A general route to reduce pinhole defects in paint coating on glass substrate

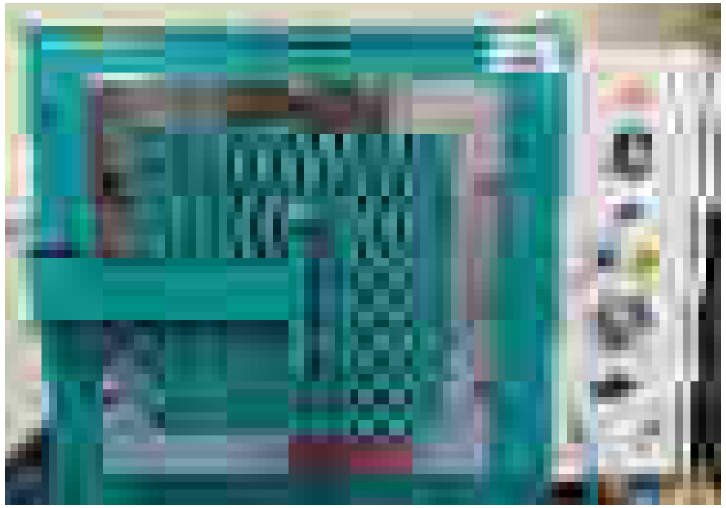
Work Updates

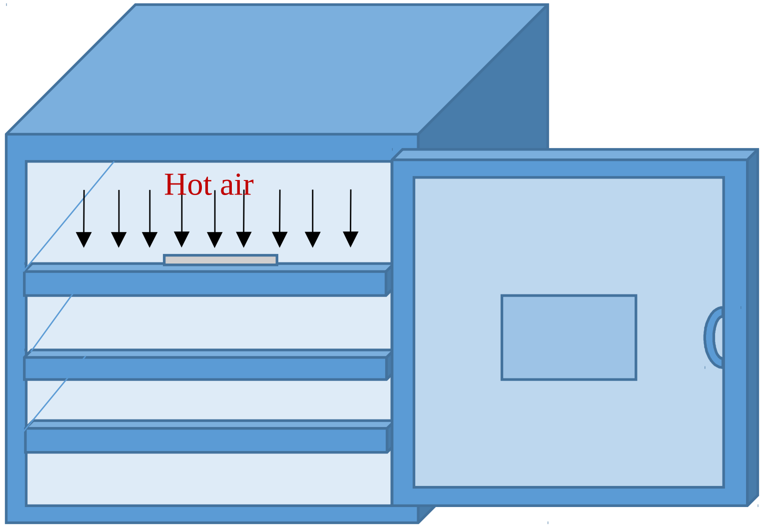
June 2025

Outline

- Introduction
- Method of drying the coating - Top/Bottom heating
- Major parameters affecting the pinhole formation
  - Heating rate
  - Flash-off time
  - Substrate pre-heating temperature
  - Coating speed
  - Thickness
  - Substrate geometry
- Image processing of pinholes
- Conclusion

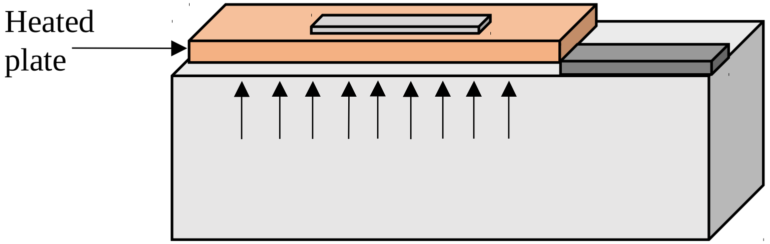
Top and bottom heating methods





Can control the heating rate

Top heating in hot air oven (RT - 80°C)



Bottom heating on hot plate (RT - 80°C)

Digital videos of bottom heating

Digital videos of bottom heating at 60°C, and 80°C

Calculation of Peclet number

Peclet number is a class of dimensionless numbers relevant in the study of transport phenomena in a continuous medium. It is defined to be the ratio of the rate of advection of a physical quantity by the flow to the rate of diffusion of the same quantity driven by an appropriate gradient.

