Ultraviolet Curing of Epoxy Coating on Wood Surface

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ABSTRACT: Different formulations were developed with EB-600 (Ebcryl-600), an epoxy acrylate oligomer in the presence of *N*-vinylpyrrolidone and trimethylol propane triacrylate. Thin films were prepared with these formulated solutions under ultraviolet (UV) radiation. These solutions were coated on a low-grade wood substrate (simul) and cured under UV light. Both UV-cured thin films and surface coatings were characterized, and the best formulations for coating wood surface were evaluated. © 1997 John Wiley & Sons, Inc. J Appl Polym Sci **66:** 1997–2004, 1997

Key words: surface coating; UV radiation; polymer films; formulations; epoxy coating; wood coating

INTRODUCTION

Wood is a carbohydrate polymer. It is an excellent construction material. It has the highest tensile strength (modulus) per unit density among all other construction materials, including steel and metals. Wood is natural and abundantly available at a relatively cheap price. Quality of products is ensured with the quality of starting material. Good quality wood is expected to deliver good quality end products. Good quality wood is depleting very fast from the world forest reserve because of the high demand of this material due to increased population growth and improved modern technology. Scarcity of high-grade wood is becoming acute in most of the countries in the world; but it is so in almost all the highly populated countries, like Bangladesh, where population density is the highest in the world. Wood is randomly cut down in Bangladesh to meet the demand. Thus, not to speak of high-quality wood alone, there is high scarcity of low-grade wood as well. Wood that was used for fueling purposes is nowadays used for making household articles, like bedsteads, chairs, tables, beams, and pillars for cottages and huts. Recently, some novel impregnating solutions[1–3] were developed to improve quality of low-grade wood through the formation of wood plastic composite with low quality wood under radiation. The method, so developed, is also easy, and it is a simultaneous process for making composite with timber of any shape and size.[4] Quality and products of low grade wood can also be improved through curing of surface coating.[5–6] The present study is related to the improvement of surface of simul wood (a low quality fuel wood) of Bangladesh through curing of epoxy coating on this surface under ultraviolet (UV) radiation. Different formulations are developed with an epoxy oligomer in the presence of acrylamide and triacrylated monomers. Some additives are incorporated in order to increase adhesion and hardness of the coating on the wood surface.

EXPERIMENTAL

Materials

Ebcryl-600 is a diacrylated epoxy oligomer of Radcure product. Irgacure 369 (200–450 nm absorption

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Table I Composition of Different Formulations

Chemicals (w/w %)	T1	T2	T3	T4	T5
EB-600	50	50	50	50	50
NVP	24	24	30	20	22
TMPTA	24	20	16	27	22
IRG-369	2	2	2	2	2
$CaCO_3$	—	4	—	—	3
MEK	—	—	2	1	1

band) was procured from Ciba–Geigy (Dhaka). Reactive monomer diluents, *N*-vinylpyrrolidone (NVP) and trimethylol propane triacrylate (TMPTA) were obtained from Merck, Germany. Filler calcium carbonate is a product of BDH Ltd. Methyl ethyl ketone (MEK) used as antibubbling agent was purchased from Aldrich Chemical Co. Simul (*Salmalia malabarica*) a low quality wood, mainly used for making match sticks, was collected from the local market and used as the substrate for the coating. Most of the chemicals were obtained from local agents in Dhaka.

Methods

A set of formulations was developed with ebcryl-600 combined with other additives in the proportions, as shown in Table I. These formulations were used to prepare thin polymer films on glass plates, as well as on wood substrate that was thoroughly polished with suitable sand papers. These films were characterized. The substrate (wood or glass plate, $10 \times 5 \times 0.2$ cm) was coated with the formulated solution using a bar coater no. 0.18 of Abbey Chemicals Co. (Australia). The thickness of the film was 36 ± 3 μm. The substrate was passed under a UV lamp (254–313 nm, 2 kW intensity) of 1ST Technik (model U-200-M-Tr, Germany) several times in order to ensure curing of the coated film on the substrate. The speed of the conveyor was 4 m/min.

