High Performance Energy-Curable Coatings

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Regulatory needs are consistently being refined in an effort to address regional and global environmental concerns resulting in the limitation or elimination of certain catalysts, metals, inhibitors, and solvents for raw materials and formulations. Consumers, original equipment manufacturers, and aftermarket suppliers are not lowering performance criteria to help ease the introduction of more eco-friendly approaches. To meet new regulatory and performance standards, we have developed a novel waterborne technology that meets high scratch and abrasion resistance standards established by highly functional energy-curable coatings typically diluted in solvents. In addition, a more eco-friendly urethane synthesis process that eliminates the use of tin catalyst and limits (methyl) hydroquinone inhibitor has been developed. Incorporating these more eco-friendly synthesis approaches with new product design has resulted in highly functional aliphatic urethanes that offer outstanding scratch and abrasion resistance for low curl and low-film-build hardcoat applications.

INTRODUCTION

Energy curing of acrylated resins is a well-established coating technology that has been gaining further market acceptance because it is a more environmentally friendly chemistry and offers outstanding protection for decorative surfaces in many applications such as flooring, consumer electronics, and forward lighting. For the most part, energy-curable resins are considered to be nonhazardous. Most hazards are introduced through solvents, which typically represent volatile organic compounds (VOC) and photoinitiators that begin the polymerization process. Section I of this article presents two urethane acrylates that employ a more eco-friendly urethane synthesis process that addresses regulatory concerns regarding tin catalysts, heavy metals, and (methyl) hydroquinone. Section II presents two waterborne urethane acrylates based on a patent-pending emulsification procedure. The data shown demonstrates that being more eco-friendly does not necessarily mean compromised performance, since these products are comparable to current state-of-the-art commercial products.

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SECTION I

EXPERIMENTAL

In this section, EXP8602 and EXP8415 are compared to a current state-of-the-art hexafunctional urethane acrylate ALUA-HC that is used in applications requiring outstanding scratch and abrasion resistance properties. EXP8602 and EXP8415 are aliphatic urethane acrylate oligomers with a (theoretical) double bond functionality of 9 and 10, respectively. They were synthesized using a tin-free catalyst process. Quinones were not intentionally added; however, they are present in many raw materials. So, the overall quinone content is reduced, but it is not zero. A variety of tests will allow the benchmarking of ALUA-HC with EXP8602 and EXP8415. The formulations in these tests also make use of a lower functional aliphatic urethane ALUA-FLEX, which was used to flexibilize resins to help control cracking or curl upon cure. The characteristics of all four oligomers are summarized in *Table* 1.

Other compounds used in the formulations were:

- Diluting acrylates
    - ◊ 1,6-Hexanediol diacrylate (HDDA) with a viscosity of 10 cP at 25°C
    - ◊ Trimethylolpropane triacrylate (TMPTA) with a viscosity of 115 cP at 25°C
- 1-Hydroxycyclohexylphenylketone (HCPK), a solid, Type I photoinitiator
- Solvents
    - ◊ Commercial grade of methyl ethyl ketone (MEK)
    - ◊ Commercial grade of 1-methoxy-2-propanol

FORMULATIONS

To develop a baseline and achieve a uniform thickness, the oligomers were formulated with MEK and HCPK photoinitiator in the following proportions: oligomer/MEK/HCPK (60/40/3).

For determining other coating properties, the generic formulation shown in *Table* 2 was used.

For low coat weight and low energy-curing evaluations, 30% 1-methoxy-2-propanol was added to each formulation to ease flow and leveling with a barcoater application and maintain consistent film build.

SUBSTRATES

The following commercial substrates were considered and used as received: 175 and 250 µm thick polycarbonate (PC) sheets, and 3 mm x 100 mm x 200 mm poly(methyl methacrylate) (PMMA) panels.

