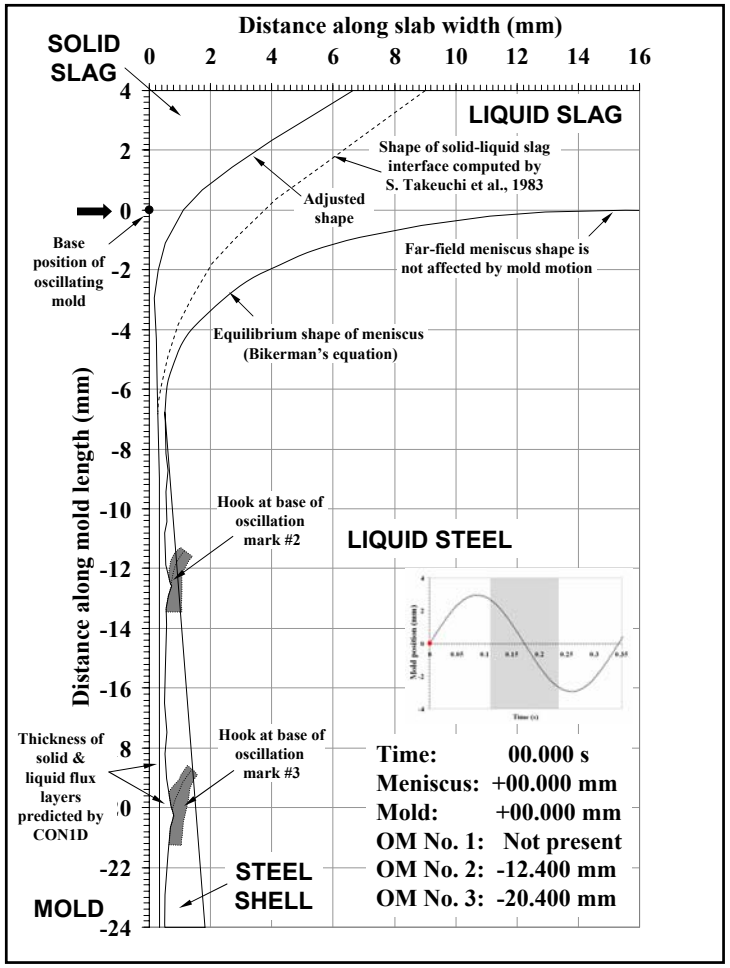
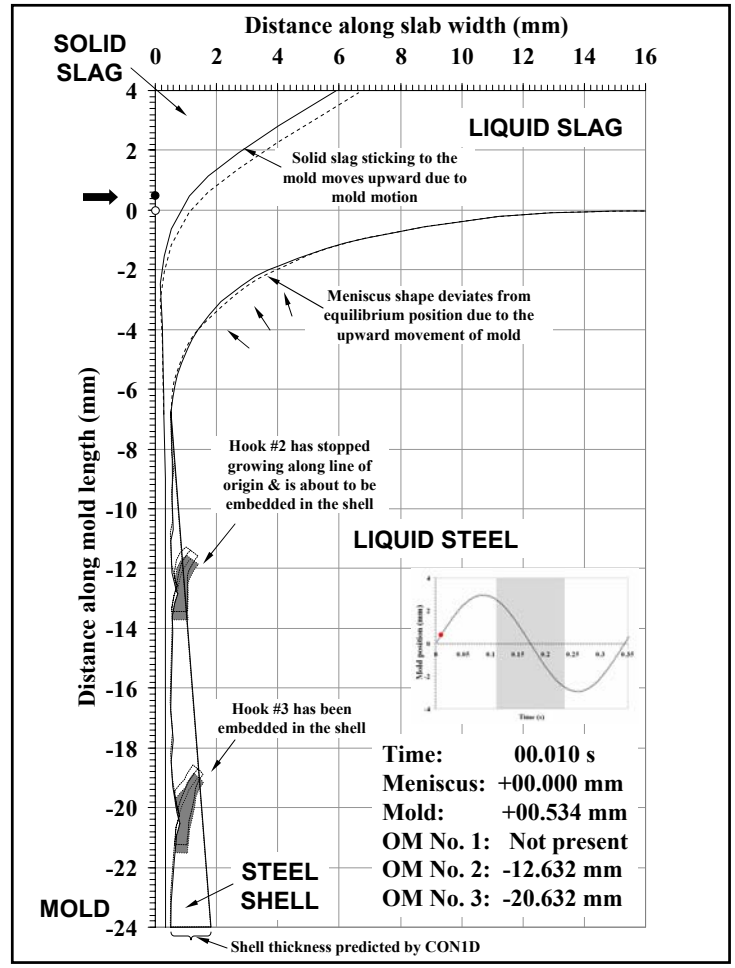
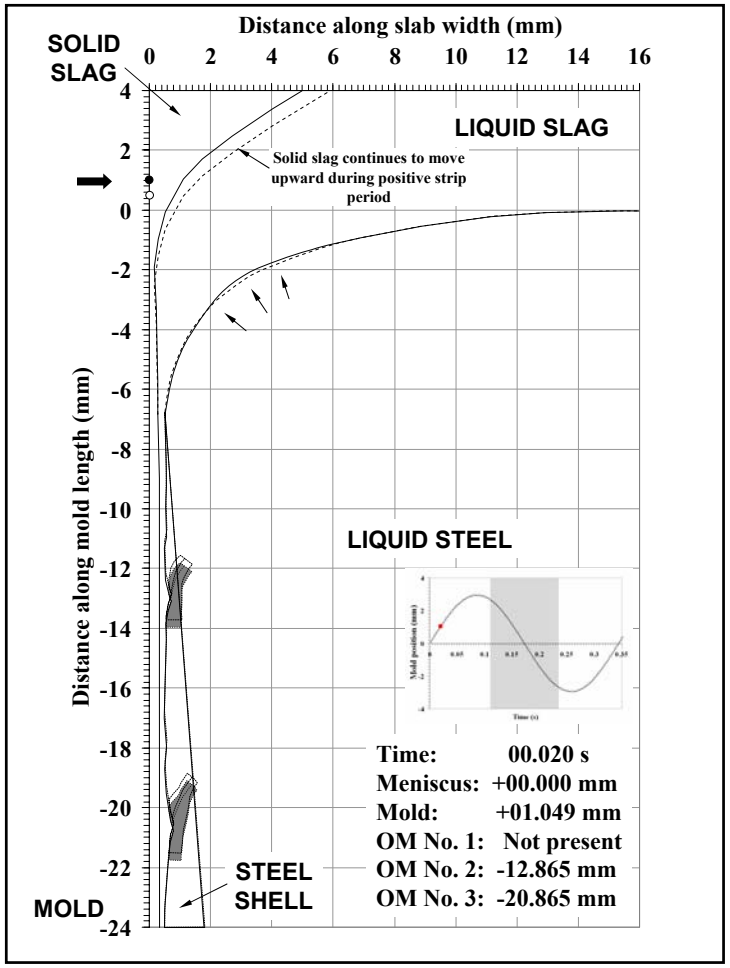
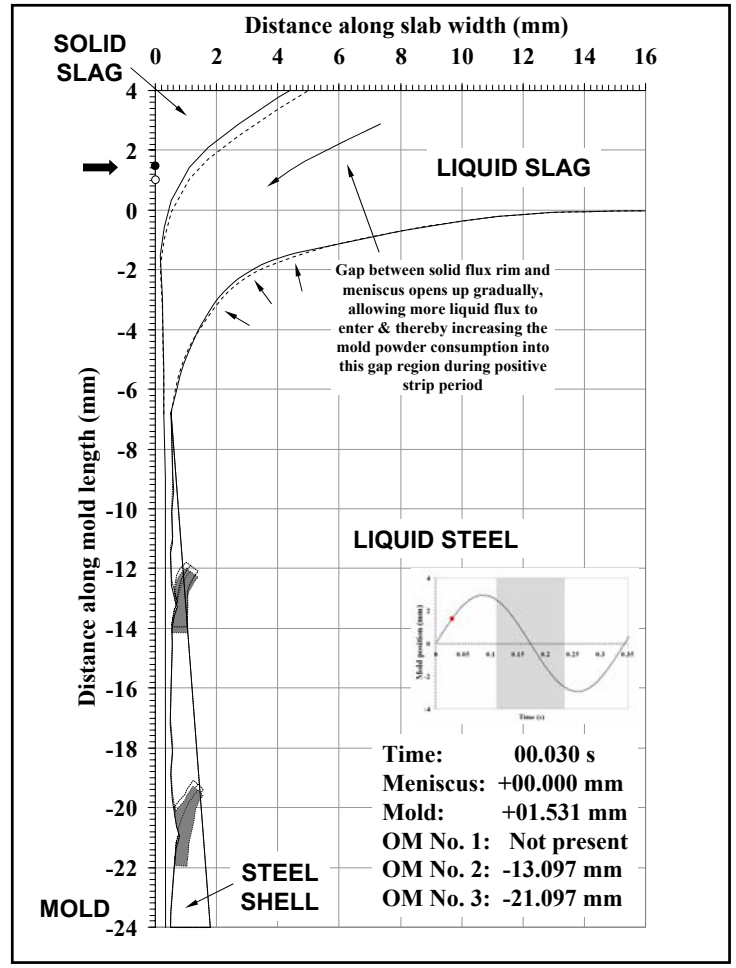
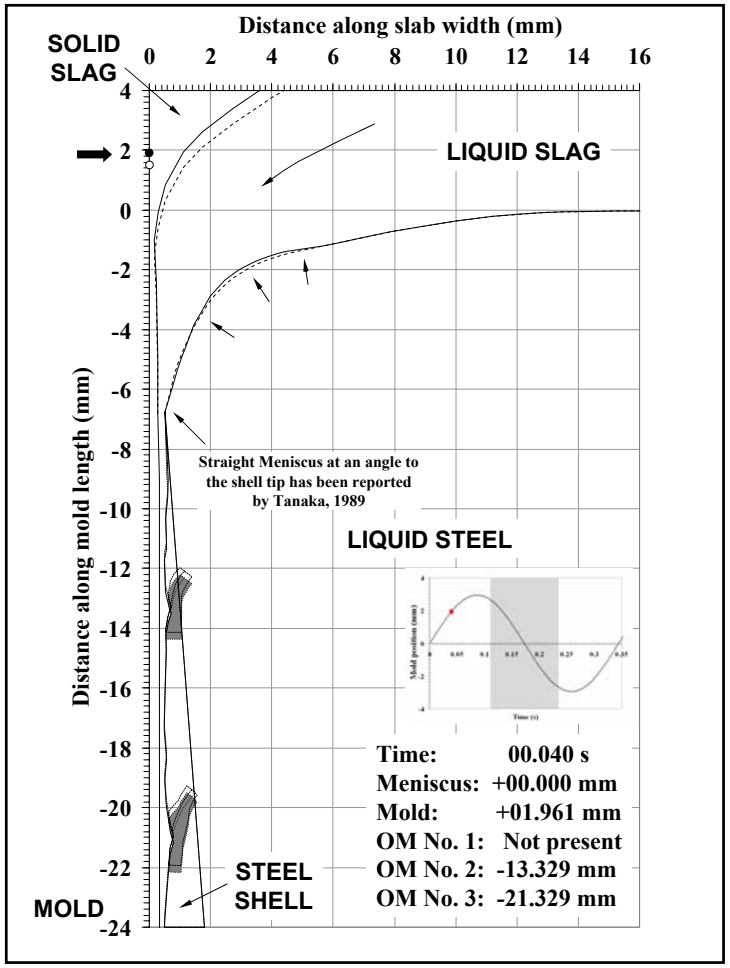
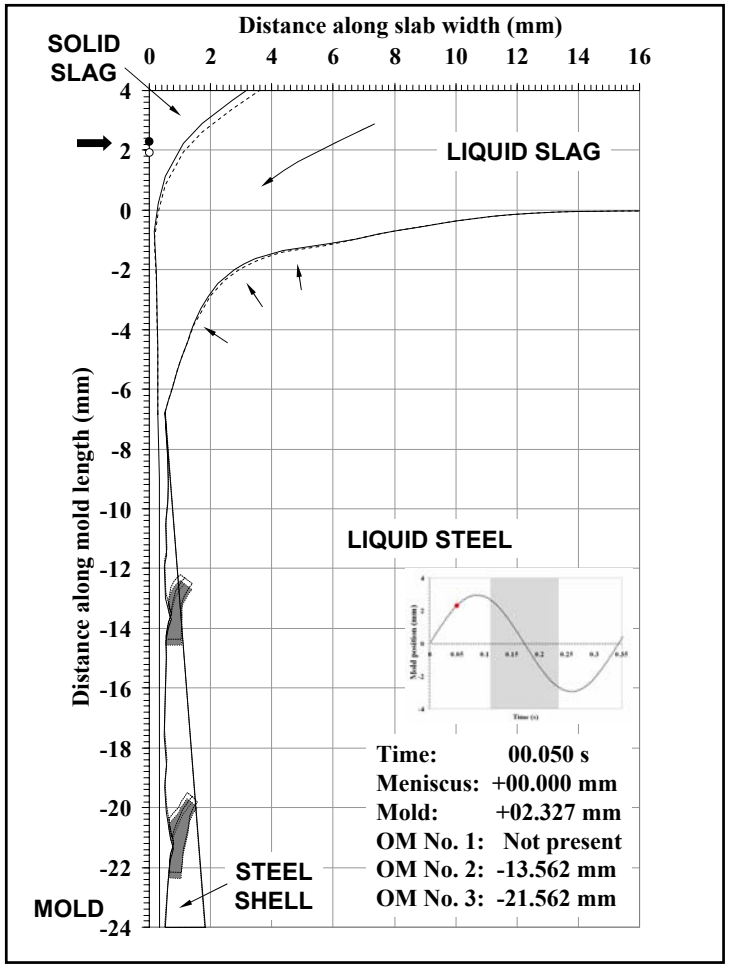