Film hardness of the UV-cured film was determined while the film was still on the substrate for about 24 h. Several techniques were adopted to measure films hardness. Pendulum hardness of the UV-cured film was directly measured with the help of a Pendulum Hardness Tester (model 5854, BYK, Labotron, Germany). Scratch resistance, Buchhloz resistance, and macro- and microhardness were determined using a Universal Hardness Tester (model 43/E, Erichsen, Germany). Indent depth, length, and adhesion of the film were determined with the help of a PIG Universal Tester (model 3410, BYK, Labotron, Germany). Adhesion strength and chipped off area of the cured coated film were determined by an Adhesion Tester (model 525, ASTM, D4541, Erichsen, Germany). Gloss of the UV-cured film on the wood surface was measured at 60° and 20° angles using a Gloss Meter, (model Sheen 155, Germany).

Gel content of the polymer film was determined by extracting a known weight of the cured film with hot benzene for 48 h in a soxhlet because benzene easily dissolves NVP, TMPTA, and the urethane acrylate oligomer EB-600. The known amount of the film was wrapped in a stainless steel net that was put into the soxhlet and extracted with the solvent. The final weight of the extracted dry film leads to determination of the gel content using the formulation $\%\text{gel} = 100 - 100(W_o - W_e)/W_o$, where W_o is the weight of the cured film before the extraction, and W_e is the weight of the extracted film after drying it at 105°C until a constant weight was achieved.

Tensile properties such as tensile strength (TS) and elongation at break (EB) of the UV-cured film were measured directly with INSTRON (model 1011, UK), a machine for measuring tensile properties. The crosshead speed was 0.003 m/min with gauge length of 0.005 m. The efficiency of INSTRON is within ±0.1%.

RESULTS AND DISCUSSION

It is necessary to characterize UV-cured polymer films before measuring various properties of the UV-cured coatings on wood surface. Most of the data presented in this report are averaged values of at least five samples, and the results obtained are within ±2%.

Polymer Films

Films Hardness

Surface hardness of UV-cured thin polymer films prepared on glass plate was determined by the pendulum method. Results of pendulum hardness (PH) of films prepared with different formulations against different UV doses, represented by the number of passes, are graphically shown in

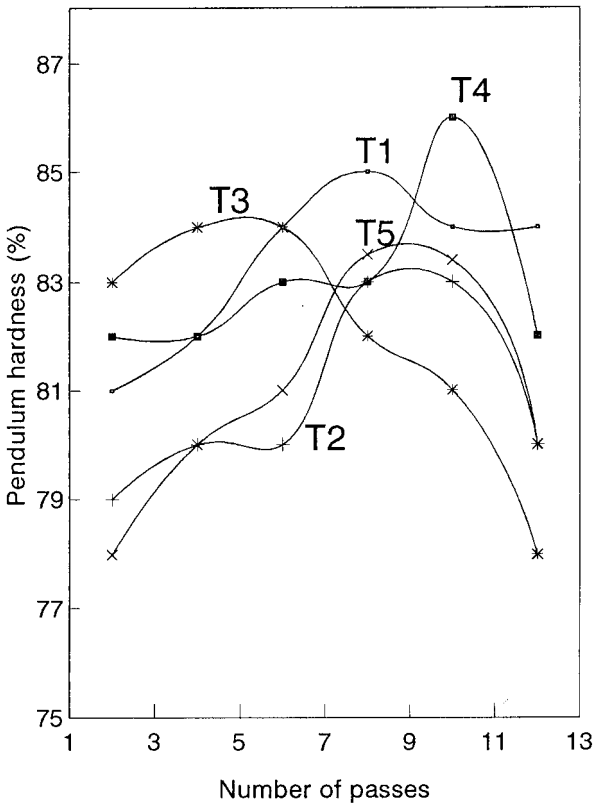

Figure 1 Pendulum hardness of UV-cured films against the number of passes.

