CCC Annual Report

UIUC, August 14, 2013

Nailboard Measurements of Surface Flow at Severstal

Mihir Chavan

Department of Mechanical Science & Engineering
University of Illinois at Urbana-Champaign

Overview

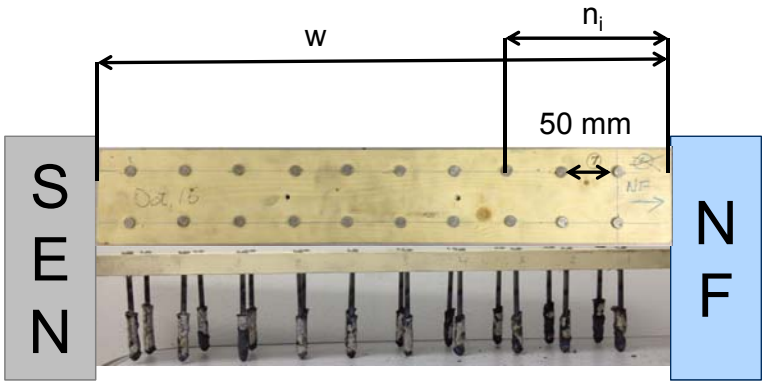
- 16 Nail board experiments were conducted Oct. 14-15, 2012 at Severstal
- Preliminary analysis is conducted here on both rows of nails, all 16 boards, with 2 positions and 2 heights measured on each nail
- Results are presented for
  - Slag/steel and powder/slag interface heights
  - Surface velocity, before and after tilt of nail is factored in
  - Angle of flow

List of Cases

Date & Time	Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
10/15, 5:23:49 pm	1	55.2	67.19	5.0	15.1	221
10/15, 5:26:56 pm	2	48.0	67.3	5.0	15.38	221
10/15, 5:27:56 pm	3	45.4	67.4	5.01	15.51	221
10/15, 5:28:28 pm	4	45.4	68.2	5.02	15.45	221
10/15, 5:28:48 pm	5	45.4	69.3	5.01	15.48	221
10/16, 12:14:40 pm	6	35.6	53.87	6.8	19.08	187
10/16, 12:17:42 pm	7	35.8	53.87	6.8	19.04	187
10/16, 12:18:00 pm	8	35.8	53.87	6.8	19.04	187
10/16, 12:22:46 pm	9	45.6	53.87	7.0	19.01	187
10/16, 12:23:13 pm	10	45.4	53.87	7.0	19.01	187
10/16, 3:28:54 pm	11	65.0	54.99	7.0	18.07	222
10/16, 3:29:20 pm	12	65.0	54.99	7.0	18.07	222
10/16, 3:29:41 pm	13	65.0	54.99	7.0	18.07	222
10/16, 3:35:50 pm	14	25.5	54.99	6.3	19.18	222
10/16, 3:36:16 pm	15	25.5	54.99	6.2	19.18	222
10/16, 3:36:36 pm	16	25.5	54.99	6.2	19.18	222

Calculating the Distance from SEN

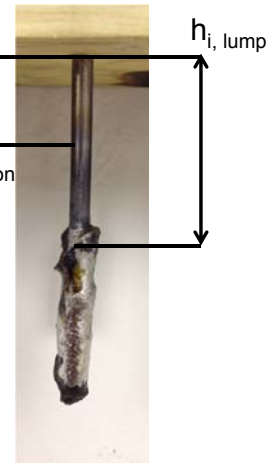
- w = strand width, given (in.) convert to (mm)
- n_i = Distance from NF measured for every nail(mm)
- s_i = Distance from SEN (mm)
- $\mathbf{s_i = w/2 - n_i}$



Board 7 is pictured in image. Boards 1-5 have 13 nails a side (26 nails total) and boards 6,7,9,11-16 have 10 nails a side (20 nails total) and boards 8 and 10 have 11 nails a side (22 nails total).

Calculating the Distances from the Steel Interface

- Need to calculate the average steel interface (h_{avg}) to find new heights (from the steel interface) of both:
  - lump (steel-slag interface)
  - Discolored region (near slag-powder interface)
- $h_{i,lump}$ = height to lump (mm)
- $h_{i,\ discoloration}$ = height to discoloration (mm)
- h_{avg} = ($\sum h_{i,\ lump}$ of all nails) / (# of nails) (mm)
- y_i = new heights (mm)
- $y_i = h_{avg} - h_i$

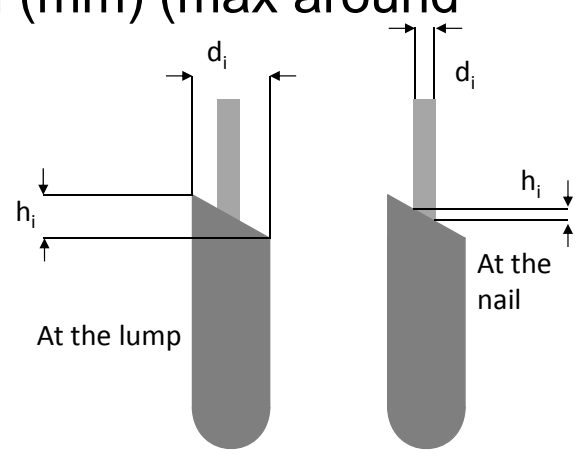


Picture of Board 1, Inner Radius, Nail 10

Calculating the Velocity

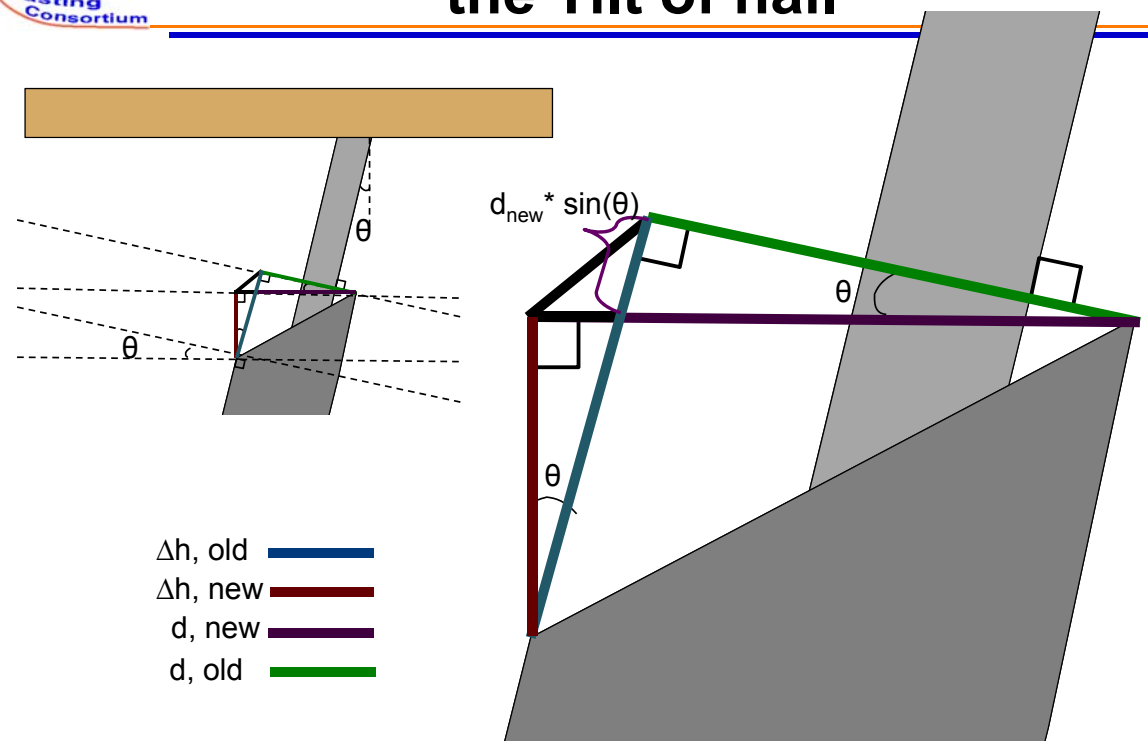
$$v_i = 0.624 * d_i^{-0.696} * h_i^{0.567}$$

- d_i = diameter measured (mm) (nail or lump)
- h_i = height measured (mm) (max around perimeter)
- v_i = velocity (m/s)



Equation From:
R. Liu, J. Sengupta, D. Crosbie, S. Chung, M. Trinh and B.G. Thomas, "Measurement of Molten Steel Surface Velocity with SVC and Nail Dipping during Continuous Casting Process," in *Sensors, Sampling, and Simulation for Process Control,* B.G. Thomas, J.A. Yurko and L. Zhang, eds., John Wiley & Sons, Hoboken, New Jersey, (TMS Annual Meeting Symposium, San Diego, CA, Feb. 27- Mar. 3, 2011), 2011, 51-58.

