SAND2020-8978C

Underpinning Physics of Defect Formation in Gravure Printing and Defect Prediction via Machine Learning

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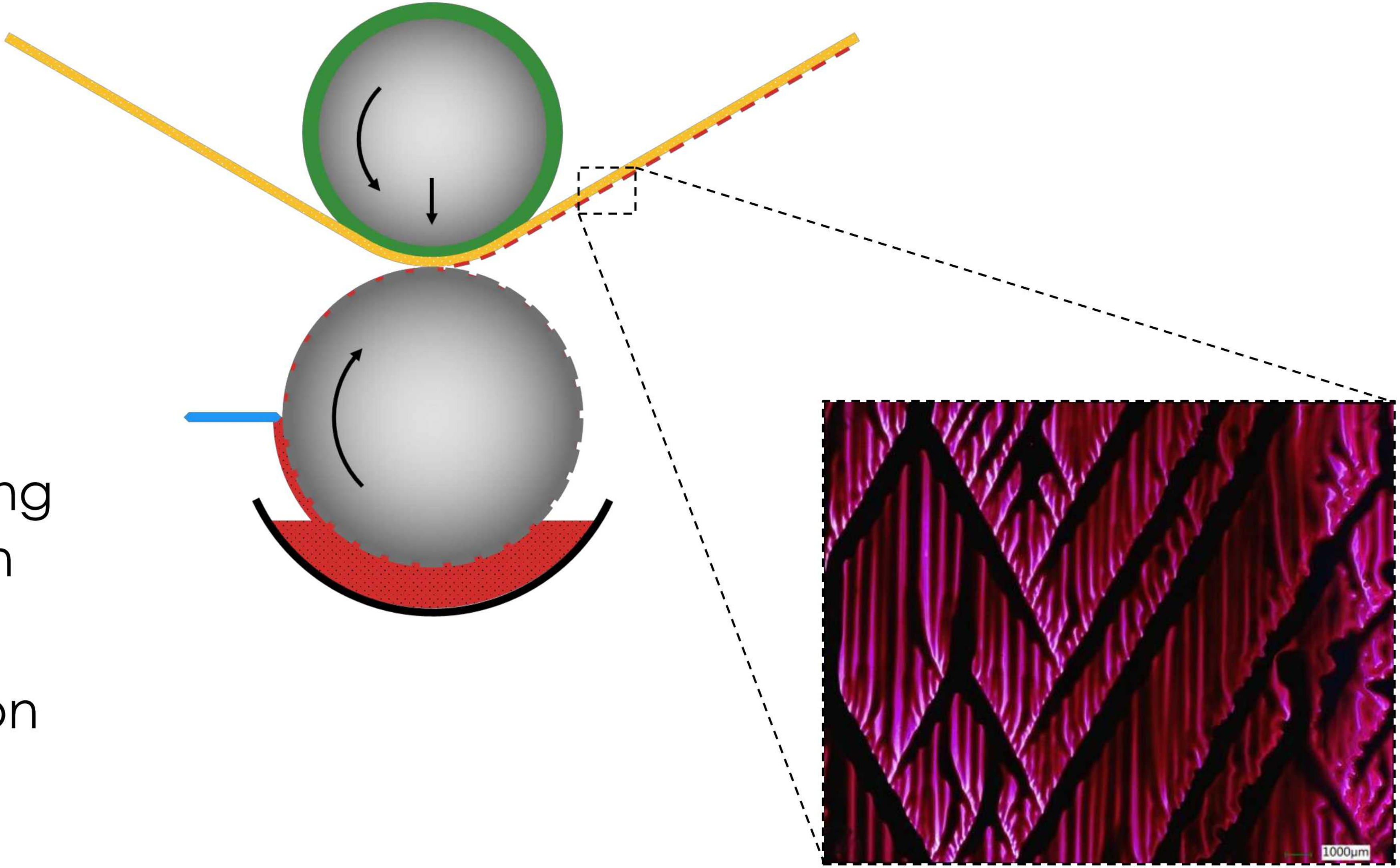
Summary

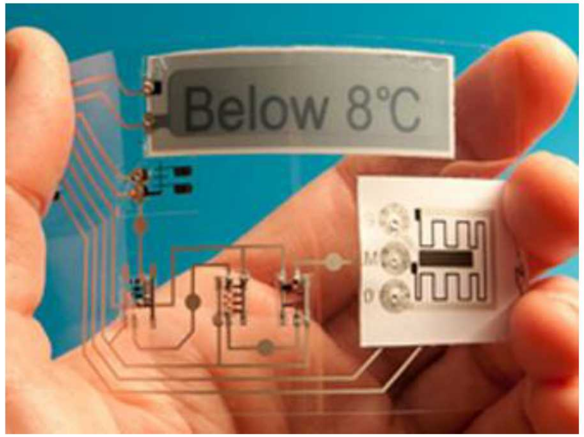
- Background
  - Process
  - Application
  - Defects
- Methods
  - Experimental
  - Machine Learning
  - Computer Vision
- Results
  - Defect Prediction
- Discussion



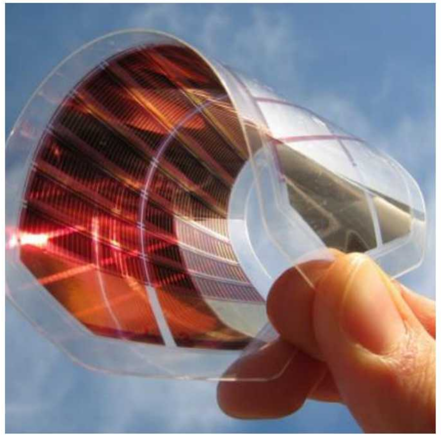
Enabling the Future

- Printed Electronics and Flexible Systems enable future innovations and applications
  - Low cost sensors in smart and connected devices (Internet of Things (IoT))
  - Smart-packaging, RFID tags
  - Healthcare wearable devices
  - Flexible displays
  - Organic Photovoltaics
  - $9.8 billion (2019)
$19.8 billion (2024)
(2019 Markets and Markets)

