FILM COATINGS

Studies of orange peel formation in high-speed film coating

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ABSTRACT

Misting and orange peel formation, the two dominant runnability and quality issues in high-speed film coating, originate from the film splitting of coating color in the application nip. A great deal of work has been directed at understanding misting on high-speed film coaters, but much less work has been reported on the factors that impact orange peel formation. This study is part of a more systematic evaluation of the factors controlling orange peel formation in high-speed film coating. The effect of coating color, base paper, and machine variables on the orange peel pattern has been studied experimentally.

We used Prüfbau printed strips to evaluate the degree of orange peel formation. The relationship between orange peel formation and coating variables is complex. In some cases, orange peel and misting are correlated, while in other cases, they are not. Increasing coating solids decreased both misting and orange peel formation. The degree of orange peel also depends on the speed at which the coating levels after the film splitting in the application nip.

Application:

The results of this study demonstrate some practical means to reduce orange peel formation in high-speed film coating.

METERED FILM COATING IS becoming a popular alternative to conventional blade coating of paper. Unlike a blade coater, the metered film coater has a film split of the coating color in the exit of the application nip, which may lead to misting and/or orange peel formation. These are the two dominant runnability and quality issues in high-speed film coating that limit its applicability. A great deal of work has been directed at understanding misting on high-speed film coaters, but much less work has been reported on the factors that impact orange peel formation *(1, 2)*.

We have observed instances of high levels of misting accompanied by both high and low degrees of orange peel formation as well as instances of low levels of misting accompanied by both high and low degrees of orange peel formation. This suggests that the factors controlling orange peel formation are different from those controlling misting. This study is part of a more systematic evaluation of the factors controlling orange peel formation in high-speed film coating. The objective was to investigate the influence of various coating, base paper, and machine parameters on the quality of film splitting. These are the same variables that were studied earlier for their impact on the degree of misting *(3–5)*.

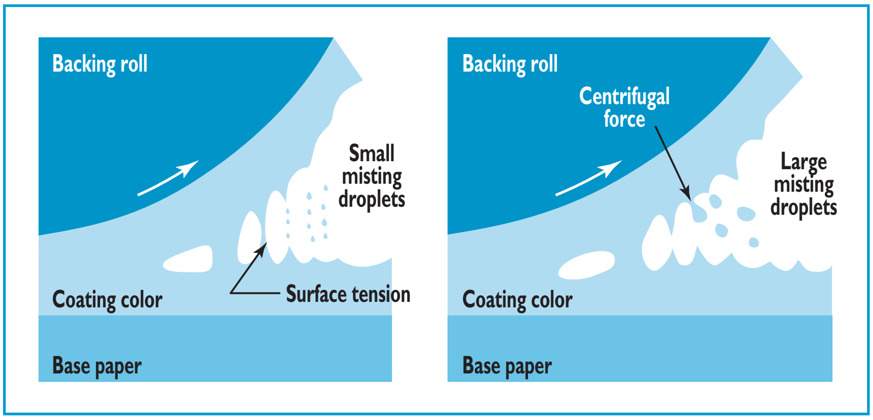
This paper starts with a discussion of the mechanisms of film splitting and how they may relate to orange peel formation. We then present experimental results from a pilot trial and try to relate those results to the mechanism of film splitting as well as any positive or negative correlations between misting behavior and orange peel formation.

ORANGE PEEL FORMATION MECHANISM

In our earlier studies, we have proposed that the film-splitting process consists of three different stages: (a) an immobilization stage, (b) a filament formation and breakup stage, and (c) a coating leveling stage. Many previous discussions *(6–11)* of misting and orange peel formation have focused only on coating immobilization without considering the mechanism of filament formation and breakup or the role of coating leveling afterward.

The generally accepted theory suggests that film splitting is determined by the thickness of the nonimmobilized coating layer as well as by the formation and breakup of filaments in the extensional flow field of the application nip. Immobilization rate (coating solids, dewatering rate, and immobilization solids), coat weight, coating elasticity, and coating viscosity have, therefore, been found to be important variables in controlling film splitting.

In the case of orange peel formation, it is important to recognize that orange peel is a function of (a) the degree of nonuniformities in the coating layer caused by the film-splitting process and (b) the degree that these nonuniformities can flow and level after the film-splitting process in the nip. Coating leveling may partially or completely eliminate the surface unevenness because of filament breakup, but leveling will not affect droplet formation. In a case of extreme coating leveling, one would therefore not expect a linear correlation between misting and orange peel formation. In this study, we will consider both the role of film splitting and the role of coating leveling on orange peel formation for high-speed film coating.



