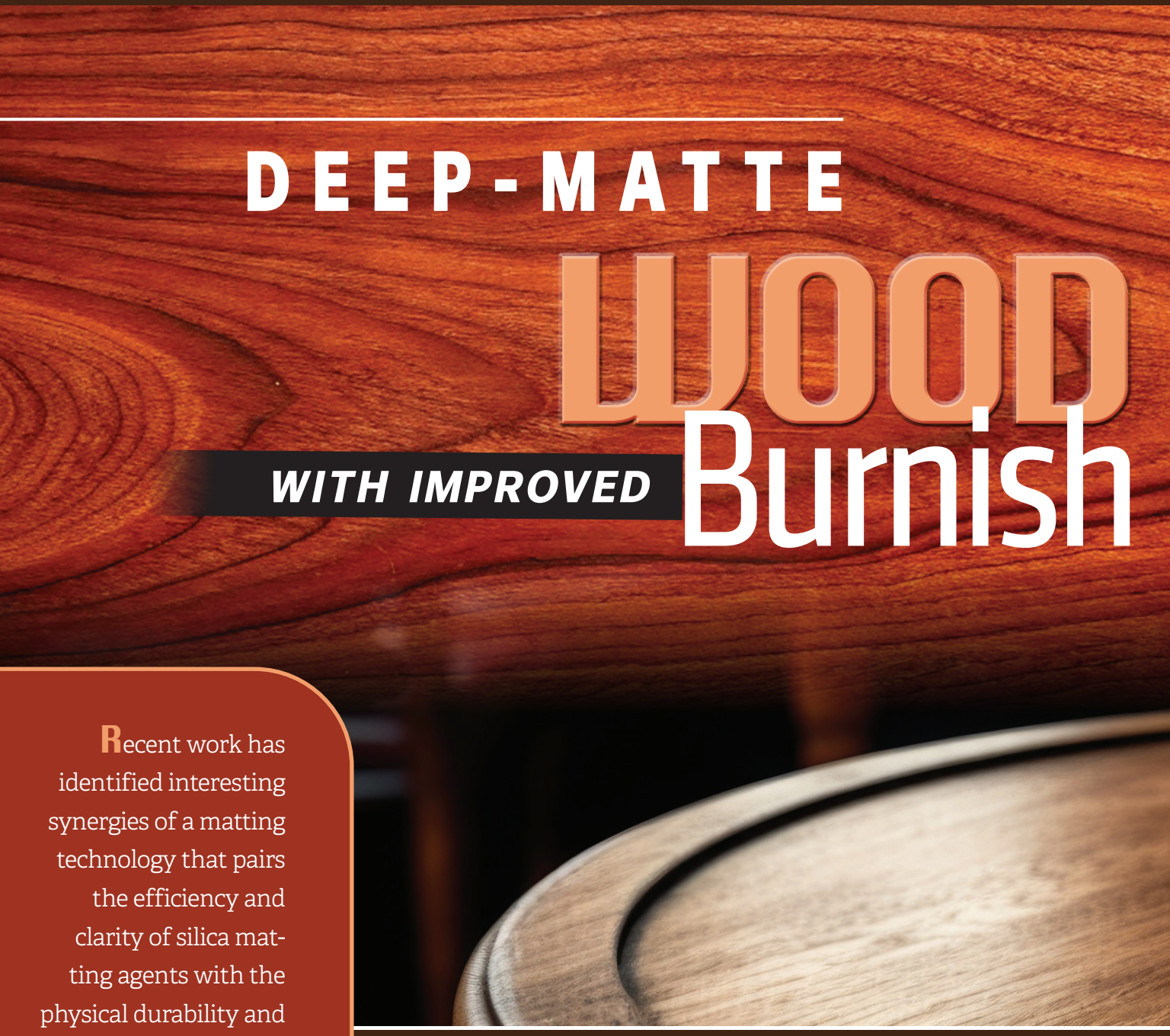
DEEP-MATTE WOOD WITH IMPROVED Burnish



Recent work has identified interesting synergies of a matting technology that pairs the efficiency and clarity of silica matting agents with the physical durability and protective ability of organic particles.

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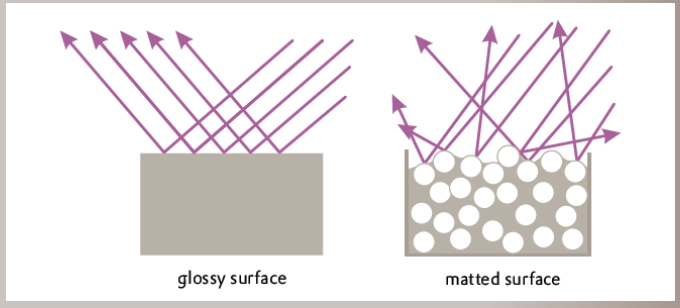
Matting of clear wood coatings is a critical aspect in capturing the natural beauty of the substrate and appealing to consumer demands. Maintaining this visual appearance is vital to coating during product lifespan, and with deep-matte finishes, resistance to burnish and polishing is of particular concern. Recent work has identified interesting synergies of a matting technology that pairs the efficiency and clarity of silica matting agents with the physical durability and protective ability of organic particles. The plastic deformation and energy dissipation of these particles resist polishing forces and protect the matting structure of the silica. This combination has shown excellent synergy and allows formulation of durable deep-matte finishes with excellent burnish resistance. There are also significant benefits in reduced viscosity build at high matting-agent levels. This article will review the technical details of the synergy and characteristics in different wood coating systems.

COATINGS Resistance

Introduction

The use of particles to reduce the gloss of coatings is a very well-known practice. A wide variety of products and technologies are available to develop wood coating formulations. The use and choice of a specific product is often driven by a variety of factors, but fundamentally particle technologies all function through a similar mechanism. The particles, dispersed in the liquid coating, provide a surface roughness after application and drying/curing that serves to scatter light providing a visual differential and reduction in gloss **(Figure 1)**. Their

FIGURE 1
Light reflection on smooth surface develops a glossy coating while a matted coating with a rough surface scatter lights in different angles.



effectiveness is heavily contingent on film shrinkage around the particles during the drying and curing of the coating, and their utility is often judged based on secondary effects to the coating film such as rheology, clarity, haptic properties, chemical resistance, and resistance to burnish.[1]

Deep-matte coatings, where the gloss has been significantly reduced, typically require higher loads of particles to achieve the necessary surface roughness. These higher loadings often result in greater impact on the secondary effects to the coating film, and require far more attention to product selection and formulation to balance the performance needs of the coating. Of particular interest is the aspect of burnish resistance—the increase in gloss caused by the polishing of the finished coating by handling, touching, brushing, or other physical contacts. Burnishing and reduction of the matting effect can be an issue with all matted coatings, but is particularly problematic with deep-matte coatings, as the visual differentiation can be significant. Burnish resistance of a deep-matte coating is also very dependent on the nature and chemistry of the particles themselves due to their higher concentration on the coating surface that is needed to achieve the necessary surface roughness.

TABLE 1
Water-Based UV-Curable Coating Formulation

Component	Weight (g)
UCECOAT 7788	25
Omnirad 500	0.375
Matting agent	1
TEGO Foamex 822	0.13

The morphology of the particles, their chemical and physical properties, and interaction with the coating film can play a pronounced role in resistance to burnish and is an area of significant interest.

The work described in this article is part of an ongoing effort to better understand the role of matting agents in achieving a deep matte-finish with higher resistance to burnishing. While only a snapshot of the broader investigation is reviewed here, the best-in-class products within a variety of technologies were evaluated in different systems and the results are compared and assessed. Matting-agent combinations are also explored, and results suggest synergistic benefits are possible when pairing silica matting agents with organic particles. Deep-matte water-based UV-curable coatings, water-based air-dry systems, and deep-matte 100%-solid UV-curable coatings will be discussed.