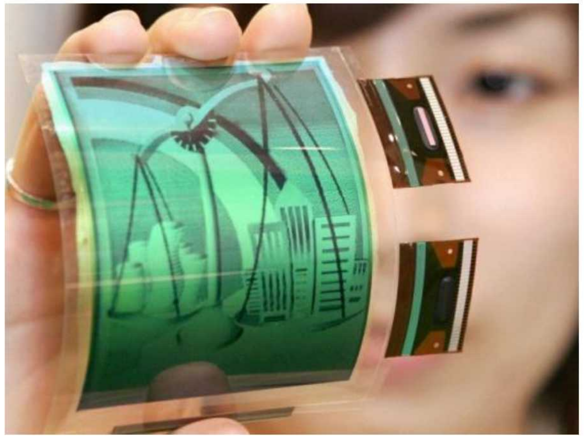
Sensors



Printable Electronics



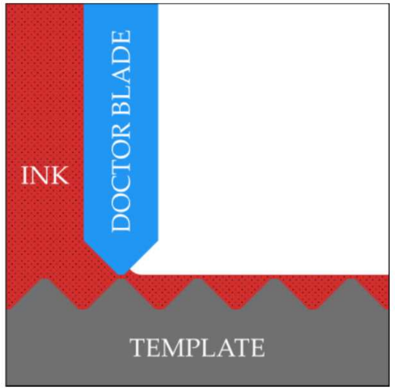
Organic Photovoltaics



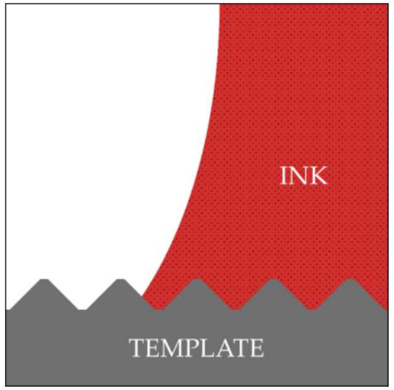
Flexible Screens

Challenge lies in generating smaller features for PE

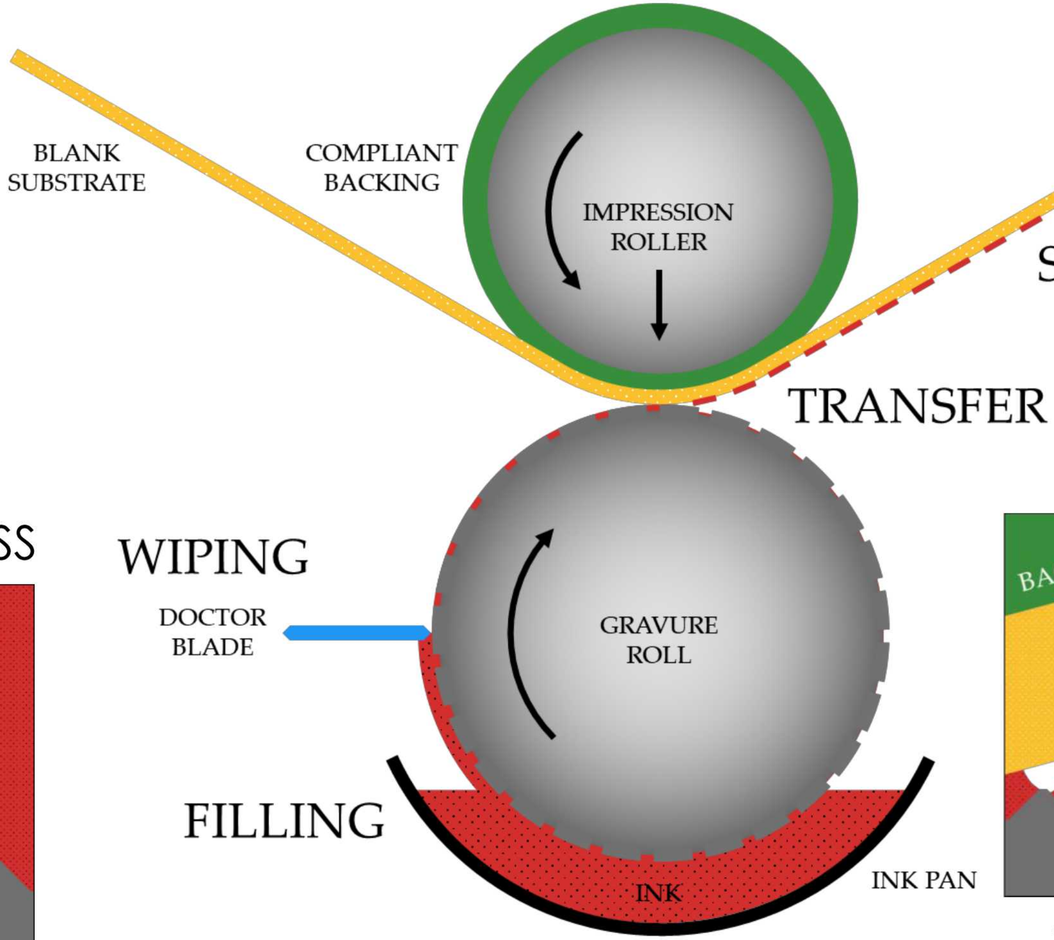
Gravure Printing Process



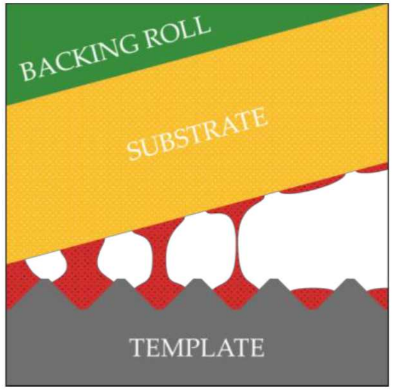
2. Wiping
Blade removes excess



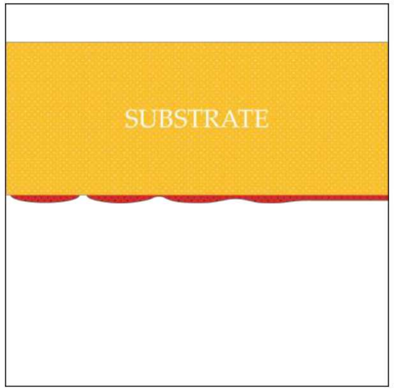
1. Filling
Cells filled with ink



Gravure printing is a complex process with multiple steps and physical mechanisms