1. Filament breakup due to two types of forces

The right side of Fig. 1 illustrates an alternative mechanism for filament splitting. As coating speeds are increased, the amount of kinetic energy to be dissipated by the coating increases to the point that it exceeds the cohesive energy of the coating. This manifests itself in the form of centrifugal forces acting on the uneven coating film and causes droplets of coating color to be flung into the air or causes regions of uneven coating to become even more nonuniform at these high speeds. The unevenness of the coating can be due to broken-up filaments, surface roughness of the base paper, or uneven coating metering. According to this mechanism, the droplet formation is possible only when the centrifugal forces are higher than the surface tension that holds the filaments onto the bulk coating color. This is true when the filament exceeds a certain critical size. The critical filament size decreases as the coating speed increases, and a greater number of smaller droplets can be ejected. However, at an industrial coating speed, the droplets generated according to the centrifugal force model are expected to be an order of magnitude larger than those broken up due to surface tension forces.

One key parameter that controls misting at high speeds is the viscosity of the coating. A high viscosity serves to retard the flow of coating due to centrifugal forces and to increase the amount of kinetic energy the coating can dissipate at high coating speeds. Another key factor is the rate of coating immobilization, since this rate controls the thickness of the nonimmobilized layer that participates in filament formation. We also found that the smoothness of the base paper played a major role in the degree of misting, particularly at very high speeds (1700 m/min). Therefore, in this study, we were interested in understanding the relationship between these factors and orange peel formation as well as the relationship between misting and orange peel at high speeds. In addition, we wanted to investigate the role of coating leveling through the choice of thickener systems that differ in the degree of leveling and recovery of structure after shear.

Standard formulation	
Fine ground calcium carbonate, parts	50
English clay, parts	50
Styrene butadiene latex, parts	10
Carboxymethylcellulose (CMC), parts	1
Optical brightening agent, parts	0.1
pH	8.5
Solids, %	61
Standard operating conditions	
Base paper basis weight, g/m^2 (LWC* wood-containing base)	43
Speed, m/min	1400
Coat weight, g/m^2	13
Coating	One side at a time
Application rod diam., mm (smooth)	12
Deaerator	On
Web setting	Along steel master roll (see Fig. 2)

*Lightweight coated

I. Standard formulation and operating conditions

We believe that there are two mechanisms that operate during filament formation and breakup. These two mechanisms may occur alone or simultaneously. The left side of **Fig. 1** shows the conventional mechanism of the coating filament breakup as a result of the surface tension *(12, 13)*. The coating is extended in the outgoing nip into longer filaments until the surface tension forces break them up to small misting droplets. A recent review gives a unified view of the film-splitting process and the factors that control it *(14, 15)*. The critical parameters in this mechanism are the film thickness, coating immobilization, and coating speed along with surface tension and the viscoelastic properties, including the extensional viscosity of the coating color.

EXPERIMENTAL

These experiments were carried out at the Dow pilot coater in Horgen, Switzerland. The standard formulation and operating conditions are listed in **Table I.**

This study was carried out in two parts. The first part, using the standard formulation, looked at the effect of operating conditions and base paper parameters. The sec-

