Effect of Excess Air Foil Length on Mottle

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Abstract

Many industrial ovens are designed using air bars and air foils that supply drying gas against the backside of the coated substrate. See for example Shu.[1] The purpose of these devices is to heat the substrate in order to cause evaporation of a carrier solvent and to provided substrate flotation. Typically, the air bars and foils are installed in one standard width in a given oven, while the coated substrate may take on a variety of widths depending on the product. If the air bars or foils are wider than the substrate, high velocity or turbulent air flow can result at the edge of the coated film. When the coating is susceptible to mottle, drying patterns can result at the edge which do not occur in the center. This paper will present some experimental data demonstrating this excess air foil effect on mottle. It will also describe smoke tests performed to better understand the phenomena and some simple theories to explore the mechanism behind the effect.

Drying Experiments

A series of drying experiments were performed on photothermographic coatings with the objective of minimizing mottle. The coatings were applied onto a 19 inch wide substrate and then dried in an oven with the configuration shown in Figure 1. This oven consisted of air foils below the substrate and air bars above it. The top side air bars were retracted from the substrate surface in order to minimize the disturbance on the coated surface. The pressure was maintained at 0.5 and 0.1 inches H_2O in the air foils and bars respectively. For some of the trials, the excess air foil slot beyond the substrate was covered with tape in order to prevent air flow from this region of the slot. Gray images, prepared from the coatings at an average optical density of 1.2, were visually evaluated for mottle (Table 1).

The center of the substrate always had a low level of mottle. When there was no tape covering the excess air foils length, the last few inches near the edge of the substrate had a much higher degree of mottle. When the same end of each air foil slot was taped closed, that edge of the image had mottle levels equivalent to the center, while the opposite edge still had a high level of mottle. Furthermore, taping closed both excess ends of the air foil slot resulted in an image with the same uniformly low level of mottle throughout. The solution to avoiding edge mottle is therefore to cover, or deckle, the excess length of the air foil extending beyond the substrate.[2] This technique should be important not only for air foils, but for air bars, perforated plate, air turns, or any other source of high velocity air that is wider than the substrate and is primarily directed at the backside of the coating.

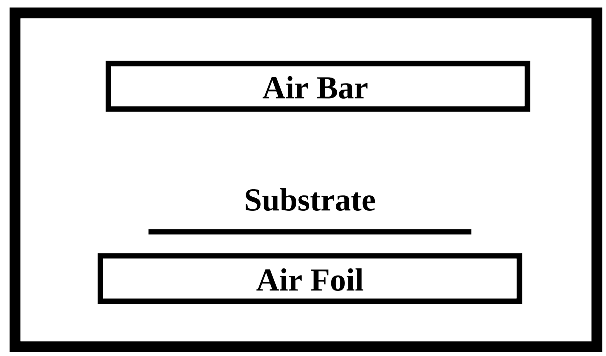

Figure 1. Oven configuration for edge mottle experiments.

Table 1. Edge Mottle Observations

Trial	Tape on Left Edge	Tape on Right Edge	Mottle Observations
1	No	No	Heavy on both edges
2	Yes	No	Heavy on right edge only
3	Yes	Yes	Light mottle throughout film

Smoke Observations

The environment at the edge of the coated substrate was simulated in the lab using an air knife and a flat aluminum plate. As shown in Figure 2, the plate was set over the top of the air knife in a manner such that that the flow of air from the knife was essentially parallel to, but slightly impinging on the plate. This was done to insure that the high velocity air flow was present at the edge of the plate. The plate was moved relative to the air knife to simulate different distances of excess air foil length. Smoke was created by pouring liquid $TiCl_4$ onto the plate. The reaction of this liquid with air created a visible smoke above the plate. The fumes were collected by an exhaust duct placed far enough away that it did not significantly affect the air flow over the plate and air knife. The air velocity from the knife was measured to be ~ 1500 ft/min at the slot exit and ~1000 ft/min at a distance of 3 cm away.

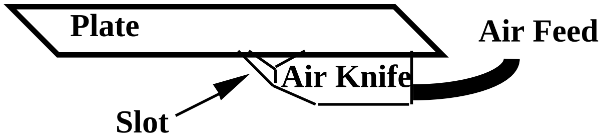

Figure 2. Smoke test experimental set-up.

A summary of the smoke test data is shown in Table 2. When there was no flow from the air knife, smoke injected above the plate simply drifted very slowly towards the exhaust. Turning on the air flow, but keeping it completely covered by the plate, resulted in a similar drifting airflow pattern. However when high velocity air was exposed at the edge, smoke over the plate moved quickly towards this air flow at edge of the plate. It also had a component of flow in the direction of the high velocity air flow so that it moved at an angle to the edge that was not perpendicular. Doubling the exposed air flow length tended to increase the flow rate of smoke towards the edge. For some of the experiments, there appeared to be turbulence in the smoke flow. This turbulence was close to the plate surface and at the edge of the plate. It appeared as a swirling or pulsing in the smoke cloud as it was being pulled off from the edge of the plate into the high velocity air stream.

Table 2. Smoke Test Observations

Trial	Air Flow	Excess Air Length	Smoke Movement
A	Off	-	drifting
B	On	0 cm	drifting
C	On	2.5 cm	towards edge
D	On	5.0 cm	more strongly towards edge

Mechanism

One postulated mechanism for the edge mottle is that the high velocity air flow at the edge of the substrate induces air flow from the center of the substrate towards the edge. This air flow is the highest at the edge and likely of large enough magnitude that it causes mottle. A second possible mechanism is that the difference between the air velocity above the substrate and off the edge of the substrate causes a Kelvin-Helmholtz instability. This turbulent disturbance grows to the point where mottle occurs at the edge.