3. Transfer
Substrate pressed and separated



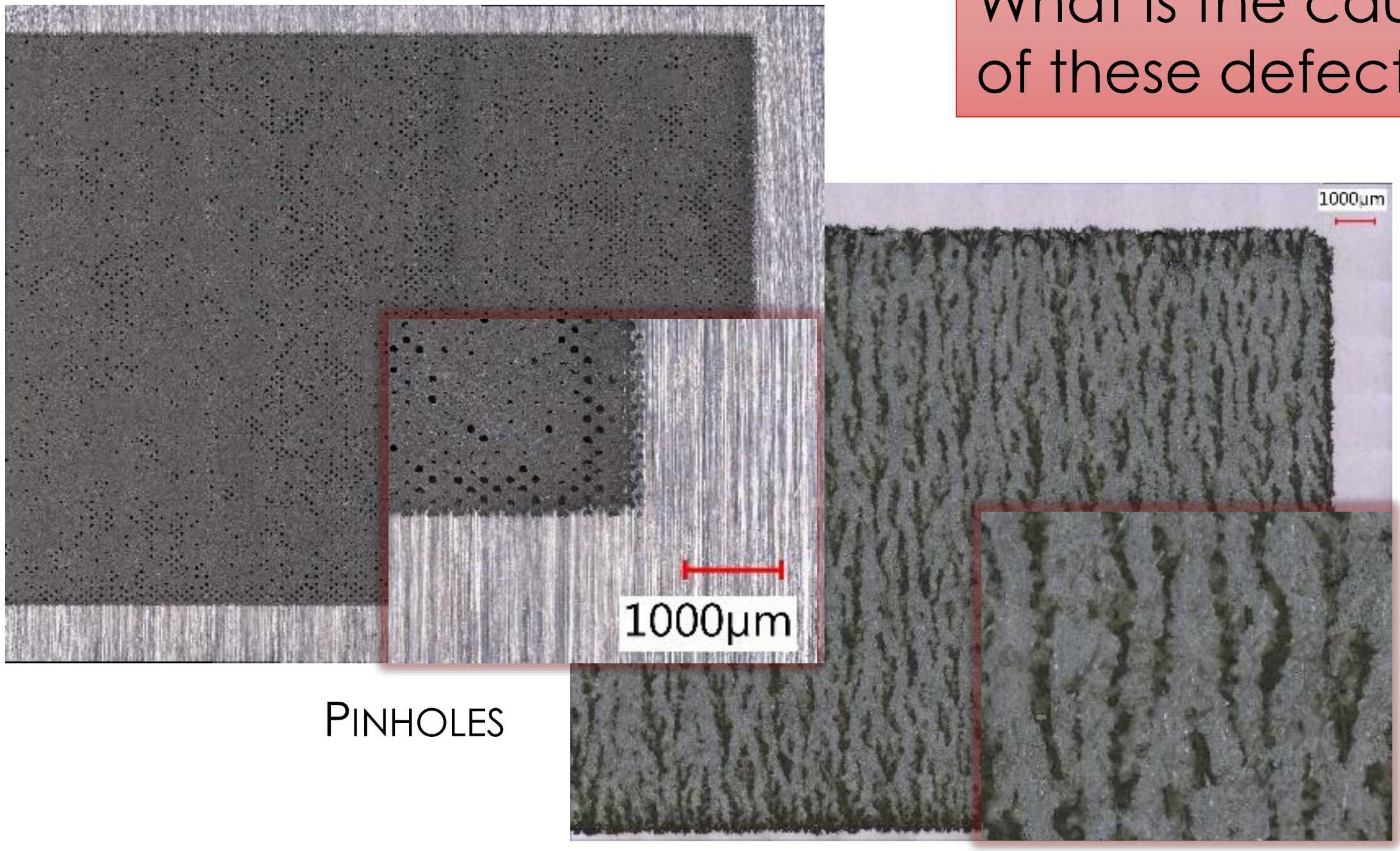
4. Solidification

<u>Ideal for PE:</u>

+ Over wide areas
+ High throughput
+ Durable
+ Wide solvent compatibility
+ Combine with other mechanisms
+ **Pattern resolution**
+ **Print speed**
- Overlay and registration is challenging

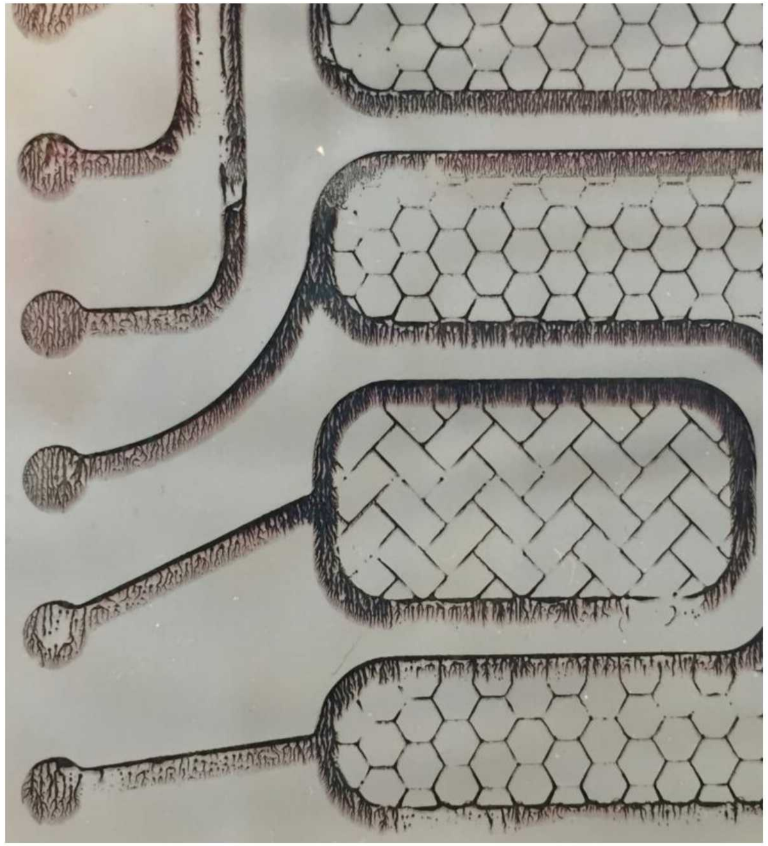
Defects Lead to Performance Degradation

What is the cause of these defects?