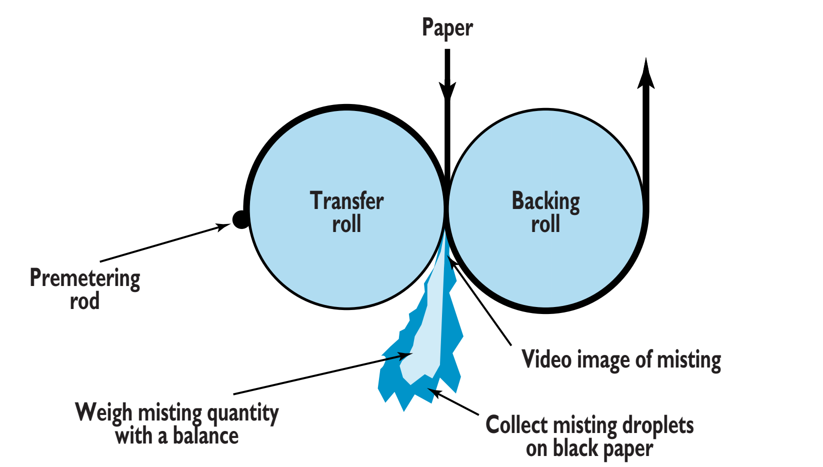
Description	Solids, %	Brookfield (100 rpm)	η at 5 s⁻¹, mPa·s	η at 5000 s⁻¹, mPa·s	G′, Pa	G″, Pa	Phase angle, °
Standard (1.0 pt. CMC[a])	61.1	3110	3190	35	148	18	7.1
High CMC (2.0 pts.)	60.7	4980	4200	71	466	64	7.8
Low CMC (0.5 pts.)	60.3	1380	1250	31	90	12	7.7
High solids (1.0 pt. CMC)	63.8	4800	4270	77	418	51	6.9
Low solids (1.0 pt. CMC)	56.6	1410	1070	24	78	12	8.4
0.3 pts. HEURASE[b] 1	61.4	2630	3840	54	163	23	8.2
0.2 pts. HEURASE 2	61.1	2140	2610	53	132	19	8.8
No thickener, high solids	64.6	510	680	34	18	5	15.3
3.0 pts. SLS[c], deaerator on	60.7	3160	2310	40	285	52	11.4
3.0 pts. SLS, no deaerator	60.7	4490	-	-	-	-	-

[a]Carboxymethylcellulose
[b]Hydrophobically modified ethoxylated urethane alkali-swellable thickener
[c]Sodium laural sulfate

II. Solids and rheological data for coating formulations

ond part looked at the effect of formulation parameters at constant (standard) machine conditions. The variables in this study included the following:

- coating solids (57–64%)
- carboxymethylcellulose (CMC) level (0–2 parts)
- two types of hydrophobically modified ethoxylated urethane alkali-swellable (HEURASE) thickeners
- smooth vs. grooved metering rod
- web path around backing roll and air turn
- calendered and uncalendered base paper
- deaerator on and off.

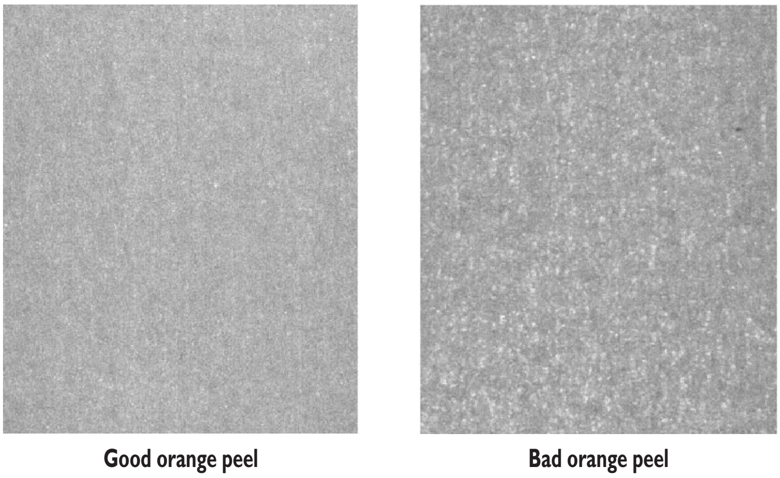


2. Observing misting during trials

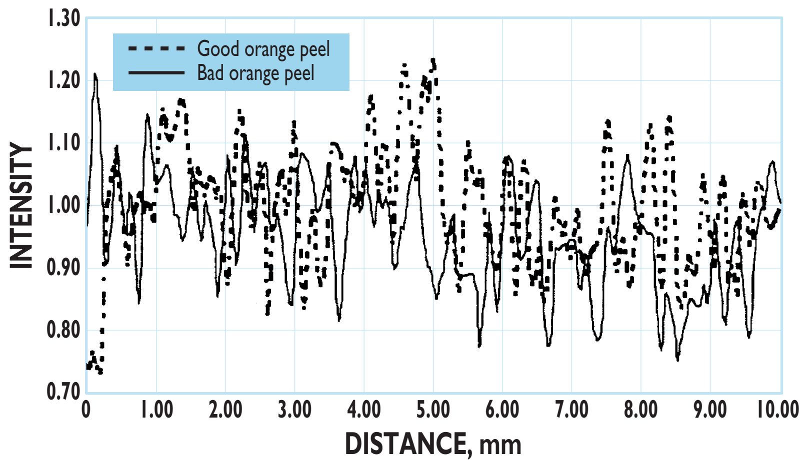
Some of the formulation and rheological parameters for the coatings are given in **Table II.** The steady shear and viscoelastic properties were measured using a 1 degree 75 mm cone and plate geometry on a Physica UDS 2000 rheometer. The storage modulus (G') and loss modulus (G'') were measured in Pascals at 1% strain at a frequency of 1 Hz.