APPLICATION CONDITIONS

All coatings tested and reported on in Section I were applied with a barcoater, giving a coat weight of approximately 10 g/m^2 dry, unless stated otherwise. Typical flash-off conditions for evaporating solvent (when present in the formulation) were 5 min at 80°C in a ventilated oven. UV curing was carried out with one or multiple pass(es) at 10 m/min belt speed under air, using a 120 W/cm Hg lamp, with 30 cm distance between the belt and lamp bulb. This corresponds to a total UV dose (UVA, UVB, UVC, and UVV) of 1.1 J/cm^2 per pass. Alternative curing conditions involved one or two passes at 50 m/min belt speed under air, using the same 120 W/cm Hg lamp, and giving an energy density of 210 mJ/cm^2 per pass.

TEST METHODS

Abrasion resistance was evaluated by using the Taber haze test method where a 250 µm PC sheet bearing a coating was subjected to 100 and 300 cycles (the same run with intermediate stop and dusting) of abrasion with CS10F wheels (23°C, 50% relative humidity) and the resulting haze (%) is measured (ASTM D1044). Results are reported as average ± standard deviation, calculated from two coated disks (10 cm diameter), four measurements per disk.

Table 1—Aliphatic Urethane Acrylate Oligomer Characteristics

	ALUA-HC	ALUA-FLEX	EXP8602	EXP8415
Solids (%)	100	100	100	100
Appearance	Clear liquid	Clear liquid	Clear liquid	Clear liquid
Color	100 APHA	2 Gardner	100 APHA	1 Gardner
Viscosity at 60°C (mPa.s)	2000	3000	3000	1700
Double bond functionality (theoretical)	6	2	9	10
End use	Hardcoat oligomer	Flexibilizer	Hardcoat oligomer	Hardcoat oligomer

Table 2—Generic Formulation for Coating Evaluation

Ingredient	Parts
Oligomer	60
ALUA-FLEX	10
TMPTA	16
HDDA	10
HCPK	4

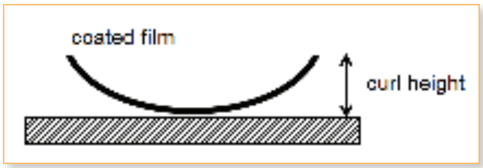

Figure 1—Curl height–flexibility determination.

Adhesion was evaluated using the crosshatch tape adhesion test (DIN EN ISO 2409).

Flexibility was evaluated using the cylindrical mandrel test method as described in the BS EN 435:1994 standard. The test reports the smallest mandrel diameter around which the coated substrate can be bent without generating cracks (the larger the mandrel diameter, the lower the flexibility of the coating).

Scratch resistance was evaluated by abrading the coated surface with a specified number of double rubs (DR) of a grade 00 steel wool under a 1 kg pressure. Coating performance was assessed visually by making use of a scale ranging from 1 (meaning severe damage on the surface) up to 5, (meaning no visible damage).

For curl determination, the UV-oligomer formulation was applied on a 250 µm thick PC sheet and flashed for 5 min at 80 °C, targeting coat weight of 10 g/m² dry. UV curing was carried out with two passes at 19 m/min with an 80 W/cm medium pressure Hg lamp, giving a total energy density of 800 mJ/cm². The coated sheet was conditioned for one hour at room temperature and two squares (10 cm x 10 cm each) were cut out of it. The curl height (see *Figure* 1) was measured from the eight corners that are averaged.

Solvent resistance was evaluated by submitting the coated surface to 100 DR of a cellulose bud soaked with acetone (100 ADR = 100 acetone double rubs). If the coated surface was intact at the end of the test, this indicated that the material had been cured sufficiently to resist solvent attack.

Table 3—Curl Values

Oligomer	Curl Height (mm)
ALUA-HC	4.1 ± 1.2
EXP8602	4.8 ± 0.5
EXP8415	7.9 ± 0.8

Table 4—Mandrel Flexibility Values (mm)

	10 g/m² Dry Coat Weight	20 g/m² Dry Coat Weight
ALUA-HC	20	35
EXP8602	20	30
EXP8415	30	100

RESULTS AND DISCUSSION

This section details the evaluation of the coating properties of the new high functional resins, namely shrinkage, flexibility, and abrasion resistance. Applications at low coat weight and under lower curing-energy condition are also investigated.