Pinholes

Striations

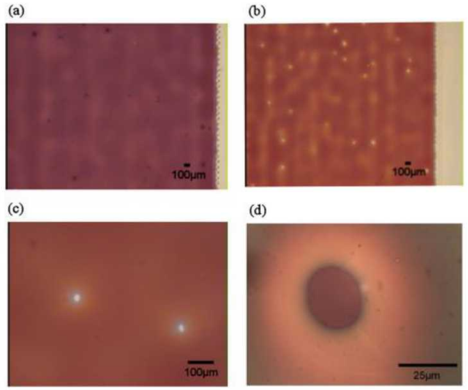


Loss of conductivity

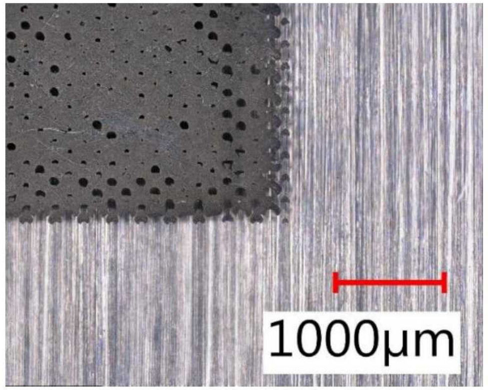
PINHOLES: NOT ALL PINHOLES ARE THE SAME

- May be controlled for
  - Template defects
  - Ink impurities
  - Missing particulate
  - Irregular template contact
  - Environmental contaminants
- Less understood
  - Ink spreading / leveling
  - Gravure cell gas trapping

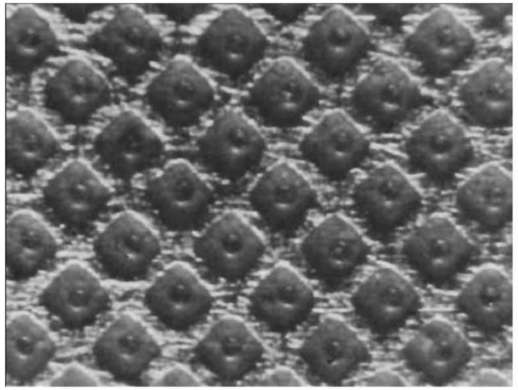
What is the cause of these process-based pinholes?



MISSING DOTS 2015 APILO ET AL.



NOT ENOUGH INK SPREADING



GAS TRAPPING 1985 BERY ET AL.

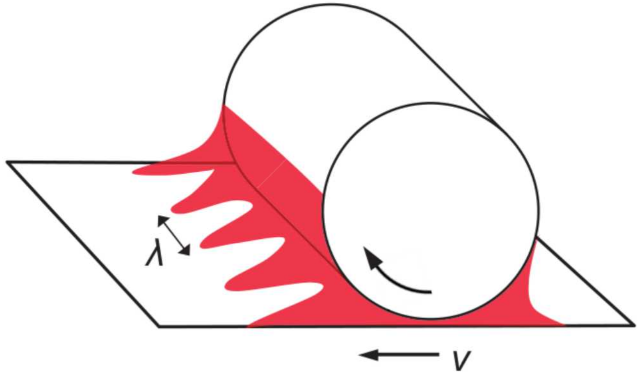
ENVIRONMENTAL CONTAMINANTS

Striations: Viscous Fingering vs Ribbing

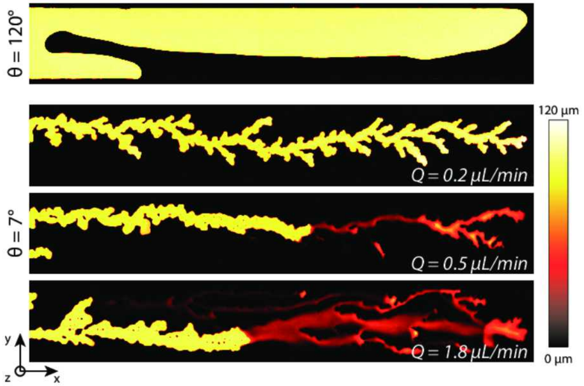
What is the cause of these striations?

Viscous Fingering

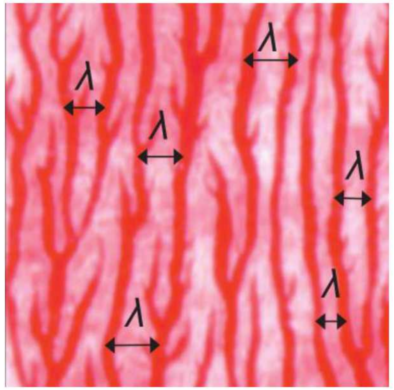
- Brumm et al. speculated due to viscous fingering
- Upstream transfer nip instabilities generate air fingers that index striations
- Can only occur in transfer nip where gas can be entrained



2019 Brumm et al.



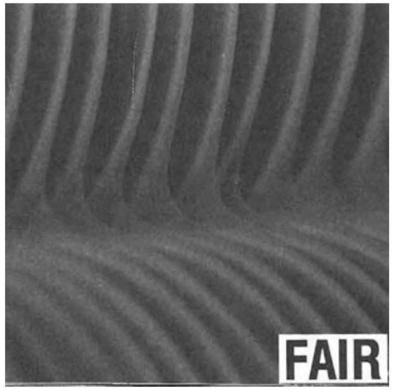
2014 Levanche et al.