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Shape of solid-liquid slag interface computed by S. Takeuchi et al., 1983
Adjusted shape
Base position of oscillating mold
Far-field meniscus shape is not affected by mold motion
Equilibrium shape of meniscus (Bikerman's equation)
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Hook at base of oscillation mark #2
LIQUID STEEL
Thickness of solid & liquid flux layers predicted by CON1D
Hook at base of oscillation mark #3
Time: 00.000 s
Meniscus: +00.000 mm
Mold: +00.000 mm
OM No. 1: Not present
OM No. 2: -12.400 mm
OM No. 3: -20.400 mm
STEEL SHELL
MOLD

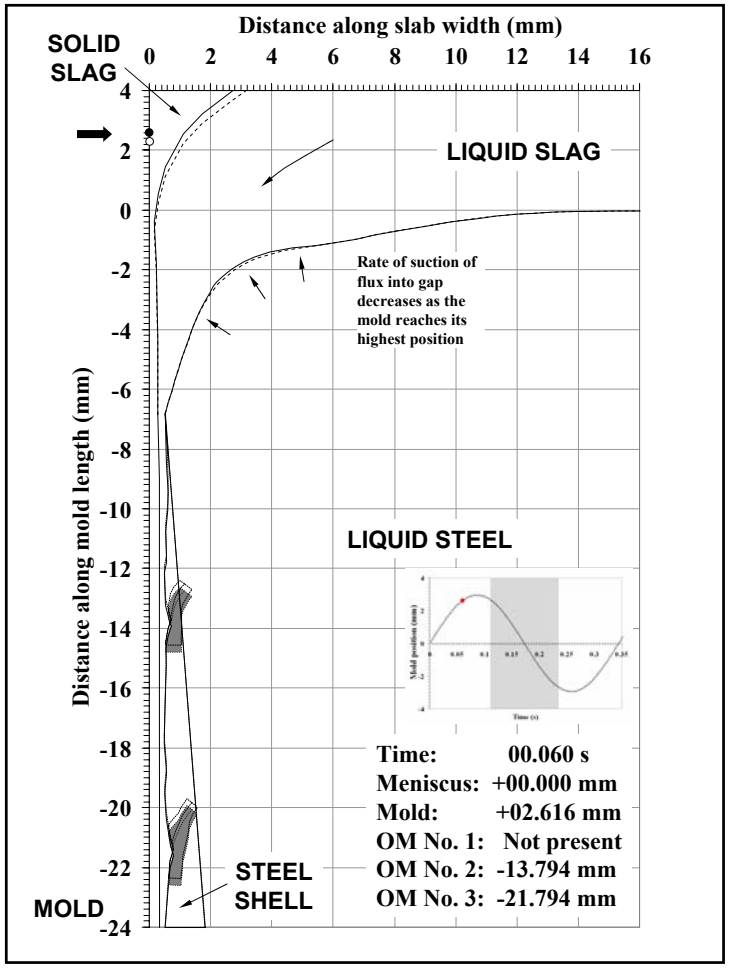

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Solid slag sticking to the mold moves upward due to mold motion
Meniscus shape deviates from equilibrium position due to the upward movement of mold
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Hook #2 has stopped growing along line of origin & is about to be embedded in the shell
LIQUID STEEL
Hook #3 has been embedded in the shell
Time: 00.010 s
Meniscus: +00.000 mm
Mold: +00.534 mm
OM No. 1: Not present
OM No. 2: -12.632 mm
OM No. 3: -20.632 mm
STEEL SHELL
MOLD
Shell thickness predicted by CON1D

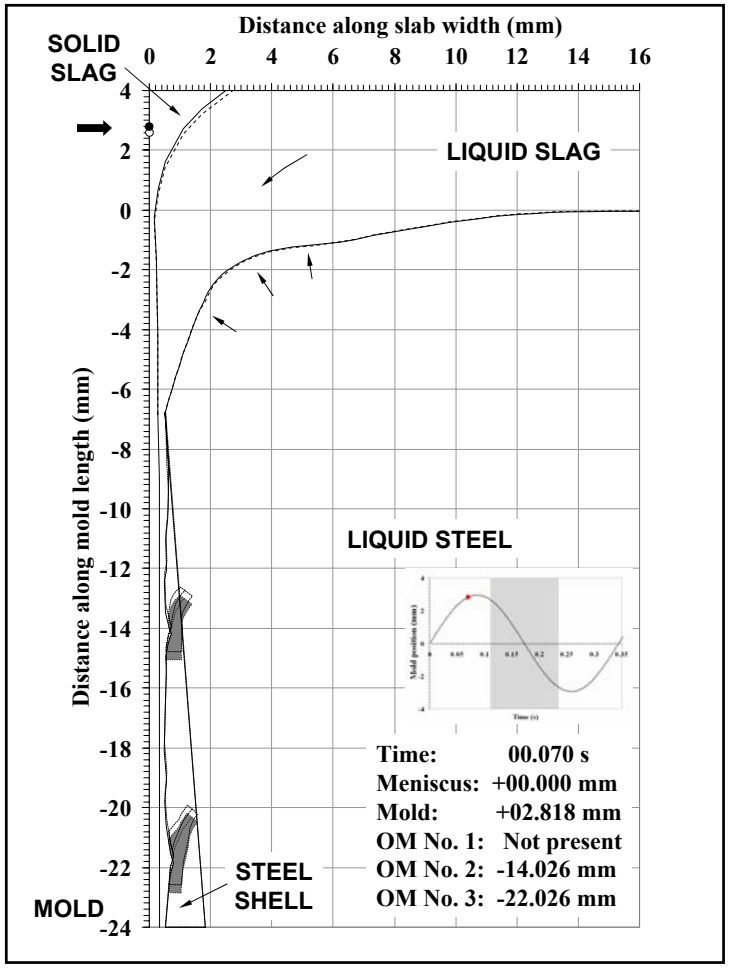

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Solid slag continues to move upward during positive strip period
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Time: 00.020 s
Meniscus: +00.000 mm
Mold: +01.049 mm
OM No. 1: Not present
OM No. 2: -12.865 mm
OM No. 3: -20.865 mm
STEEL SHELL
MOLD

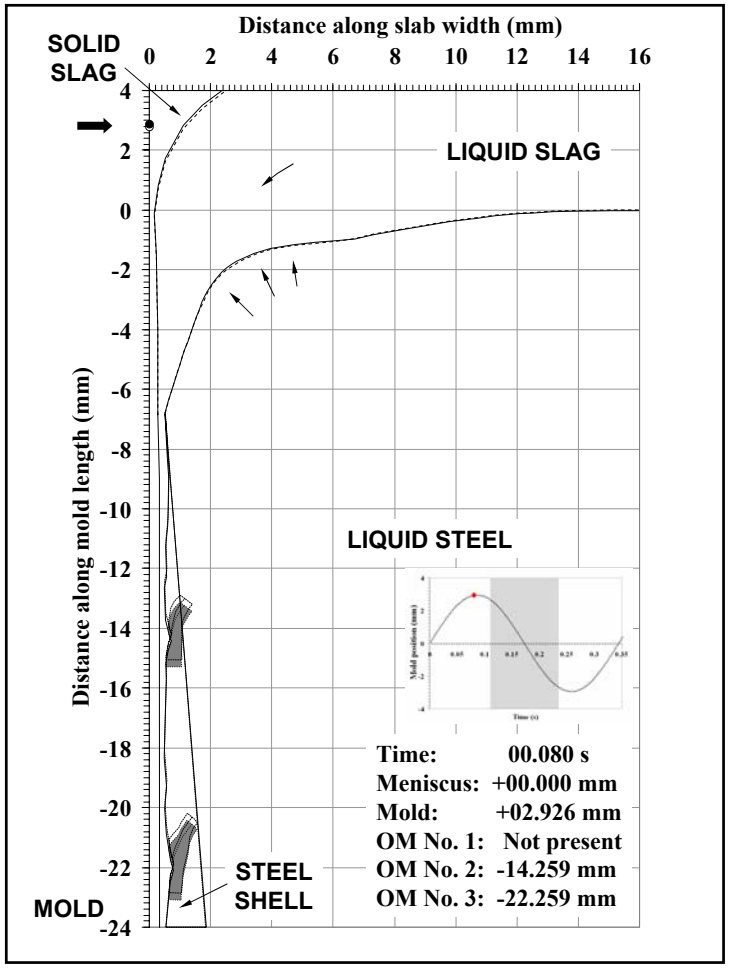

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Gap between solid flux rim and meniscus opens up gradually, allowing more liquid flux to enter & thereby increasing the mold powder consumption into this gap region during positive strip period
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Time: 00.030 s
Meniscus: +00.000 mm
Mold: +01.531 mm
OM No. 1: Not present
OM No. 2: -13.097 mm
OM No. 3: -21.097 mm
STEEL SHELL
MOLD

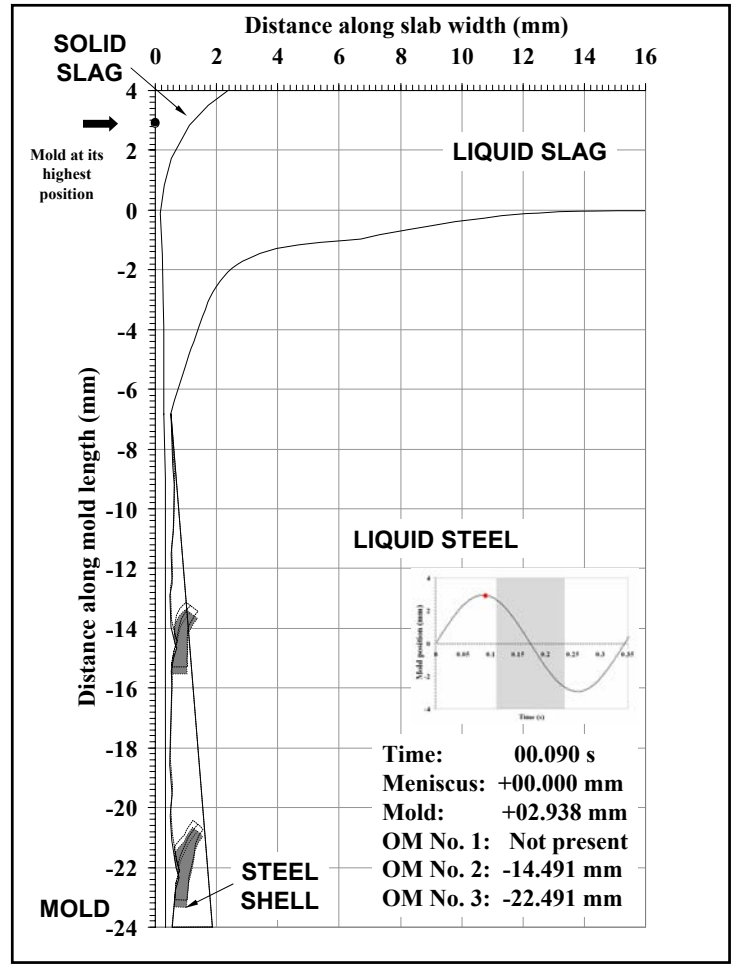

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Straight Meniscus at an angle to the shell tip has been reported by Tanaka, 1989
LIQUID STEEL
Time: 00.040 s
Meniscus: +00.000 mm
Mold: +01.961 mm
OM No. 1: Not present
OM No. 2: -13.329 mm
OM No. 3: -21.329 mm
STEEL SHELL
MOLD