Figure 1. The hardness increases with radiation. This indicates that the process of curing continues with UV radiation up to a certain UV dose, at which it gains the maximum hardness; some are at the 10th pass, while others are at 5th, 8th, and 9th passes. After attainment of the maxima, the hardness decreases with radiation. This may indicate that the polymer film prepared at the radiation dose of maxima starts degrading at a higher dose. This means the polymer gets decomposed at higher radiation. The highest PH value (86%) is obtained with formulation T4, followed by T1 and T3. The lowest PH is obtained by T5 and T2. It appears that TMPTA is possibly responsible for inducing such hardness to the polymer surface.

Gel Content

The extent of crosslinking among monomers and between oligomer and monomers is reflected by the gel content of the polymer film. With an increase of UV radiation, the gel content increases within the polymer film (Fig. 2). The maximum gel content is achieved at different radiation doses depending on the nature of the formulations. Most of the films, such as T1, T2, and T3, possess maximum gel at the 10th pass under the UV lamp, while formulation T4 yields the maximum gel at the 6th pass. The gel content varies between 95.5 and 98.5%. This is a sign of a very good crosslinking phenomena among the various constituents present in different formulations. Pendulum hardness is the highest for film T4 (Fig. 1), while gel content is the highest for T1 (Fig. 2). Although both hardness and gel are represented by the crosslinking density, hardness is reflected by the crosslinking density at the surface of the cured film; while the gel is represented by the crosslinking density of the entire film.

Tensile Properties

Tensile strengths (TS) of polymer films of different formulations are different because of different constituents present in the formulations at different proportions. This can be seen in Figure 3, where TS values of the different films are plotted against number of passes. The highest TS value

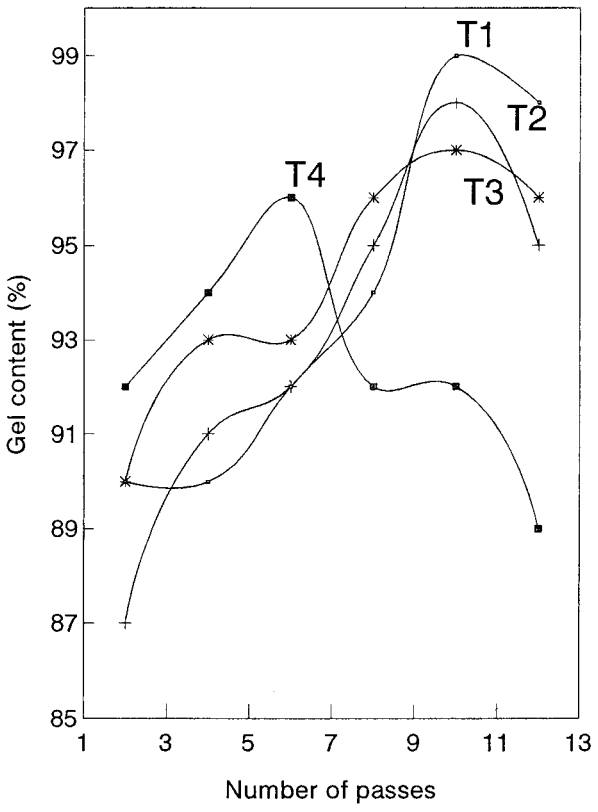

Figure 2 Gel content of UV-cured films against the number of passes.

