ANNUAL REPORT 2005

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Multiphase Flow, Inclusion Nucleation, Growth, Removal and Entrapment in Molten Steel and Continuous Casting

Lifeng Zhang (Research Scientist) &
Brian G. Thomas

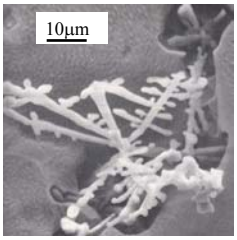
Department of Mechanical & Industrial Engineering
University of Illinois at Urbana-Champaign

Acknowledgements

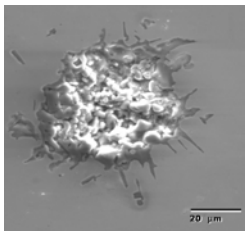
- Continuous Casting Consortium at UIUC (Nucor, Postech, LWB Refractories, Accumold, Algoma, Corus, Labein, Mittal Riverdale)
- Fluent Inc.
- National Science Foundation
- National Center for Supercomputing Applications

Inclusion Morphologies

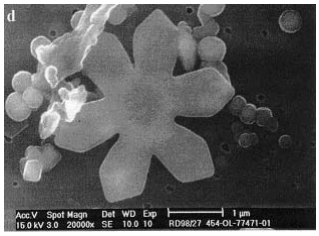
Dendritic alumina



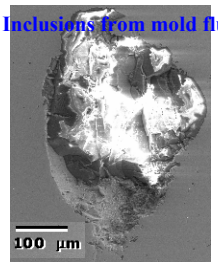
Alumina cluster



Flower-like plate alumina



Inclusions from mold flux

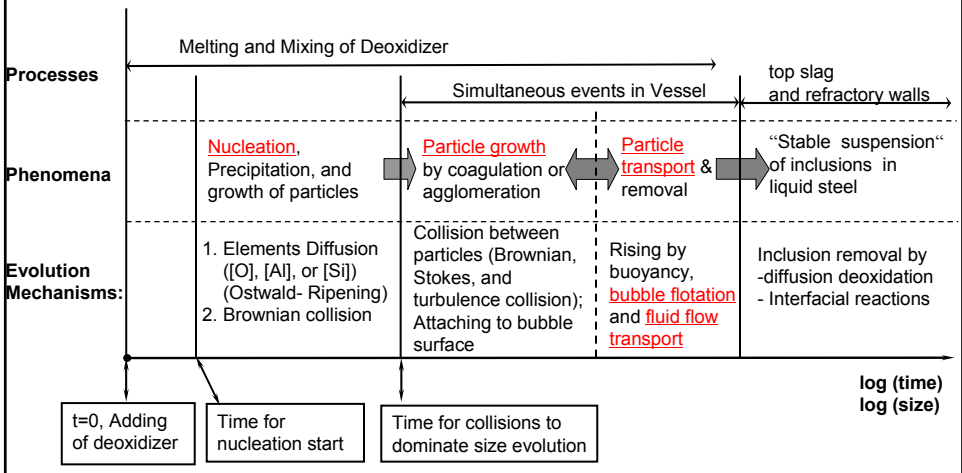


Slag inclusions

Refs:

1. L. Zhang, B. Thomas. ISIJ 2003, No.3, pp271-291
2. L. Zhang, B. Thomas, B. Rietow. Investigation of Ingot Inclusions Using Microscope and SEM . Univ. of Illinois at Urbana-Champaign. IMF project report. May. 04, 2004
3. R. Dekkers, B. Blanpain and P. Wollants: *Metall. mater. trans.*, (2003), **34B**, 161.

Nucleation, Growth and Removal of Inclusions



Outline

Part I: Physical, Numerical and Industrial Investigation of Fluid Flow and Steel Cleanliness in the Continuous Casting Mold (Collaborating with Univ. of Sci. & Tech. Beijing and Pansteel, China)

Part II: Inclusions during CSP Thin Slab Casting Process (Univ. of Sci. & Tech. Beijing and Handan Steel, China)

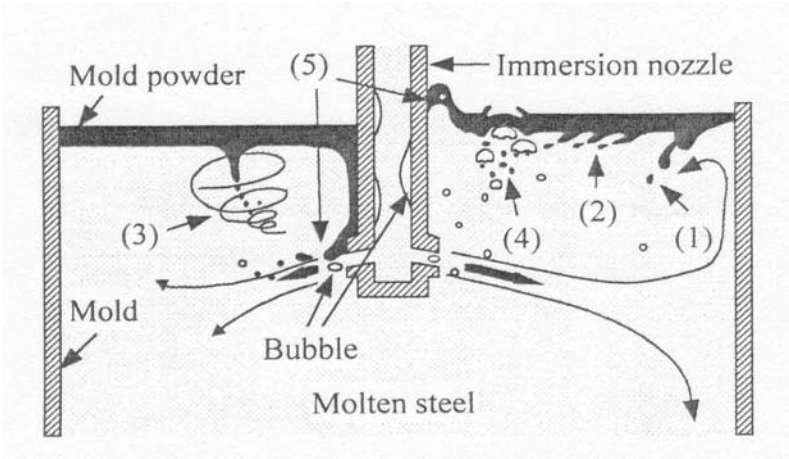
Part III: Inclusion Removal by Bubble Flotation in Continuous Casting Mold