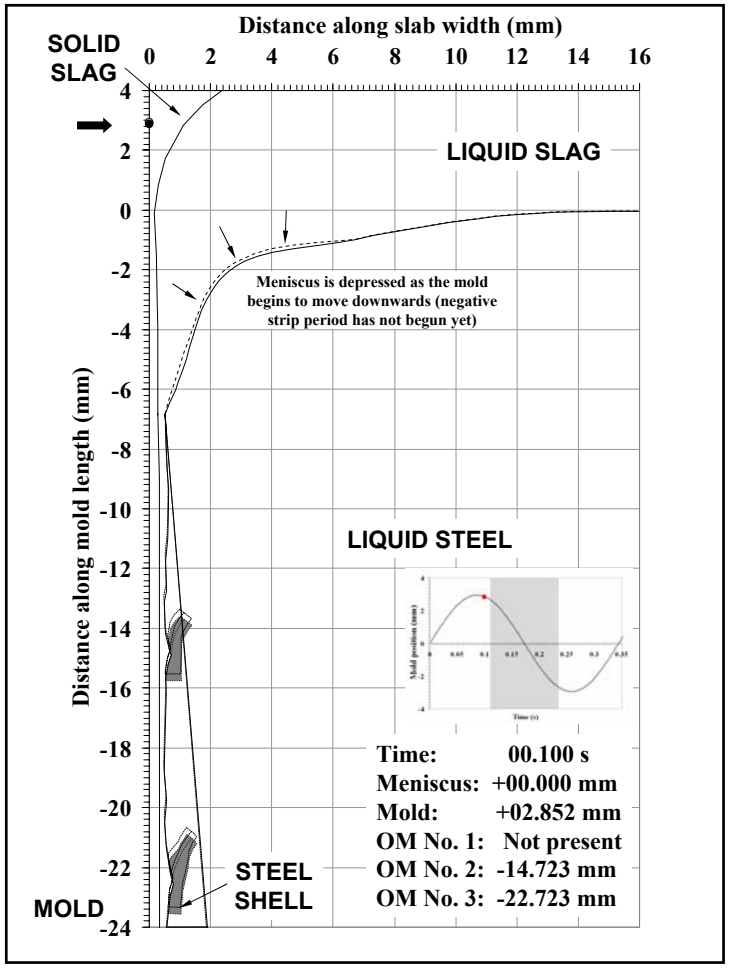

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Time: 00.050 s
Meniscus: +00.000 mm
Mold: +02.327 mm
OM No. 1: Not present
OM No. 2: -13.562 mm
OM No. 3: -21.562 mm
STEEL SHELL
MOLD

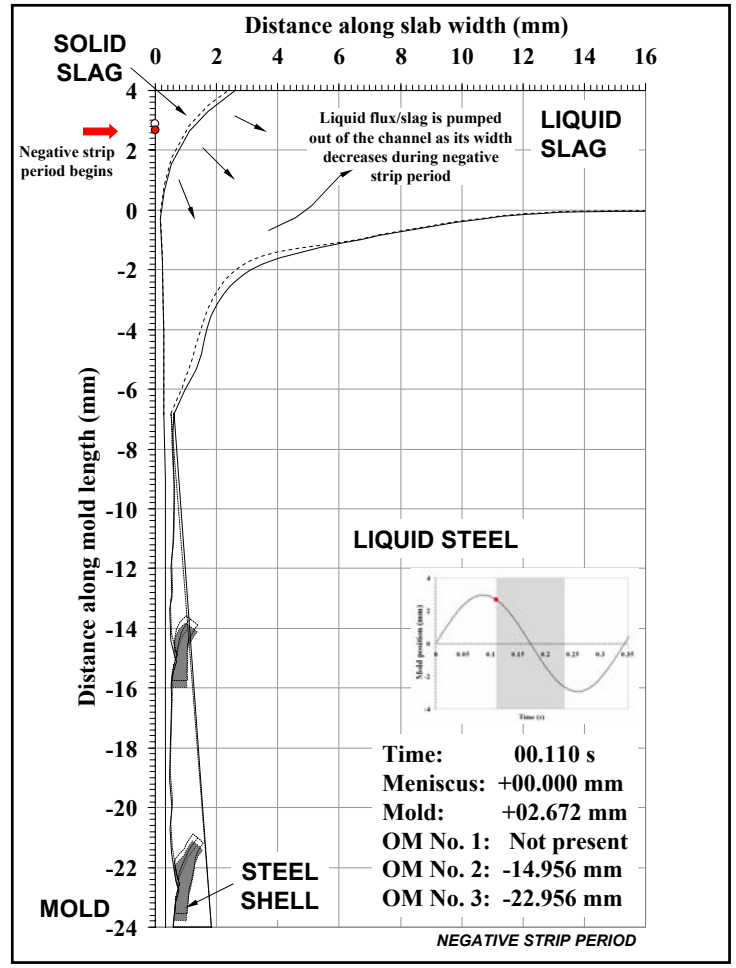

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Rate of suction of flux into gap decreases as the mold reaches its highest position
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.060 s
Meniscus: +00.000 mm
Mold: +02.616 mm
OM No. 1: Not present
OM No. 2: -13.794 mm
OM No. 3: -21.794 mm

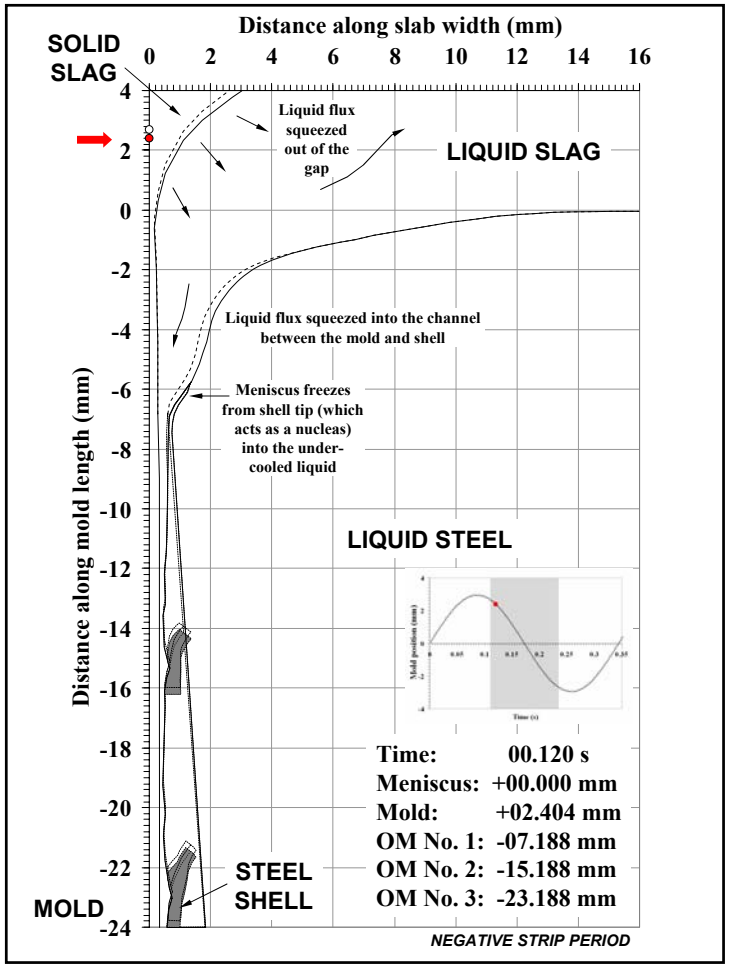

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.070 s
Meniscus: +00.000 mm
Mold: +02.818 mm
OM No. 1: Not present
OM No. 2: -14.026 mm
OM No. 3: -22.026 mm

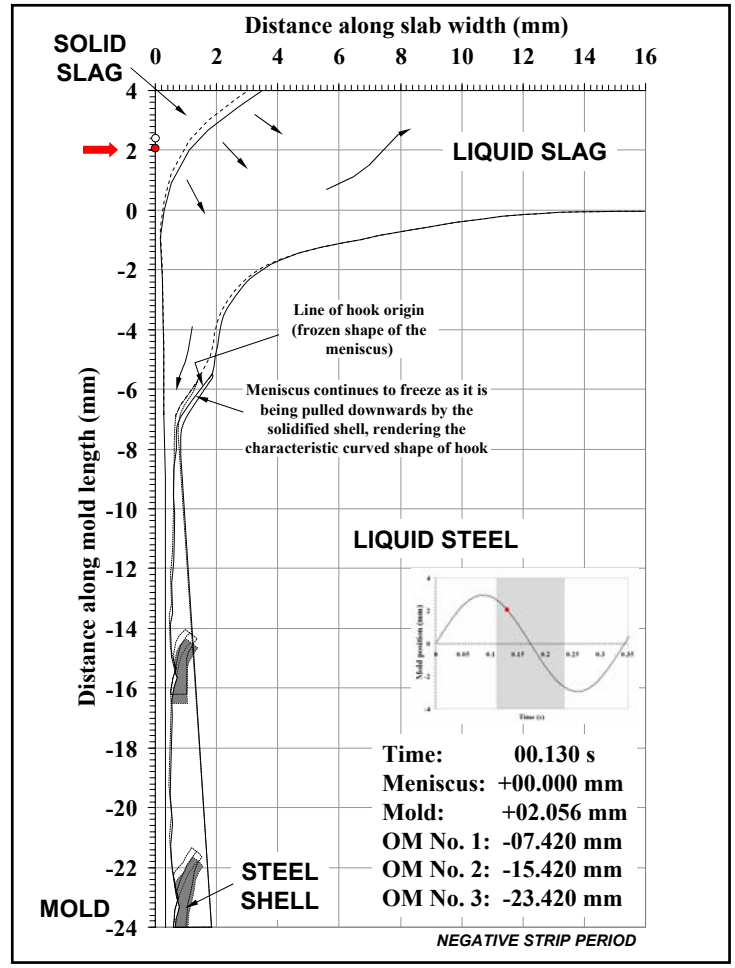

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.080 s
Meniscus: +00.000 mm
Mold: +02.926 mm
OM No. 1: Not present
OM No. 2: -14.259 mm
OM No. 3: -22.259 mm