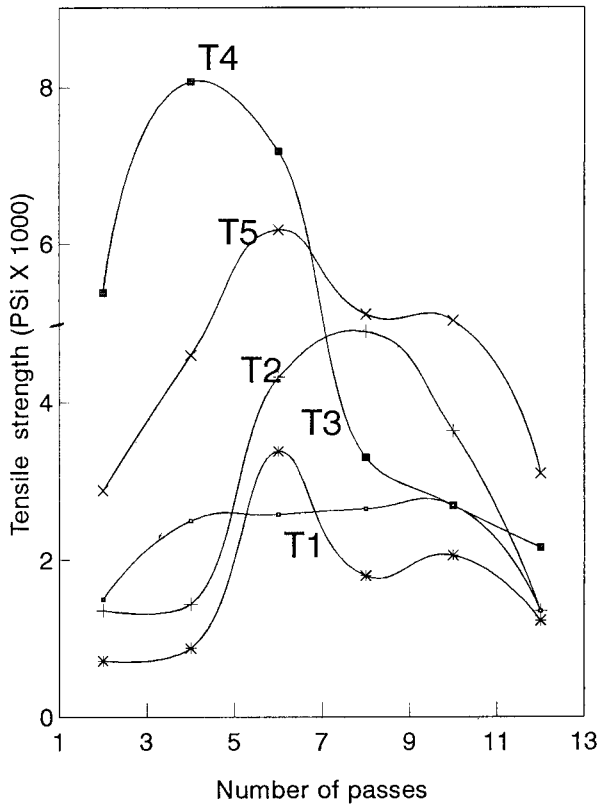

Figure 3 Tensile strength of UV-cured films against the number of passes.

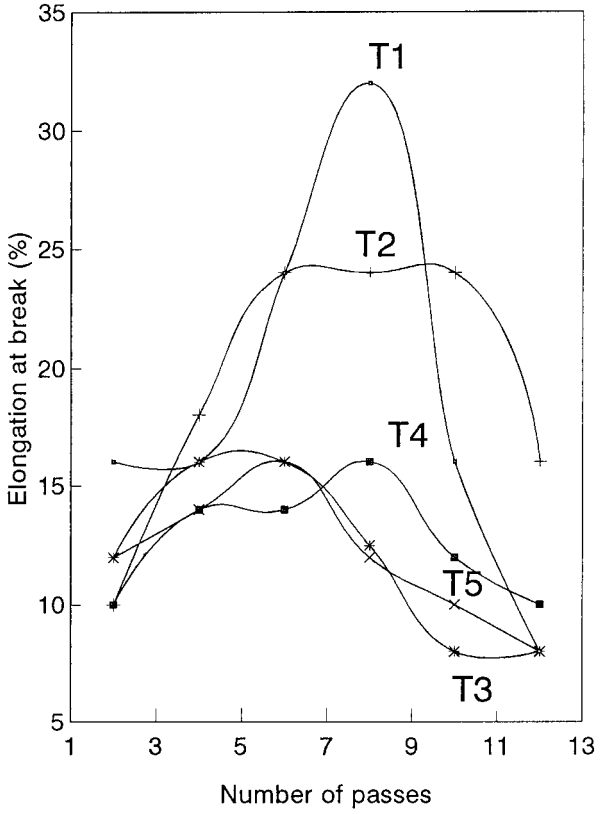

Figure 4 Elongation at break of UV-cured films against the number of passes.

is achieved by T4 at the 4th pass. The presence of 3% $CaCO_3$ in T5 has reduced the tensile strength (Fig. 3) and hardness (Fig. 1). The lowest tensile strength is yielded by the formulation T1 in which both NVP and TMPTA are at equal proportions 24 : 24 w/w). It appears that TMPTA is playing a better role in inducing higher tensile strength to the film than the NVP, because TMPTA is a trifunctional monomer. NVP has been known to be a better augmenting agent in other systems, like wood plastic composite[7] and jute plastic composite.[8] Different films have required different UV doses to attain the highest tensile strength; for example, T3 and T5 films have given the highest TS values at the 6th pass, while that for T2 is at the 8th pass and that for T4 is at the 4th pass. There may be many reasons that the tensile strengths have decreased with increase of UV dose after attainment of the TS maxima. One of the reasons could be the degradation of polymer at higher radiation. Stretchibility, i.e., elongation ability, of the film is a property that is very important during the selection of the polymer in diverse applications. This again depends on the physical character of the ingredient used in the formulation. Elongation at break (Eb) measured for the different polymer films is shown in Figure 4, where Eb is plotted against number of passes.