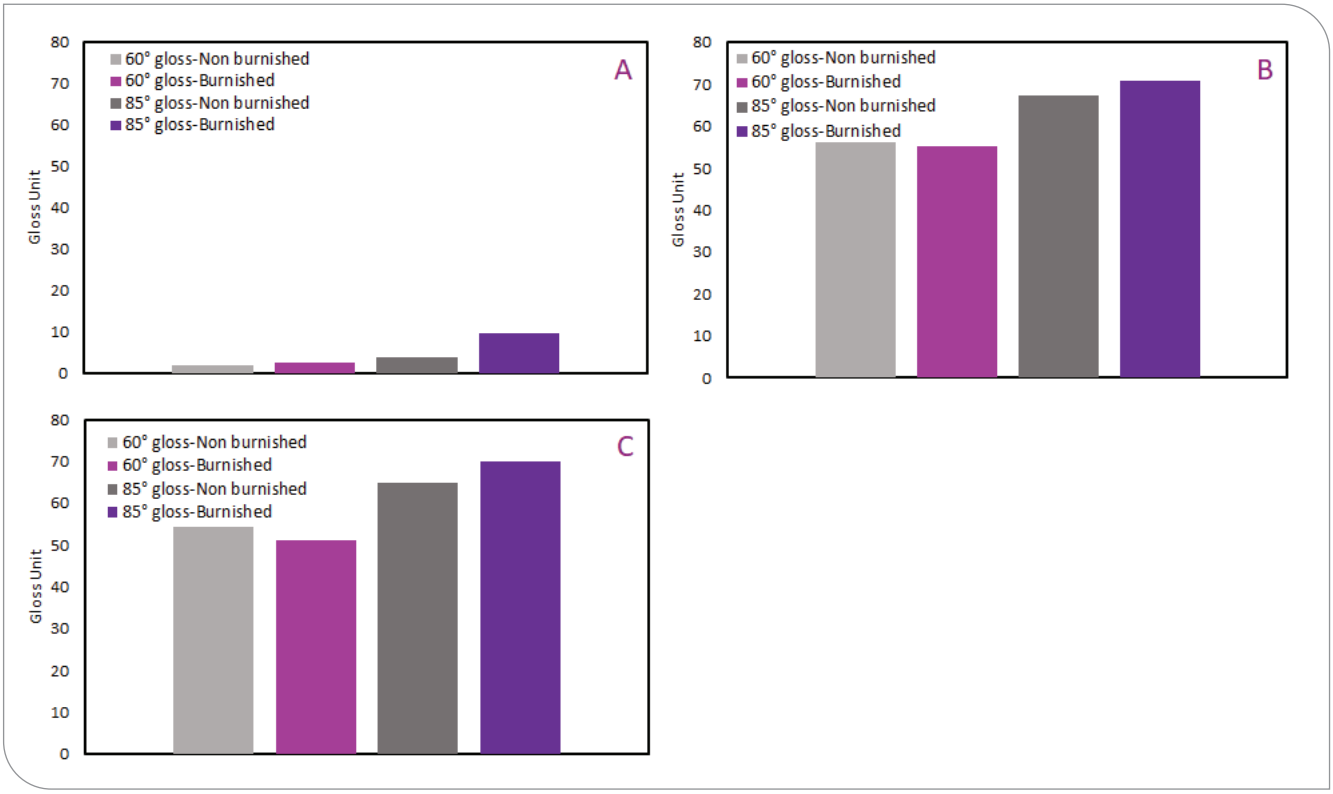
Results and Discussion

The matting capability of three different matting agent types of similar particle size were tested in the water-based UV-curable formulation shown in **Table 1**. In this formulation, UCECOAT® 7788 (Allnex) is a UV-curable aliphatic polyurethane dispersion and Omnirad 500 (IGM Resins) is a water-soluble photoinitiator. TEGO® Foamex 822 (Evonik Corporation) is a compatible defoamer emulsion based on polyether siloxane technology.

Figure 2 shows the initial matting and burnishing results for coatings containing particles of (A) surface-treated thermal silica, (B) polyamide, and (C) micronized polypropylene matting agents in this system. A deep-matte sheen and excellent burnish resistance can be obtained by using 10 wt % of the surface-treated thermal silica in the formulation, as visible in **Figure 2A**.

Defining the deep-matte sheen as a coating with 0<G60<10 and 0<G85<15,[2] the results in **Figure 2A** demonstrate that, even after the burnish test, the coating keeps its deep-matte sheen. Here, G60 and G85 mean gloss at 60° and gloss at 85°, respectively. These results are consistent with the high surface roughness shown in **Figure 3**. Silica particles are clearly visible in the image

FIGURE 2
Gloss and burnish resistance of a water-based UV-curable coating with dried film thickness 29 microns containing 10 wt % of matting agent based on (A) surface-treated thermal silica, (B) polyamide, and (C) micronized polypropylene. The burnish test was done using a Crockmeter.



on the left, and this results in a significant reduction in both gloss 60° and 85°.

After burnishing test, limited particle deformation and flattening of the coating's surface is observed **(Figure 3B)**, and the coating still shows significant surface roughness that allows it to retain its deep-matte sheen.

On the other hand, **Figures 2B** and **2C** show that no deep-matte sheen can be obtained with the organic polyamide or micronized polypropylene particles used as the matting agent in this system. The sizes of the three particles are comparable: the surface-treated thermal silica has an average particle size of 10 microns, the polyamide 11 microns, and the average range of the particle size of micronized polypropylene is 8-12 microns.

This means that significant differences in matting capability and burnish resistance exist though the sizes of the particles are just 1-2 microns different from each other. These size comparisons highlight the importance of the particle chemistry (organic versus inorganic) as well as binder-particle interaction as other important parameters affecting matting capability of the particles.

Among all three tested particles, surface-treated thermal silica provides excellent burnish resistance and matting capability and appears to be an excellent choice for this water-based UV-curable coating. However, this performance does not extend directly to a second, water-based air-dry coating.

The instrument used for testing burnish resistance of the coatings is called Crockmeter. It contains a moving head to which a cheese cloth is attached. The head sits on the coating surface and moves back and forth for 20 cycles. Rubbing of the surface by the cheese cloth may cause removal of the matting-agent particles and a change in coating gloss.

In **Figure 4,** capabilities of the same three matting agents in a water-based air-dry formulation are tested. The formulation

FIGURE 3
Surface SEM micrographs of the water-based UV-curable coating with a thickness of 15 microns containing surface-treated thermal silica (A) before before burnish testing and (B) after burnish testing using a Crockmeter.

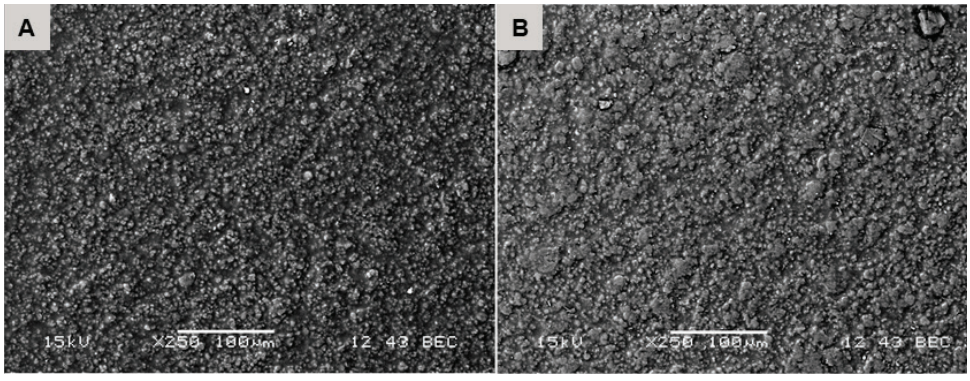


FIGURE 4
Different gloss values and burnish resistance of a water-based air-dry coating containing 15 wt % of matting agent based on (A) surface-treated thermal silica, (B) polyamide, and (C) micronized polypropylene. The burnish test was performed using a Crockmeter.