If Pe >> 1, then the system displays skinning and large discontinuities in volume fraction are expected
If Pe << 1, diffusion is strong and uniform particle profiles are expected

The particle of radius with diffusion coefficient are contained in a film of initial thickness H and the top surface reduces at a evaporative rate E.

Evaporative time   - H/E

Diffusive time - /

Peclet number   -HE/

Also for colloidal particles the Stokes-Einstein diffusion coefficient,

Where,   - solvent viscosity

k   -Boltzmann's constant

T   - absolute temperature in Kelvin

Also;

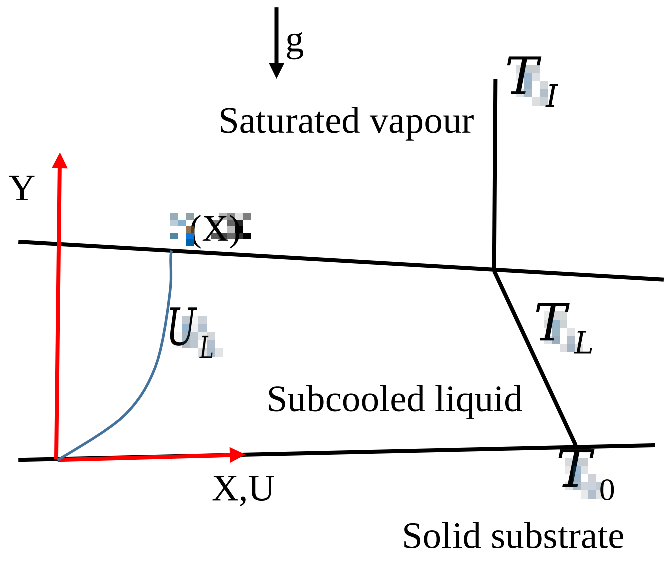
$$\text{Peclet number} = \frac{6\pi\mu R_0 HE}{kT}$$

Calculation of evaporation velocity

For a horizontal substrate facing upward, the horizontal velocity of evaporation from the horizontal film, as given by GSH Lock (1996), is

where the Jacob number, , is the ratio of sensible heat to latent heat, the Rayleigh number, , is the ratio of buoyancy to dissipative effects, with the subscript denoting property values of the vapour, L s the length of the film, λ is the latent heat of vaporisation, and are the temperature and density differences between the liquid surface and the ambient, is the specific heat at constant pressure, α is the thermal diffusivity, is the kinematic viscosity and ρ is the density. By continuity, the vertical evaporation velocity is then

=



Using the following properties of acetone vapour, C_{pv}=1263 $Jkg^{-1}K^{-1}$, ν_v =0.53×10^{-5} Nsm^{-2}, ρ_v=2 kgm^{-3}, λ_v =534×10^3 Jkg^{-1}, β =2887 ×$10^{-6}K^{-1}$, ΔT =55K, α_v=0.000124 m^2s^{-1} and the mean length of the film L=70 mm, we obtain

$$Ja = C_{pv}\Delta T/\lambda_v$$

$$= 0.130$$

$$Ra = g\left(\frac{\Delta\rho}{\rho_v}\right)L^3/\nu_v\alpha_v$$

$also, Ra = g\beta\Delta T L^3/\nu_v\alpha_v$

Where β is the coefficient of thermal expansion

Ra = 812538

Evaporative velocity, V_e= 5.26×10^{-3} m/s

For a particle radius of 100 nm contained in a film of initial thickness 1mm and an evaporative rate of V_e= 5.26×10^{-3} m/s