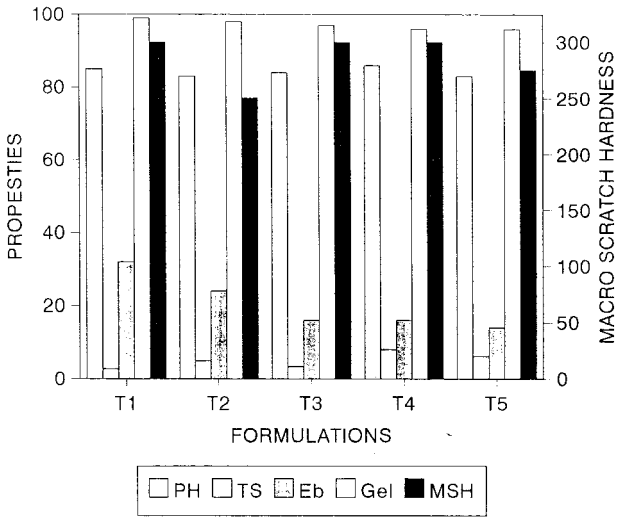

Figure 5 Various physical properties of UV-cured films against the number of passes (only macroscratch hardness is represented by the Y_2 axis).

Table II Various Physical Properties of UV-Cured Coating on Wood Surfaces

Properties	No. of Passes	Base Coat T2			Base Coat T5		
		T1	T3	T4	T1	T3	T4
Hardness macroscratch (g)	2	260	225	250	250	275	250
	4	280	225	250	250	250	275
	6	280	250	250	275	275	275
	8	300	250	275	275	300	300
	10	300	250	275	275	300	300
	12	300	250	275	275	275	300
Hardness (indent) length (mm)	2	0.73	0.90	0.80	0.90	1.00	0.80
	1	0.66	0.80	0.80	0.85	0.90	0.80
	6	0.53	0.80	0.80	0.80	0.80	0.70
	8	0.53	0.73	0.70	0.70	0.66	0.70
	10	0.60	0.78	0.60	0.70	0.66	0.66
	12	0.53	0.78	0.60	0.70	0.66	0.66
Indent depth (μm)	2	< 5	7	5	7	8	5
	4	< 5	5	5	7	7	5
	6	< 5	5	5	5	5	< 5
	8	< 5	< 5	< 5	< 5	< 5	< 5
	10	> 5	< 5	< 5	< 5	< 5	< 5
	12	< 5	< 5	< 5	< 5	< 5	< 5
Indent Buchholz resistance	2	> 125	111	125	111	110	125
	4	> 125	125	125	111	111	125
	6	> 125	125	125	125	125	> 125
	8	> 125	> 125	> 125	> 125	> 125	> 125
	10	> 125	> 125	> 125	> 125	> 125	> 125
	12	> 125	> 125	> 125	> 125	> 125	> 125
Adhesion (% chipped off area)	2	0	4	4	4	6	4
	4	0	4	4	4	4	4
	6	0	4	4	4	4	0
	8	0	0	2	0	0	0
	10	0	0	0	0	0	0
	12	0	0	0	0	0	0
Adhesion (N/mm^2)	2	0.75	0.75	0.75	0.75	0.55	0.75
	4	0.75	0.75	0.75	0.75	0.75	0.75
	6	1.00	0.75	0.95	0.75	0.75	1.00
	8	1.00	0.85	0.95	0.95	0.88	1.25
	10	1.00	0.85	0.95	0.95	0.88	1.25
	12	1.00	0.95	0.95	0.95	0.88	1.00
Taber index (abrasion test)	6	700	786	800	900	882	742

Although T4 renders the highest TS value, it has the lowest elongation among the series. The highest Eb is obtained by T1, followed by T2, which contains 4% $CaCO_3$. The maximum Eb is obtained at the 8th pass, except for T3 and T5, which yield maximum Eb values at the 6th pass. The attainment of 32% elongation by T1 is good, but its TS value is quite low compared to that of T4.