Bernoulli Flow

Movement of air at different velocities in two locations can result in a pressure difference between these locations. For an inviscid, incompressible fluid, the Bernoulli Equation is be used to describe the physics and takes the following form:[3]

$$\Delta p = 1/2\, \rho\, (v_1^2 - v_2^2)\ .$$

Here, Δp is the pressure difference between the locations, ρ is the density of air, and v_1,v_2 are the velocity values. For a typical case, the velocity of air off the edge of the substrate, v_1, can be taken as the velocity of air out of the air foil, or approximately 1000 ft/min. The air velocity above the substrate, v_2, can be taken to be the velocity of the substrate, or about 100 ft/min. The pressure difference between the area above the substrate and just off the edge of the substrate would then be approximately 0.05" H_2O. This is sufficient pressure drop to induce air flow between the two locations. Applying the Bernoulli equation again suggests the air velocity at the edge of the substrate would be on the same order as that exiting the air foil. Air flow rates of this magnitude tend to cause mottle.

Kelvin-Helmholtz Instability

When two streams of different velocity or density come into contact, there is a natural instability between them as illustrated in Figure 3. The entire class of these unstable mixing flows are referred to as Kelvin-Helmholtz instabilities. Linear instability analysis[4] for the case illustrated in Figure 3 shows that the interface will be unstable whenever the velocities are not equal ($v_1 \neq v_2$). These types of flows have been the study of numerous experimental and theoretical investigations.[5-8] The experimental studies by Brown and Roshko[5] have shown that the growth rate of disturbance depends on a dimensionless ratio of the two velocity components,

$$\lambda = | v_1 - v_2 | / (v_1 + v_2)\ .$$

They published growth rates for a range of λ values.

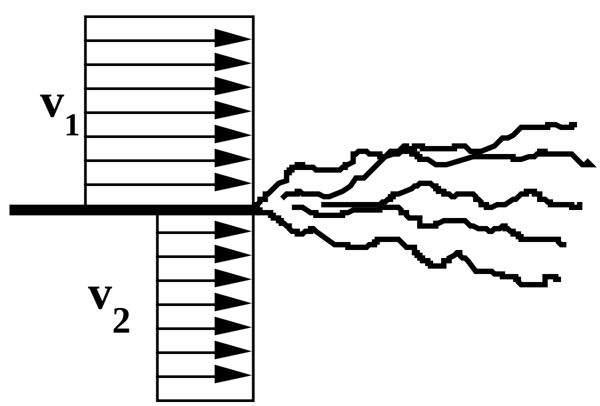

Figure 3. Kelvin-Helmholtz plane mixing instability.

If one considers the situation at the edge of the substrate, Figure 4, it is a version of the Kelvin-Helmholtz problem with different velocities. For the typical situation described above for Bernoulli Flow, a value of 0.81 can be calculated for λ. The corresponding growth rate of a disturbance would be approximately 0.28 based on the data presented in Brown and Roshko. For 10 cm (approximate width of an air foil), an initially small disturbance would grow to approximately 2.8 cm in size. For subsequent air foils, the disturbance may preexist and could grow even larger. Furthermore, if the air velocity out of the air foil is higher than 1000 ft/min, the disturbance would grow faster.

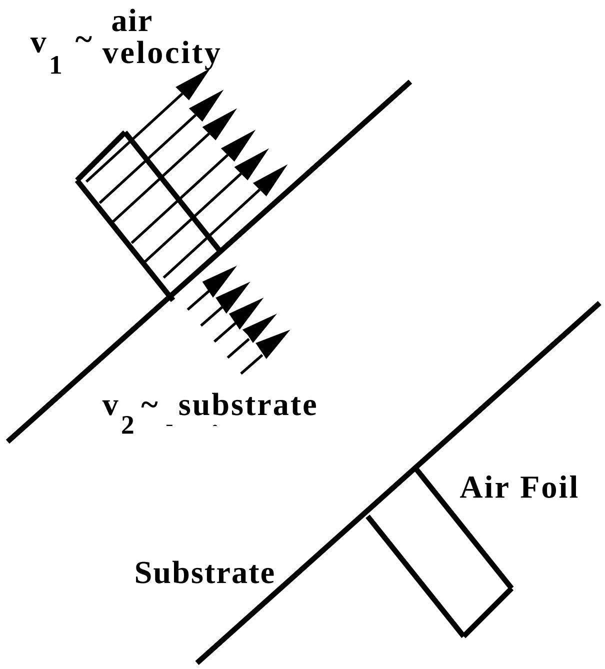

Figure 4. Kelvin-Helmholtz problem as it occurs in oven using air foils.

A Kelvin-Helmholtz instability is likely occurring in the air flow at the edge of the substrate. The turbulent or pulsing smoke flow is probably a demonstration of its existence. Furthermore, the disturbance is likely to grow to a size where it can cause mottle at the edge of the coated film. The fact that the disturbance does not grow to cover the entire width of the film could be explained by the fact that the high air velocity flow is not persistent. As the substrate moves between air foils, the air velocity drops considerably. Also, the width of the high velocity air is not infinite but equal only to the width of the excess air foil length beyond the substrate, which may limit the size of the unstable area.

Conclusions

Air foils that extend beyond the width of a substrate can cause mottle at the edge of coatings which are susceptible to mottle. Smoke tests demonstrated that air flow was induced towards the edge of the coating when there was excess air foil length beyond the edge. Also, smoke behavior suggested that there was turbulent flow at the edge of the coating. Finally, two theories were put forth to explain the induced air flow and edge turbulence, either of which may be responsible for the edge mottle.

Acknowledgments

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