Shrinkage

Nearly all chemically crosslinked systems undergo some form of free volume loss or shrinkage during cure, leading to various effects on the substrate. With flexible or malleable substrates, deformation or curling may occur. Often these phenomena can be overcome by using lower functional oligomers or diluents such as ALUA-FLEX.

The experimental curl test in this article does not measure volumetric contraction of the resins, but rather the curl of a coated film after curing. This is an empirical test dependent on several parameters such as substrate thickness, coat weight, and curing energy density. This test method provides an estimation of behavior under certain curing conditions. *Table* 3 summarizes the results.

EXP8602 does not follow the traditional logic of higher curl with higher functionality, especially since its volumetric shrinkage is 40% greater than ALUA-HC (data not shown, ~12% vs 9%). It can be deduced that the structure of EXP8602 limits rotation and/or bending of chains during network formation. EXP8415 adheres to logic demonstrating a 90% increase in curl when compared with the lower functional ALUA HC. This suggests that its preferred use could be for rigid substrates (flexible substrates could curl), provided adhesion is confirmed.

Flexibility

Table 4 summarizes the mandrel flexibility at coat weights of 10 and 20 g/m² dry.

As can be seen, EXP8602 shows flexibility equal to that of the benchmark ALUA-HC. This should validate its use for both rigid and flexible substrates (for which oligomers like ALUA-HC are used). Comparatively, EXP8415 displays a much lower flexibility, most likely due to the higher crosslinking density originating from its high functionality. This makes the coating stiffer and hence more prone to cracking upon bending. As already indicated by the shrinkage evaluation, this could make EXP8415 more suitable for rigid substrates. As expected, an increase in coat weight leads to a decrease in flexibility for all oligomers.

Abrasion Resistance

Abrasion will occur whenever the coated article undergoes mechanical wear from the environment. The ability of protective coatings to resist this degradation is one of their essential features. The various oligomers were formulated as per *Table* 2, applied at 10 g/m^2 dry on 175 µ PC sheet, and cured with 1.1 J/cm^2 of energy. *Table* 5 summarizes the Taber haze results.

Initial haze values before the test were all less than 0.1%, meaning the various coatings had no impact on the transparency of the PC sheet. After abrasion, uncoated PC showed severe abrasion with a Δhaze close to 17% (at 100 cycles), while the various hardcoated PC show limited abrasion with a Δhaze lower than 3.5% (at 100 cycles). When comparing the various coatings, it follows that EXP8602 and EXP8415 provide higher abrasion resistance (lower Δhaze) than ALUA-HC. The differences are moderate, but both statistically and practically significant, especially for those applications where demanding requirements need to be met (for example, hardcoats for structural plastic panels, polycarbonate glazing, or PC glazing). In that respect, EXP8415 provides the lowest haze development at 300 cycles.

Table 5—Taber Haze CS10F Results

System	Initial Haze (%)	ΔHaze[a] (%) after 100 Cycles	ΔHaze[a] (%) after 300 Cycles
Uncoated PC	0.08	16.6 ± 0.2	16.8 ± 0.5
ALUA-HC formulation	0.05	3.3 ± 0.2	5.5 ± 0.2
EXP8602 formulation	0.08	2.6 ± 0.2	4.0 ± 0.3
EXP8415 formulation	0.04	2.8 ± 0.3	3.7 ± 0.4

(a) Average ± standard deviation.

Low Coat Weight Applications

Applying at or below 5 g/m^2 dry coat weight can make economic sense in terms of lower coating cost (provided the coating properties are met), but the conversion of UV coatings at these low coat weights can be impeded by oxygen inhibition. Although this can be solved by using amine synergists (possibly acrylated) combined with benzophenone as photoinitiator, this might have a negative impact on coating properties, such as color upon cure, hardness, or yellowing. Thus, the ability of the new high functionality resins to overcome oxygen inhibition was investigated.