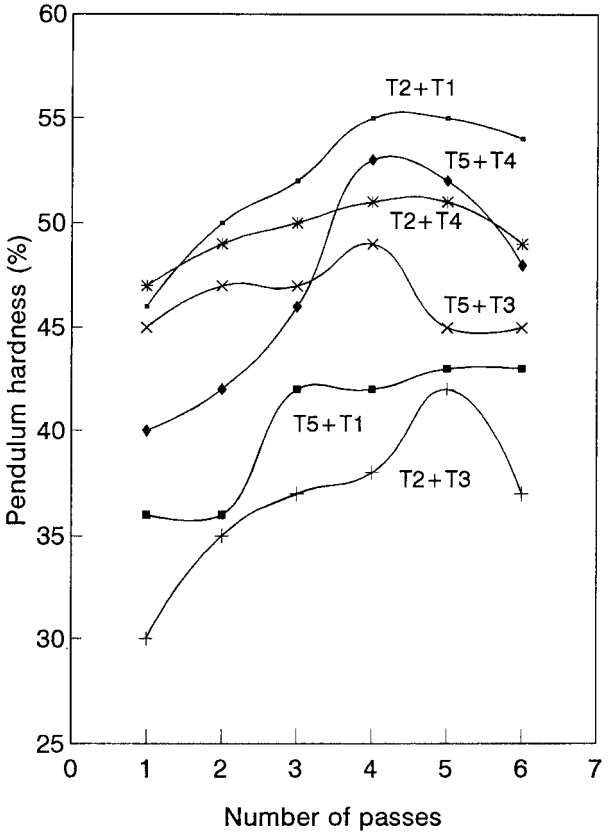

Figure 6 Pendulum hardness of UV-cured surface coating on wood surface against the number of passes.

A macroscratch hardness (MSH) test of the cured film was performed while the film was still on the glass plate. Results are shown in Figure 5, where MSH is plotted in Y_2 axis against formulation (X axis). Results of other physical parameters, such as pendulum hardness (PH), tensile strength (TS), elongation at break (Eb), and gel content are also shown in the Figure 5 for the sake of comparison; the highest values of the corresponding parameters are plotted in Figure 5 to have a comparative look at a glance of different properties of the different formulations (T1–T5).

Application on Wood Surface

On having characterized the UV-cured polymer films, the different formulations were applied on polished wood surface. Two of these formulations, namely T2 and T5, were arbitrarily chosen as base coats. The base coats were partially cured on wood surface with UV radiation, and then the substrates were polished with sandpaper before final coating with other formulations. The final coatings were cured on the wood surface with different number of passes under UV lamp. Various physical parameters, particularly macroscratch hardness, indent length and depth, Buchhloz resistance, film adhesion strength, and chipped off area, were determined as a function of number of passes. The results are shown in Table II.

Hardness Test

Macroscratch hardness of the coatings is measured in terms of load (weight) in gm required to manifest a scratch on the surface of the coatings. More weight is needed if the coating puts resistance to scratch due to its better physical properties. Thus, the more the index of macroscratch hardness, the better the coating. Coatings T1 and T4 appear to possess higher MSH indices. In fact, T1 is the best film to yield the highest MSH. The MSH test carried out for the coatings was found to be out of range for all samples, indicating that better coatings were formed with these formulations. The indent length is the width of the scratch. If the indent length is small, it indicates