Velocity after taking into account the Tilt of nail

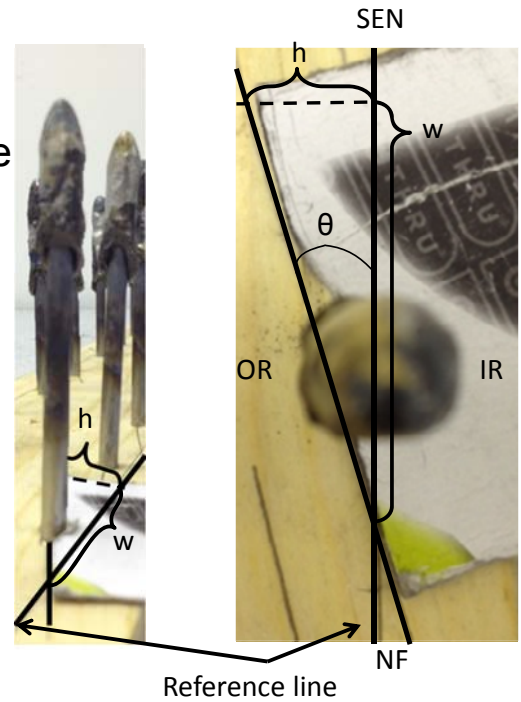


Calculating the new velocity due to the tilt of the nail

- $\mathbf{d_{old}}$ – diameter of the nail as first measured (mm)
- $\Delta\mathbf{h_{old}}$ – height difference as first measured (mm)
- **θ** – angle of tilt as measured (radians)
- $\mathbf{d_{new} = d_{old}/\cos(\theta)}$
  - diameter of the nail due the tilt of the nail (mm)
- $\mathbf{\cos(\theta) = \Delta h_{new} / (\Delta h_{old} - d_{new} * \sin(\theta))}$
- $\mathbf{\Delta h_{new} = \Delta h_{old} * \cos(\theta) - d_{new} * \sin(\theta)\cos(\theta)}$
  $\mathbf{= \Delta h_{old} * \cos(\theta) - d_{old} * \sin(\theta)}$
  - Height difference due to the tilt of the nail (mm)
- v_{new} – velocity due to the tilt (m/s)
- $v_{new} = 0.624 * d_{new}^{-0.696} * h_{new}^{0.567}$

Calculating the Velocity Angle

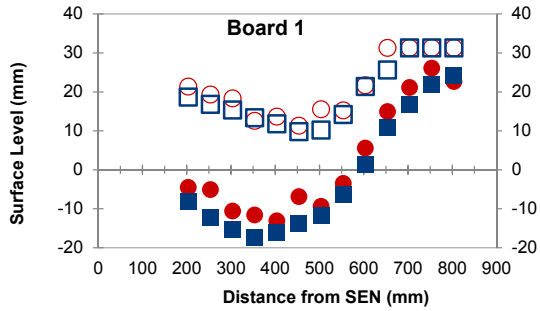
- h – height of angle
- w – distance from point where height crosses reference line to where the drawn line crosses reference line
- $\theta = \tan^{-1}(h/w)$
  - Positive theta is in the counterclockwise direction

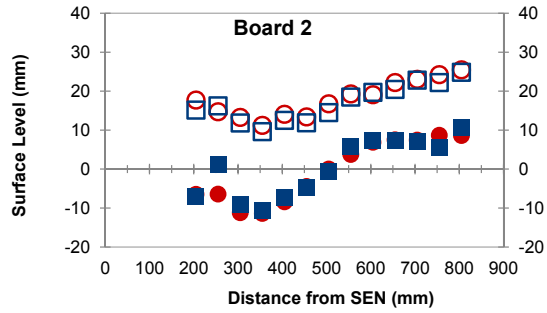


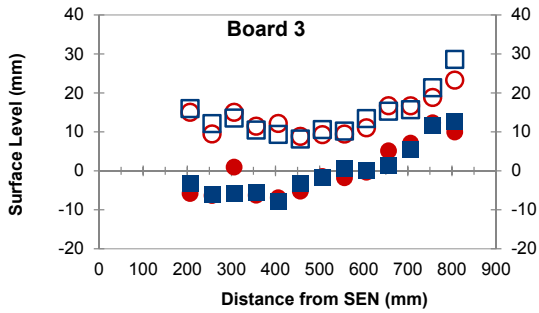
Surface Level

Distance from Steel/Slag Interface measured at 50 mm intervals from SEN

Surface Level Boards 1 – 3







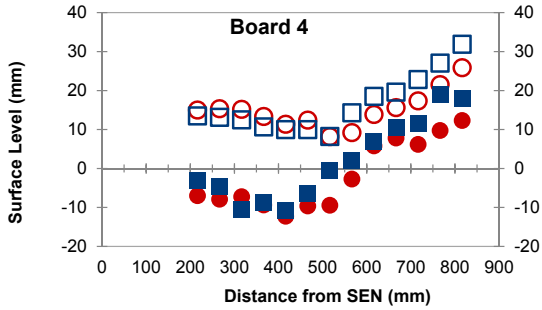
Legend

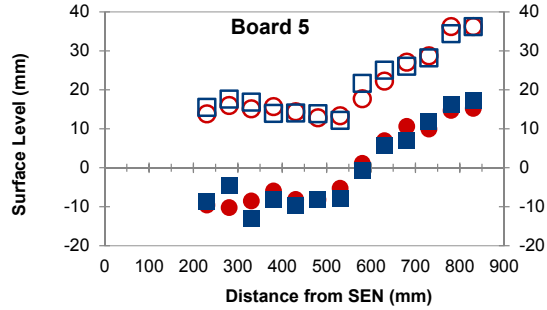
- Lump (IR)
- Lump (OR)
- Discoloration (IR)
- Discoloration (OR)

Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
1	55.2	67.19	5.0	15.1	221
2	48.0	67.3	5.0	15.38	221
3	45.4	67.4	5.01	15.51	221

Surface Level Boards 4 – 5





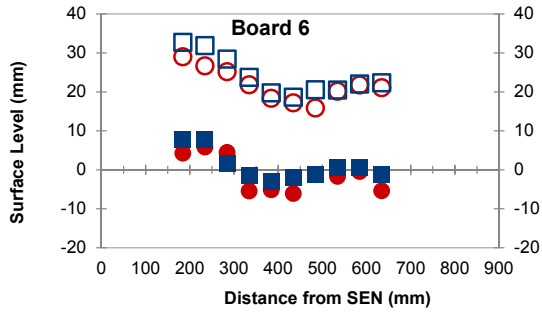
Legend

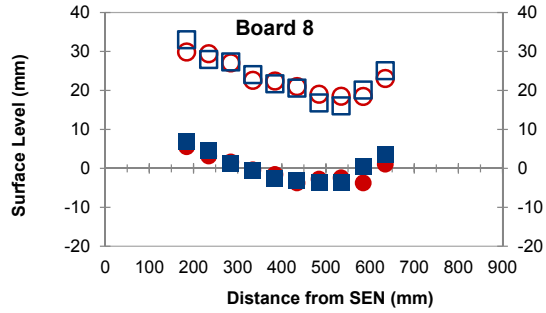
- Lump (IR)
- Lump (OR)
- Discoloration (IR)
- Discoloration (OR)