To achieve a consistent low-film-build, each formulation (based on *Table* 2) was diluted with about 30% 1-methoxy-2-propanol, applied on PMMA panels and flashed for 5 min at 80°C. Dry coat weight was between 3 and 5 g/m^2 and UV curing proceeded with 1.1 J/cm^2. *Table* 6 summarizes the basic coating properties (solvent resistance, adhesion, scratch resistance).

Table 6—Coating Properties of Low Coat Weight Applications

System	Solvent Resistance (100 ADR)	Cross-Hatch Tape Adhesion	Visual Inspection (Microscope) after 10 DR of Steel Wool
Uncoated PMMA panel	OK	—	Severe damage
ALUA-HC formulation	OK	100%	Many scratches
EXP8602 formulation	OK	100%	Some scratches
EXP8415 formulation	OK	100%	Very few scratches

Results showed that all coatings displayed full solvent resistance and adhesion. After scratching the various coated surfaces with 10 double rubs of steel wool, some differentiation appeared, especially when the coated panels were examined with a magnifying glass. The formulations based on the EXP8415 displayed significantly fewer scratches when compared with the standard 6f ALUA-HC (uncoated PMMA in these conditions was severely damaged). This differentiation is illustrated in the various pictures taken through the eye piece of the magnifying glass, shown in *Figure* 2. This improvement in scratch resistance could prove especially beneficial for hardcoated optical displays.

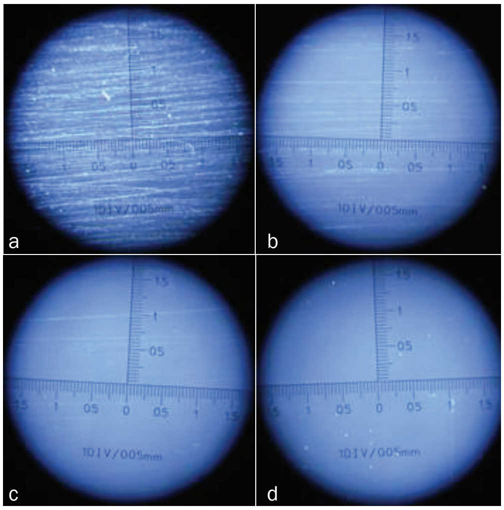

Figure 2—Photographs of coated PMMA after 10 DR of steel wool wear, one graduation on the scale bar is 50 µ; the full field of view is around 3.5 mm. (a) Uncoated PMMA panel: severe damage; (b) 6f ALUA-HC formulation on PMMA panel: many scratches; (c) 9f EXP8602 formulation on PMMA panel: some scratches; and (d) 10f EXP8415 formulation on PMMA panel: very few scratches.

Low Curing Energy Applications

Protective UV coatings are generally cured with energies from 600 mJ/cm^2 up to 2,000 mJ/cm^2. UV curing with lower energy levels can be attractive for economic reasons as well as for substrates which are heat sensitive. Obtaining full cure with low curing energy is a challenge. Increasing the photoinitiator content will not necessarily help and

Table 7—Coating Properties of Low Curing Energy Applications, 12 to 14 g/m^2 Dry Coat Weight

System	Curing Energy (mJ/cm^2)	Solvent Resistance (100 ADR)	Cross-Hatch Tape Adhesion (%)	Scratch Resistance (10 DR Steel Wool)
ALUA-HC formulation	210	OK	100	2
	420	OK	100	2.5 to 3
EXP8602 formulation	210	OK	100	3 to 3.5
	420	OK	100	4
EXP8415 formulation	210	OK	100	5
	420	OK	100	5

Table 8—Coating Properties of Low Curing Energy Applications, 3 to 5 g/m^2 Dry Coat Weight

System	Curing Energy (mJ/cm^2)	Solvent Resistance (100 ADR)	Cross-Hatch Tape Adhesion	Scratch Resistance (10 DR Steel Wool)
ALUA-HC formulation	210	Slight surface attack	100	1
	420	OK	100	2
EXP8602 formulation	210	OK	100	2
	420	OK	100	4
EXP8415 formulation	210	OK	100	3
	420	OK	100	5

might even have a detrimental effect on coating properties such as loss of adhesion or lower double bond conversion. Higher functional oligomers such as EXP8602 and EXP8415 may aid in applications requiring lower energy output for curing.