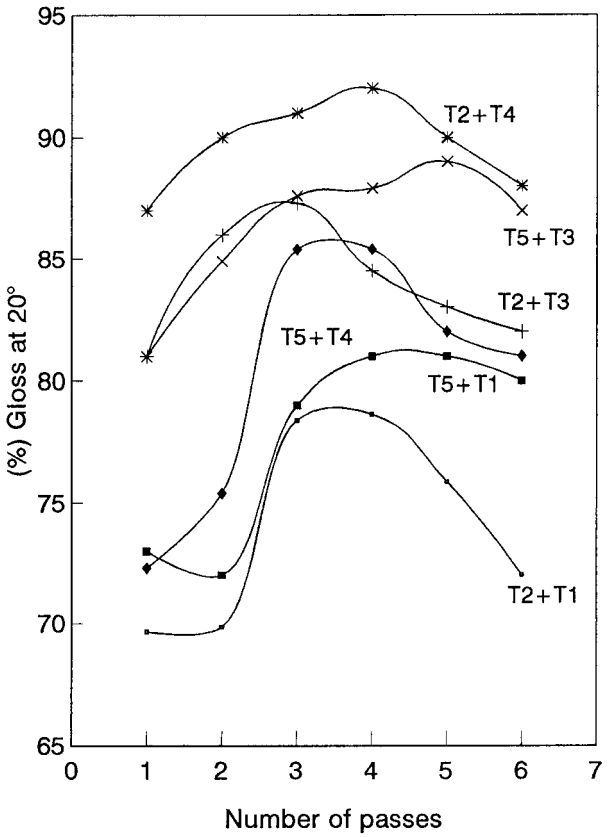

Figure 7 Gloss properties of UV-cured surface coating at a 20° angle against the number of passes.

that there is better cohesion among the polymer matrix. In this respect, formulation T1 induces the smallest indent length on the coating. This certifies further that the T1 film is the best with the base coat T2. Similarly, indent depth is the depth of scratch. The less the depth, the better the film, because the film resists scratching on its surface because of better physical properties. Again, T1 film gives the least depth (less than 5).

Adhesion Test

Adhesion of the UV-cured coating on the wood surface was measured through the crosscut method, and it is observed from Table II that the coating of formulation T1 with base coat T2 has good adhesion and that there is no chipping off area during the crosscut technique. This is also consistent with adhesion strength measured to pull the coated film off the substrate. More strength is required if the adhesion is stronger. This is reflected in the Table II, where the coating of T1 with base coat T2 requires the highest strength to take off the coating. Thus, film of T1 + T2 appears to be the best among all of them.

Abrasion Test

The Taber abrasion test was carried out with the substrates that were cured with six passes of UV radiation. The lowest Taber index indicates the highest abrasion resistance. Results of Taber index (Table II) indicates that the formulation T1 with base coat T2 yields the best surface-coated product. Similarly, formulation T4 with base coat T5 produced the lowest abrasion index in the respective group, indicating maximum resistance towards abrasion wear.

Pendulum Hardness

Surface hardness of the film coating measured by pendulum technique is plotted against number of passes in Figure 6. The coating of T1 with base coat T2 has yielded the highest PH. This is consistent with the results mentioned in Table II. The lowest PH values are given by T3 with base coat T2. Pendulum hardness increases with an increase in UV doses, represented by the number of passes. This reflects that there is increase of crosslinking density in the polymer with an increase in the UV dose. However, the maximum PH values of the surface coating are attained mostly at the 4th pass. This is unlike the case of the PH of a polymer film of the same formulations.