Both degree-of-misting (**Fig. 2**) and orange-peel-formation data were collected. The misting data were obtained as previously described *(3, 4).* Droplets were collected on black paper, and their size distributions were measured. The impact of film splitting on coated surface nonuniformity was assessed by ammonium chloride burnout testing and Croda Red staining (1 min and 2 min data) as well as by Prüfbau print strips. These samples were then visually ranked by a panel of judges. The printed Prüfbau samples were ranked by ten judges using an all-pairs Thurston *(16)* comparison procedure to establish a numerical scale for the degree of orange peel formation. In this procedure, each sample was compared with every other sample, and the judges selected which sample was the worse of the pair. This analysis was used to construct a scale for orange peel ranging from 0 to 5. The best sample in the data set was assigned a value of 0, while the worst one was assigned a value of 5. On this scale, a difference of 0.6 units is statistically significant based on the replicate samples included in the analysis.

Image analysis was carried out on the stained and printed samples using a flatbed scanner (600 dpi resolution) and a commercial software package. A quality index based on the square of the standard deviation of variation divided by the mean value was calculated from the image analysis data *(17).* These image analysis results were then compared to the Thurston rankings. In addition, a stepwise multivariate regression analysis was carried out between the Thurston orange peel rankings and



3. Examples of Prüfbau printed strips



4. Image analysis profile for Prüfbau samples

several process and rheological parameters to try and discover which parameters correlated best with orange peel formation.

RESULTS AND DISCUSSION

Assessment of orange peel

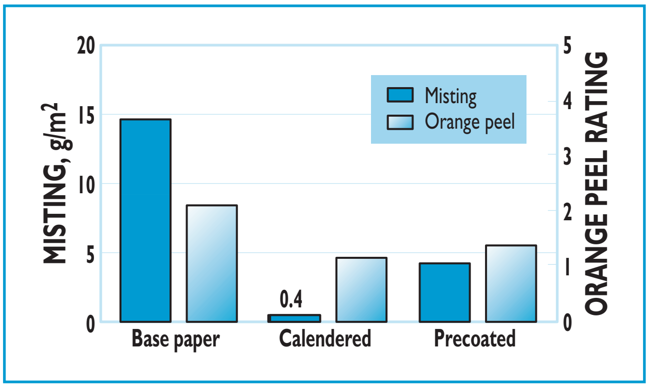
The degree of orange peel formation was assessed in several different ways. An ammonium chloride burnout test (BOT) was carried out on uncalendered coated samples and analyzed using a procedure described in the literature *(18)* for determining variations in coat weight distributions. We hoped that the nonuniformity of the coating layer due to film splitting would show up as nonuniform coat weight distributions in the BOT and that this could be correlated to orange peel formation. We found a good linear response of the average intensity of the BOT samples to coat weight, indicating that the test was indeed picking up coat weight variations. However, there was no correlation between these coat weight variations and the ranking of orange peel determined from the print samples. Likewise, the Croda Red stains also show coating nonuniformities, but the Croda visual rankings did not correlate with either the BOT results or with the ranking of the printed samples.

The visual evaluation of Prüfbau printed strips was chosen as the best method for determining orange peel. **Figure 3** shows an example of a "good" and "bad" orange peel pattern. As described earlier in "Experimental," a Thurston all-pairs analysis was used to rank the degree of orange peel for the Prüfbau printed samples. These Thurston rankings were compared with the results from the image analysis, but there was no correlation between the two methods of analysis.

