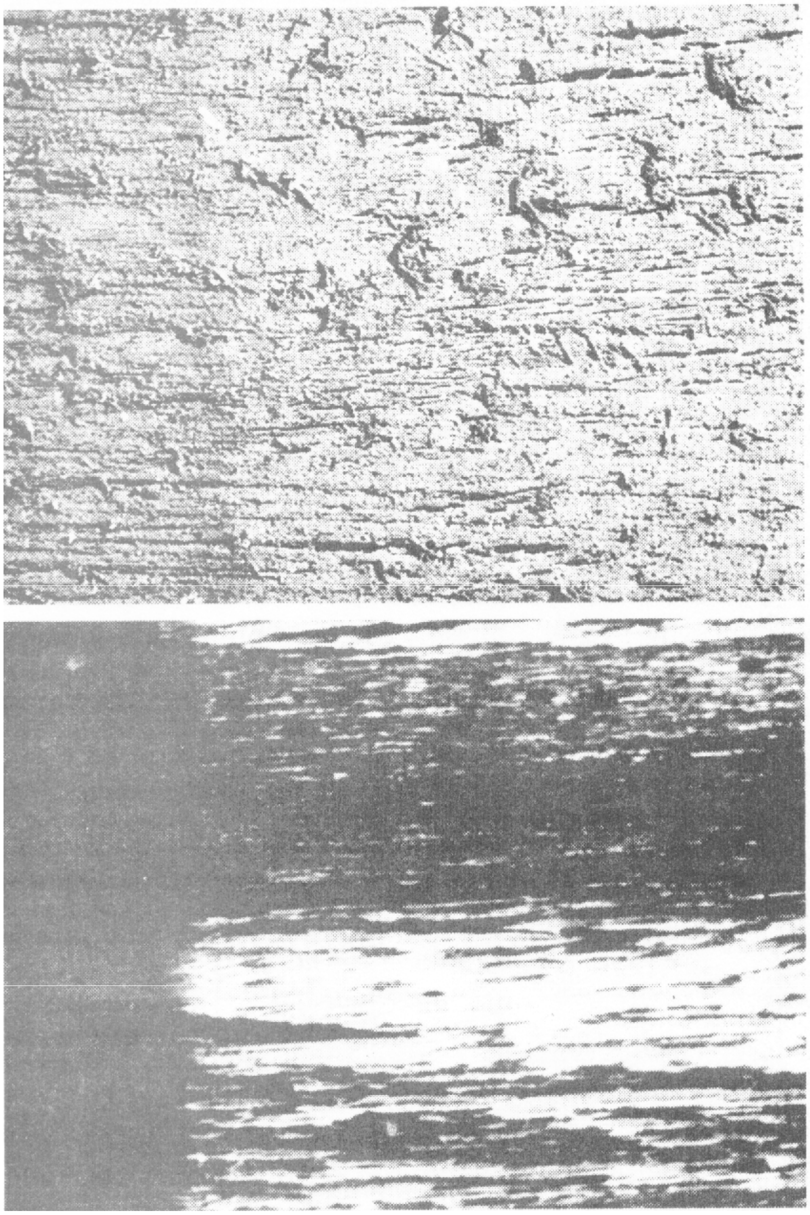

Figure 5.— Microphotograph of a flat-grained, sanded, western redcedar specimens (top) and a flat-grained, planed, southern yellow pine specimens (bottom) after 2,400 hours of accelerated weathering. The darker areas on the left were covered in the weather-o-meter and allow a comparison to the exposed surfaces.

CONCLUSIONS

Surface roughness produced by sanding or sawing can affect the performance of finishes in several ways. It has been quantified that finish spreading rates and surface roughness are related and that rough surface substrates need more finish coverage per area than smooth surface substrates. Very rough stained wood performed well in long-term exposure mainly because of the high spread necessary to cover the surface, whereas rough wood finished with the same amount of stain as applied to smooth surfaces (limited amounts) failed completely after only short-time weathering. The best stain performance was found on sanded surfaces, with performance ratings even better than those found for very rough wood, but with less than half the amount of finish applied.

In contrast to what is concluded in numerous studies on adhesive performance, sanding seems to be a perfect surface preparation for coatings because it levels off inherent differences in wood surface properties resulting in an equal and homogeneous finish spread. The light roughening allows sufficient finish penetration in dense latewood zones and avoids an over penetration in earlywood tissue, areas that are usually severe failure zones on planed wood. A stabilization effect and reinforcement for the finish layer by upstanding fibers and cell wall material is conceivable.

Surface sanding has proved to be an advantageous processing step prior to paint application. Sanded surfaces needed a relatively low quantity of paint for coverage and showed best paint performances even on low-grade wood, which can improve the furture competitiveness of wood siding.

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