Part IV: Inclusion Nucleation and Growth and Removal in Molten Steel Systems

Part I: Physical, Numerical and Industrial Investigation of Fluid Flow and Steel Cleanliness in the Continuous Casting Mold

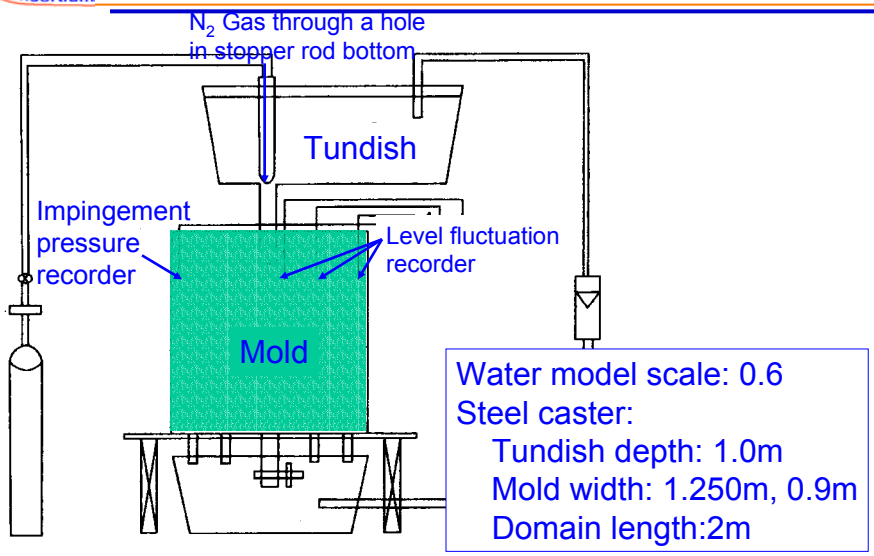
Collaborating with K. Cai at Univ. of Sci. & Tech. Beijing and S. Yang at Pansteel, China

Causes of Slag Entrainment in the CC Mold



J. Yoshida et al, Tetsu-to-Hagane, (2001), 87(8), 529.

Water Model Experiment



Flow Pattern Evaluation Criteria

Nozzle Flow Condition: bubbly flow *versus* annular flow

Flow Pattern in the mold: single roll *versus* double roll

Level fluctuations: the mean of the 5 largest level fluctuations during each 40s measurement;

Impingement pressure: the mean of the measured pressure in 40s measured near the impingement point of the narrow face, subtracting the static water pressure;

Lower roll location: the distance from the top surface to the center of the lower roll.

Multiphase Fluid Flow in the SEN

Bubbly Flow
(desired)

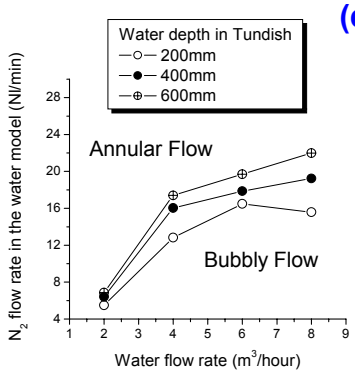
Critical Flow

Annular Flow

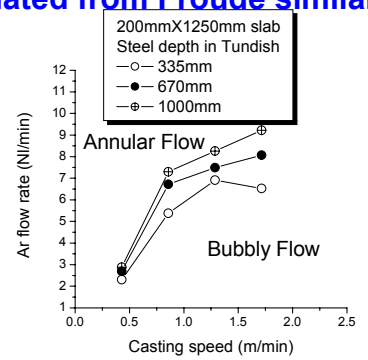
(biased flow and level fluctuations in mold)

How to Get Bubbly Flow (SEN)

Water

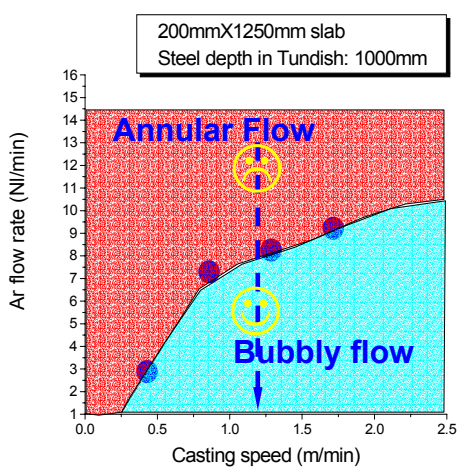


Molten Steel (estimated from Froude similarity)



Smaller gas flow is needed for bubbly flow during ladle change (lower tundish height).