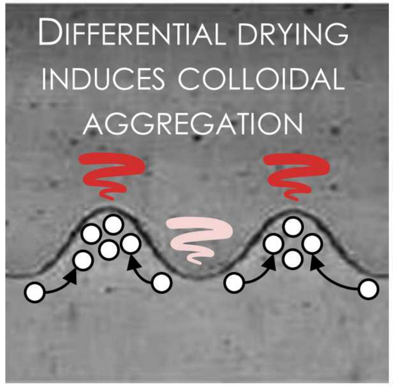
2019 Brumm et al.

Ribbing

- Our hypothesis is that striations are due to the ribbing instability, common in separating flows
- Local pressure gradients cause reverse flow
- Ribbing instability in the transfer nip leads to peaks and troughs immediately after transfer
- Film variation drives differential drying inducing colloidal aggregation that index striations



1988 Soules et al.



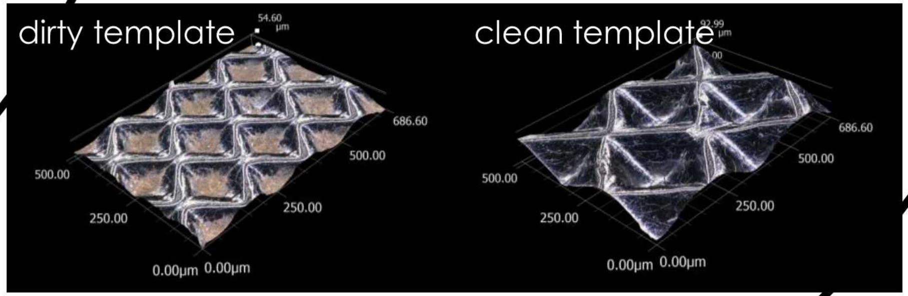
2002 Varela Lopez et al.

Informatics Approach & Results Collection

Gravure is a complex process so use machine learning to see big picture!

Extensive Database of Many Features → Machine Learning → Predictions via Algorithms