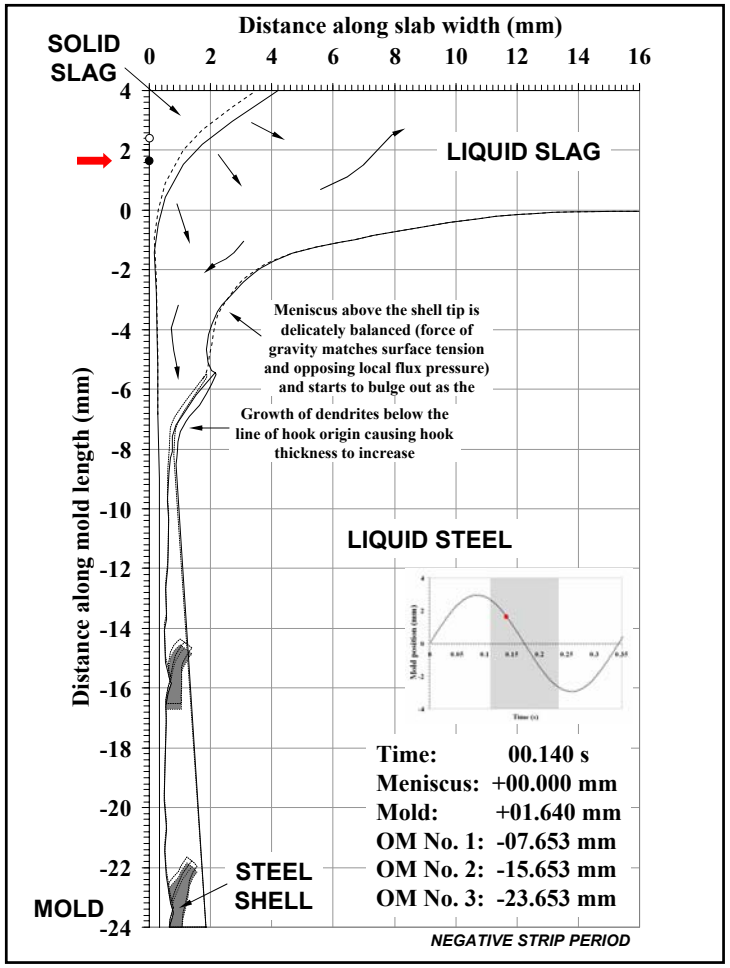

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
Mold at its highest position
LIQUID SLAG
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.090 s
Meniscus: +00.000 mm
Mold: +02.938 mm
OM No. 1: Not present
OM No. 2: -14.491 mm
OM No. 3: -22.491 mm

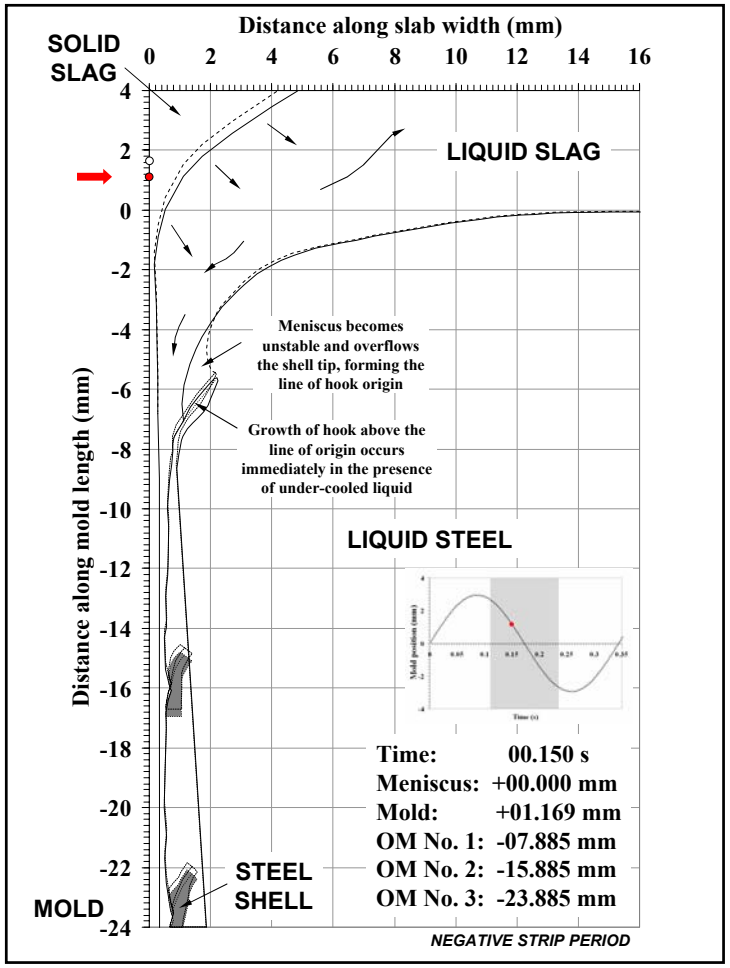

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Meniscus is depressed as the mold begins to move downwards (negative strip period has not begun yet)
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Time: 00.100 s
Meniscus: +00.000 mm
Mold: +02.852 mm
OM No. 1: Not present
OM No. 2: -14.723 mm
OM No. 3: -22.723 mm
STEEL SHELL
MOLD

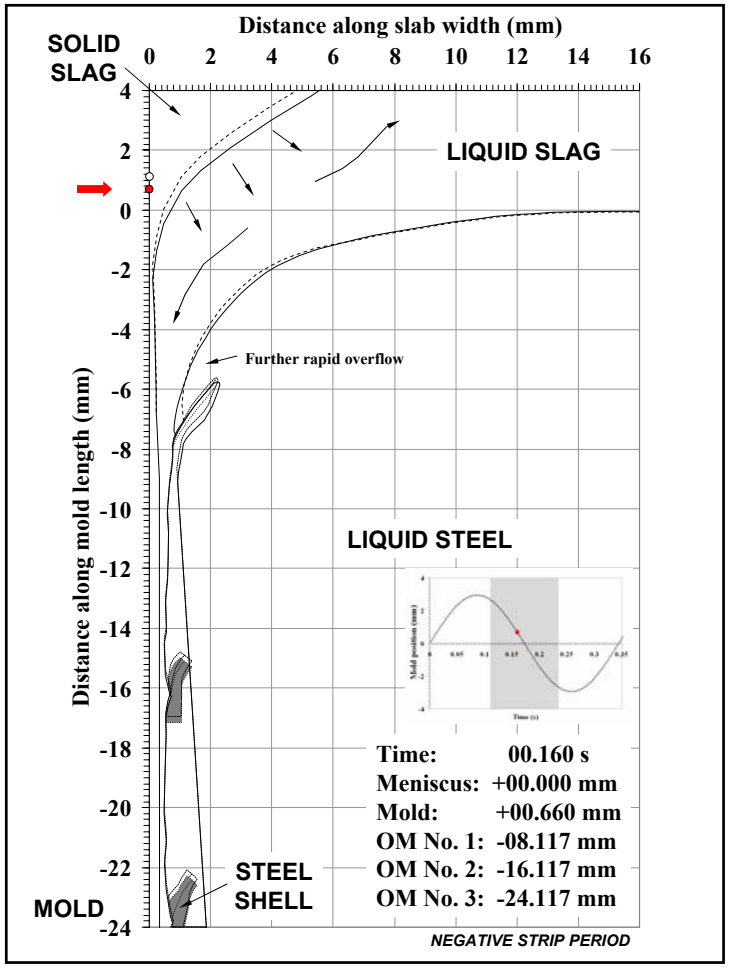

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
Negative strip period begins
Liquid flux/slag is pumped out of the channel as its width decreases during negative strip period
LIQUID SLAG
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Time: 00.110 s
Meniscus: +00.000 mm
Mold: +02.672 mm
OM No. 1: Not present
OM No. 2: -14.956 mm
OM No. 3: -22.956 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

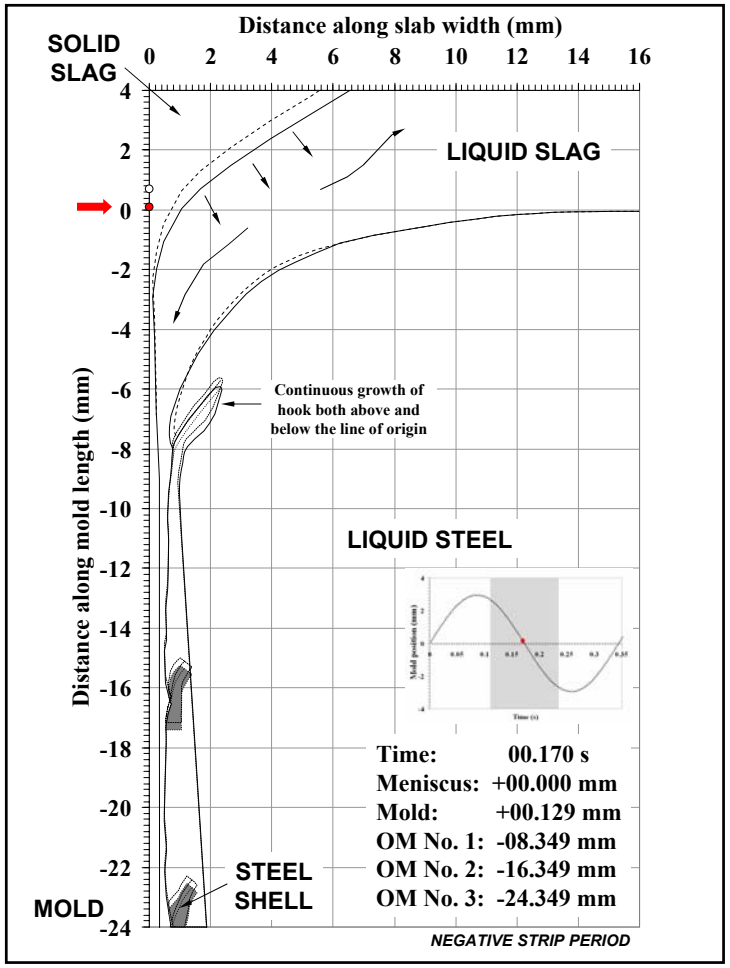

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
Liquid flux squeezed out of the gap
LIQUID SLAG
Liquid flux squeezed into the channel between the mold and shell
Meniscus freezes from shell tip (which acts as a nucleas) into the under-cooled liquid
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.120 s
Meniscus: +00.000 mm
Mold: +02.404 mm
OM No. 1: -07.188 mm
OM No. 2: -15.188 mm
OM No. 3: -23.188 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

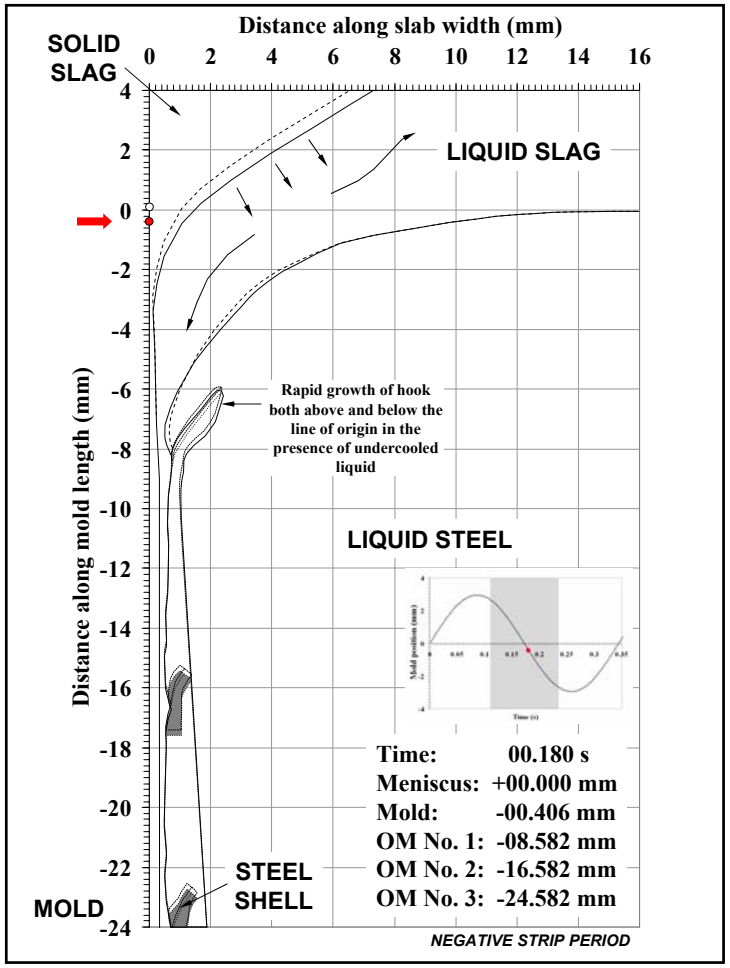

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Line of hook origin (frozen shape of the meniscus)
Meniscus continues to freeze as it is being pulled downwards by the solidified shell, rendering the characteristic curved shape of hook
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.130 s
Meniscus: +00.000 mm
Mold: +02.056 mm
OM No. 1: -07.420 mm
OM No. 2: -15.420 mm
OM No. 3: -23.420 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