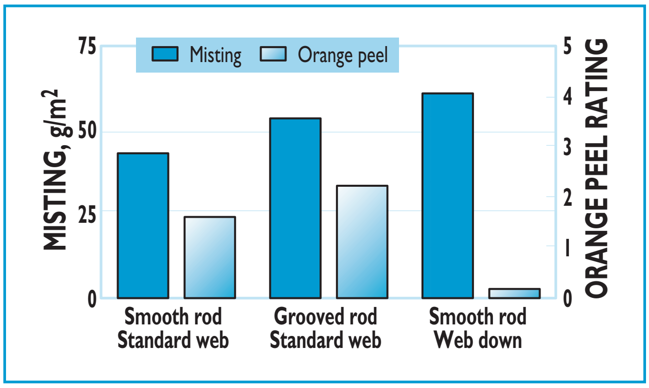
Figure 4 shows a normalized intensity scan over 10 mm for the two samples shown in Fig. 3. Note that the amplitude of variation in intensity is similar for the two samples. One slight difference is the wavelength scale of the variation in intensity. The "good" sample has a smaller wavelength scale (approximately 0.1–0.2 mm) than the "bad" sample, which has a wavelength scale of approximately 0.2–0.5 mm. Some attempts were made to conduct a Fourier analysis and filtering by wavelengths to improve the correlation between the visual rankings and the image analysis with limited success. Taken together, these results suggest that orange peel is a two-dimensional defect that will require more sophisticated image analysis techniques to find the right correlation between the image parameters and the visual ranking. For the remainder of this paper, the discussion is based only on the Thurston rankings of the Prüfbau printed samples.

Effect of base paper and machine parameters

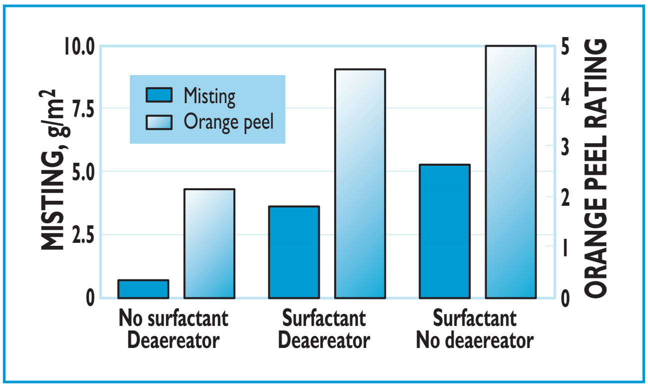
The effect of several base paper and machine parameters was evaluated using the standard coating formula-

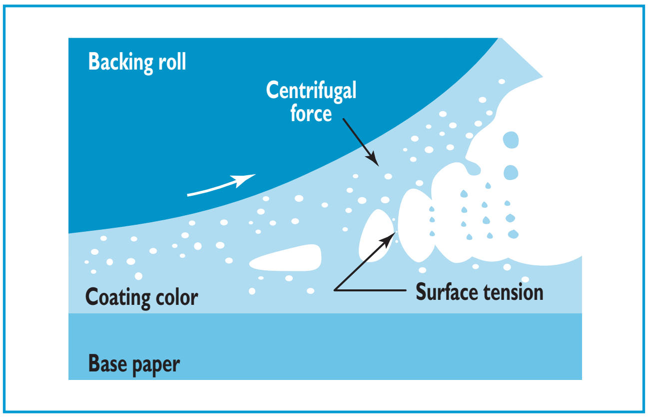


5. Effect of base paper on misting and orange peel



6. Effect of grooved rod and web configuration





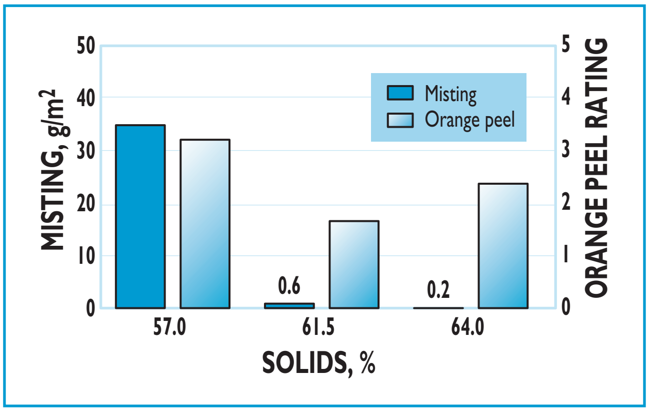
tion. In our earlier work *(4),* we showed that a smoother base paper can reduce misting at high speeds. In this study, we again investigated the impact of precalendering and precoating of the base paper on misting and orange peel formation. The base paper in this study was a 43 g/m^2 wood-containing lightweight-coated (LWC) base. Stylus profilometry was done on uncalendered and calendered samples to determine the surface roughness. The uncalendered base paper had a roughness of 4.7 µm on the wire side and a roughness of 3.3 µm on the felt side. After calendering, the felt side had a roughness of 2.8 µm. These numbers compare favorably with Parker Print Surf values of 4.5 µm (wire) and 4.2 µm (felt) for the uncalendered sample, and 2.8 µm for the calendered felt side.