What is the SEN Flow Condition (Steel Caster)



Plant observations:
Casting speed: 1.2m/min,

1) 10-20Nl/min gas: periodic "jumping of the fish" at ¼ width of the mold surface
- annular flow in SEN
- biased flow pattern in the mold
- serious level fluctuation and slag entrainment.

2) 5Nl/min gas: good

Increasing Gas Fraction Encourages Single Roll Flow Pattern

Bubbles escape near SEN

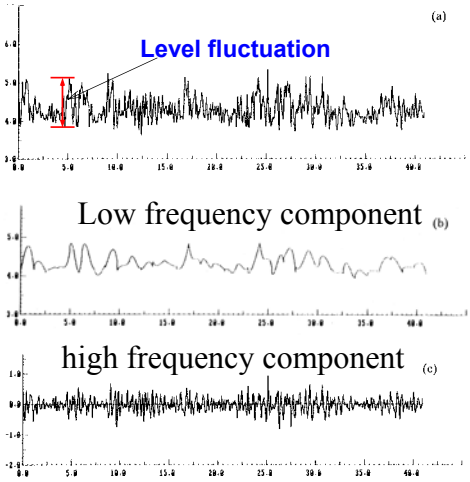
Bubbles escape near narrow face

2.0 m^3/hour (0.43m/min) 6.6 m^3/hour (1.41m/min)

Water flow rate

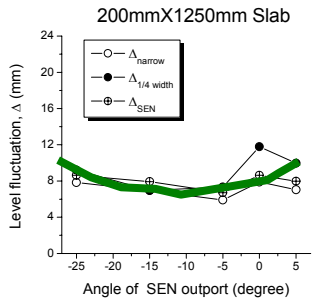
SEN bore diameter: 45mm
Gas flow rate: 5.344 Nl/min,
SEN submergence depth : 100mm^3/hour

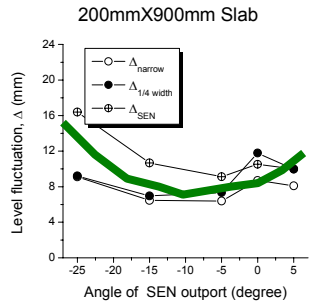
Split Level Fluctuation into Components



- High frequency fluctuation from turbulence;
- Low frequency oscillation from asymmetrical flow.
- Both frequency components have same magnitude (~ 10mm);

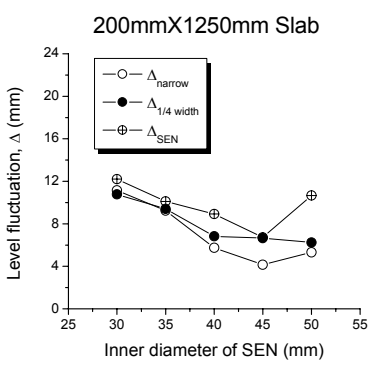
Effect of SEN Outport Angle on Mold Level Fluctuations

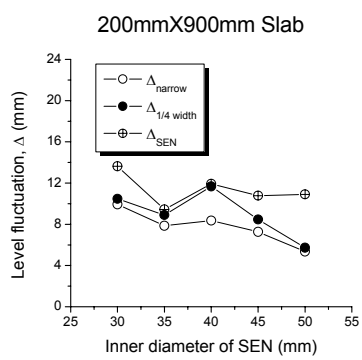


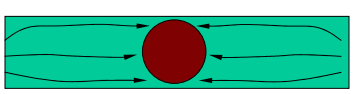


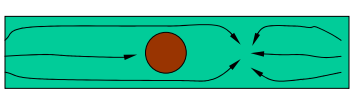
- Raising angle encourages single roll flow pattern, which has larger level fluctuations.
- Excessive downward angle may generate flow pattern asymmetry, with corresponding larger level fluctuations.

Level Fluctuations Decrease with Increasing Bore Diameter of the SEN









Industrial Cleanliness Investigation Conditions

- 3-heat sequence (240 tonne total)
- CC slab size of 200mm×1250mm
- Casting speed of 1.0-1.2m/min.
- Trace oxide La_2O_3 to the mold flux before casting
- Compare two strands:

  strand 1: the recess well SEN,

  strand 2: pointed-bottom SEN.