The various oligomers were formulated as indicated in *Table* 2, diluted with about 30% 1-methoxy-2-propanol, applied on PMMA panels, and flashed for 5 min at 80°C. Dry coat weight was either 12 to 14 g/m^2 or 3 to 5 g/m^2, and UV curing proceeded with one or two passes of 210 mJ/cm^2 each.

Table 7 summarizes the basic coating properties of the 12 to 14 g/m^2 applications and shows that all systems exhibit full solvent resistance (100 ADR) and adhesion on the substrate. The scratch resistance correlates with the increasing functionality: EXP8415 is the best (maximum score of 5, no scratch visible), EXP8602 is second best (3.5 to 4, depending on the energy) and ALUA-HC scores lowest (2 to 3).

As summarized in *Table* 8, decreasing the coat weight to around 3 to 5 g/m^2 further highlights the differentiation between oligomers. With 210 mJ/cm^2, ALUA-HC shows loss of solvent resistance and poor scratch resistance (score of 1), while the higher functional oligomers show low to fair scratch resistance (scores of 2 to 3) with full solvent resistance. Increasing the curing energy to 420 mJ/cm^2 (two passes at 210 mJ/cm^2) is enough to restore full scratch resistance (score of 5) with EXP8415. Comparatively, EXP8602 performance is close (score of 4) while that of 6f ALUA-HC remains low (score of 2). The overall lower scratch resistance at 210 mJ/cm^2 is attributed to oxygen inhibition of cure at the surface of the coating.

Table 9—WB UV Formulations

Ingredient	WBUV-7200 Formulation	Reference UVPUD Formulation
WBUV-7200	100	
UVPUD1 topcoat		100
Photoinitiator	2.8	1.5
FLW1 (anticratering and flow agent)	0.5	
FLW2 (flow and wetting agent)		0.4
Thickener/water 50/50 pre-mix		1.5

Table 10—Reference SB UV Formulation

Ingredient	Parts
ALUA1[a]	60
1-Methoxy-2-propanol (solvent)	40
Photoinitiator	2.8
FLW3 (flow and wetting agent)	0.25

(a) market reference for UV hardcoat applications

SECTION II

NEW WB UV RESINS

The novel products, WBUV-7200 and EXP-1800, were prepared using a patented emulsification process that is described elsewhere (Tielemans, 2013). Both emulsions are white liquids with a density of 1.1 g/cm³, a maximum viscosity of 700 mPa.s at 25°C, a solids content of 65%, a particle size of approximately 500 nm, a pH ranging between 3 and 5, and a stability of 10 days at 60°C. The theoretical backbone functionality (acrylate double bonds per molecule) of the hardcoat WBUV-7200 is six, and the flexibilizer EXP-1800 is three.

FORMULATIONS

ALUA1 = commercial grade of hexafunctional aliphatic urethane acrylate for hardcoat applications, 100% solids, 2000 mPa.s viscosity at 60°C. This ALUA1 is the aliphatic urethane that is considered state-of-the-art in the UV-curable hardcoat market.

UVPUD1 = commercial grade of UV polyurethane dispersion (UVPUD) for hardcoat applications, 35% solids in water, particle size 100 nm max., pH 7 to 8.5; viscosity is less than 200 mPa.s (25°C).

UVPUD2 = commercial grade of UV polyurethane dispersion (UVPUD) for flexible and durable (outdoor) topcoat applications, 35% solids in water, particle size 100 nm max., pH 7 to 8.5; viscosity is less than 200 mPa.s (25°C).