1. Print Sample



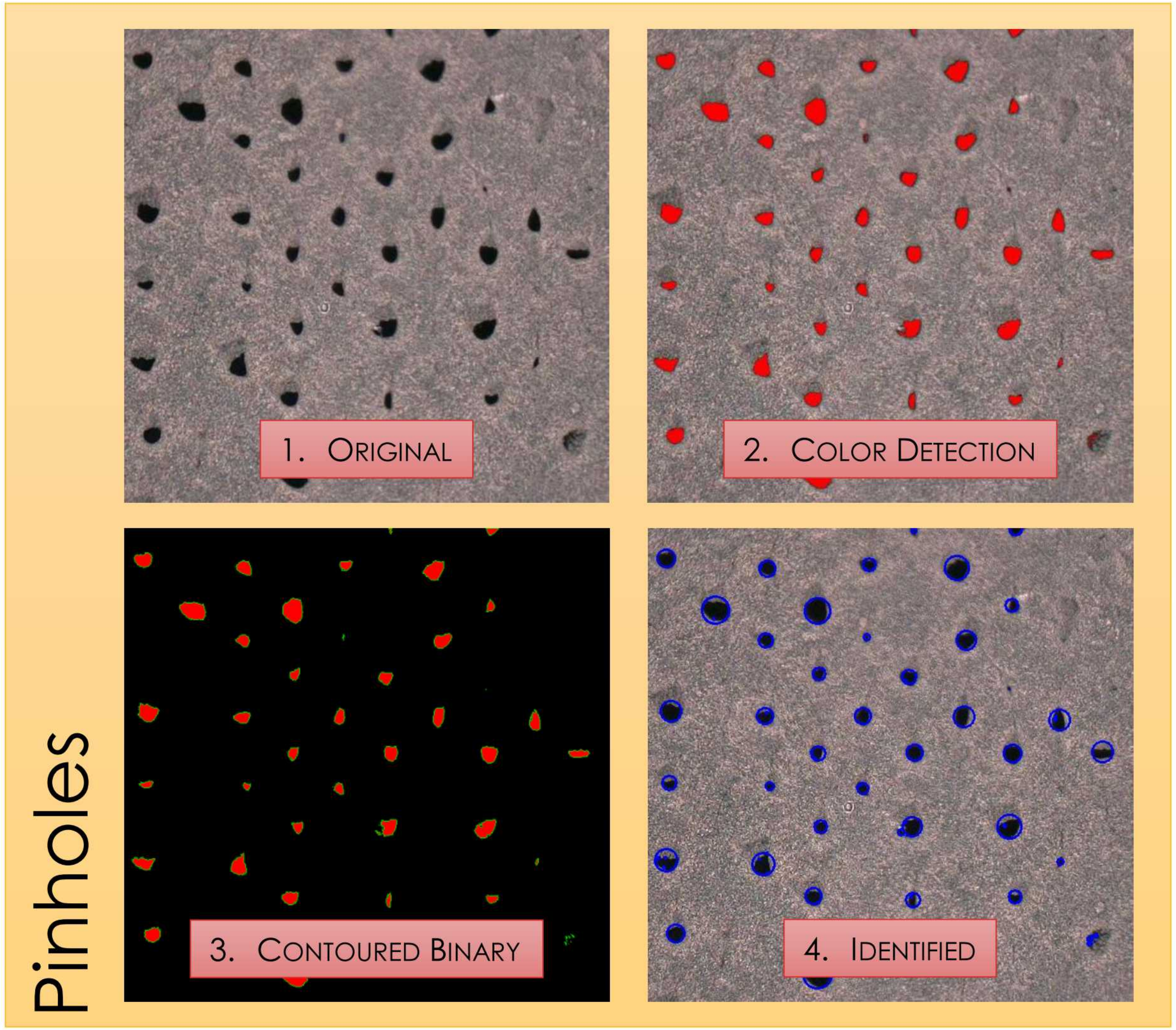
2. Clean Template

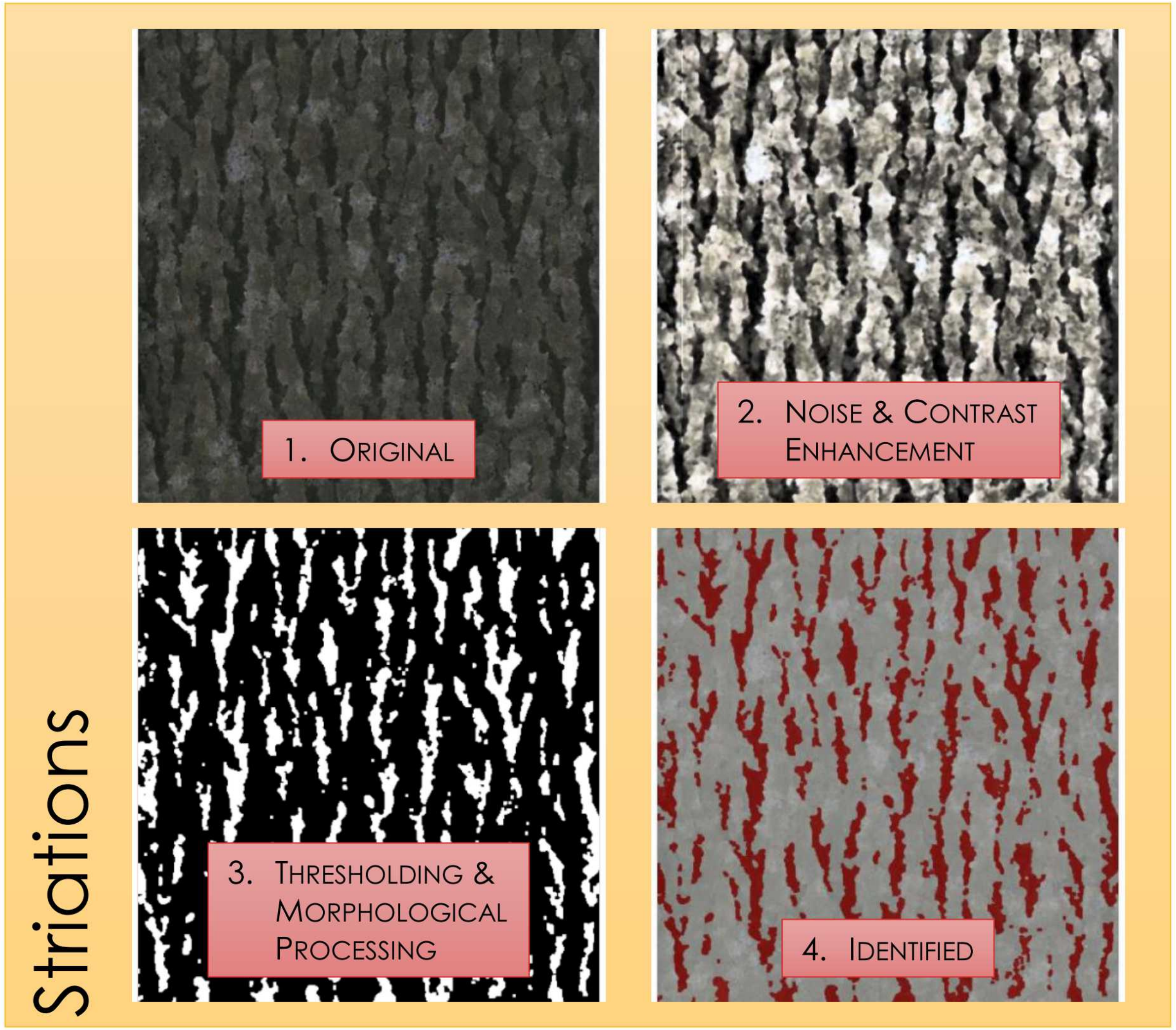
3. Dry with minimal dust and handling

4. Characterize Prints

5. Input Data

Characterization via Computer Vision





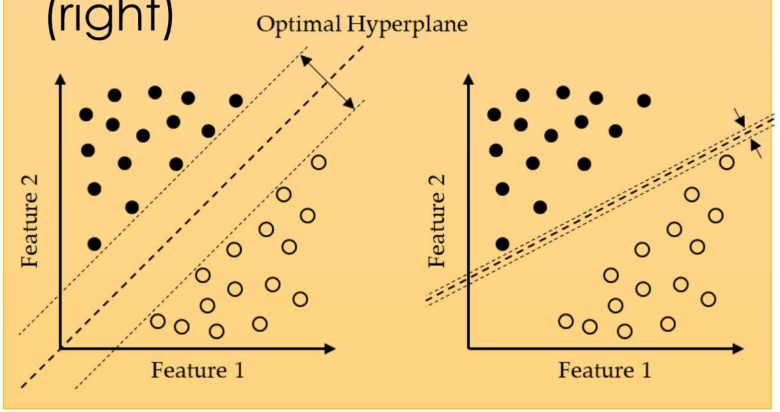
ML Algorithms

Learn which features are most sensitive and which set of features is enough to accurately predict defects

Support Vector Machine (SVM)

Separates data into groups (classifications) in n-dimensional feature space

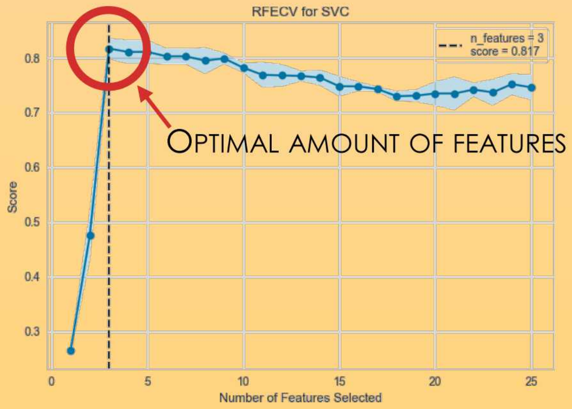
Uses the large margin principle to find a hyperplane with a large margin (left) versus that of a small margin (right)



Recursive Feature Elimination (RFE)