As shown in **Fig. 5,** there is a reduction in both misting level and orange peel formation for the precalendered as well as the precoated paper. The explanation for this is a reduction in the unevenness of the coating film after the film split. This in turn reduces the impact of centrifugal forces, leading to droplets of coating color being flung into the air and back to the paper surface. The difference in misting between the calendered and precoated papers may be due to differences in the degree of coating immobilization due to dewatering.

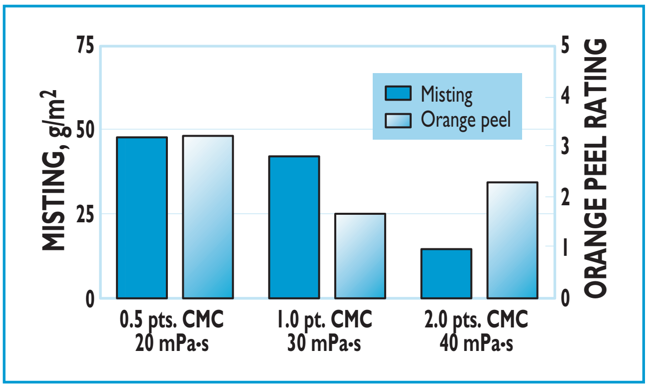
Figure 6 compares the standard conditions against grooved rod application and setting the web to run straight down from the nip, not around the steel backing roll. Compared to the smooth rod, the grooved rod appears to have a negative effect on both misting and orange peel formation. This result agrees with the proposed model, which suggests that surface unevenness caused by uneven coating metering can result in misting and orange peel.

The result for the web configuration is even more interesting, but not fully understood. We believe that the increase of misting when running the web straight down is primarily caused by the instability and irregularity of the film splitting when the web is not supported by the steel backing roll. Interestingly, this was one of the few samples that exhibited a bimodal misting droplet size distribution with the appearance of larger droplets. On the other hand, the favorable orange peel effect of running the web straight down may be explained by the lack of centrifugal forces acting on the coating layer on the base paper.

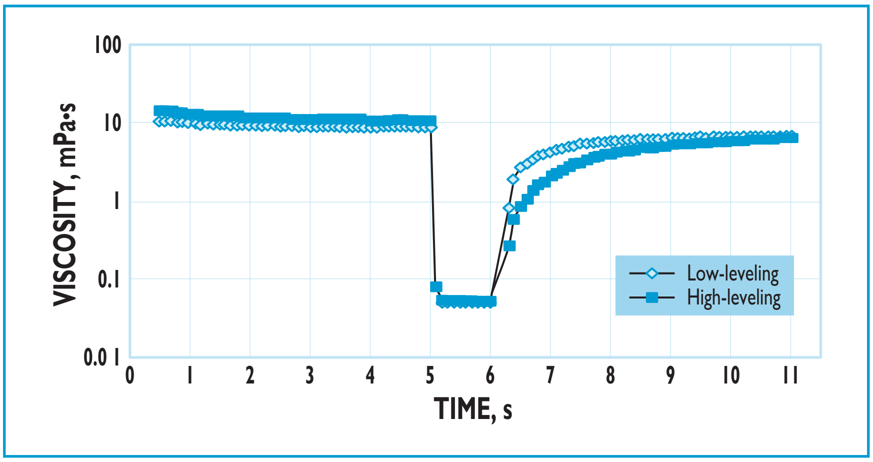
The effect of air on coating color was studied by blending three parts of foam-generating surfactant into the standard coating color and by not deaerating the coating color. These modifications caused the coating density to drop from the standard level of about 1400 kg/m^3 first to 900 kg/m^3 and further to 700 kg/m^3. The effect of dispersed air appears to be



9. Effect of solids on misting and orange peel



10. Effect of CMC level on misting and orange peel



11. Step shear experiment

detrimental to both misting and orange peel formation, as shown in **Fig. 7.** In fact, some of the worst orange peel patterns were observed in the high-air-content, low-density coatings.

We believe that the air-coating interfaces in the coating color accelerate misting and orange peel formation because of (a) easier breakup of filaments into small droplets due to surface tension forces and (b) the centrifugal forces more easily ejecting large droplets into the air. Putting it simply, the air weakens the coating color so that the effects of surface tension and centrifugal forces become even more important. This is illustrated in **Fig. 8.** Another factor to consider is that in the outgoing nip, the coating experiences a negative pressure pulse. The rapid expansion of an entrained air bubble could contribute to the nonuniformity of the coating surface, resulting in increased orange peel as well as increased filament breakup—which leads to misting.