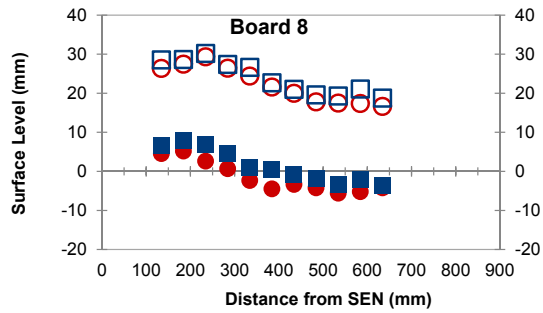
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
4	45.4	68.2	5.02	15.45	221
5	45.4	69.3	5.01	15.48	221

Surface Level Boards 6 - 8







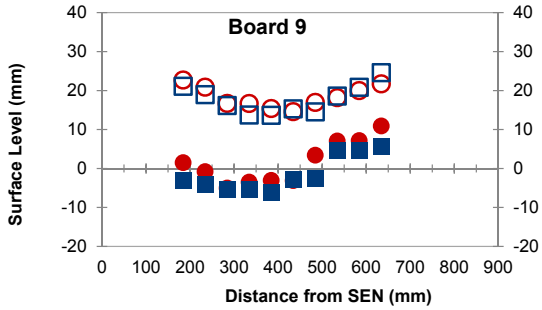
Legend

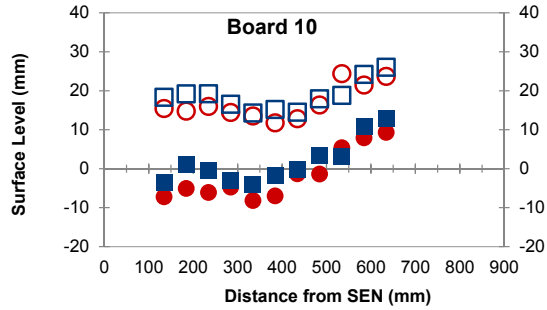
- Lump (IR)
- Lump (OR)
- Discoloration (IR)
- Discoloration (OR)

Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
6	35.6	53.87	6.8	19.08	187
7	35.8	53.87	6.8	19.04	187
8	35.8	53.87	6.8	19.04	187

Surface Level Boards 9 – 10





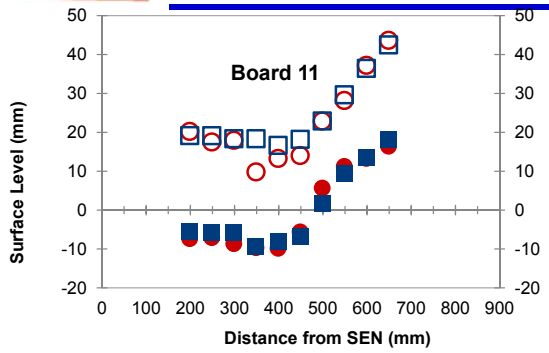
Legend

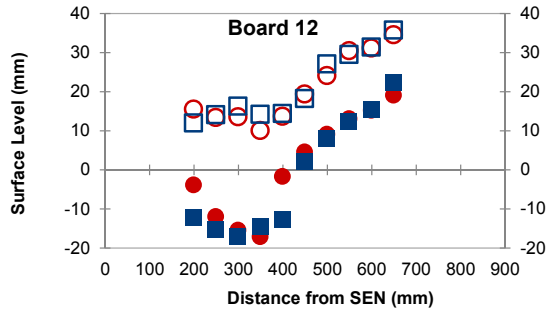
- Lump (IR)
- Lump (OR)
- Discoloration (IR)
- Discoloration (OR)

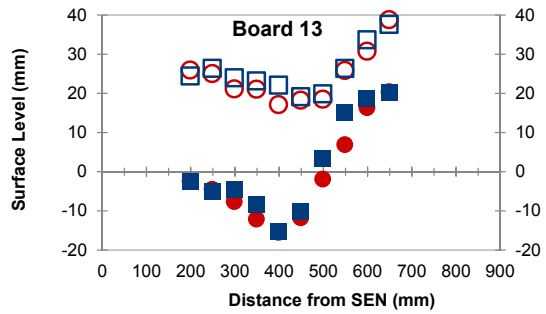
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
9	45.6	53.87	7.0	19.01	187
10	45.4	53.87	7.0	19.01	187

Surface Level Boards 11 – 13







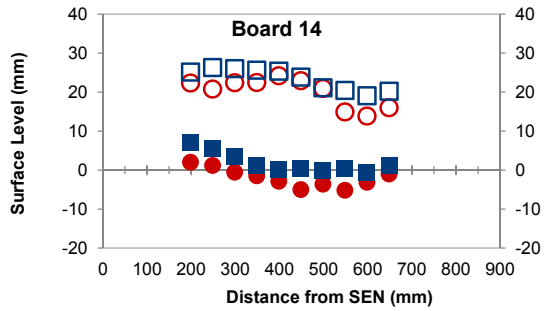
Legend

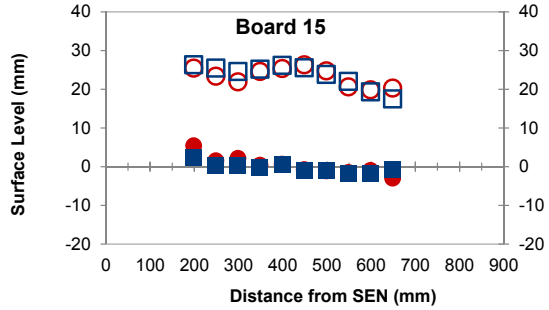
- Lump (IR)
- Lump (OR)
- Discoloration (IR)
- Discoloration (OR)

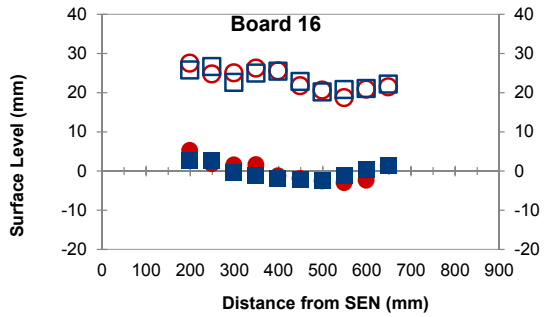
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
11	65.0	54.99	7.0	18.07	222
12	65.0	54.99	7.0	18.07	222
13	65.0	54.99	7.0	18.07	222