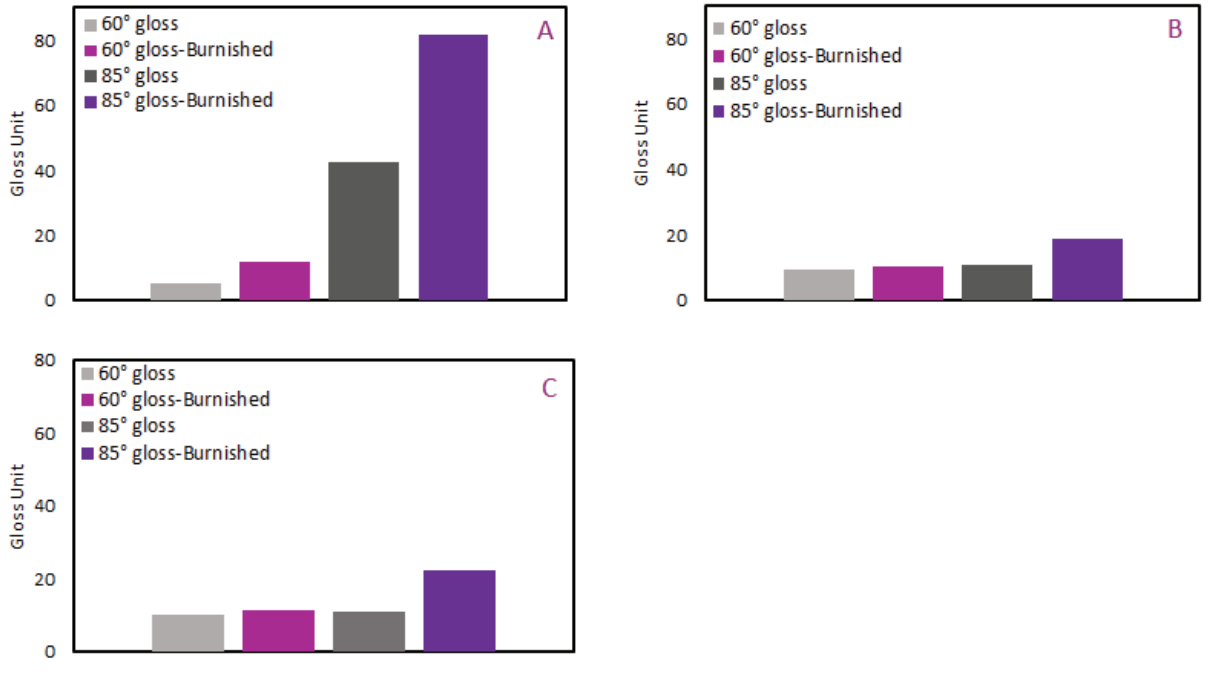


TABLE 2
Water-Based Air-Dry Clearcoat Formulation

Component	Weight (g)
Alberdingk AC 3630	68
TEGO Foamex 825	0.6
TEGO Airex 902W	0.2
Water	24.2
Dipropylene glycol n-butyl ether (DPnB)	3
Dipropylene glycol methyl ether (DPM)	3
TEGO Viscoplus 3010	0.2
TEGO Viscoplus 3030	0.4
DYNOL 980	0.3
TEGO Glide 496	0.1
Total	100

of the blank clearcoat, based on an acrylic binder, is shown in **Table 2.** The loading level of the matting agents was selected to reach approximately 15 wt % of the matting agent in the dried coating. The dried film thickness of all three coatings is approximately 26 microns, and all were applied via a wire-wound rod.

Figure 4A shows that the surface-treated thermal silica matting agent is effective in reducing 60° gloss but poor at reducing 85° gloss. Moreover, this silica matting agent has much lower burnish resistance compared with the polyamide and micronized polypropylene matting agents.

Figure 4B shows that the polyamide matting agent significantly lowers both 60° and 85° gloss, and it has the highest burnish resistance among the three tested matting agents. Coatings containing micronized polypropylene particles show 10 units and 11 units of gloss at 60° and 85°, respectively, in **Figure 4C.**

Like before, as the sizes of these three particles are close to each other, these significant differences in matting capability and burnish resistance can be attributed to their different chemical natures (organic versus inorganic), different surface chemistries, and the interactions with the binder. Understanding these differences is critical to optimizing matting efficiency and burnish performance.

Later in the discussion, we will show that blending the silica with organic particles as a viable option. SEM images shown in **Figure 5** help to highlight why this may be a practical approach to improving burnish resistance.

The SEM images from the surface of the coatings before and after burnish test are shown in **Figure 5.**

Figure 5A shows the rough surface of the coating containing the surface-treated thermal silica. However, many of the particles are broken and polished out of the surface after rubbing with a cheese cloth for 20 cycles using a Crockmeter **(Figure 5B)**.

The white small spots in **Figure 5B** are the polished silica particles, and the flat surface correlates with high 85° gloss of the burnished sample, as shown in **Figure 4A.** On the other hand, the coating containing polyamide particles not only shows surface roughness before burnishing **(Figure 5C),** but also keeps its surface roughness even after burnish testing though limited deformation of particles can be seen in **Figure 5D.**

Unlike silica, which is an inorganic rigid material, the polyamide is a material with high impact resistance and has the capability for plastic deformation. Unlike silica which gets polished and leaves a flat surface, burnish forces are dissipated by polyamide particles via plastic deformation and their viscoelastic behavior that allows them to stay on the surface of the coating even after the burnish test. This is the reason that the coating with polyamide particles shows high resistance to burnish forces, compared to the one that contains silica.

Finally, the surface roughness observed in both SEM micrographs **Figures 5C** and **5D** correlates to low gloss and high burnish resistance seen in **Figure 4B.**

The very different gloss-reduction capability and burnish resistance of the surface-treated thermal silica in water-based UV-curable and water-based air-dry systems raises a question regarding why these different behaviors are observed. One possibility may be the chemistry of the binders used in these systems and their interactions with the particles.

An acrylic dispersion is used as the film forming component in the water-based air-dry system while an aliphatic polyurethane dispersion was the film-forming polymer in the water-based UV-curable coating. If the polyurethane binder shows higher affinity for the surface-treated thermal silica, it has a greater chance to penetrate the pores of the silica; however, lower affinity of the acrylic binder for the silica prevents its penetration into the pores. The penetration of the binder into the silica pores can cause higher surface roughness and higher chance of plastic deformation of silica particles under burnishing forces. Thus, the different behavior of the same silica matting agent in the aqueous acrylic versus the aqueous UV-curable polyurethane binder implies that matting-agent performance can be system specific.

Like the surface-treated thermal silica, the polyamide and micronized polypropylene matting agents also show very different matting capabilities in the water-based air-dry and water-based UV-curable systems.

FIGURE 5
Surface SEM micrographs of water-based air-dry coating containing a surface-treated thermal silica matting agent before (A) and after (B) burnish testing. The same coating containing polyamide particles before (C) and after (D) burnish testing using a Crockmeter.

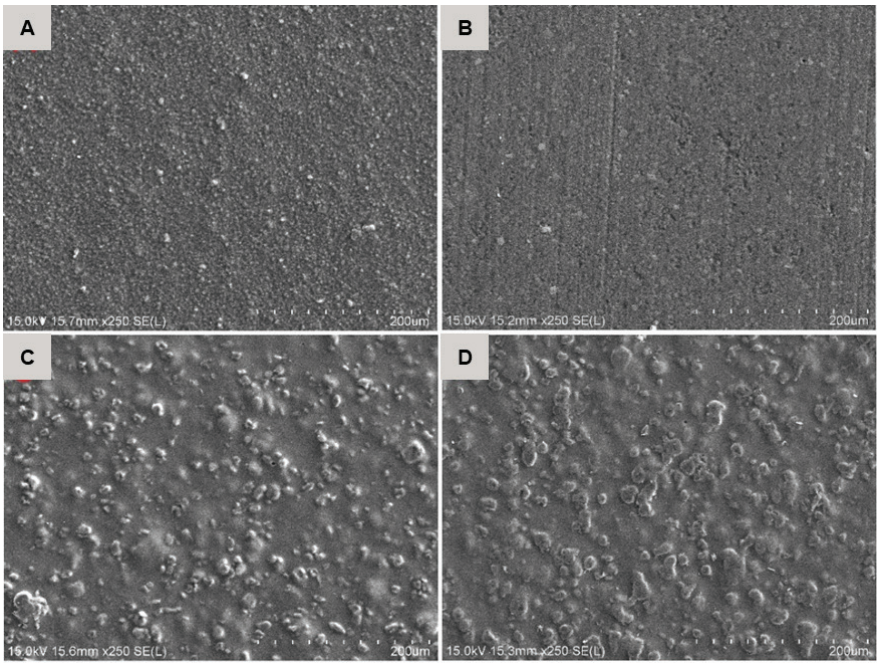


Figure 4 demonstrates that polyamide and polypropylene particles work well as matting agent to get a deep-matte sheen in the water-based air-dry system, whereas **Figure 2** shows that they are not suitable matting agents for water-based UV-curable coatings. This reinforces the core premises of this investigation: to better define the fundamentals of performance, understanding matting agent interactions in different systems and with different binder chemistries, and to develop methods to troubleshoot and improve performance.