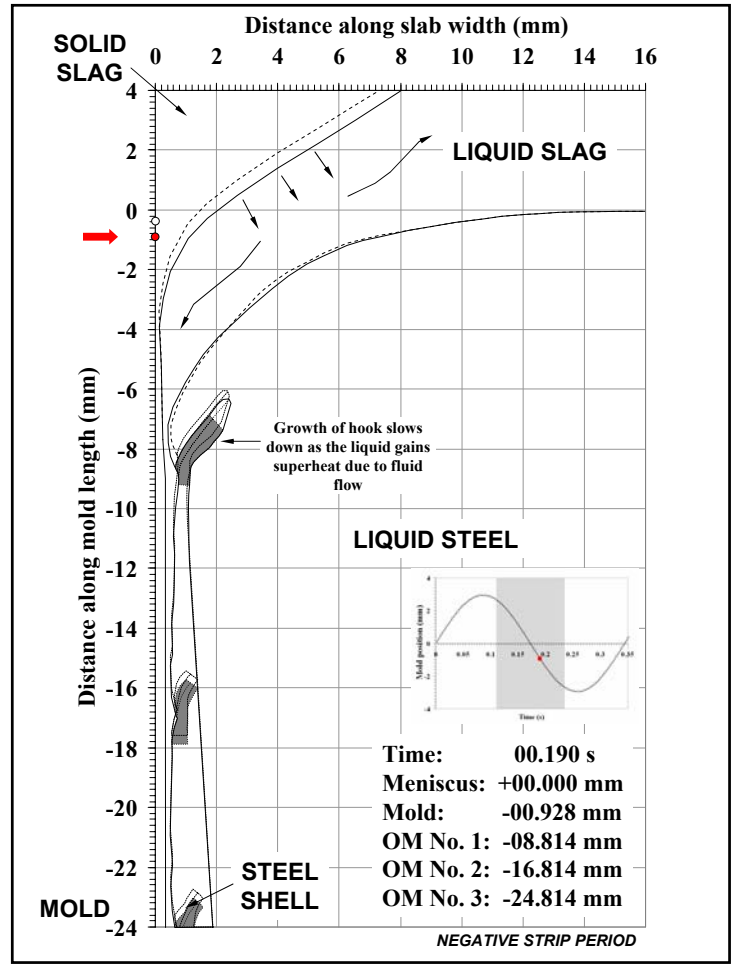

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Meniscus above the shell tip is delicately balanced (force of gravity matches surface tension and opposing local flux pressure) and starts to bulge out as the
Growth of dendrites below the line of hook origin causing hook thickness to increase
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.140 s
Meniscus: +00.000 mm
Mold: +01.640 mm
OM No. 1: -07.653 mm
OM No. 2: -15.653 mm
OM No. 3: -23.653 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

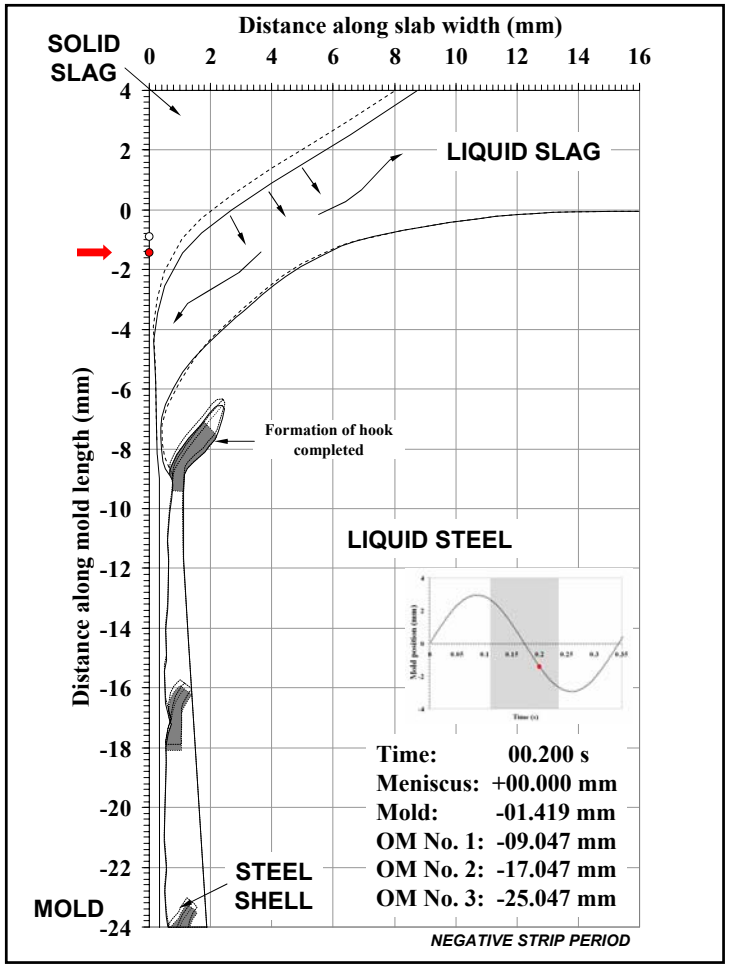

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Meniscus becomes unstable and overflows the shell tip, forming the line of hook origin
Growth of hook above the line of origin occurs immediately in the presence of under-cooled liquid
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.150 s
Meniscus: +00.000 mm
Mold: +01.169 mm
OM No. 1: -07.885 mm
OM No. 2: -15.885 mm
OM No. 3: -23.885 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

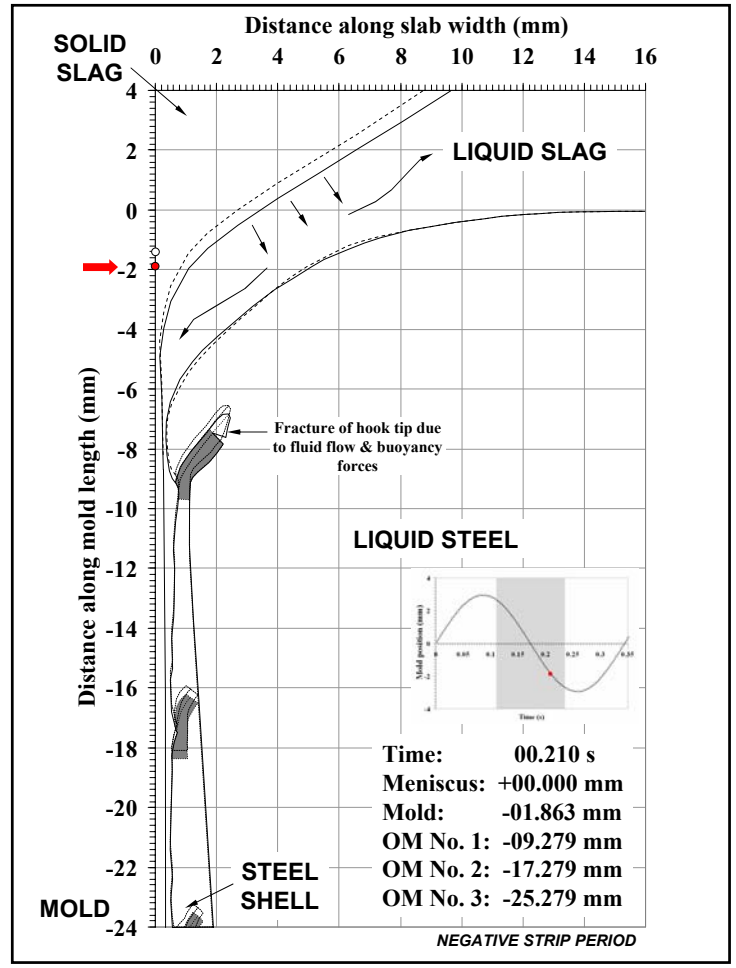

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Further rapid overflow
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.160 s
Meniscus: +00.000 mm
Mold: +00.660 mm
OM No. 1: -08.117 mm
OM No. 2: -16.117 mm
OM No. 3: -24.117 mm
NEGATIVE STRIP PERIOD

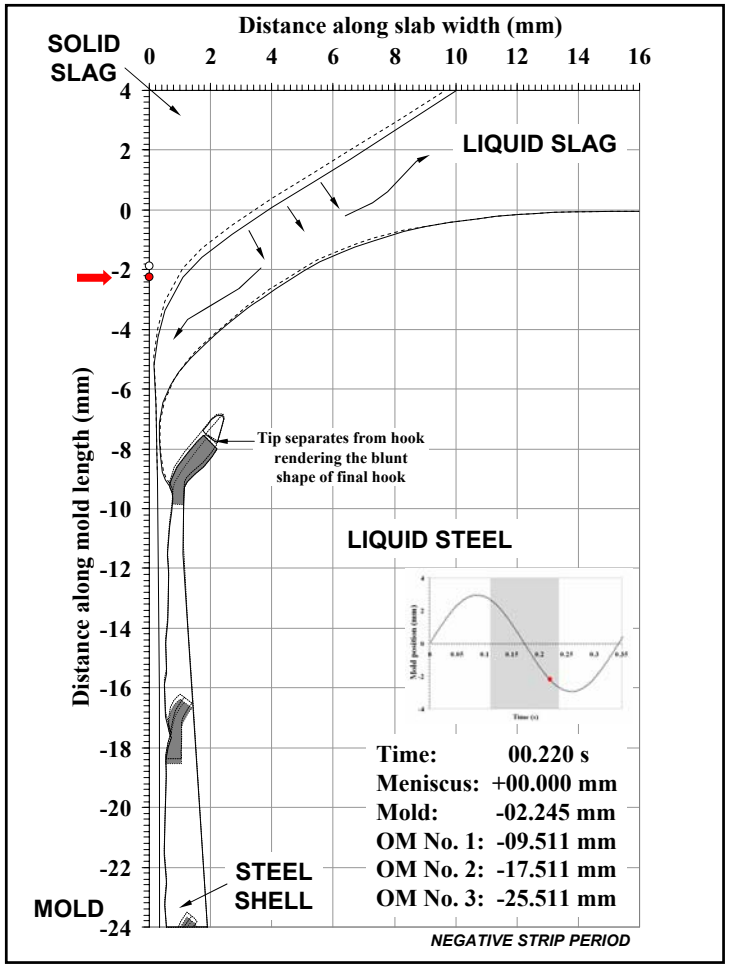

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Continuous growth of hook both above and below the line of origin
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.170 s
Meniscus: +00.000 mm
Mold: +00.129 mm
OM No. 1: -08.349 mm
OM No. 2: -16.349 mm
OM No. 3: -24.349 mm
NEGATIVE STRIP PERIOD