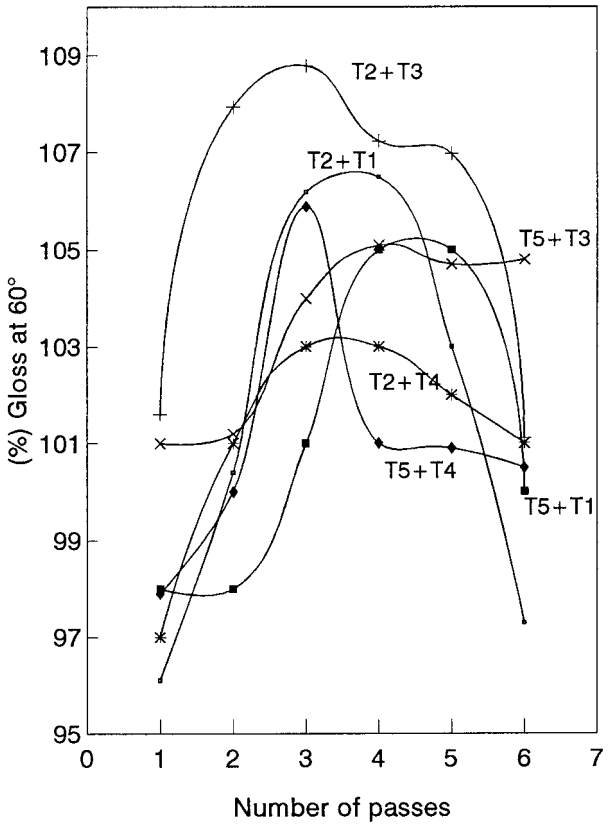

Figure 8 Gloss properties of UV-cured surface coating at a 60° angle against the number of passes.

The maximum PH values of the polymer films were mostly obtained at the 6th and 8th passes (Fig. 1). Formulation T1 contains the second highest amount of TMPTA compared to other formulations. It also does not contain any filler. TMPTA is known to be a very good crosslinking agent[5] because of its branch-like structure with the three acrylated functional groups. Thus, T1 renders the highest hardness to the film coating.

Film Gloss

Film gloss measured at 20° and 60° angles on the coating is shown in Figure 7 (20°) and Figure 8 (60°). The lowest gloss at the 20° angle is observed by the film of T1 with base coat T2, and the highest gloss at 20° is given by T4 with base coat T2. It is different when the gloss is measured of the same coating at 60° angle. This is shown in Figure 8. Gloss is also related to the extent of curing of the film. Thus, the gloss increases with an increase in crosslinking density, i.e., an increase in UV dose. Though the film T4 shows the highest gloss at 20°, the film T3 gives the highest gloss when looked at 60° angle.

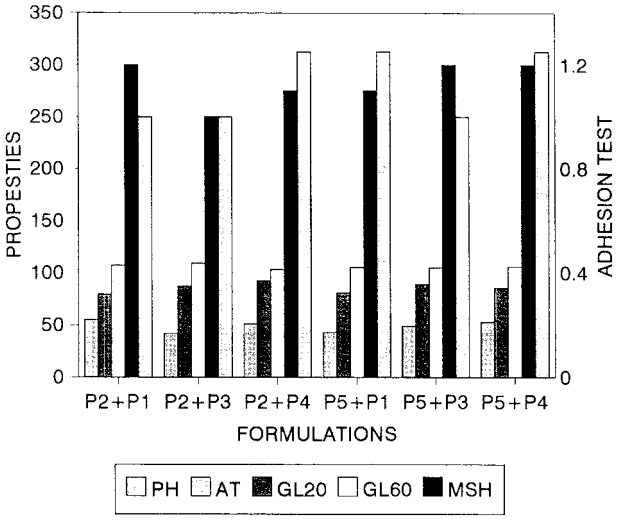

Figure 9 Various physical properties of UV-cured surface coating against the number of passes; only adhesion test (AT) is represented by the Y_2 axis.

All these above characteristic parameters can be summarized and represented in Figure 9, where the highest values are plotted against the corresponding film. This makes a comparative look at a glance for each parameter possible. Only the adhesion test is plotted by the Y_2 axis.

CONCLUSION

UV-cured polymer films and wood surface coating were obtained with different formulations made with urethane acrylate, NVP, and TMPTA at different proportions, containing some fillers. Characterization of these films and coatings reveals that the polymer films with T4 formulation attain the highest PH and TS, but the same formulation (T4) does not induce and/or produce the highest physical and mechanical properties to the wood coatings. Instead, the formulation T1 yields the best wood coating. It induces the best physical characters to the coatings. This formulation (T1) also does not contain any filler. Simul is a very soft wood, and the formulation T1 with base coat T2 appears to be the best formulation amongst all the formulations investigated. Thus, simul can be used as a substitute, in some cases, to high-density quality wood.

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