Simply a parameter sensitivity analysis

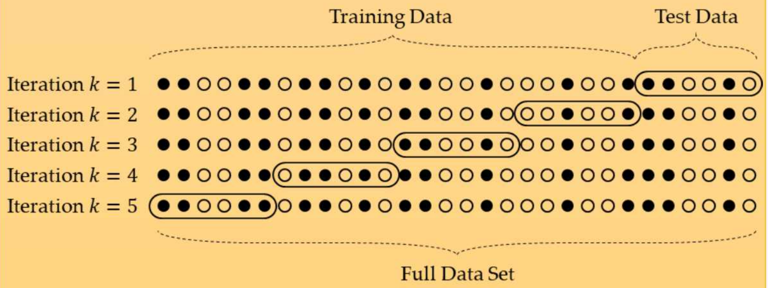
Tests removal of least sensitive features to minimize features necessary to accurately predict the classification



Stratified K Fold Cross-Validation

Makes sure all the data is used in training and testing

Semi-random partitioning of data so that all data (including each classification) is used once in the training and once in the testing of the model



Predictions & Confidence

Pinholes

Classification	0.94±0.01
Optimal Features	viscosity, substrate

- Viscosity
  - Higher viscosity resists complete filling of gravure cells
  - Multiple components including particle size, shape, loading, temperature, etc.
- Substrate
  - Porosity difference between paper and plastic
  - Surface energy variation causing incomplete wetting or dewetting mechanics

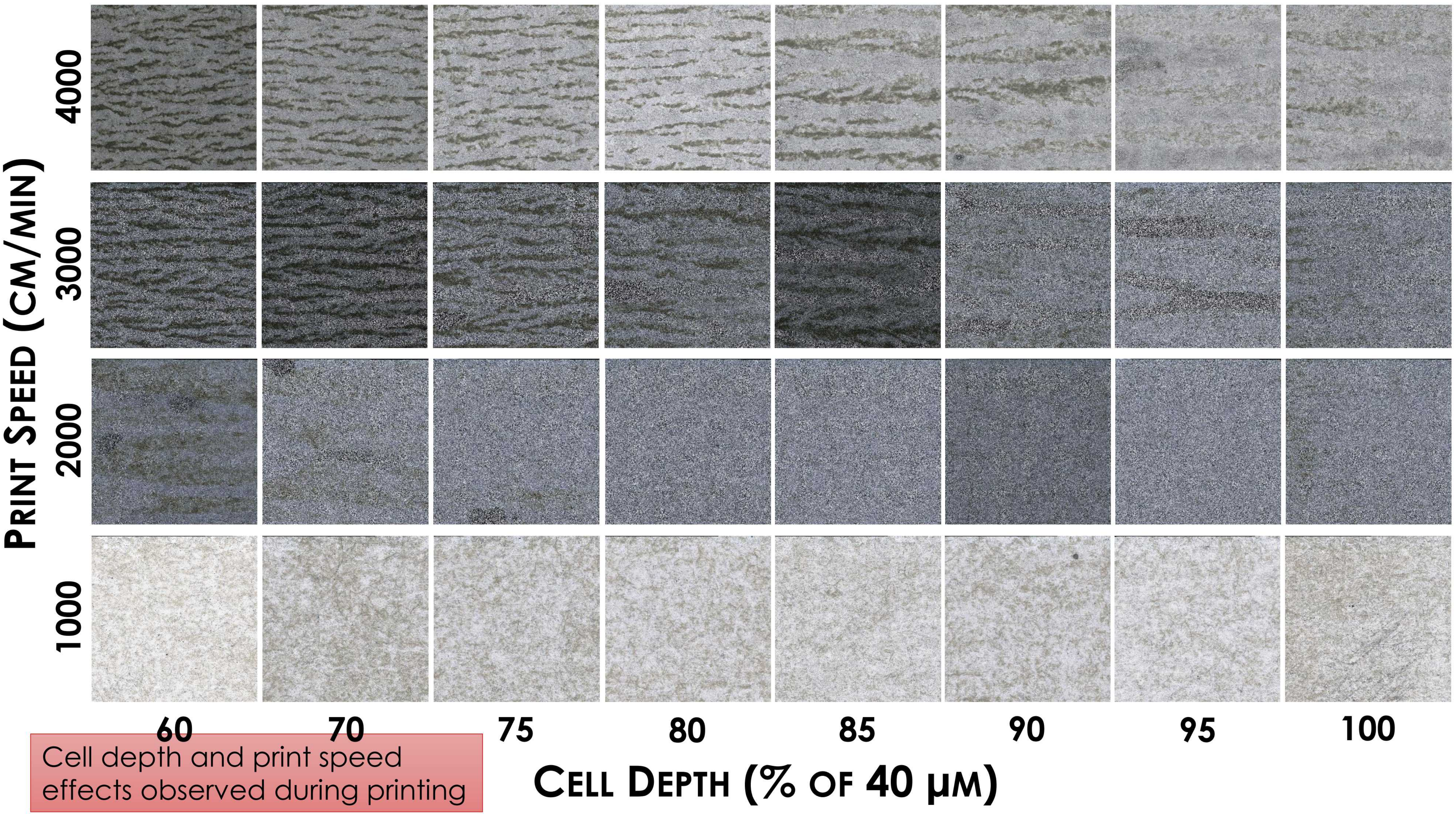
Managing cell filling and transfer vital

Striations

Classification	0.87±0.05
Optimal Features	particle size, cell depth, print speed

- Particle Size
  - Unexpected result from the ML
  - Fewer large particles fit in a cell
  - Reduced mobility affecting leveling when drying
- Cell Depth
  - Smaller cells deposit thinner films that dry before particles can level
- Print Speed
  - Main ribbing instability criterion

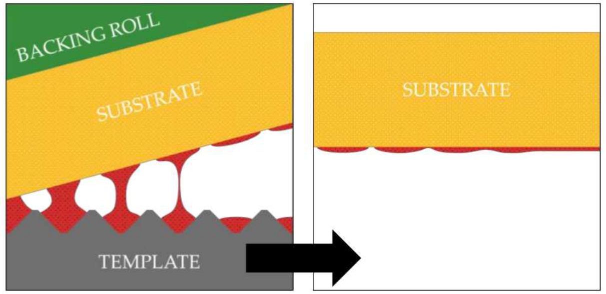
Ribbing consistent with critical features