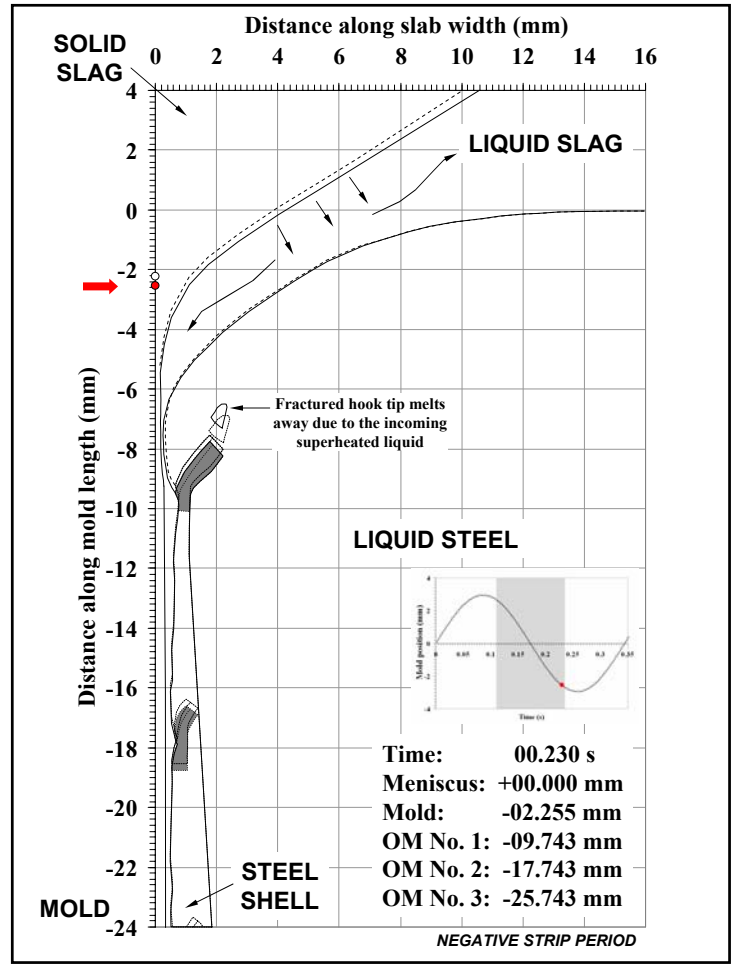

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Rapid growth of hook both above and below the line of origin in the presence of undercooled liquid
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.180 s
Meniscus: +00.000 mm
Mold: -00.406 mm
OM No. 1: -08.582 mm
OM No. 2: -16.582 mm
OM No. 3: -24.582 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

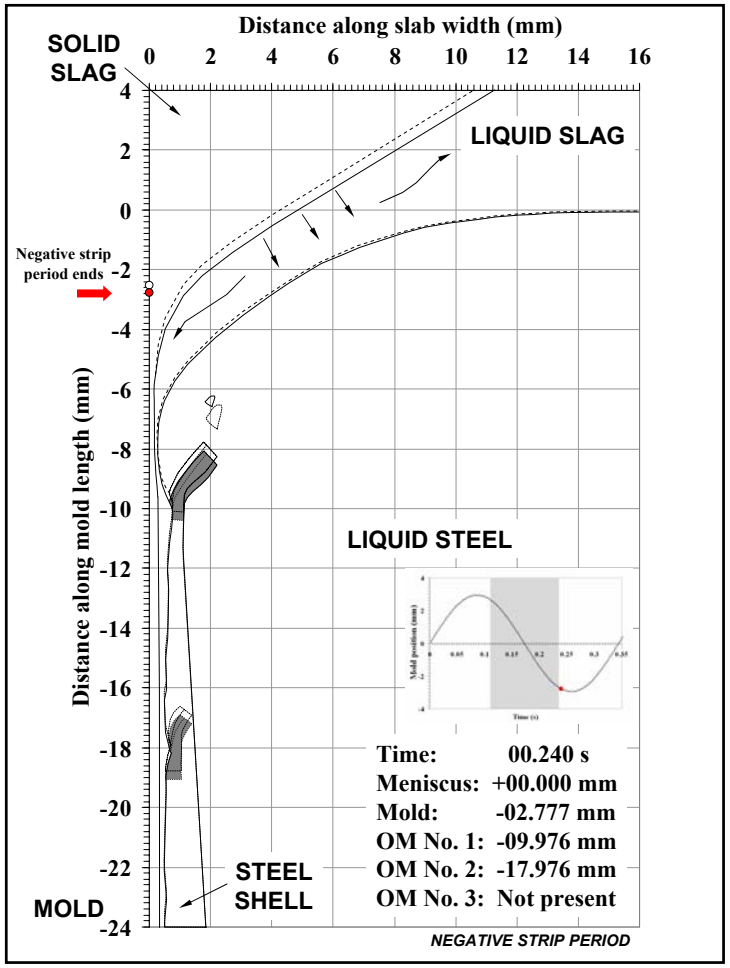

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Growth of hook slows down as the liquid gains superheat due to fluid flow
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.190 s
Meniscus: +00.000 mm
Mold: -00.928 mm
OM No. 1: -08.814 mm
OM No. 2: -16.814 mm
OM No. 3: -24.814 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

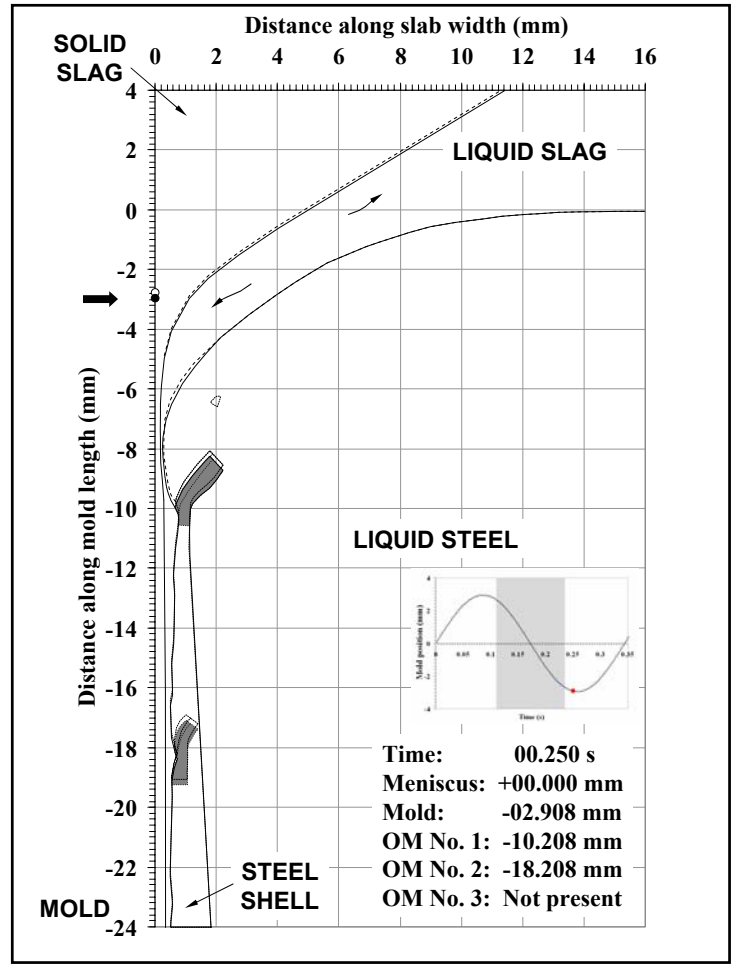

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Formation of hook completed
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.200 s
Meniscus: +00.000 mm
Mold: -01.419 mm
OM No. 1: -09.047 mm
OM No. 2: -17.047 mm
OM No. 3: -25.047 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

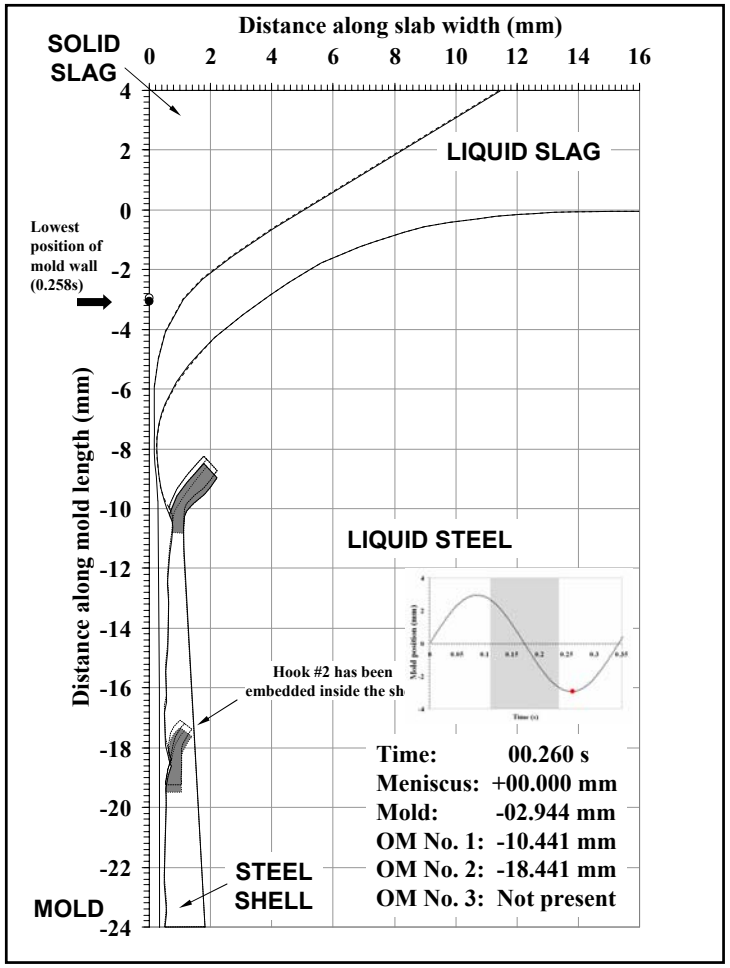

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Fracture of hook tip due to fluid flow & buoyancy forces
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.210 s
Meniscus: +00.000 mm
Mold: -01.863 mm
OM No. 1: -09.279 mm
OM No. 2: -17.279 mm
OM No. 3: -25.279 mm
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

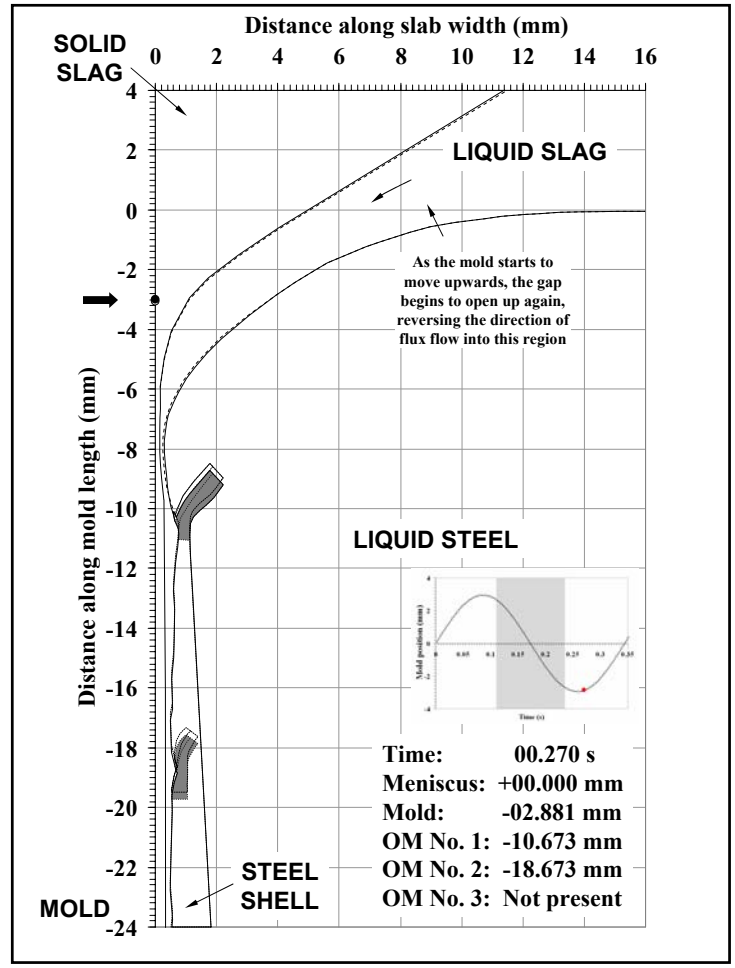

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Tip separates from hook rendering the blunt shape of final hook
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.220 s
Meniscus: +00.000 mm
Mold: -02.245 mm
OM No. 1: -09.511 mm
OM No. 2: -17.511 mm
OM No. 3: -25.511 mm
NEGATIVE STRIP PERIOD