Then the **Peclet number, Pe = 2.15×10^4**

Parameters affecting the pinhole formation

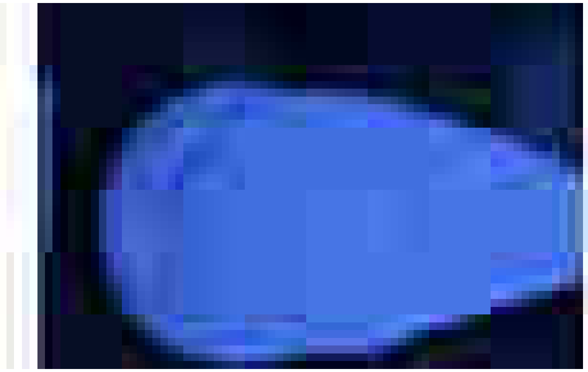
- Heating rate
- Flash-off time
- Substrate pre-heating temperature
- Coating speed
- Thickness
- Substrate Geometry

Image processing to study pinhole defects

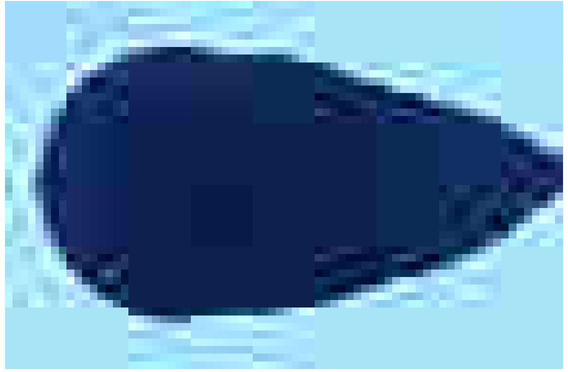
Front Lighting

Imaging from Bottom

Imaging from Top



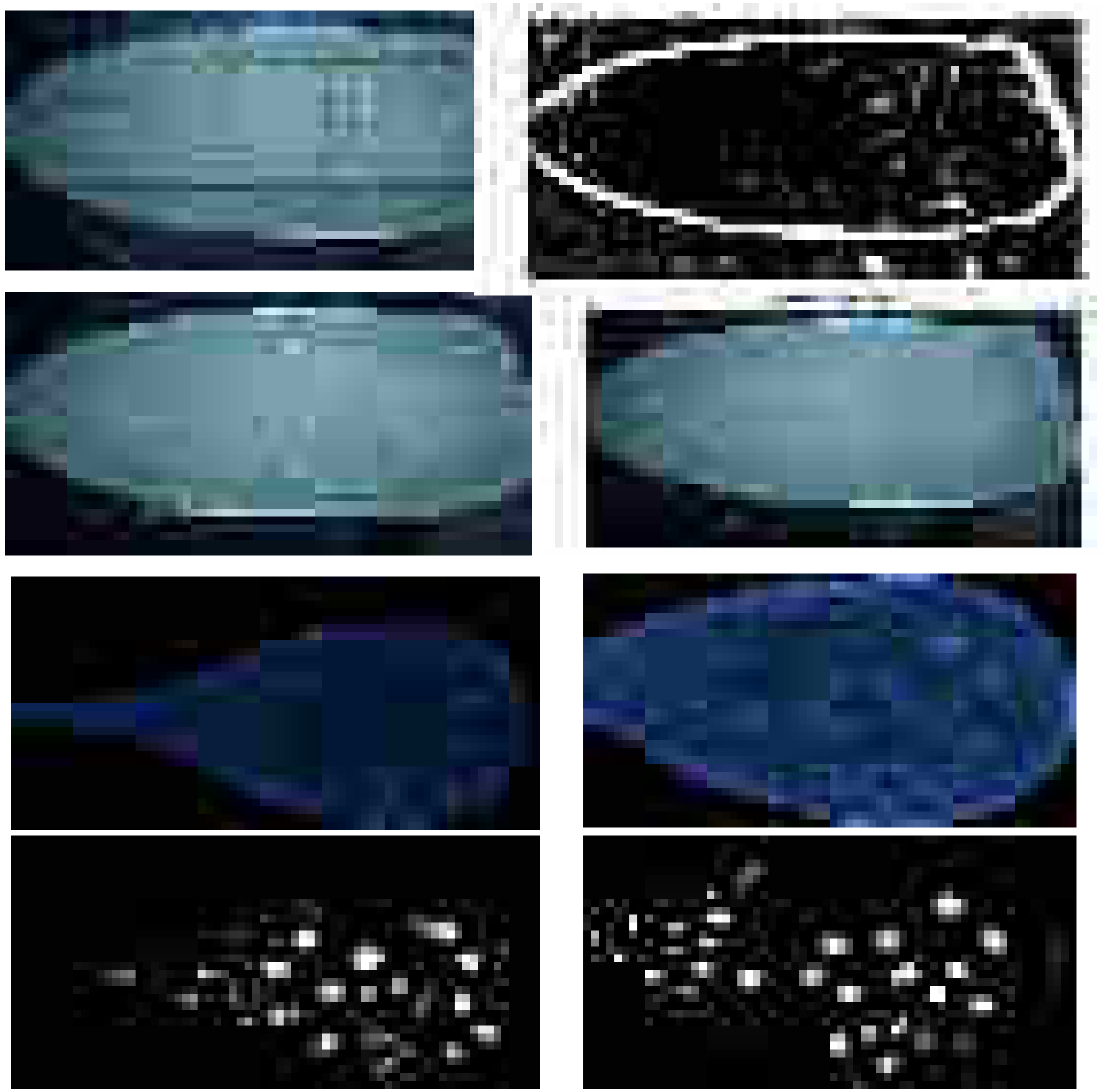
Back Lighting



Imaging from Bottom

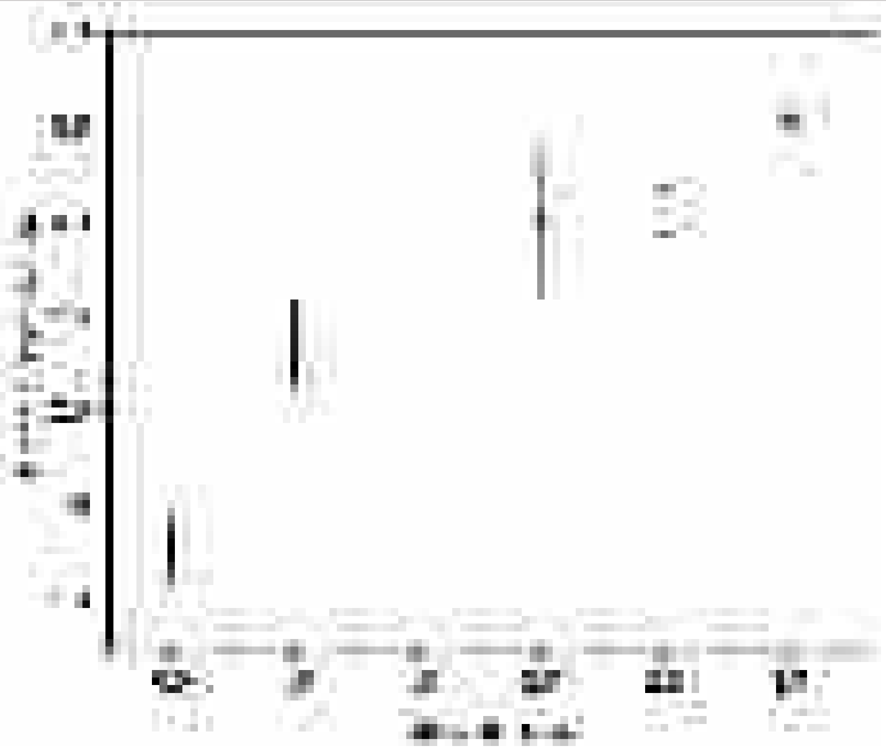
Imaging from Top

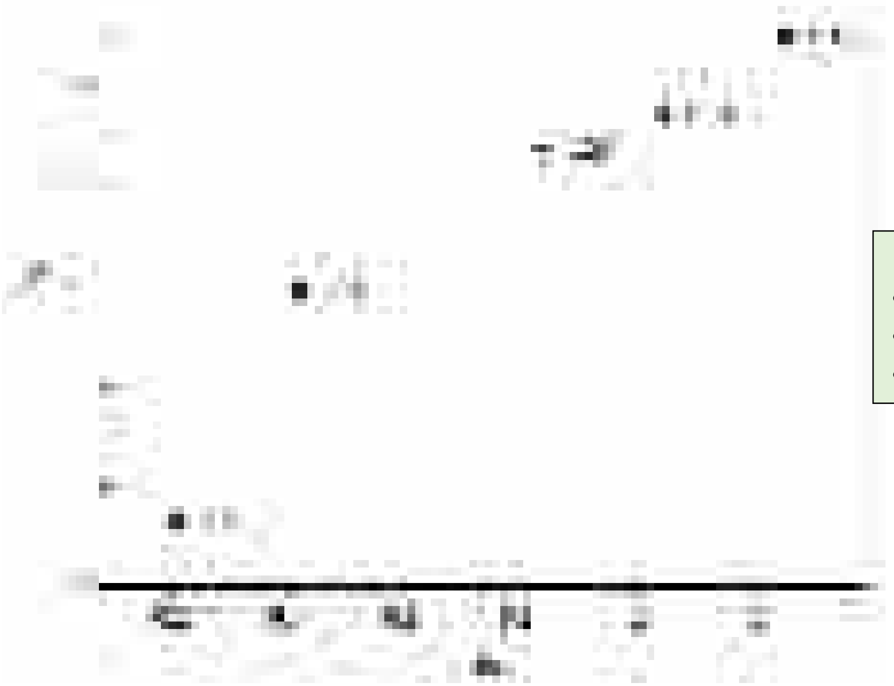