A side-by-side comparison of these three matting agents in a 100%-solid system was then undertaken. This formulation was difficult to matte due to the lack of evaporating solvent. In solvent- or water-based systems, the evaporation of the liquid phase results in film shrinking around the matting-agent particles and contributing to an increase in surface roughness. However, in 100%-solid systems where there is no liquid evaporation, surface roughness can be caused just by solid particles protruding out of the coating surface and possibly by polymerization-induced shrinkage. Relying mostly on solid particles for surface roughening necessitates the incorporation of a significant amount of the particles to the system to develop a deep-matte sheen. The side effect is the viscosity buildup at a high matting-agent concentration that is unfavorable for coating application.

Considering the same surface-treated thermal silica, micronized polypropylene, and polyamide particles as the matting agents for a 100%-solid system, **Figure 6B** shows that, at a similar loading level of 15 wt%, the sample containing surface-treated thermal silica results in a non-flowing paste. On the other hand, **Figure 6A** shows that samples containing polyamide and micronized polypropylene particles are still fluid and can be applied by usual techniques like spray or roll coaters. When the surface-treated thermal silica was replaced by an acrylate-functionalized precipitated silica, the viscosity problem was solved.

The latter silica is specifically designed for reduced viscosity build in 100%-solid systems and its average particle size is 5 microns. Our previous results, not presented here, showed that this acrylate-functionalized precipitated silica, which is suitable for 100%-solid systems, is not suitable for water-based systems. Thus, one can conclude that surface-treatments of silica-based matting agents determine their suitability for different coating systems. The morphology of this acrylate-functionalized precipitated silica, polyamide, and micronized polypropylene are shown in **Figure 7.**

FIGURE 6
(A) Rheological behavior of 100%-solid UV-curable coatings containing different types of matting agent measured using an Anton Paar rheometer. (B) Paste formation upon addition of a silica matting agent that is not designed for 100%-solid UV-curable systems.

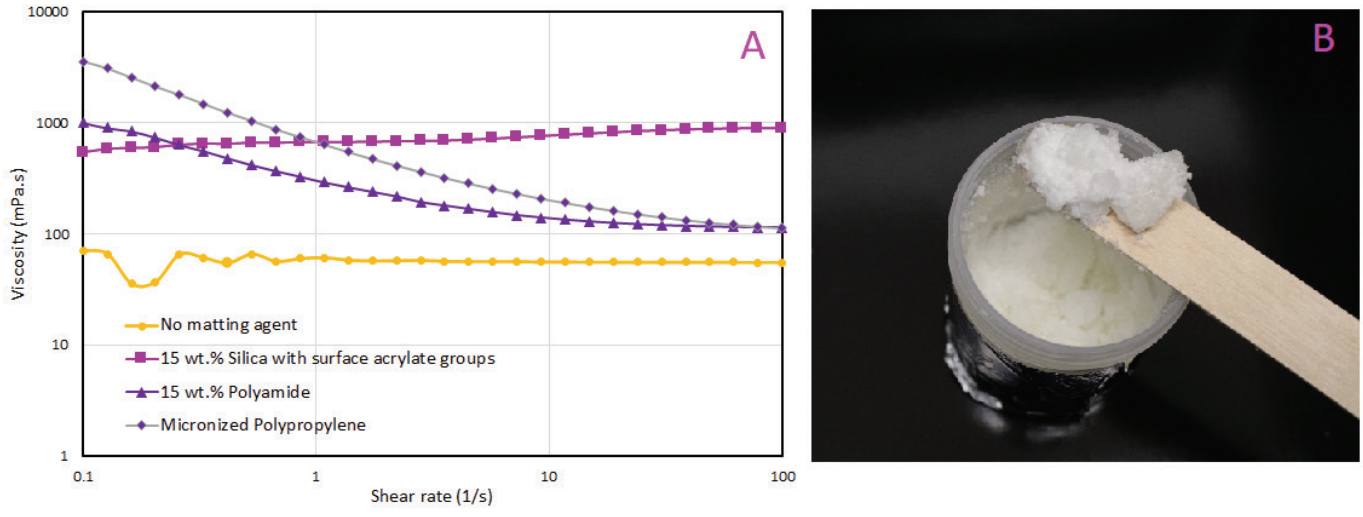
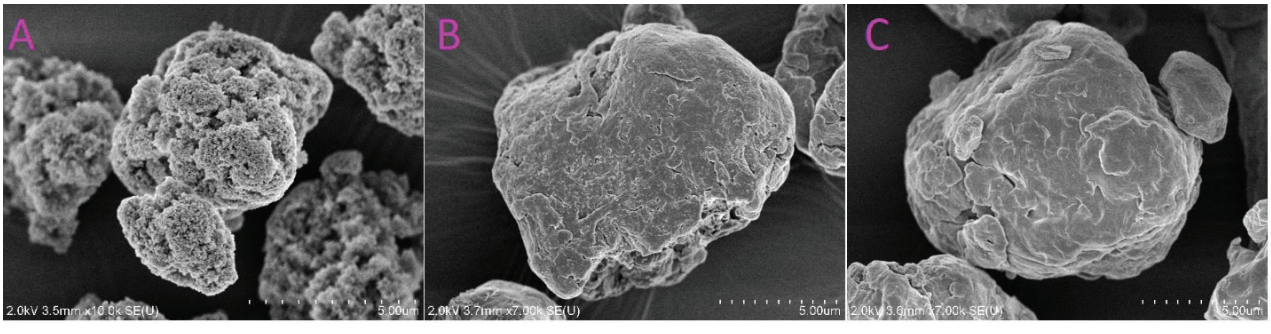


FIGURE 7
SEM images of (A) acrylate-functionalized precipitated silica, (B) polyamide, and (C) micronized polypropylene matting-agent particles.



The particles that are added to a 100%-solid system to adjust gloss level, also affect rheological properties of the formulation. In the final part of this article, we will show that, by using a blend of surface-treated precipitated silica and polyamide particles and changing the ratio of the particles, it is possible to alter rheological behavior of the formulation from shear-thickening to shear-thinning and *vice versa*.

Figure 6A also shows that the type of matting agent affects the rheological behavior of a formulation. Compared with the control coating formulation without matting agent, the addition of polyamide and micronized polypropylene particles change the viscosity behavior from Newtonian to shear thinning. In addition, the viscosity at low shear rates increases, which is favorable for in-can stability of the particles. On the other hand, the addition of acrylate-functionalized precipitated silica changes the rheological behavior to shear-thickening.

Continuing the side-by-side comparison, a 100%-solid UV-curable formulation based on PHOTOMER® oligomers (IGM Resins) shown in **Table 3** was developed to test the matting capability of acrylate-functionalized precipitated silica, polyamide and micronized polypropylene particles. **Figure 8** shows that the acrylate-functionalized precipitated silica works better than the two other matting agents in reducing both the 60° and 85°gloss; however, it also shows the acrylate-functionalized silica to have the poorest burnish resistance among the three tested matting agents.

It is interesting that the acrylate-functionalized precipitated silica with a particle size of 5 microns, approximately half of the size of the other two matting agents, has excellent performance in gloss reduction at 60°. Effective reduction of gloss at 60° is the advantage that most silica-based matting agents possess, regardless of the coating system, as seen in **Figures 8A, 4A,** and **2A.** Results in **Figure 8** show that none of the tested matting agents enables a deep-matte sheen (0<G60<10 and 0<G85<15) to be obtained. These results agree with the abovementioned statement that getting a deep-matte sheen is challenging in 100%-solid systems. All the coatings shown in **Figure 8** were applied on a non-sealed Leneta card using a wire-wound rod #3 that theoretically forms a film thickness of 7.5 micron.

Figures 9A, 9C, and **9E** show that there is not enough roughness on the surface of the coatings to develop a deep-matte sheen. In fact, the matting-agent particles that are responsible for the generation of surface roughness have sunk into the liquid layer of monomers and oligomers. The results of these SEM images agree with the gloss results shown in **Figure 8.** The SEM images from the cross-section of the same coatings are shown in **Figure 10.** In **Figures 10A, 10D,** and **10G,** matting-agent particles are observed inside the coating and almost a non-roughened surface on top. These cross-sectional images imply that the ratio of particle size to film thickness is an important parameter in 100%-solid systems. Here, this parameter is abbreviated as PS/FT and two different possibilities of PS/FT < 1 as well as PS/FT ≈ 1 are considered. In the former case, the film thickness is greater than the particle size and, in the latter, the film thickness is less than or equal to the particle size of the matting agent.