Surface Level Boards 14 – 16







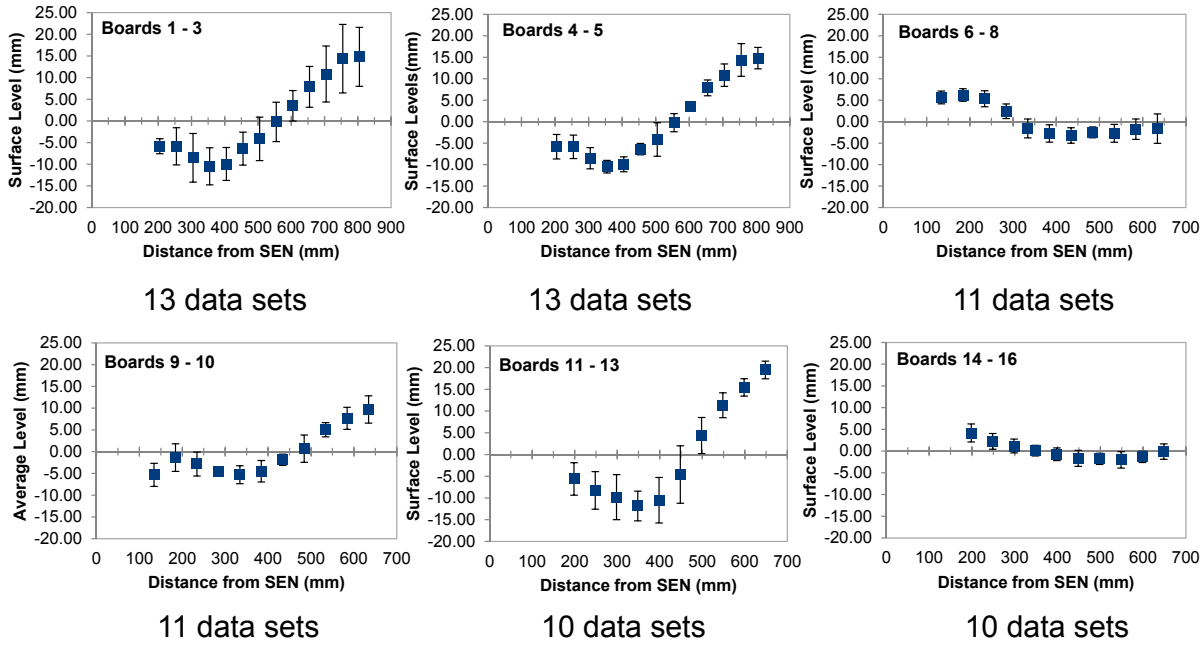
Legend

- Lump (IR)
- Lump (OR)
- Discoloration (IR)
- Discoloration (OR)

Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
14	25.5	54.99	6.3	19.18	222
15	25.5	54.99	6.2	19.18	222
16	25.5	54.99	6.2	19.18	222

Summary: Surface Level
Averages and Standard Deviations

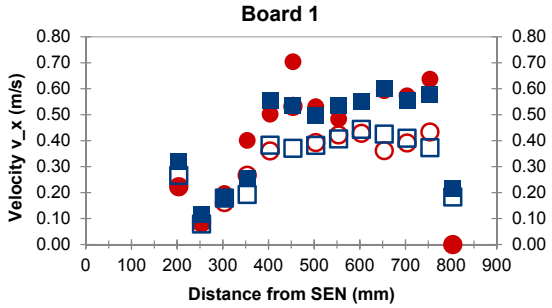


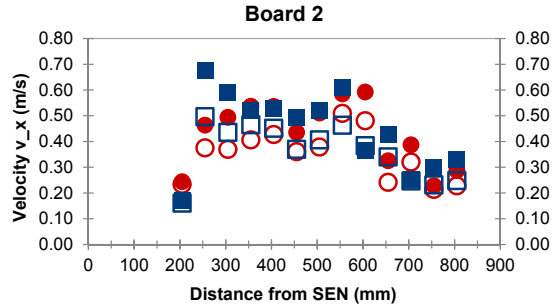
Velocity Measurements

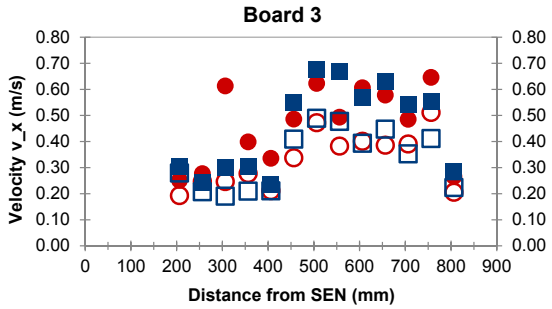
For each board, measure:

1) Velocity Magnitude
   measured at 50 mm intervals from SEN
   at the edge of the lump and at the nail
2) Adjusted Velocity Magnitude
   - taking tilt into account
3) Velocity Vectors
   - top view of board showing both direction and magnitude of both rows of nails

Velocity Boards 1 – 3







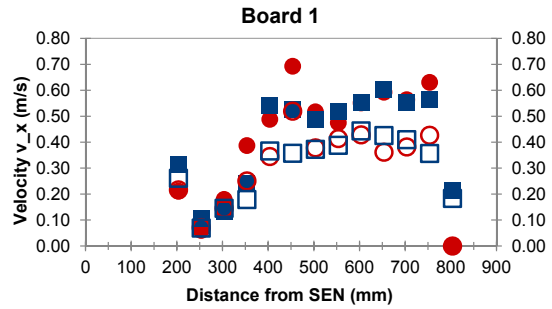
Legend

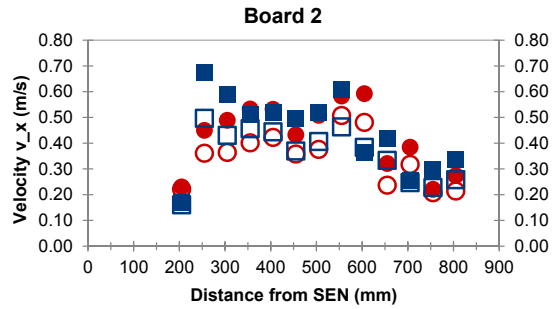
● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

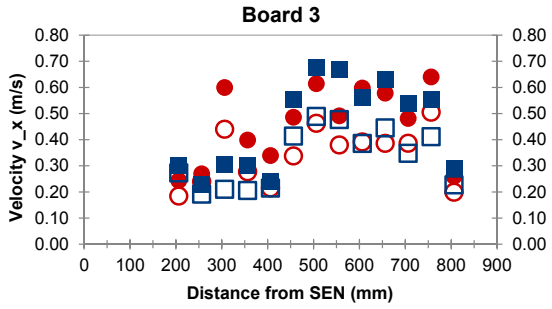
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
1	55.2	67.19	5.0	15.1	221
2	48.0	67.3	5.0	15.38	221
3	45.4	67.4	5.01	15.51	221