Additives

The following products were used in the formulations detailed in this section; all are commercial grades:

- DG1—silicone-free de-aerator for waterborne systems, 100% active substance.
- FLW1—siloxane-based surfactant, 100% active matter content.
- FLW2—modified acrylic copolymer, 55% active substance in solution in water.
- Thickener—polyether polyurethane thickener in deionized water and butyl diglycol, 30% active substance.
- FLW3—acrylic flow modifier, 100% active substance.
- FLW4 (flow and wetting agent)—neutralized acrylic copolymer, 50% active substance in 1-methoxy-2-propanol and butanol.
- FLW5 (flow and wetting agent)—polyether siloxane copolymer, 100% active matter.
- FLW6 (flow and wetting agent)—polyether siloxane copolymer, 100% active matter.
- Photoinitiator—50/50 liquid mix of 1-hydroxycyclohexyl-phenyl-ketone + benzophenone.

Substrates

The following substrates were considered and used as received unless stated otherwise: paper-based opacity charts or a 250 µm thick polycarbonate (PC) sheet.

Application Conditions

Unless otherwise indicated, all coatings tested in Section II were applied using a barcoater, giving a dry coat weight of approximately 10 g/m² dry on the substrates mentioned above. Typical flash-off conditions for evaporating the solvent or water were 5 min at 50°C in a ventilated oven. UV curing was carried out with one or multiple pass(es) at 10 m/min belt speed under air, using a 120 W/cm Hg lamp, with 30 cm distance between belt and lamp bulb. This corresponds to a total UV dose (UVA, UVB, UVC, and UVV) of 1.175 J/cm² per pass.

Test Methods

Adhesion was evaluated using the crosshatch tape adhesion test (DIN EN ISO 2409).

Scratch resistance was evaluated by abrading the coated surface with a specified number of double rubs of a grade 00 steel wool under 1 kg pressure. Coating performance was assessed visually by making use of a scale ranging from 1 (severe damage on the surface) up to 5 (no visible damage).

Abrasion resistance was evaluated by using the Taber haze test method where a coated 250 µm PC sheet was submitted to 100 cycles of abrasion with CS10F wheels under a 500 g load and the resulting haze (%) was measured (ASTM D 1044). The lower haze development after abrasion meant a better performance.

Stain resistance was evaluated on coated (10 g/m² dry) opacity charts following a standard protocol where, after 16 hours' exposure time under a glass slide, the staining substance was removed from the coated surface using water and detergent and the state of the surface was evaluated using a 1 to 5 scale (similar to scratch resistance). For shoe polish and permanent black marker stains, exposure times were 1 hr and 5 min, respectively, and the cleaning agent was isopropyl alcohol.

Hardness was evaluated either by the Persoz method (pendulum hardness, DIN EN ISO 1522) or by the pencil hardness method (ASTM D3363).

Flexibility was evaluated using the cylindrical mandrel test method, as described in the BS EN 435:1994 standard. The test reports the smallest mandrel diameter around which the coated substrate can be bent without generating cracks. The smaller the mandrel, the more flexible the coating has to be due to increased stress required for a rigid coating to bend.

RESULTS AND DISCUSSION

Benchmarking of WBUV-7200 with SB UV and UVPUD Coating Technologies

The coating performance of WBUV-7200 was compared to established technologies for protective UV coatings, namely UVPUD and SB UV formulations. *Tables* 9 and 10 detail the formulations that were considered for that purpose.

All coatings were applied using a barcoater, at 10 g/m² dry on a 250 µm PC sheet and opacity chart, and 30 g/m² dry on cleaned glass. The flash-off step was 5 min at 50°C; UV curing consisted of two passes at 10 m/min under a 120 W/cm Hg lamp. *Table* 11 summarizes the main coating properties of all systems: hardness (pencil, Persoz), scratch resistance, and gloss. The data shows that the new WBUV-7200 emulsion equals or outperforms the UVPUD or SB UV coatings for all properties. The same conclusion can be drawn from the stain resistance results presented in *Table* 12.

WBUV-7200 as Property Enhancer for UVPUDs

WBUV-7200 was further evaluated as a co-resin for improving the abrasion resistance of UV polyurethane dispersions. For that purpose, two UVPUDs were considered: UVPUD1 (hardcoat) and UVPUD2 (flexible topcoat). The generic formulation for these mixtures is detailed in *Table* 13. Prior to mixing, the WBUV-7200 emulsion pH is brought to neutrality by addition of triethylamine, in order to avoid destabilization resulting from low pH.