When the film thickness is lower than the size of the matting agent, the protrusion of the particles generates a rough surface, which causes light scattering, and consequently, the development of a deep-matte sheen. This is clearly observable in **Figures 9B, 9D,** and **9F**. The comparison of **Figures 9A** with **9B, 9C** with **9D,** and **9E** with **9F,** confirm that surface roughness increases by increasing the PS/FT value, regardless of the chemistry of matting agent. Cross-sectional SEM images, shown in **Figures 10B, 10E,** and **10H,** also confirm the protrusion of matting-agent particles above the surface of the coating when PS/FT≈1. This protrusion causes high surface roughness, high capability of the coating for light scattering, and, consequently, the development of deep-matte sheen. Again, the cross-sectional SEM images reveal that PS/FT is a key parameter, regardless of the chemistry of the matting agent. The significant reduction in gloss by transiting from PS/FT <1 to PS/FT≈1 is shown in **Figures 10C, 10F,** and **10I.**

The preceding results show that particle size to film thickness ratio (PS/FT) can be a key parameter in 100%-solid UV-curable systems and may significantly affect the gloss of a coating. In this 100%-solid system, it was necessary to have a ratio of less than 1 to achieve a deep-matte sheen. However, such a strong dependency of gloss-to-film

TABLE 3
100%-Solid UV-Curable Clearcoat Formulation

Component	Weight (g)
PHOTOMER 6710	8.7
PHOTOMER 4017	15.57
PHOTOMER 4149	0.6
TEGO Rad 2100	0.12
TEGO Disperse 689	0.6
Matting agent	4.7
TEGO Airex 920	0.09
Omnirad 184	0.78
Omnirad TPO-L	0.24

FIGURE 8
Gloss and burnish resistance of a 100%-solid UV-curable coating containing 15 wt % of matting agent based on (A) acrylate-functionalized precipitated silica, (B) polyamide, and (C) micronized polypropylene.

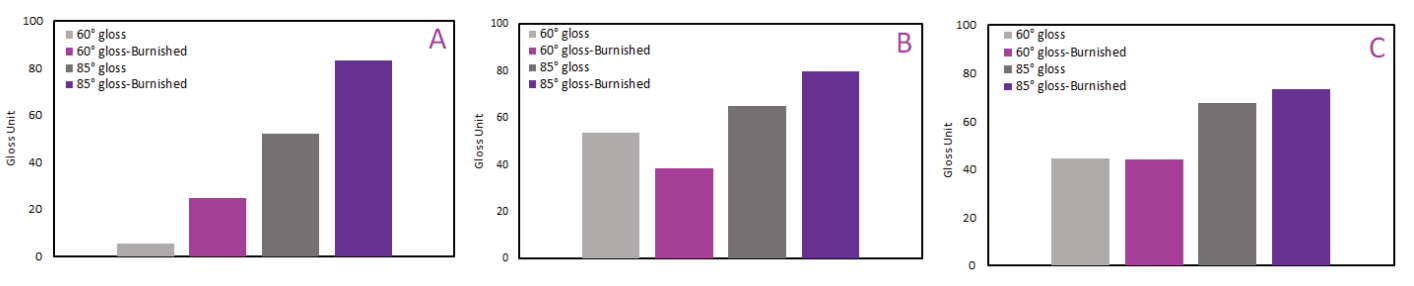


FIGURE 9
Surface SEM micrographs of 100%-solid UV-curable coatings containing 15 wt % of (A) acrylate-functionalized precipitated silica with film thickness higher than particle size; (B) acrylate-functionalized precipitated silica with film thickness close to particle size; (C) polyamide matting agent with film thickness higher than particle size; (D) polyamide matting agent with film thickness close to particle size; (E) micronized polypropylene with film thickness higher than particle size; and (F) micronized polypropylene with film thickness close to particle size.

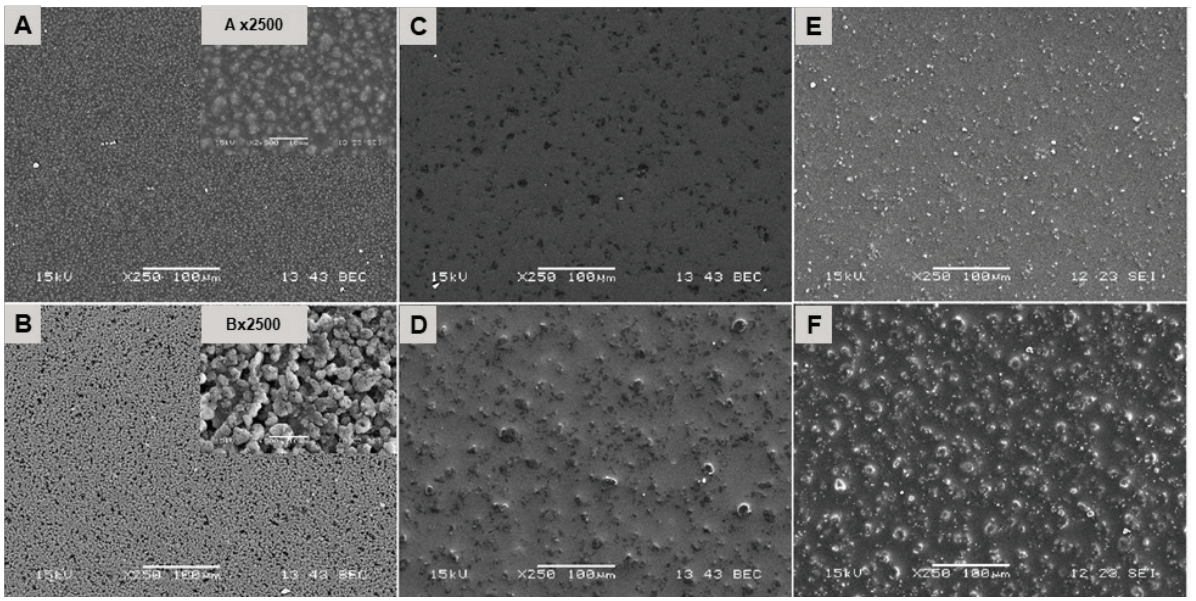


FIGURE 10
Cross-section SEM micrographs of a 100%-solid UV-curable coatings containing 15 wt % of (A) acrylate-functionalized precipitated silica with film thickness higher than particle size; (B) acrylate-functionalized precipitated silica with film thickness close to particle size; (D) polyamide matting agent with film thickness higher than particle size; (E) Polyamide matting agent with film thickness close to particle size; (G) micronized polypropylene with film thickness higher than particle size; (H) micronized polypropylene with film thickness close to particle size. Comparing the effect of PS/FT value on the gloss of the coating containing (C) acrylate-functionalized precipitated silica particles; (F) polyamide particles; and (I) micronized polypropylene particles.