Adjusted Velocity Boards 1 – 3







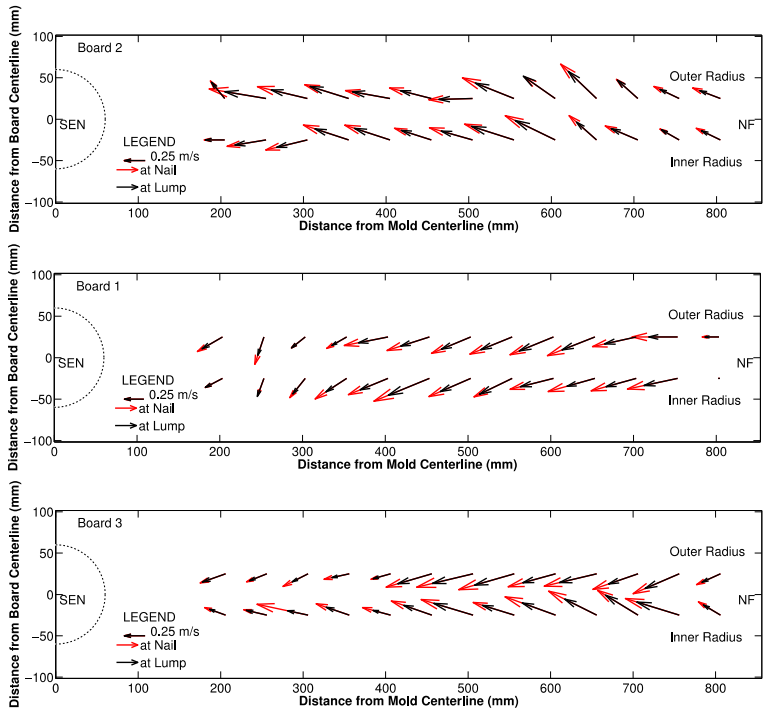
Legend

● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

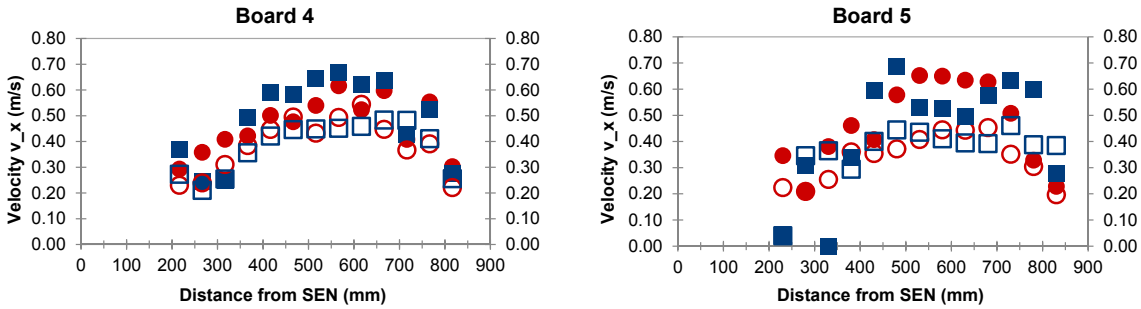
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
1	55.2	67.19	5.0	15.1	221
2	48.0	67.3	5.0	15.38	221
3	45.4	67.4	5.01	15.51	221

Velocity Vectors Boards 1 – 3



Velocity Boards 4 – 5



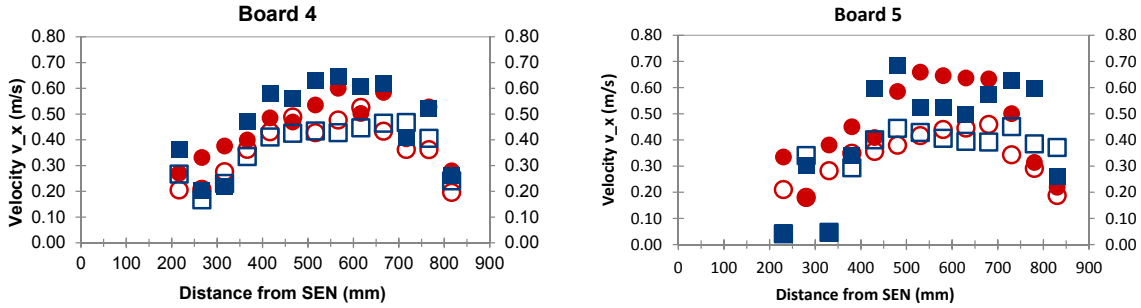
Legend

● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
4	45.4	68.2	5.02	15.45	221
5	45.4	69.3	5.01	15.48	221

Adjusted Velocity Boards 4 – 5



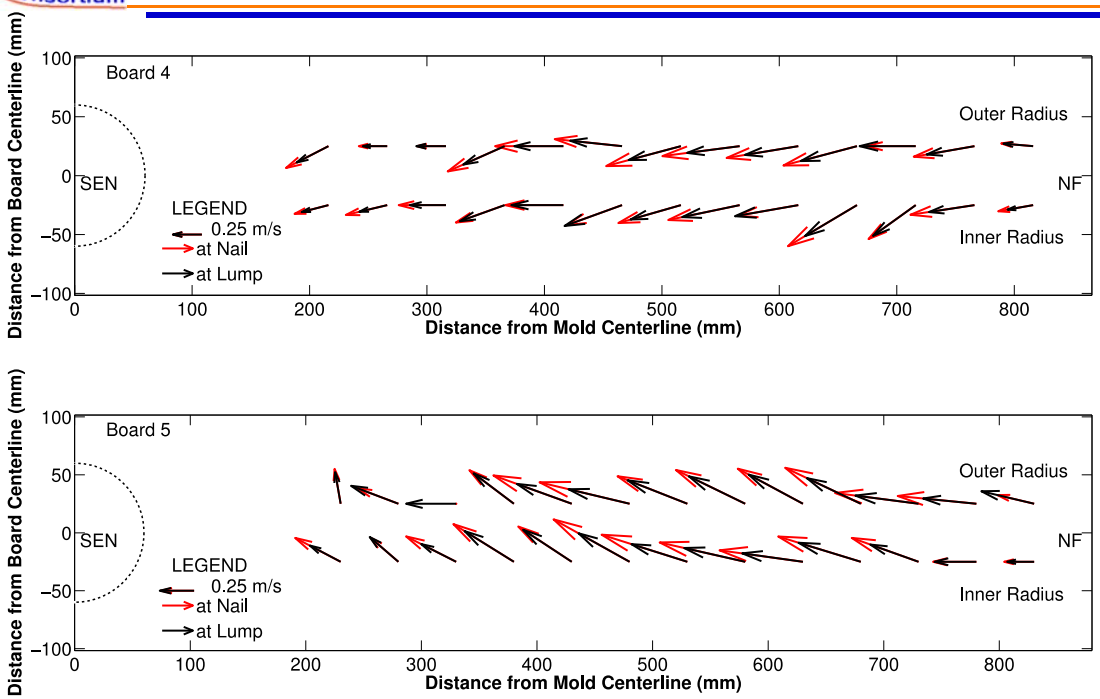
Legend

● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

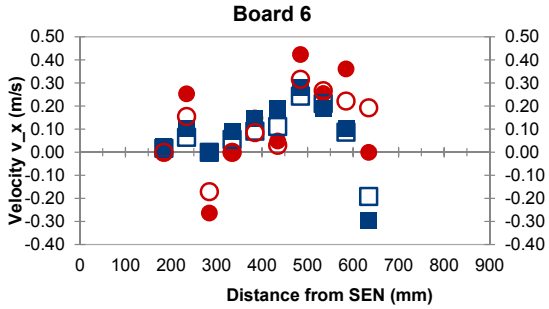
Casting Conditions

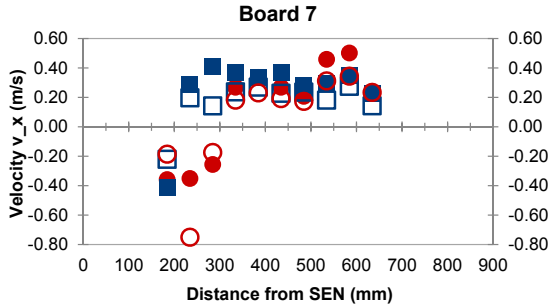
Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
4	45.4	68.2	5.02	15.45	221
5	45.4	69.3	5.01	15.48	221

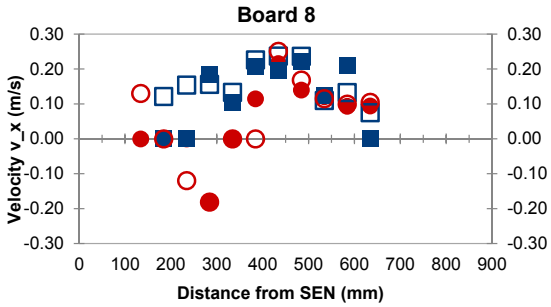
Velocity Vectors Boards 4 – 5



Velocity Board 6 – 8







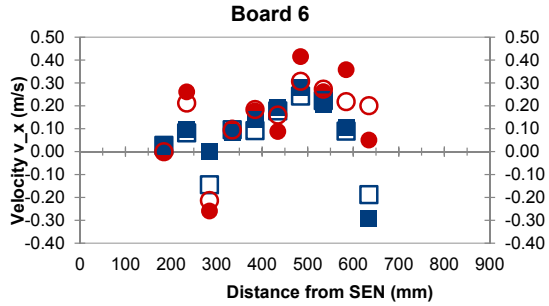
Legend

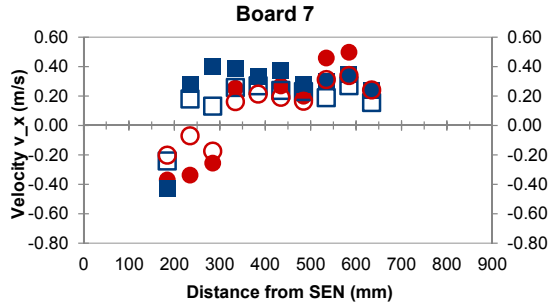
● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