It is to be noted that adding WBUV-7200 to both UVPUDs will increase the solids content from 35 to 45% solids without compromising stability. Formulations were applied at 10 g/m² dry on a 250 µm PC sheet, flashed-off for 5 min at 50°C and UV-cured with two passes at 10 m/min under a 120 W/cm Hg lamp. The abrasion resistance of both UVPUDs and their mixtures with WBUV-7200 was evaluated by the Taber haze test. Results, given in *Figure* 3, show that the incorporation of 30 parts WBUV-7200 to 70 parts of UVPUD decreases the haze from 14% to 6.4% for the UVPUD1 hardcoat and from 28.5% to 11.5% for the UVPUD2 flexible topcoat. In other words, the addition of WBUV-7200 increases abrasion resistance.

Adjusting the Flexibility of WBUV-7200

Some applications require a hardcoat with some degree of flexibility. Therefore, WBUV-7200 was blended with increasing amounts of EXP-1800, an emulsified UV flexibilizing resin; and hardness, scratch, and stain resistance were evaluated.

The following formulation additives were added to 100 parts of the blends: 5 parts deionized water,

Table 11—Coating Properties

Properties	WBUV-7200	Reference UVPUD	Reference SB UV
Pencil hardness (on glass)	8H	5H	8H
Steel wool scratch resistance[a] (10 µm dry on 250 µm PC sheet)			
10 DR	5	3 to 4	5
100 DR	3 to 4	2	3 to 4
Persoz hardness (s) on glass	342	356	361
Gloss (60°) on opacity chart	≈ 95	≈ 95	≈ 95

(a) Evaluation: 1 = severe damage on the surface; up to 5 = no visible damage.

Table 12—Stain Resistance[a] (on Opacity Chart)

Test Substance	WBUV-7200	Reference UVPUD	Reference SB UV
Black shoe polish	5	5	5
Tar	5	5	5
Black marker (Artline™ 70 N)	5	5	5
Blue colorant (BB750 H_2O)	5	5	5
Sudan red colorant (SR380-WS)	5	5	5
Yellow colorant (SG146-WS)	5	5	5
Eosine	5	5	5
Iso-betadine	4.5	4	5
Average stain resistance	4.9	4.9	5

(a) Evaluation: 1 = severe damage on the surface; up to 5 = no visible damage.

Table 13—UVPUD/WBUV-7200 Blends Formulations

Ingredient	Parts
UVPUD1 or UVPUD2	70
WBUV-7200 (adjusted to pH 7)	30
Photoinitiator	1.8
DG1	0.5
FLW4 flow and leveling agent	0.5

0.375 part of FLW5 and 0.375 part of FLW6. For UV curing, 2.8 parts of photoinitiator were added. Water was removed from the coating for 5 min at 50°C and the coating was cured using electron beam (5 MRad, 250 keV) at 50 g/m^2 on glass.

The Persoz hardness values are given in *Figure* 4 and show that the incorporation of EXP-1800 beyond 25% leads to a significant decrease in hardness.

Next, UV formulations were applied at 10 g/m^2 dry on a 250 µm PC sheet (cleaned with isopropyl alcohol), flashed-off for 5 min at 50°C and UV-cured with two passes at 10 m/min belt speed under a 120 W/cm Hg lamp. Permanent marker resistance, steel wool scratch resistance, and cylindrical mandrel flexibility results are summarized in *Table* 14.

Results show that incorporation of the flexibilizer emulsion leads to a significant increase in mandrel flexibility. The (limited) decreases in stain and scratch resistance that are observed are most likely due to the decrease in crosslinking density which follows the incorporation of the low functionality flexibilizing resin.