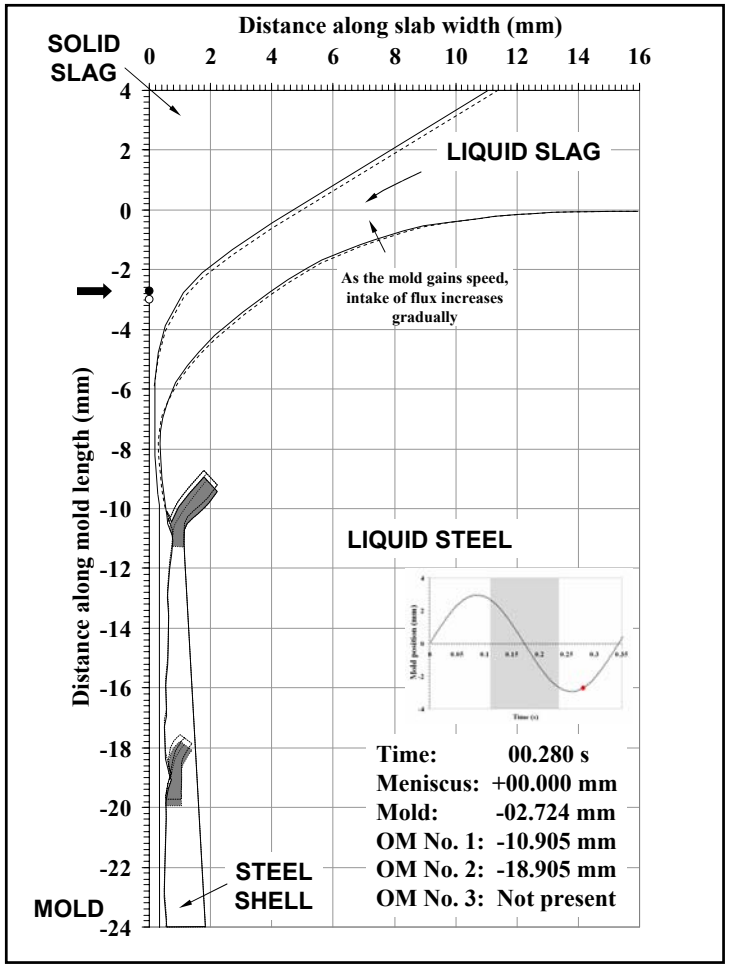

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Fractured hook tip melts away due to the incoming superheated liquid
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.230 s
Meniscus: +00.000 mm
Mold: -02.255 mm
OM No. 1: -09.743 mm
OM No. 2: -17.743 mm
OM No. 3: -25.743 mm
NEGATIVE STRIP PERIOD

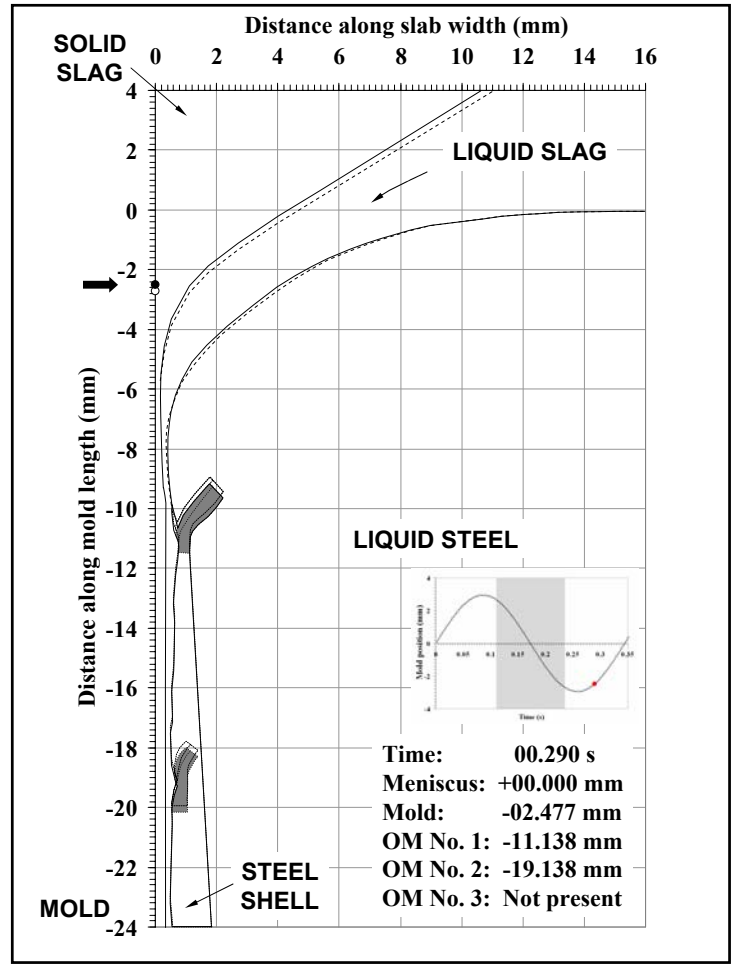

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Negative strip period ends
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Time: 00.240 s
Meniscus: +00.000 mm
Mold: -02.777 mm
OM No. 1: -09.976 mm
OM No. 2: -17.976 mm
OM No. 3: Not present
STEEL SHELL
MOLD
NEGATIVE STRIP PERIOD

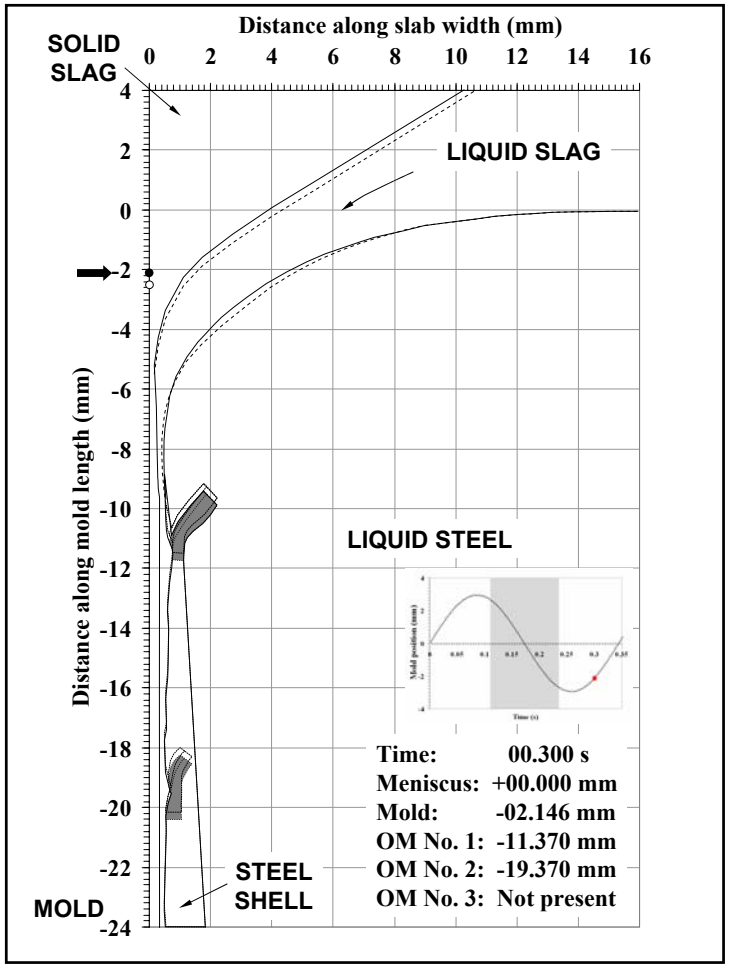

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Time: 00.250 s
Meniscus: +00.000 mm
Mold: -02.908 mm
OM No. 1: -10.208 mm
OM No. 2: -18.208 mm
OM No. 3: Not present
STEEL SHELL
MOLD

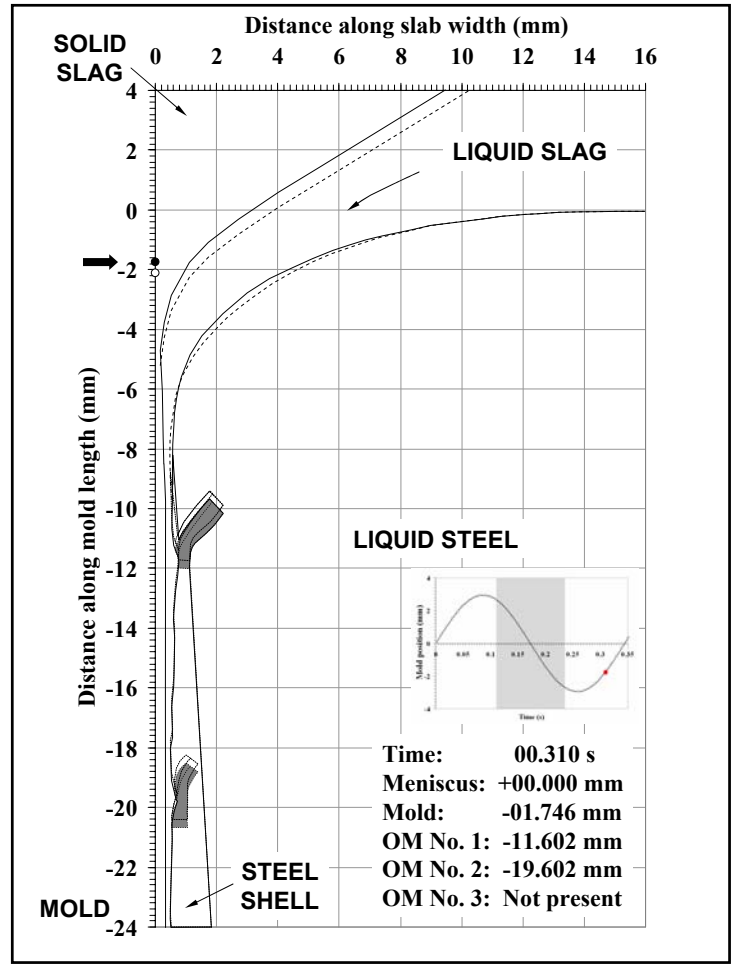

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
Lowest position of mold wall (0.258s)
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Hook #2 has been embedded inside the sh
Time: 00.260 s
Meniscus: +00.000 mm
Mold: -02.944 mm
OM No. 1: -10.441 mm
OM No. 2: -18.441 mm
OM No. 3: Not present
STEEL SHELL
MOLD

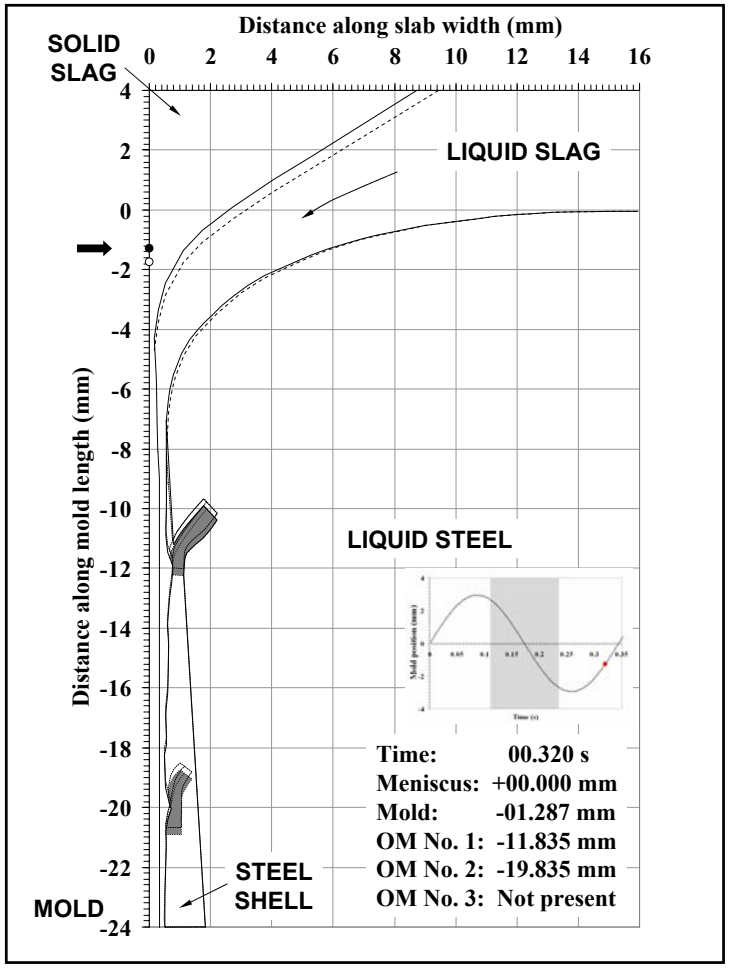

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
As the mold starts to move upwards, the gap begins to open up again, reversing the direction of flux flow into this region
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
LIQUID STEEL
Time: 00.270 s
Meniscus: +00.000 mm
Mold: -02.881 mm
OM No. 1: -10.673 mm
OM No. 2: -18.673 mm
OM No. 3: Not present
STEEL SHELL
MOLD