Print Speed (cm/min)
4000
3000
2000
1000
60
70
75
80
85
90
95
100
Cell Depth (% of 40 µm)
Cell depth and print speed effects observed during printing

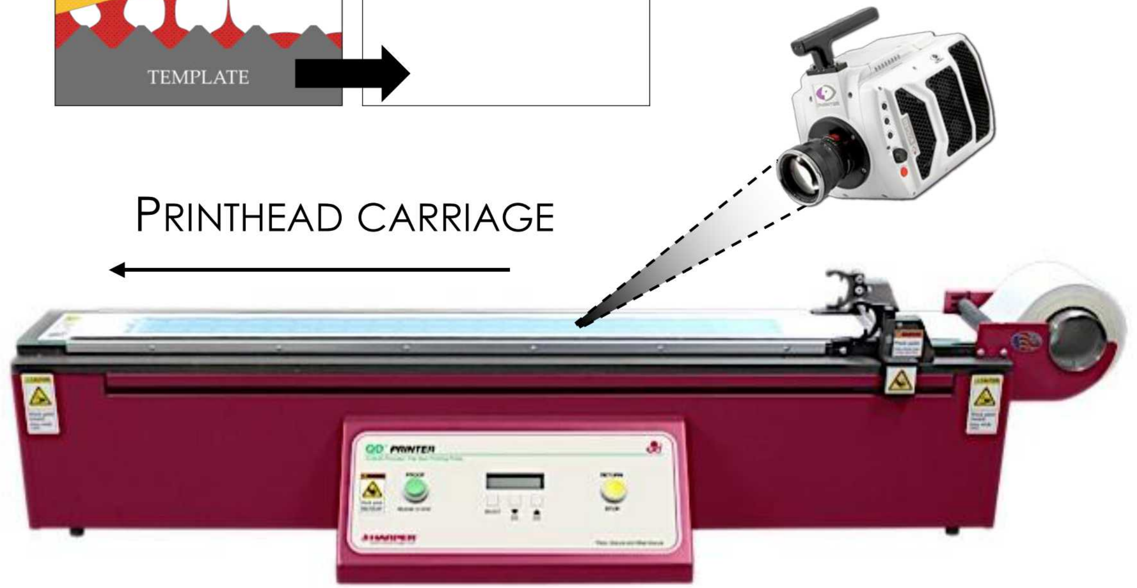
See Poster for "High-Speed Micron-Scale Gravure Printing Nip Visualization"

Visualization of Transfer

- Observe transfer + spreading

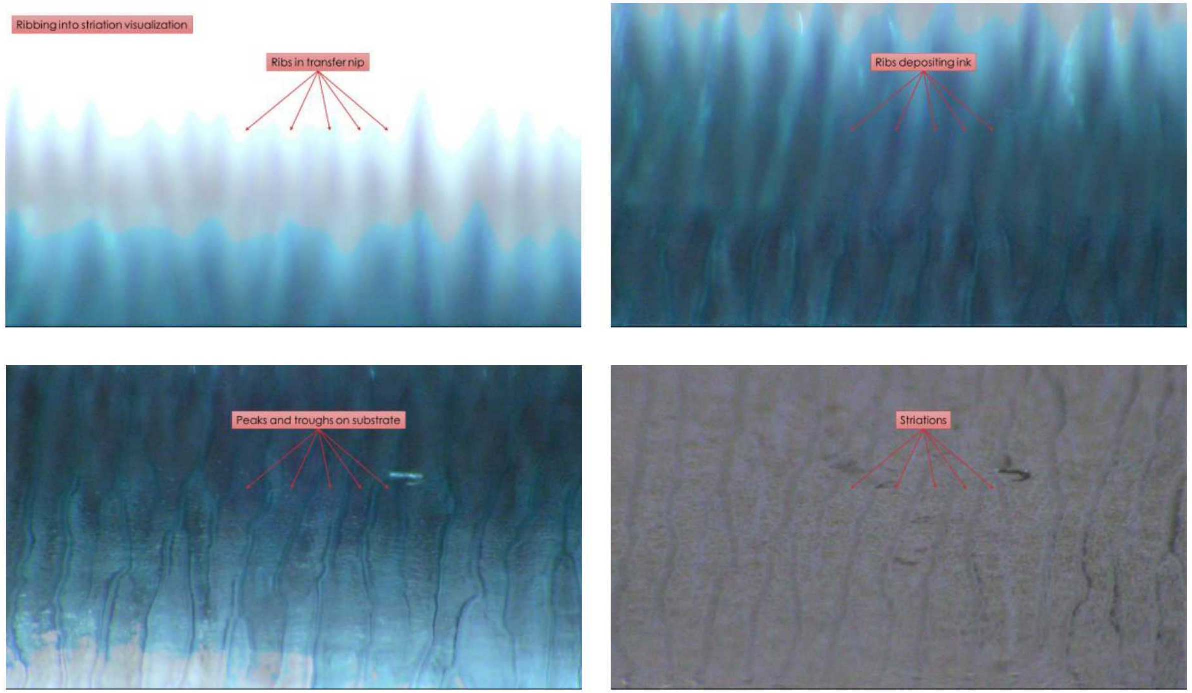


Do the striations index to ribbing?



Rib to Striation Indexing

- Count + position match



SUMMARY

- Printed and characterized 1600+ samples
- Identified pinholes and striations via computer vision
- ML prediction confidence

Pinholes	94±1%
Striations	87±5%

- Validated with visualizations
- Print speed greatest predictor of striations

Ribbing instability key mechanism in striation generation

Acknowledgements

- Lena Hoover
- Sebastian Valencia
- Chris Wall
- Steven Koskey
- Kristianto Tjiptowidjojo
- Randall Schunk

Work supported primarily by NSF:

This work is based upon work supported primarily by the National Science Foundation under cooperative Agreement No. EEC-1160494. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Work supported partially by DOE/EERE/Advanced Manufacturing Office