CONCLUSIONS AND PERSPECTIVES

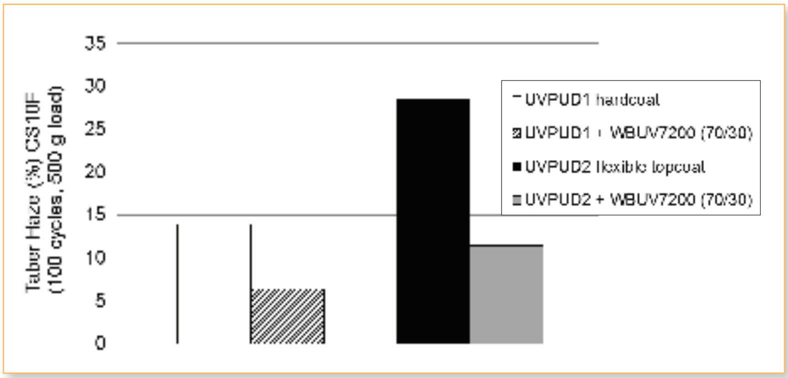

Figure 3—Taber haze abrasion resistance of UVPUD/WBUV-7200 mixtures.

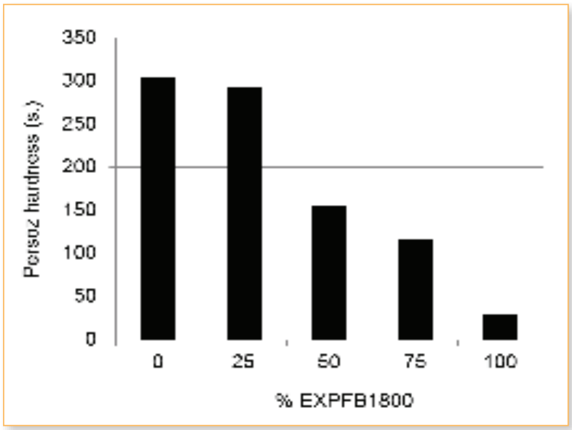

Figure 4—Persoz hardness dependence with composition of EB-cured blends of WBUV-7200 and EXP-1800.

The coating properties of new tin-free, high functionality aliphatic urethane acrylate oligomers, namely 9-functional EXP8602 and 10-functional EXP8415, have been compared to those of a standard 6-functional oligomer. Both new resins displayed higher abrasion resistance. Further, the 9-functional EXP8602 exhibits similar flexibility to the reference hardcoat, which is considered state-of-the-art for energy-curable coatings requiring high scratch- and abrasion-resistant properties. Comparatively, the 10-functional EXP8415 is characterized by a higher shrinkage and lower flexibility than the reference, making it preferred for application on rigid substrates. Applications at low coat weight and low curing energy also show the benefit of the high functional resins, especially the 10-functional EXP8415, as they provide higher performance (solvent resistance, scratch resistance) compared to the standard resin.

WBUV-7200 is a 65% solids proprietary aqueous emulsion of an aliphatic urethane acrylate with excellent stability. After curing, it displays all the typical properties of a hardcoat. It equals or outperforms the scratch, abrasion, and stain resistance of reference SB UV or UVPUD formulations. WBUV-7200 can also be used as a co-resin to enhance the abrasion resistance of UVPUDs. Finally, its flexibility can be adjusted by blending with the emulsion of an aliphatic urethane acrylate flexibilizing resin, EXP-1800. CT

Table 14—Properties of UV-Cured Blends of WBUV-7200 and EXP-1800 on 250 µm PC Substrate

WBUV-7200/ EXP-1800 Blend	Permanent Marker Resistance[a]	10 DR Steel Wool Scratch Resistance[a]	Perpendicular[b] Cylindrical Mandrel Flexibility (mm)	Parallel[b] Cylindrical Mandrel Flexibility (mm)
100/0	5	5	20	20
75/25	5	4.5	10	8
50/50	4.5	3.5	3	3
25/75	4	3.5	SF[c]	SF[c]
0/100	3	—	SF[c]	SF[c]

(a) Evaluation: 1 = severe damage on the surface; 5 = no visible damage
(b) Orientation of bending test direction respective to coating application direction (barcoater)
(c) SF = substrate failure, i.e., the substrate cracks upon bending

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