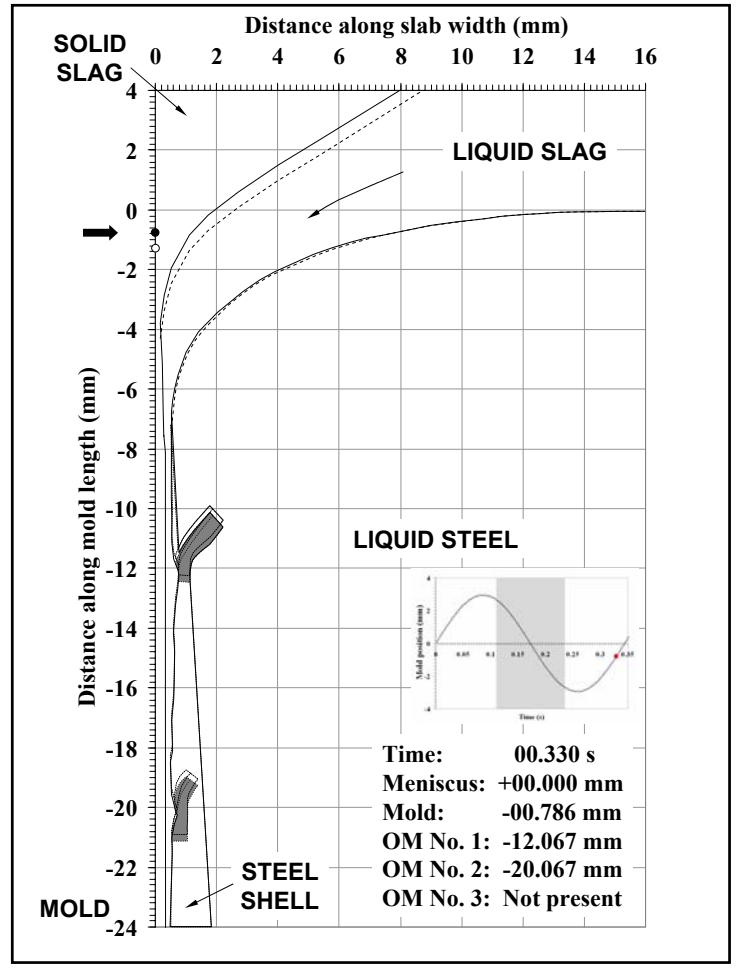

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
As the mold gains speed, intake of flux increases gradually
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.280 s
Meniscus: +00.000 mm
Mold: -02.724 mm
OM No. 1: -10.905 mm
OM No. 2: -18.905 mm
OM No. 3: Not present

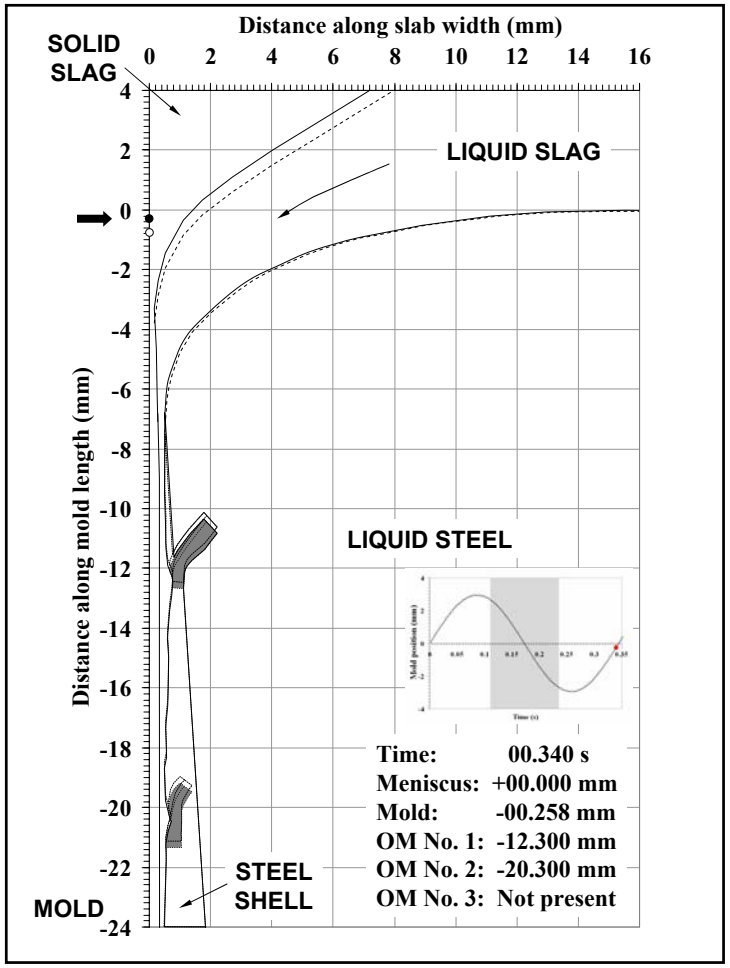

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.290 s
Meniscus: +00.000 mm
Mold: -02.477 mm
OM No. 1: -11.138 mm
OM No. 2: -19.138 mm
OM No. 3: Not present

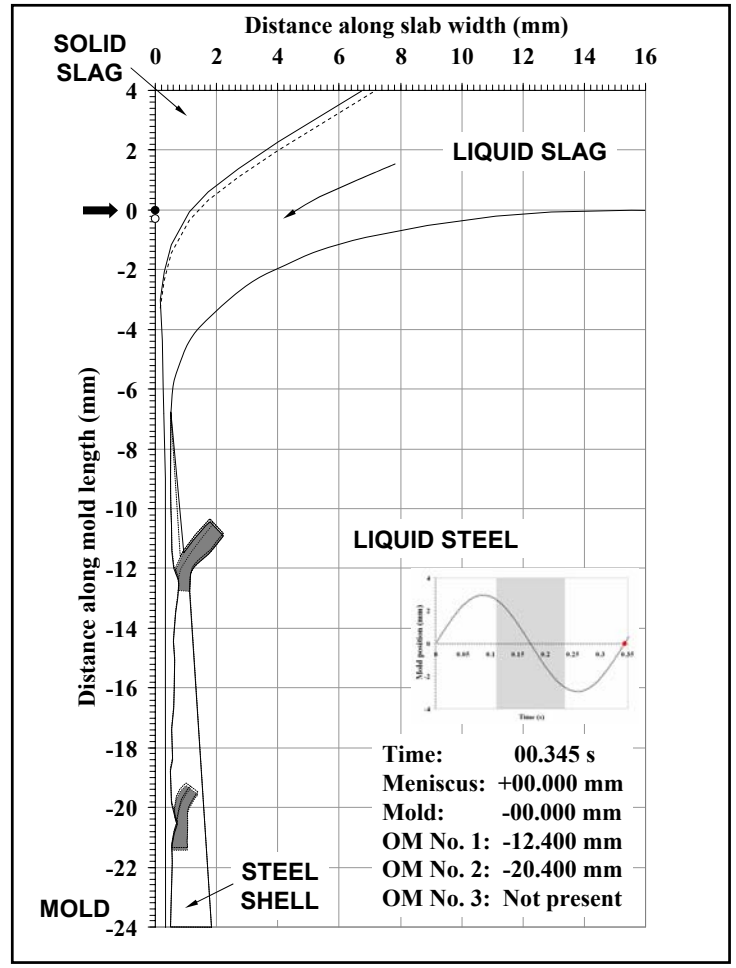

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.300 s
Meniscus: +00.000 mm
Mold: -02.146 mm
OM No. 1: -11.370 mm
OM No. 2: -19.370 mm
OM No. 3: Not present

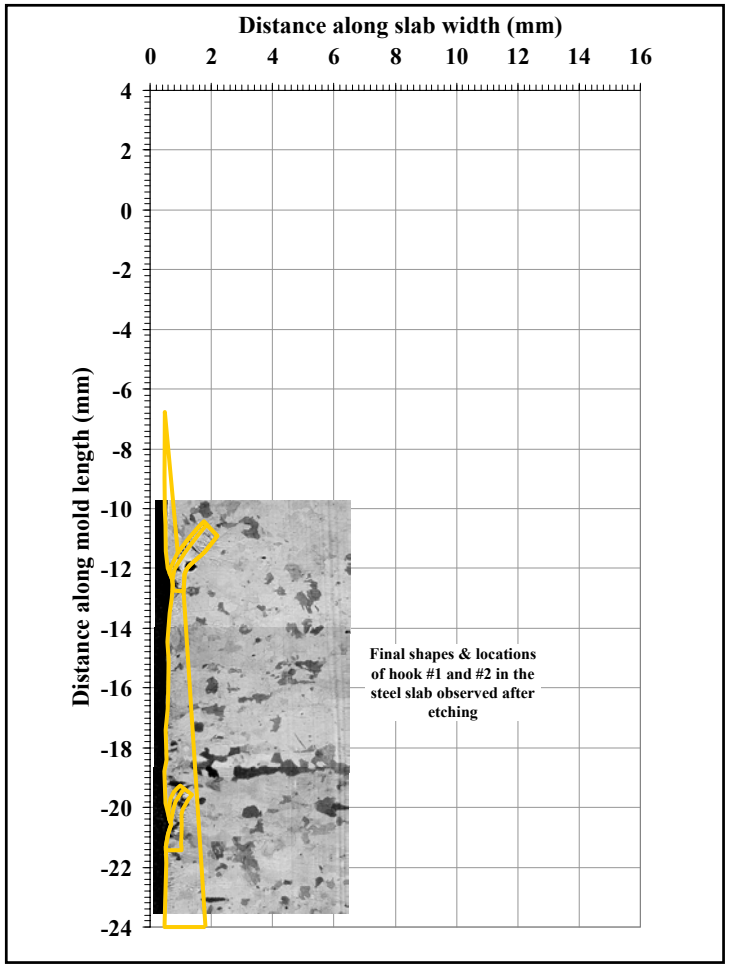

Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.310 s
Meniscus: +00.000 mm
Mold: -01.746 mm
OM No. 1: -11.602 mm
OM No. 2: -19.602 mm
OM No. 3: Not present


Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.320 s
Meniscus: +00.000 mm
Mold: -01.287 mm
OM No. 1: -11.835 mm
OM No. 2: -19.835 mm
OM No. 3: Not present


Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
STEEL SHELL
MOLD
Time: 00.330 s
Meniscus: +00.000 mm
Mold: -00.786 mm
OM No. 1: -12.067 mm
OM No. 2: -20.067 mm
OM No. 3: Not present


Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
STEEL SHELL
MOLD
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.340 s
Meniscus: +00.000 mm
Mold: -00.258 mm
OM No. 1: -12.300 mm
OM No. 2: -20.300 mm
OM No. 3: Not present


Distance along slab width (mm)
0 2 4 6 8 10 12 14 16
SOLID SLAG
LIQUID SLAG
LIQUID STEEL
STEEL SHELL
MOLD
Distance along mold length (mm)
4 2 0 -2 -4 -6 -8 -10 -12 -14 -16 -18 -20 -22 -24
Time: 00.345 s
Meniscus: +00.000 mm
Mold: -00.000 mm
OM No. 1: -12.400 mm
OM No. 2: -20.400 mm
OM No. 3: Not present


Distance along slab width (mm)
0
2
4
6
8
10
12
14
16
Distance along mold length (mm)
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
Final shapes & locations of hook #1 and #2 in the steel slab observed after etching