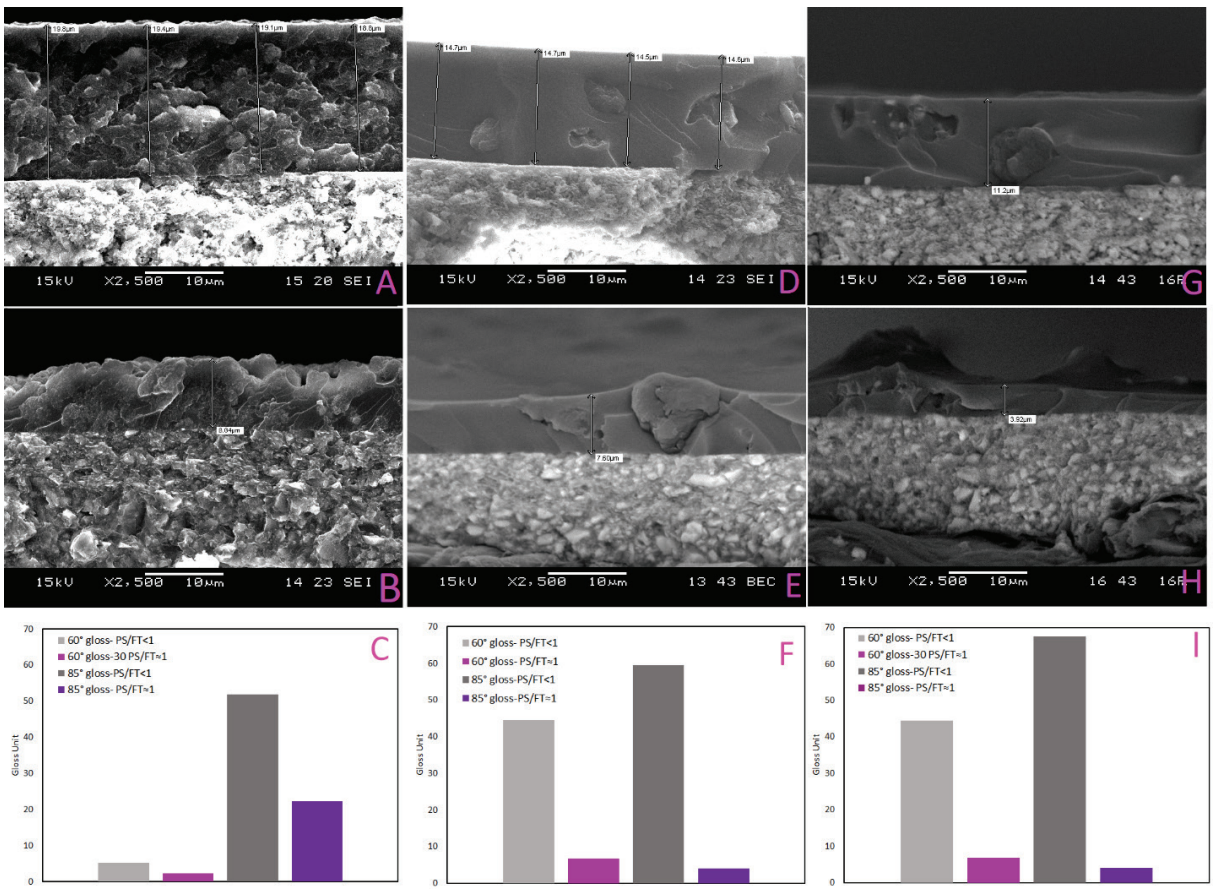


FIGURE 11
(A) and (B) show gloss dependency of the water-based air-dry coating on film thickness. (C) and (D) show gloss dependency of water-based UV-cured coating on film thickness.

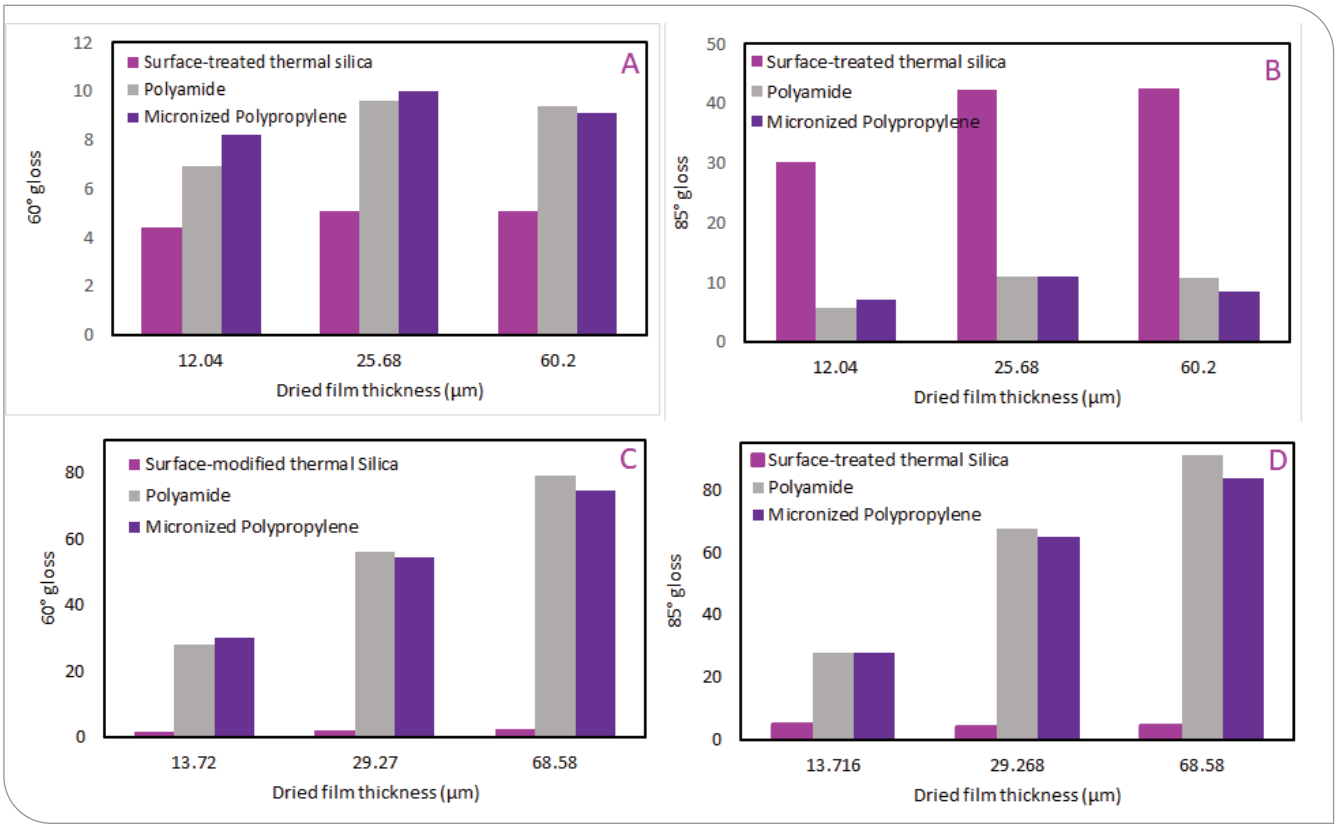
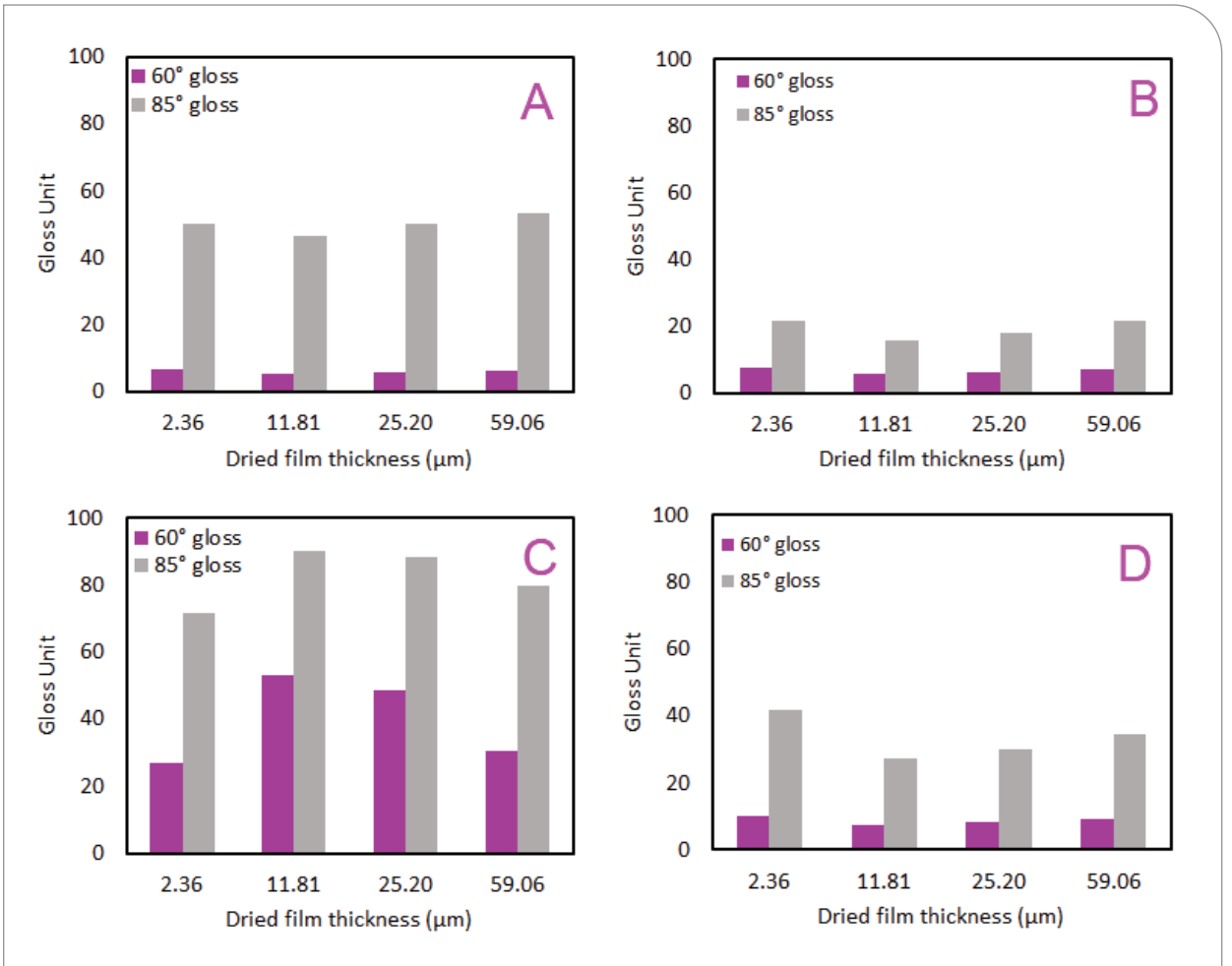