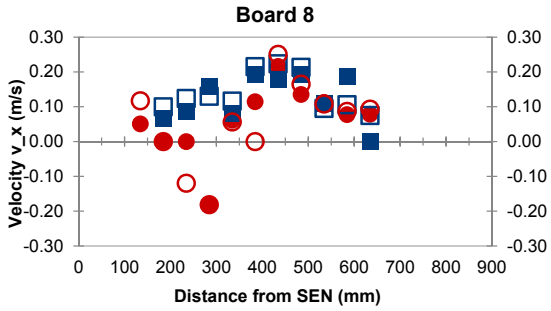
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
6	35.6	53.87	6.8	19.08	187
7	35.8	53.87	6.8	19.04	187
8	35.8	53.87	6.8	19.04	187

Adjusted Velocity Board 6 – 8







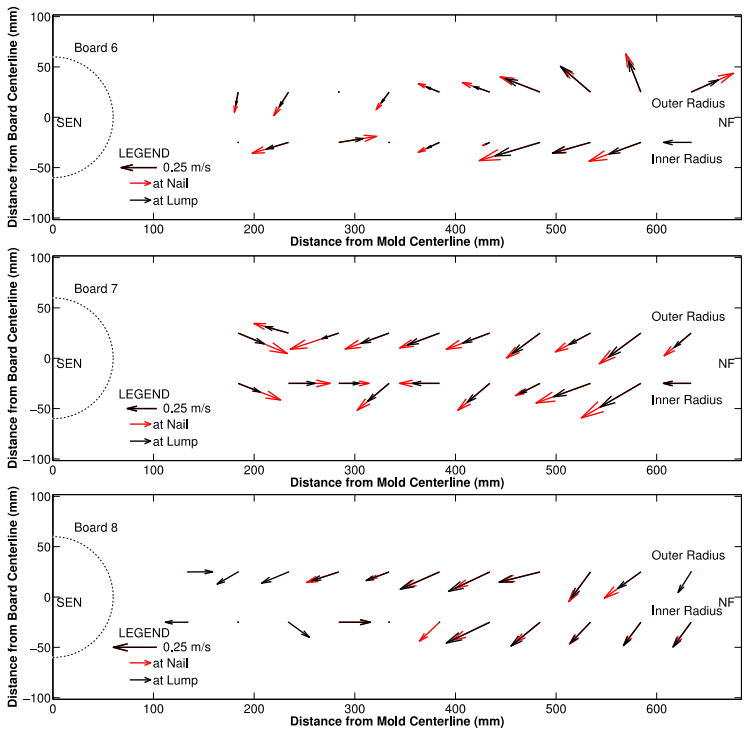
Legend

● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

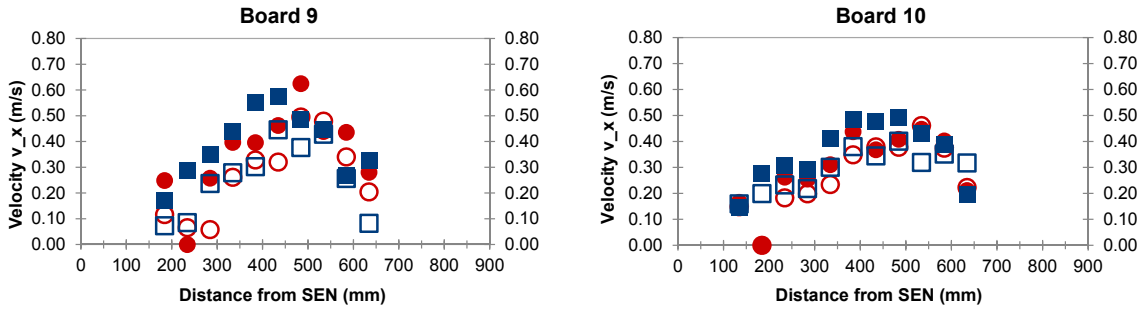
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
6	35.6	53.87	6.8	19.08	187
7	35.8	53.87	6.8	19.04	187
8	35.8	53.87	6.8	19.04	187

Velocity Vectors Board 6 – 8



Velocity Boards 9 – 10



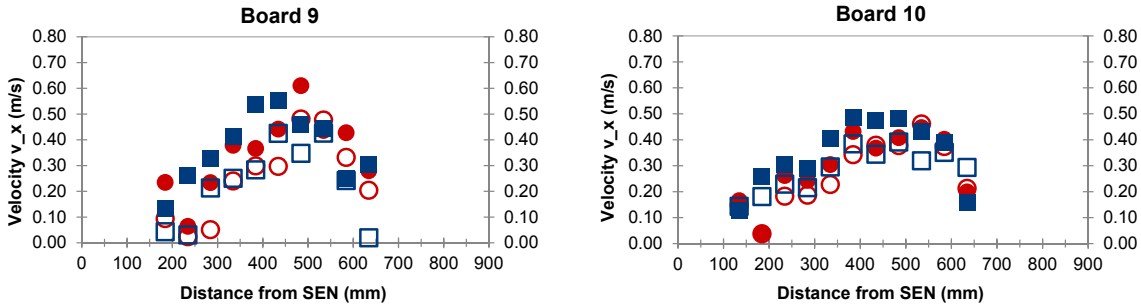
Legend

● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
9	45.6	53.87	7.0	19.01	187
10	45.4	53.87	7.0	19.01	187