Top-side imaging allows for analysis of open pinholes, while bottom-side imaging enables study of both open and closed pinholes.



Images showing pinhole detection for image processing

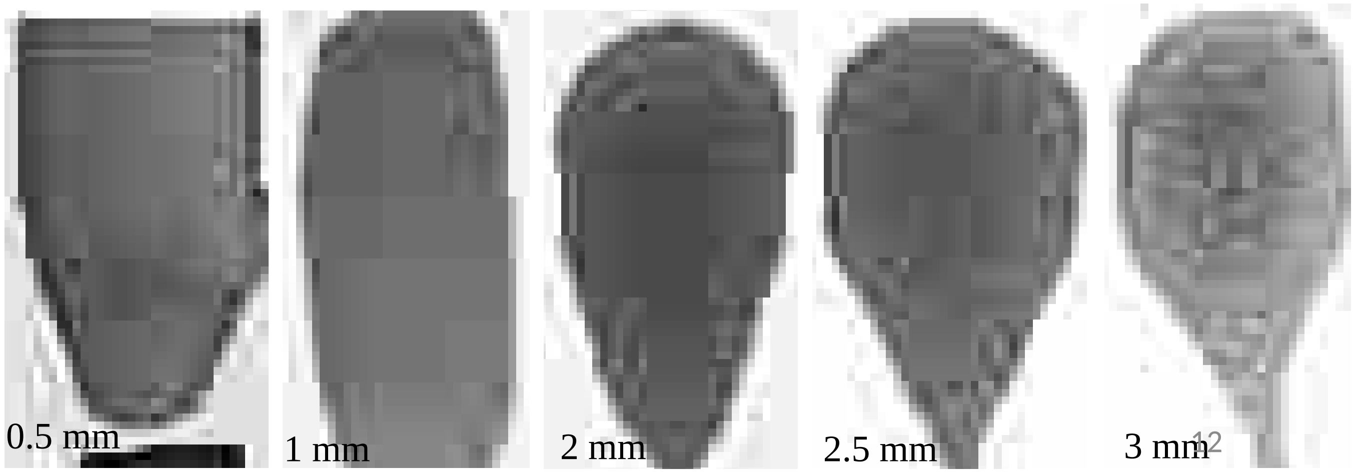
Effect of coating thickness on pinhole defects