Effect of formulation parameters

In our earlier work, we found that formulation parameters, such as coating solids and thickener level and type, influence the degree of misting. **Figure 9** shows the effect of coating solids on misting and orange peel formation.

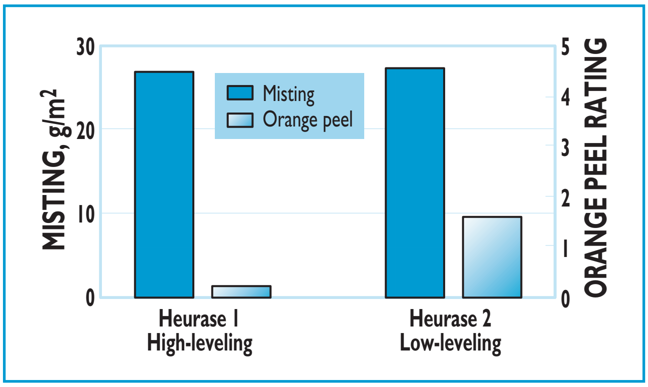
Consistent with past results, we again found a very positive effect of increasing coating solids. Misting is almost completely eliminated, and the orange peel ratings improve. We believe that two simultaneous mechanisms explain the positive effect of increasing the coating solids. The first is that high coating solids obviously minimize the thickness of the wet coating layer at the exit of the coating nip due to faster immobilization. The second explanation for the positive effect of coating solids is related to the role of viscosity in the proposed centrifugal force model. At constant thickener addition level, the higher solids level increases coating viscosity. With increasing coating viscosity, the rate of droplet ejection due to centrifugal forces will decrease because of the viscous drag and greater cohesive energy of the coating.

The role of viscosity can also be studied by changing the thickener addition level. Here we investigated the effect of CMC addition level on high-shear viscosity at 5000 s^{-1} as well as on misting and orange peel (**Fig. 10**). Note that a higher thickener level will also affect film splitting because of the effect on coating immobilization. However, the general decrease of misting and orange peel at higher thickener level suggests that the effect cannot be due to differences in immobilization rate because the effect should then be in the opposite direction. Therefore, we conclude that the effect of thickener level is best explained by the proposed role of viscosity in the centrifugal force model.

In reviewing the orange peel results, note that an increase of CMC level from 1 to 2 parts causes a slight but significant increase in orange peel despite the positive effect on misting. We believe that this result is explained by the slowing effect that the high CMC level may have had on coating leveling after the film splitting.

To further investigate the role of leveling on orange peel formation, we prepared coatings containing two different associative HEURASE thickeners. One of them was known to provide fast leveling, whereas the other was more elastic and resulted in slow leveling. The addition levels were adjusted to give similar viscosity and coating immobilization rate. The relaxation properties of these coatings were studied by two rheological experiments. The first was a stress relaxation measurement. The coating with the higher leveling had a stress relaxation time of 0.44 seconds, while the coating with lower leveling had a stress relaxation time of 0.63 seconds. For blade coatings, it has been shown that high stress relaxation times correlate with wider streaks as a result of less leveling after the blade *(14).*

The second rheological measurement was a step shear experiment to simulate the effect of sudden high shear on the coating followed by recovery. The coating is first sheared at a low 1-s^{-1} shear rate for 5 seconds. Then the shear rate is stepped to 5000 s^{-1} for 1 second followed by a return to the low shear rate. **Figure 11** shows how the two coatings respond to the step shear experiment. The low-leveling coating recovers its viscosity much faster and almost returns to the original viscosity during the time of the experiment. The high-leveling coating instead recovers its viscosity more slowly and is still not back to the original viscosity by the end of the experiment.



12. Effect of leveling

Figure 12 shows the misting and orange peel results for the two HEURASE thickeners. Misting of the two coating colors was identical, probably reflecting the similar viscosity and dewatering profiles. On the other hand, the orange peel rating of the associative thickener with higher leveling capacity was better. This result shows that it possible to optimize orange peel independently of the viscosity and immobilization properties of the coating.