FIGURE 12
(A) Gloss of water-based air-dry coatings containing 15 wt % of surface-treated thermal silica. (B) Gloss of a 1:1 mixture of the surface-treated thermal silica and polyamide. (C) Gloss of the same coatings after burnish test containing 15 wt % of surface-treated thermal silica. (D) Gloss of the 1:1 mixture of surface-treated thermal silica and polyamide.



thickness is not common in water-based or other systems where significant film shrinkage occurs. **Figure 11** shows that the extent of gloss dependency to film thickness for a specific matting agent is quite different in the previously described water-based air-dry and water-based UV-curable systems.

For example, the surface-treated thermal silica in the water-based UV-cured system shows excellent matting ability for all film thickness, while the same particle in water-based air-dry system shows an increase in 85° gloss with film thickness. In direct contrast, micronized polypropylene and polyamide particles show low gloss-dependency-to-film thickness in water-based air-dry system, while they show a linear dependency ($R^2$0.8) of gloss-to-film thickness in water-based UV-cured system

Considering these results, one can conclude that the dependency of gloss-to-film thickness is higher in 100%-solid systems, compared to water-based air-dry and water-based UV-curable systems. Also, no general comment can be made for gloss-dependency-to-film thickness for water-based systems, as it appears to be variable with the type of the matting agent.

Particle Blending

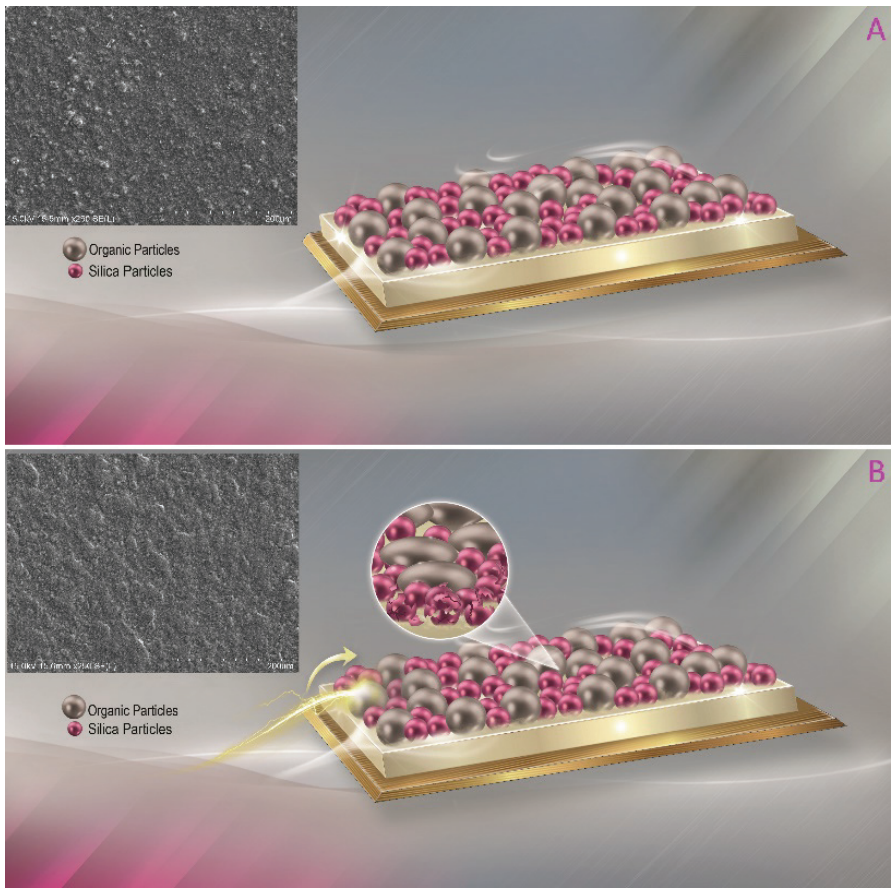
As shown previously, a matting agent may have varied efficacy in different systems as well as provide differing impacts on other properties. Blending the particles may offer a method to achieve optimal performance. **Figure 12A** shows that the surface-treated thermal silica is effective in the reduction of 60° gloss but not as effective at reducing 85° gloss. The polyamide particle evaluated is able to reduce 85° gloss effectively. So, using a mixture of the two particles seems like a practical way to obtain low gloss at both 60° and 85°.

Gloss of the coating containing 15 wt % of a 1:1 mixture of surface-treated thermal silica/polyamide particles as the matting agent is shown in **Figure 12B.** The coating shows 85° gloss values that are significantly lower than those reported for the sample that contains 15 wt % of only the surface-treated thermal silica. Like the previously discussed water-based air-dry system containing a single particle as matting agent, there is no significant gloss dependency on film thickness in this water-based air-dry coating containing a mixture of surface-treated thermal silica and polyamide particles. In addition, blending the surface-treated thermal silica with polyamide particles noticeably improves burnish resistance of the coating. Comparing **Figures 12C** with **12D** reveals that the lower burnish resistance of the surface-treated thermal silica matting agent in this system can be improved by blending it with polyamide particles.

A theory of the mechanism of this burnish-resistance improvement is shown in **Figure 13.** Using an organic particle with a size higher than silica size appears to work like a protective umbrella toward the inorganic silica particles. When there is no burnishing force, the organic particle keeps its spherical structure as seen in **Figure 13A.** Under burnishing forces, the polyamide particles exhibit deformation from the burnishing force as they are protruding the most beyond the coating surface. The polyamide particles or other type of organic particle with the capability of energy dissipation may undergo a plastic deformation to dissipate burnishing forces and prevent stress transfer to the smaller silica particles. This mechanism is shown in **Figure 13B** where the magnified schematic emphasizes that silica particles that are well protected by organic particles stay intact even after burnish testing while the silica particles that are far away from an organic particle have the chance of receiving the burnish force resulting in breakage of the brittle silica particle.

The SEM images shown as insets of **Figure 13,** appear to confirm this hypothesis. The pictures represent a water-based air-dry coating containing 15 wt % of a 1:1 mixture of surface-treated thermal silica and polyamide particles. The deformation of the polyamide particles under burnishing force is observable in SEM image of **Figure 13B.** The case study discussed here confirms that particle blending is an effective method to enhance properties of silica matting agents, if needed. For the

FIGURE 13
(A) Schematic showing both silica and an organic matting agent on the surface of a coating cause surface roughness. The inset SEM image shows the surface of an water-based air-dry coating containing both surface-treated thermal silica and polyamide as matting agent. (B) Schematic showing silica particles that are close enough to organic particles are protected from burnish forces; however, silica particles that are far from organic particles are damaged, the inset SEM image show the deformation of the polyamide particles after burnish test.



water-based UV-curable coating explored here, the gloss-reduction capability and burnish resistance of the same surface-treated thermal silica is sufficient so that there is no need for blending it with any organic particles. On the other hand, acrylate-functionalized precipitated silica used in 100%-solid system also shows poor burnish resistance. Like the water-based air-dry system, results (not shown here) showed that blending of this silica with polyamide particles resolves the problem. Thus, one can consider the blending of silica with organic particles as a universal approach for improving mechanical properties of the coatings.

The next advantage of blending silica matting agents with organic particles of different sizes is a potential matting synergy that is seen by these blends.

Synergy here means that lower 60° and 85° gloss is obtained compared to gloss values estimated through linear mixture law. Different blends of silica and polyamide with different ratios of former to latter can be used as matting agent package. Two extreme points are when the blend just contains silica (1:0 silica/polyamide) and when the blend just contains polyamide (0:1 silica/polyamide). Blends prepared with concentrations between these two extremes may show different extents of synergy. Dashed lines in

FIGURE 15
Effect of silica/polyamide ratio on the rheological behavior of a 100%-solid UV-curable coating.