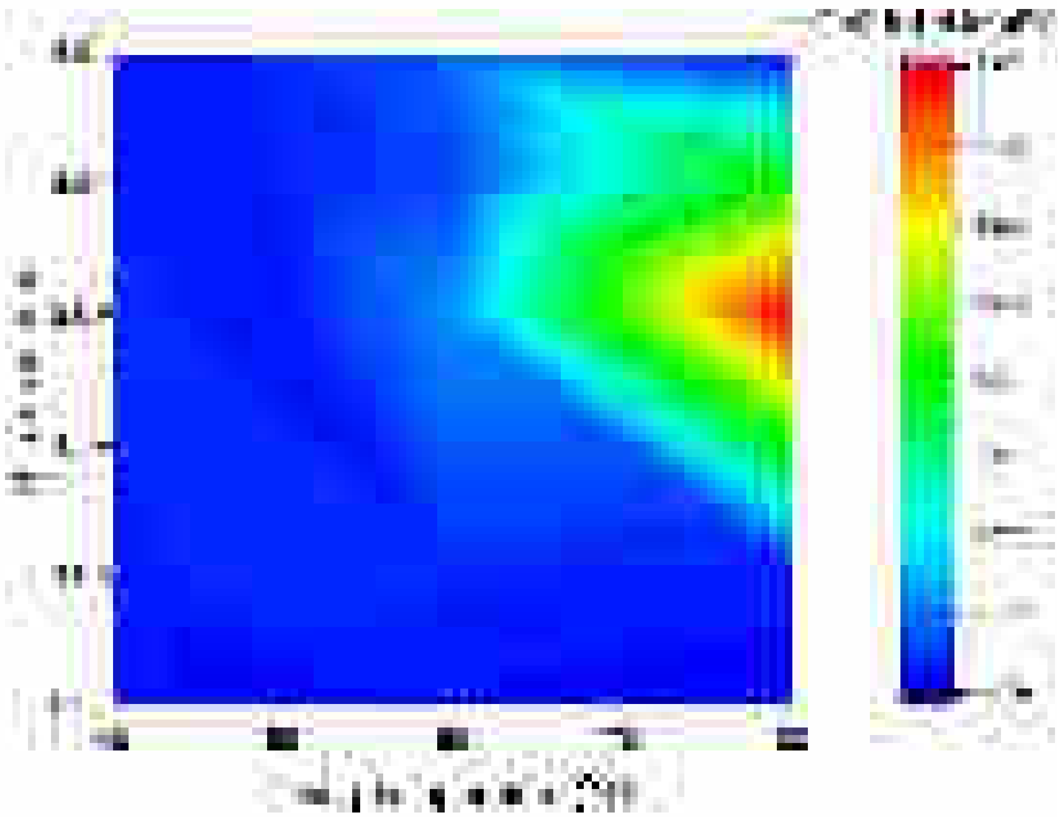
Parameters used

- Coating temperature : Room temperature
- Thickness of coating : Varying (0.5 mm to 3 mm)
- Drying temperature : 40 °C



0.5 mm 1 mm 2 mm 2.5 mm 3 mm

Area fraction against paint thickness



Coating regime map describing the effects of coating thickness and drying temperature on pinhole area

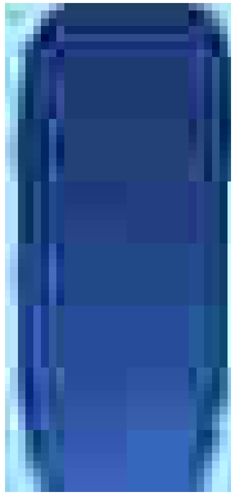
Effect of substrate-surface geometry and pinhole defects