Adjusted Velocity Boards 9 – 10



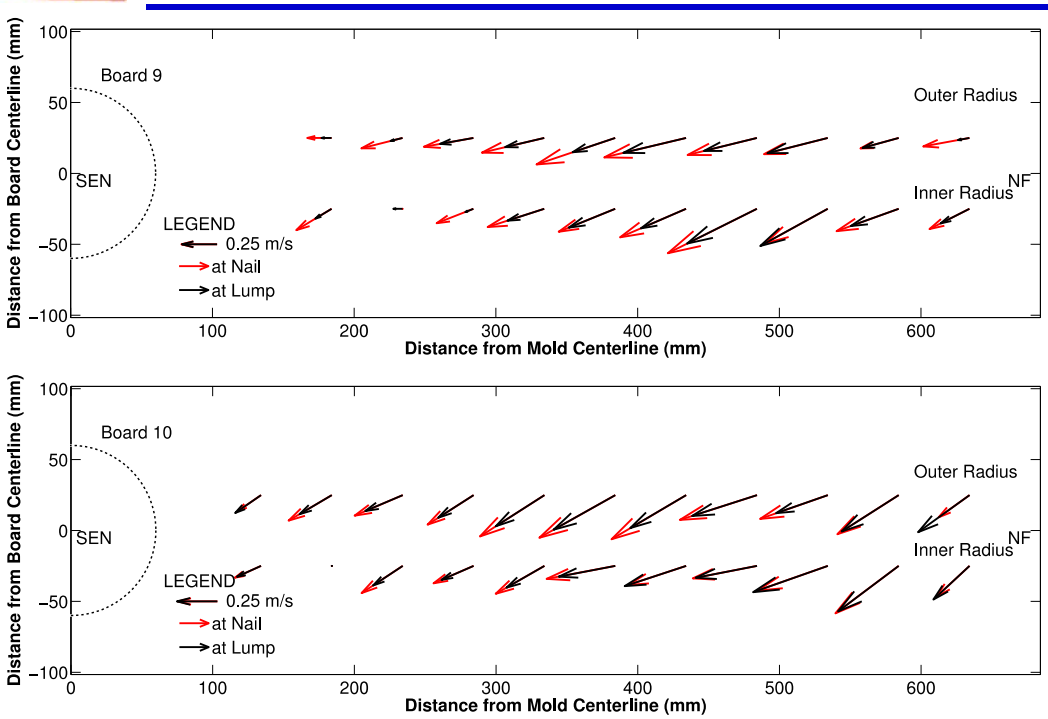
Legend

● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

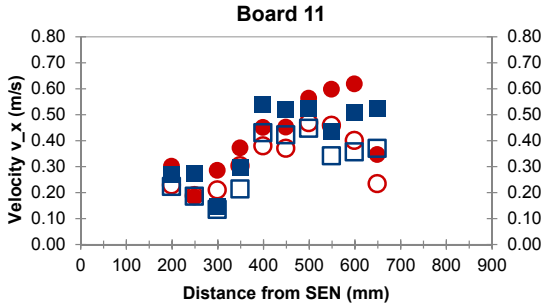
Casting Conditions

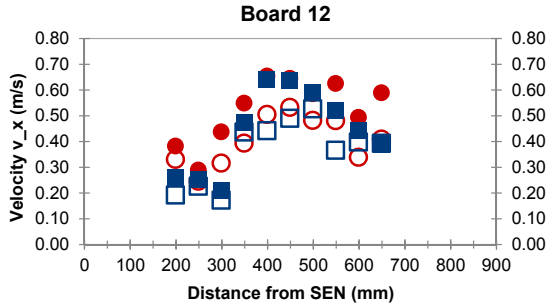
Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
9	45.6	53.87	7.0	19.01	187
10	45.4	53.87	7.0	19.01	187

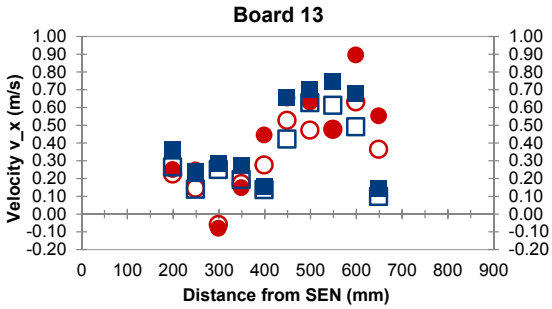
Velocity Vectors Boards 9 – 10



Velocity Boards 11 – 13







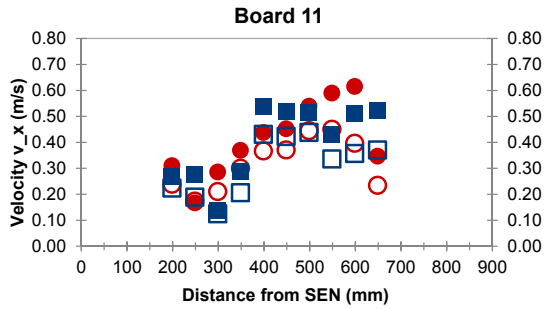
Legend

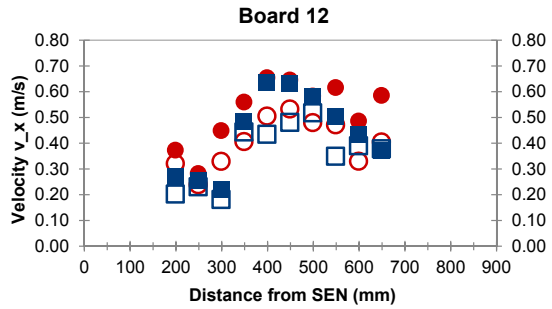
● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

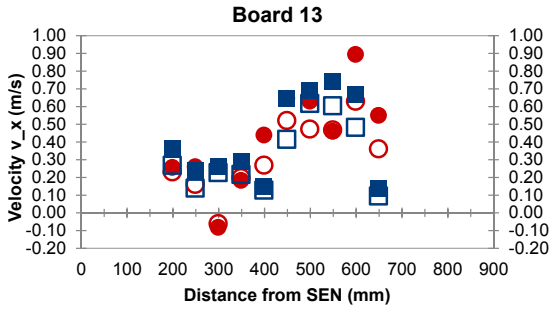
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
11	65.0	54.99	7.0	18.07	222
12	65.0	54.99	7.0	18.07	222
13	65.0	54.99	7.0	18.07	222

Adjusted Velocity Boards 11 – 13







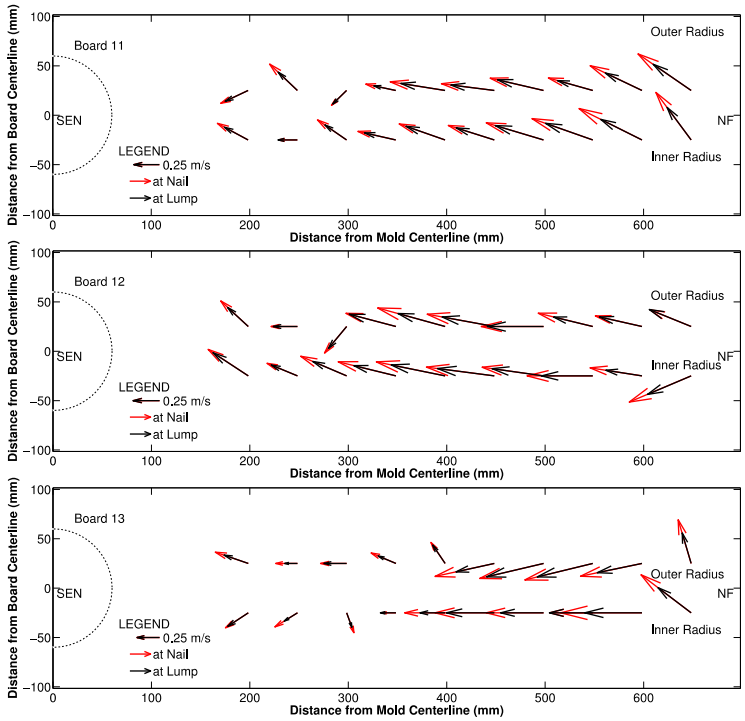
Legend

● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

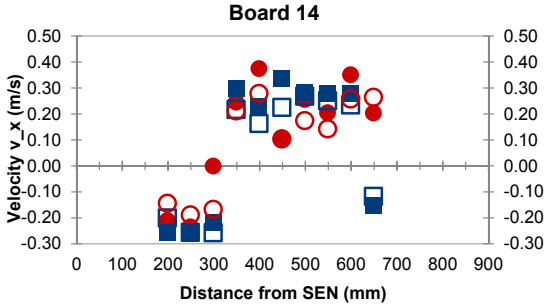
Casting Conditions

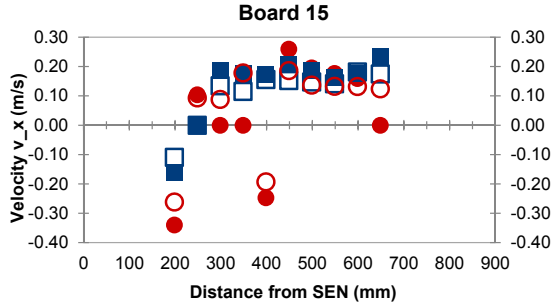
Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
11	65.0	54.99	7.0	18.07	222
12	65.0	54.99	7.0	18.07	222
13	65.0	54.99	7.0	18.07	222