Multivariate regression analysis

Once a numerical scale had been established for orange peel, we then tried to correlate it with various process, rheological, and coating parameters through the use of a stepwise multivariate analysis. Only data from coatings containing CMC were used. The factors that we considered were coating solids, coat weight, base paper parameters, low- and high-shear viscosities, storage and loss modulus, level of misting, misting droplet size, and image analysis results. The only parameters that were statistically significant were coating solids, coat weight, and base paper roughness. These factors, however, explained only 60% of the variation in the data set. The contribution of coat weight, though statistically significant, was small. This is probably because of the relatively narrow coat weight range for the samples (12.8–14.3 g/m^2). Likewise, the effect of base paper roughness was small. The only statistically significant variable with a large influence on orange peel was coating solids. This result is in agreement with the many results reported by us and others on the positive impact of higher coating solids on reducing orange peel.

The results of this regression analysis are different from our earlier analysis of misting *(3),* where there was a good correlation between coating and rheological parameters with the degree of misting. The failure of the regression analysis to find significant correlations with the rheological and process parameters further highlights the complicated nature of orange peel formation. In part, this must be due to the fact that orange peel depends both on the film-splitting process as well as on the leveling of the coating after the application nip. Future studies should include measurements of the relaxation parameters of the coatings as part of any regression analysis.

SUMMARY AND CONCLUSIONS

The prevention of orange peel arising from film splitting in the application nip is one of the key quality issues in the application of film coating technology. This study experimentally examined the effect of coating color, base paper, and machine variables on orange peel formation. Our key conclusions are as follows:

- The relationship between orange peel formation and coating variables is complex. Coating process, base paper, and formulation variables all impact orange peel.
- We believe that the proposed theory of film splitting provides a sufficient basis to understand most of the experimentally

observed effects of machine and formulation variables on misting and orange peel formation.

- In most cases, there is a positive correlation between misting and orange peel. In other words, factors that reduce misting at high speed also seem to reduce the degree of orange peel formation. These factors include higher coating solids, higher coating high-shear viscosity, and smoother base paper.
- The degree of coating flow and leveling after the nip also appears to be important. We have shown that a coating formulated with a thickener having a slower recovery of viscosity after shearing gives better leveling and lower orange peel formation.

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LITERATURE CITED

1. Glittenberg, D., *Wochenbl. Papierfabr.* 126(4): 134(1998).
2. Triantafillopoulos, N. and Lee, D., *TAPPI 1996 Metered Size Press Forum Proceedings,* TAPPI PRESS, Atlanta, p. 171.
3. Salminen, P., Roper III, J., Urscheler, R., *et al., TAPPI 1996 Metered Size Press Forum Proceedings,* TAPPI PRESS, Atlanta, p. 51.
4. Roper III, J., Urscheler, R., Salminen, P., *et al., TAPPI 1997 Coating Conference Proceedings,* TAPPI PRESS, Atlanta, p. 1.
5. Salminen, P., Urscheler, R., Roper III, J., *et al., 1997 Papiertechnische Stiftung Conference Proceedings,* in press.
6. Trefz, M., *Tappi J.* 79(1): 223(1996).
7. Letzelter, P. and Eklund, D., *TAPPI 1996 Coating Conference Proceedings,* TAPPI PRESS, Atlanta, p. 269.
8. Hiorns, A., Oak, G., Coggon, L., *et al., TAPPI 1996 Metered Size Press Forum Proceedings,* TAPPI PRESS, Atlanta, p. 161.
9. Drage, P. and Hiorns, A., *TAPPI 1996 Metered Size Press Forum Proceedings,* TAPPI PRESS, Atlanta, p. 135.
10. Gron, J., Nikula, E., and Sunde, H., *TAPPI 1996 Coating Conference Proceedings,* TAPPI PRESS, Atlanta, p. 261.
11. Gron, J., Nikula, E., and Sunde, H., *TAPPI 1996 Metered Size Press Forum Proceedings,* TAPPI PRESS, Atlanta, p. 21.
12. Taylor, J. and Zettlemoyer, A., *Tappi* 41(12): 749(1958).
13. Rayleigh, L., *Proceedings of the London Mathematical Society,* London Mathematical Society, London, 1879, p. 4.
14. Macphee, J., *American Ink Maker* 75(1): 42(1997).
15. Macphee, J., *American Ink Maker* 75(2): 51(1997).
16. Thurston, L. L., *The Measurement of Values,* University of Chicago Press, Chicago, 1959, pp. 67–81.
17. Schweizer, P. in *Liquid Film Coatings,* Chapman & Hall, London, 1997, Chap. 5.
18. Engstrom, G. and Morin, V., *TAPPI 1995 Coatings Fundamentals Symposium,* TAPPI PRESS, Atlanta, p. 41.