Pinhole defects on painted galvanized steel panel

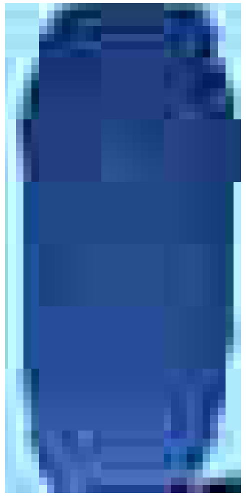
Parameters used

- Coating temperature : Room temperature
- Thickness of coating : 1 mm
- Drying temperature : 40 °C

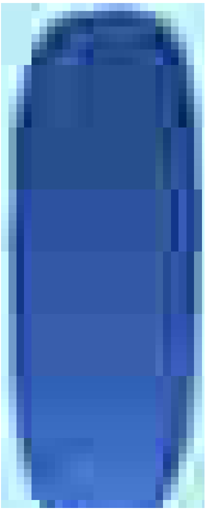
- Micro-geometry of the substrate-surface is important.
- Even an apparently smooth surfaces is inferred with microcavities.



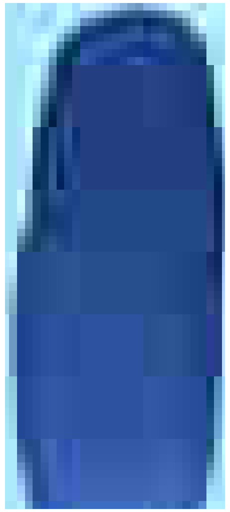
Untreated substrate



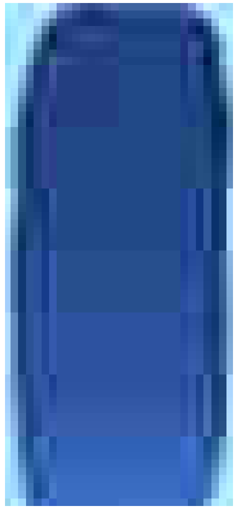
Sonication with acetone



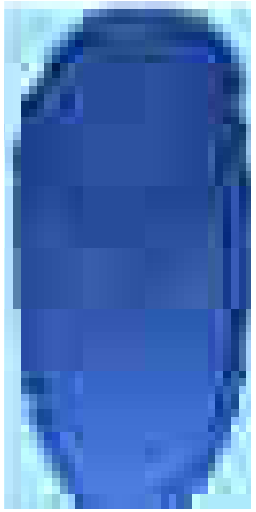
Sonication with DI Water



P1500



E224

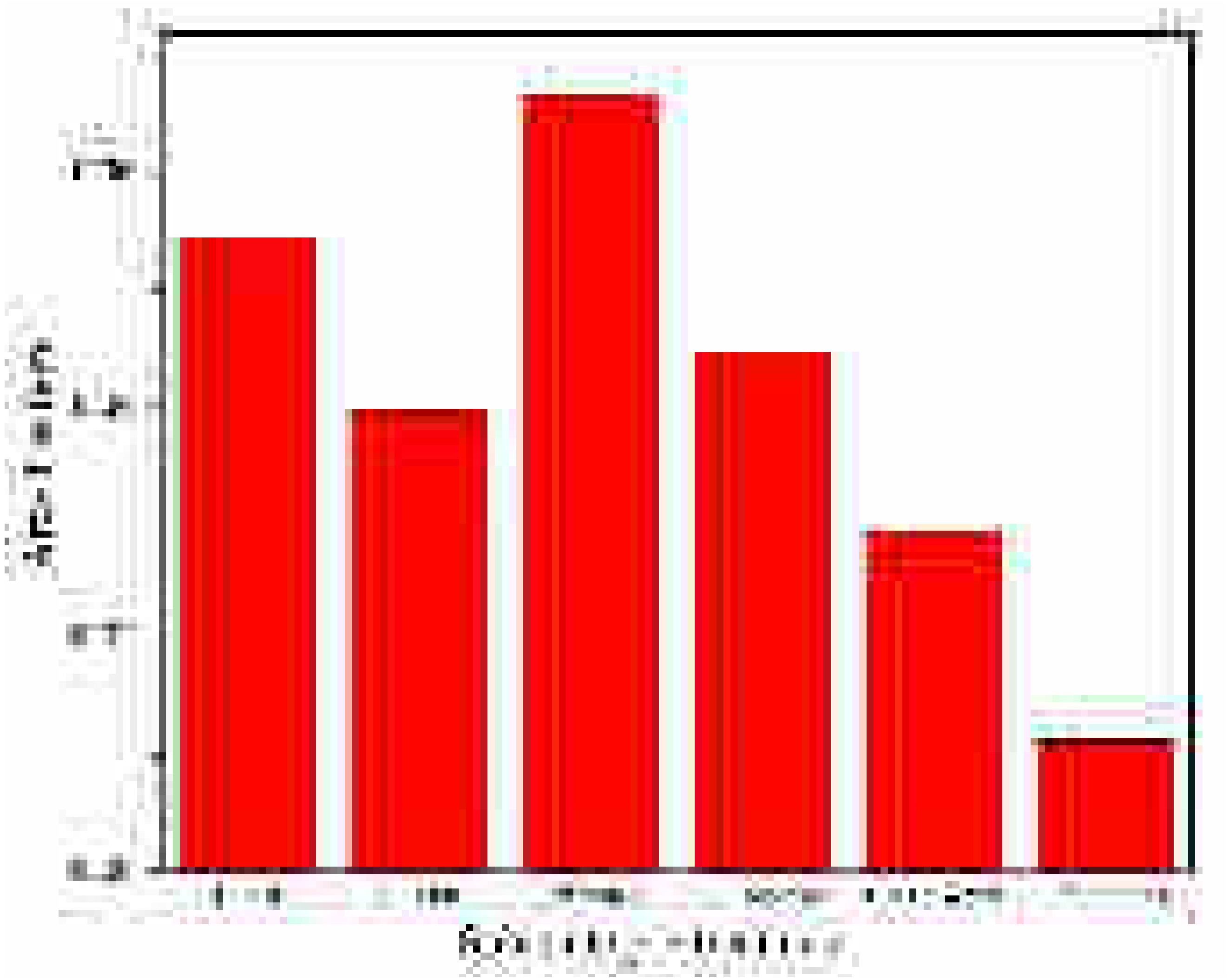


Four step cleaning

Acid etching → Sonication with DI Water → Sonication with Acetone → Sonication with Isopropanol → Drying

Jin, X., Bi, W., Wang, L., & Qian, H. (2020). Root cause analysis of pinhole defects on painted galvanized steel panel. *Engineering Failure Analysis*, *115*, 104598, LOCK, G. S. H. 1996 Latent Heat Transfer: An Introduction to Fundamentals, No. 43, p. 155. Oxford University Press.

Area fraction against substrate geometry



E 224	- Sandpaper grade
P1500	- Sandpaper grade
US acetone	- Ultrasonicated in acetone (10 min)
US DI water	- Ultrasonicated in DI water (10 min)

Conclusions

- Top heating method is more effective than bottom heating. Pe number >>1 suggests the system displays skinning.
  - Increasing substrate temperature leads to higher pinhole defects; solvent boiling occurs at higher substrate temperatures.
- Coating speed does not significantly affect pinholes.
- A combination of higher drying temperatures and higher coating thickness leads to maximum open pinhole area.
- Pinhole radius and area fraction increases with coating thickness.
- Heat transfer is by conduction rather than convection during paint drying.
- Substrate geometry influences pinhole formation.
- Bubbles do not rise and escape from the glass substrate. Oh number >1 and Bo number <<1 prevents the rising of bubbles from glass substrate.