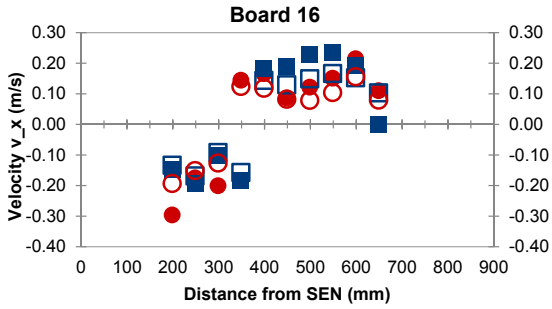
Velocity Vectors Boards 11 – 13



Velocity Boards 14 – 16







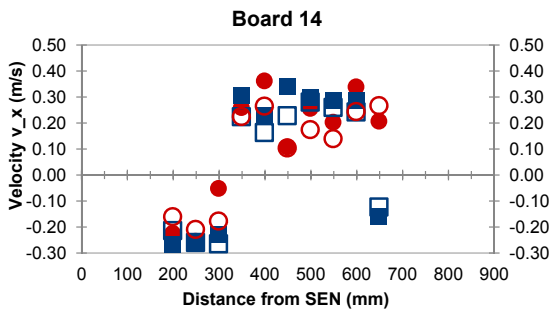
Legend

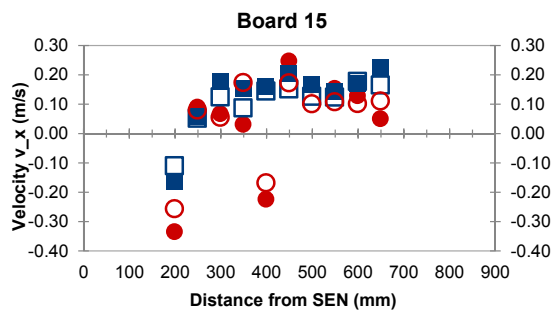
● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

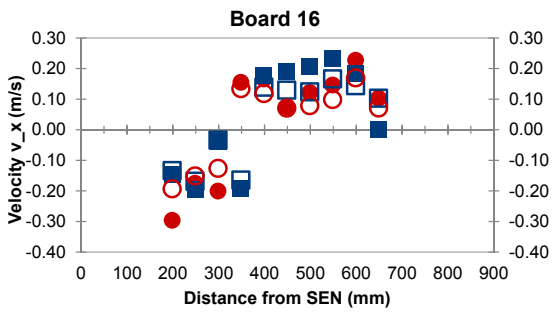
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
14	25.5	54.99	6.3	19.18	222
15	25.5	54.99	6.2	19.18	222
16	25.5	54.99	6.2	19.18	222

Adjusted Velocity Boards 14 – 16







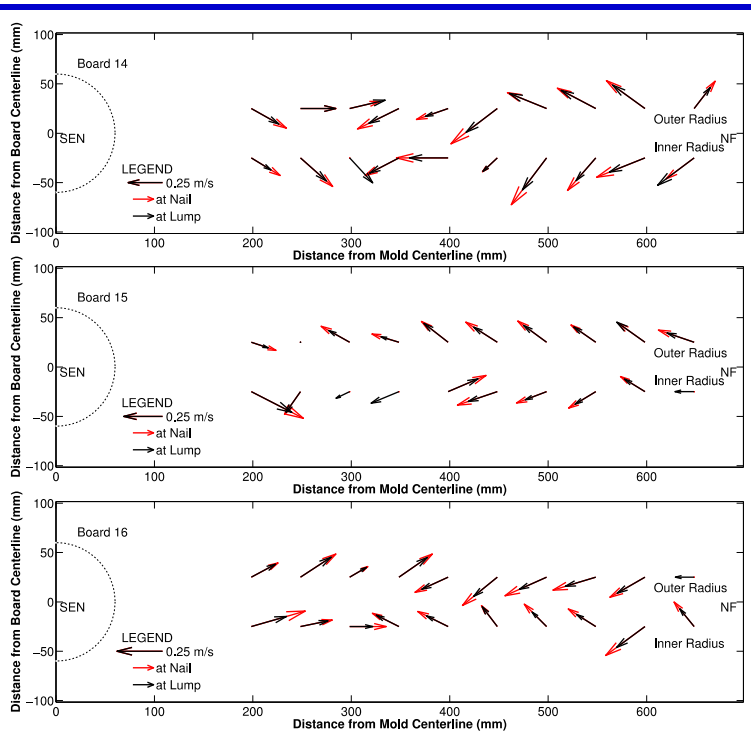
Legend

● Nail - IR ■ Nail - OR ○ Lump - IR □ Lump - OR

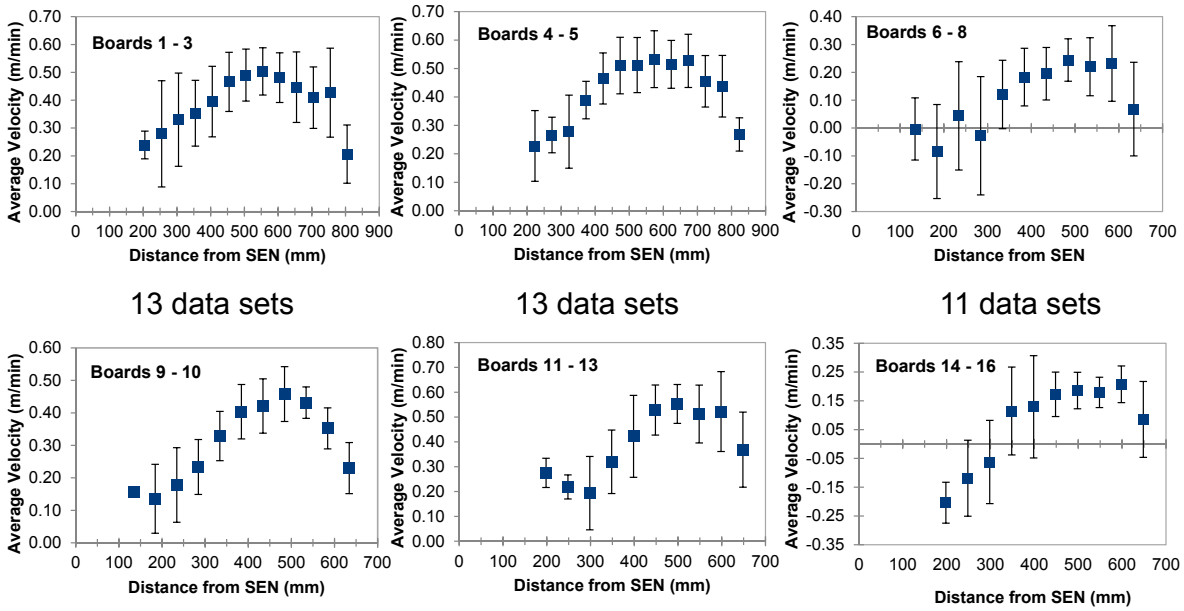
Casting Conditions

Nail board Case #	Casting Speed (inch/min)	Strand Width (inch)	Argon Flow Rate (SLPM)	Argon Back Pressure (psi)	Submergence Depth (mm)
14	25.5	54.99	6.3	19.18	222
15	25.5	54.99	6.2	19.18	222
16	25.5	54.99	6.2	19.18	222

Velocity Vectors Boards 14 – 16



Summary: Velocity
Averages and Standard Deviations



13 data sets | 13 data sets | 11 data sets

11 data sets | 10 data sets | 10 data sets

Conclusions

- Velocity measurements based at the nail(nail diameter) and at the lump (lump diameter) roughly agree
- Both rows of nails roughly agree
- Distance from steel-slag interface to discolored region is ~25mm, with similar profiles (suggesting almost constant liquid slag-layer thickness)
- For cases 1 – 5 and 9 – 13:
  - Clear double-roll flow pattern with higher interface near NF, lower interface near SEN, and surface velocity towards SEN
  - Standing wave height ~20mm
  - Surface velocity has classic profile with max near midway between SEN and NF
  - Max surface velocity seems very high, ~0.7 m/s
- For cases 6 – 8 and 14 – 16:
  - There is a complex flow pattern near the SEN due to increased argon gas injection