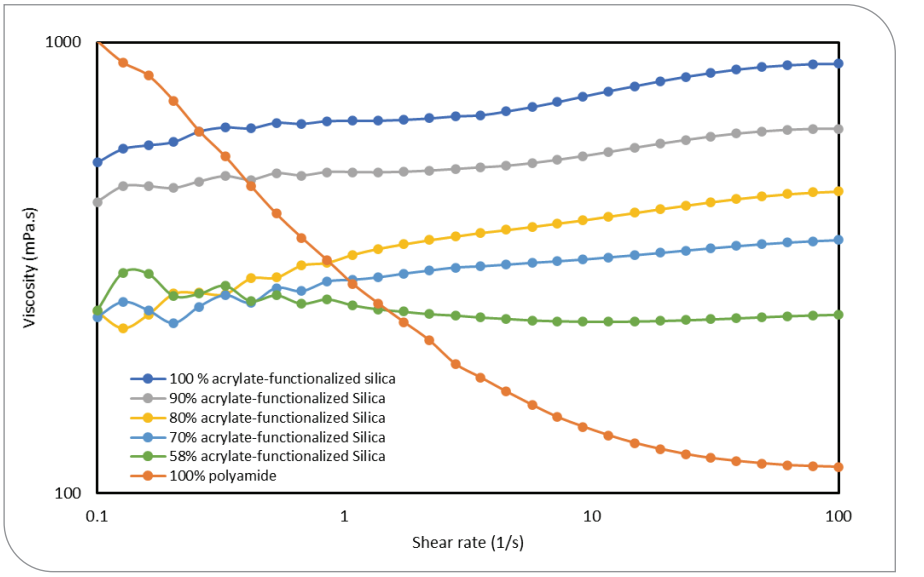


FIGURE 14
Synergy in gloss reduction by using a combination of surface-treated silica and polyamide in water-based air-dried system (A and B), and synergy by using acrylate-functionalized precipitated silica and polyamide particles in 100%-solid UV-curable coatings.

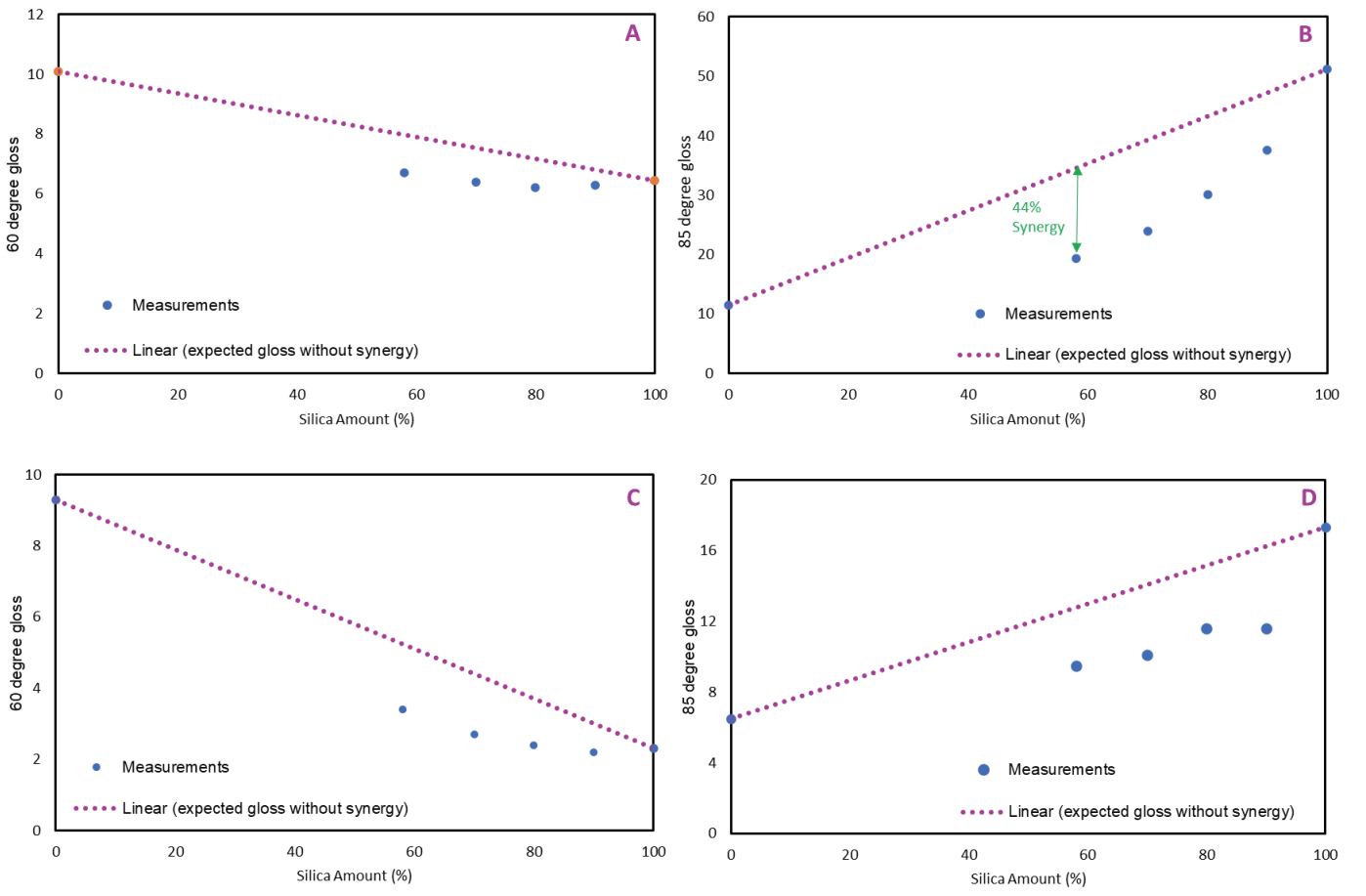


Figure 14 are linear predictions between the two extreme points and the blue dots are measurements made on the coatings. The figure clearly shows that measurements have lower gloss values compared with linear prediction line. For example, in **Figure 14B,** synergy extent up to 44% can be obtained. As **Figure 14** shows, this matting synergy exists in both the 100%-solid UV-curable and water-based air-dry systems and for both 60° and 85° gloss. This synergy can enable formulators to develop a deep-matte sheen while using lower amounts of matting agents. In addition, our results, not shown here, showed similar synergy exists in water-based UV-curable coatings.

There are some other secondary properties that can be optimized by blending silica with organic particles such as colloidal stability, clarity, mar resistance, and chemical resistance. To better describe the possibility of tuning secondary properties via particle blending technique, we show an example in **Figure 15,** where the viscosity of a 100%-solid UV-curable coating is adjusted by varying the ratio of acrylate-functionalized precipitated silica to polyamide particles. In **Figure 6,** we showed that by selecting an appropriate type of the matting agent, tuning the rheological behavior of a formulation is possible.

In addition to that, **Figure 15** discloses more details for viscosity optimization. It shows that the formulation containing just polyamide as matting agent shows a shear thinning behavior while the one that just contains acrylate-functionalized precipitated silica shows a shear thickening one. By increasing the portion of polyamide in the silica/polyamide mixture, the rheological behavior of the formulation gradually transitions from shear thickening to Newtonian at approximately a 1:1 weight ratio of silica to polyamide.

Conclusion

The side-by-side comparison of silica-based, polyamide, and micronized-polypropylene matting agents in three different coating systems confirmed that a particle may show unique properties in a system while the same particle may not show those properties in another coating system. As an example, surface-treated thermal silica showed excellent gloss reduction and burnish resistance in water-based UV-curable coating but did not show those properties in water-based air-dry system. So, a matting agent should be evaluated not only based on the system type, but also considering binder chemistry. The results of this work showed that silica particles are effective in reducing gloss in the three evaluated systems; however, achieving a deep matte finish was challenging in some. The evaluation also showed that select organic particles offer benefits in different performance aspects. Particle blending was introduced as an effective approach to develop deep-matte sheen in the formulations in which silica is used as matting agent. In addition to this particle blending technique, film-thickness optimization was discussed to help formulators to develop a deep-matte sheen specially in 100%-solid UV-curable systems. Results showed that surface-treated thermal silica has excellent burnish resistance in water-based UV-curable coatings. However, for the systems where silica does not show enough burnish resistance, particle blending is a favorable technique to tackle the problem.

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