Inclusion Removal Estimated from Slag Analysis (Alumina Pickup)

	Liquid slag on the top	Al_2O_3 in final liquid slag	Al_2O_3 in original slag	T.O. removal to mold slag	T.O. at the SEN outlet	T.O. removal at the mold
Strand 1	**10.59kg**	**7.23%**	**2.84%**	**12.2ppm**	**59±35 ppm**	**21%**
Strand 2	**8.46kg**	**8.09%**	**2.84%**	**14.7ppm**		**24%**

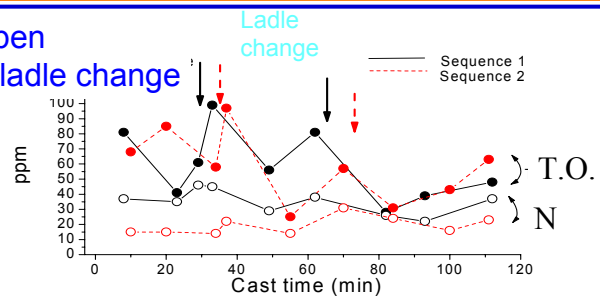
Validation:

Estimated T.O. in the slab of strand 1:
59×(100%-20.7%)= **47**±28ppm

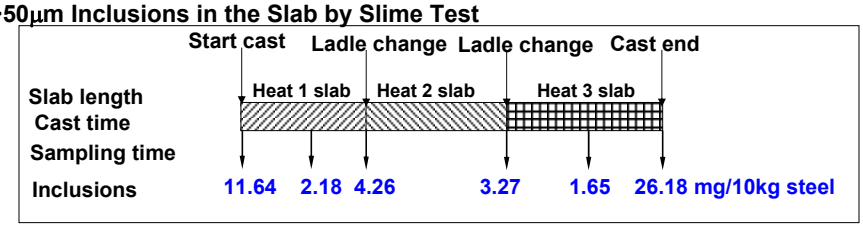
Measured T.O. in the slab: **47**±20ppm

Measured Inclusions in Slab

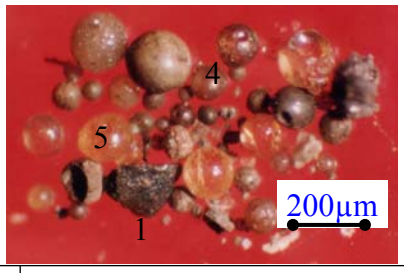
Arrow: ladle open
Green shade: ladle change

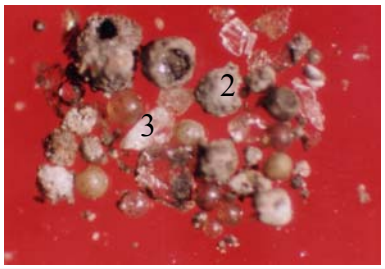


>50μm Inclusions in the Slab by Slime Test



Large Inclusions in the Slab (Slime Extraction)





1	Al_2O_3 40.11%, CaO 33.70%, SiO_2 20.02%, **Na_2O 4.62%, La_2O_3 1.56%**
2	Al_2O_3 65.30%, FeO 26.49%, CaO 2.1%, SiO_2 2.84%, MnO 0.85%, TiO_2 0.30%, BaO 0.13%, **La_2O_3 0.065%**
3	Al_2O_3 76.49%, FeO 13.82%, CaO 3.2%, SiO_2 3.47%, MnO 0.28%, TiO_2 0.06%, BaO 0.25%, La_2O_3 0.13%
4	Al_2O_3 2.86%, FeO 6.79%, CaO 0.18%, SiO_2 87.26%, MnO 0.15%, TiO_2 0.26%, BaO 0.94%, **La_2O_3 0.49%, Na_2O 0.40%, K_2O 1.12%**
5	Al_2O_3 2.38%, FeO 1.23%, CaO 4.47%, SiO_2 80.07%, MnO 0.03%, TiO_2 0.13%, BaO 0.55%, **La_2O_3 0.65%, Na_2O 9.27%, K_2O 1.96%**

Main origin of large inclusions: Mold slag
(All inclusions analyzed contain mold slag tracer)

Conclusions

- Flow patterns depend on gas fraction (gas flow rate, casting speed).
- Level fluctuations increase with both high or low port angle

- Steady operation contains few large inclusions (2mg/10kg steel)
- Head and tail of sequence is ~10X more inclusions
- Ladle change time contains ~2X more inclusions
- Entrainment of the mold slag is a critical problem

- Industrial measurement shows:~20% inclusions are removed to the mold slag.

Part II: Inclusions during CSP Thin Slab Casting Process

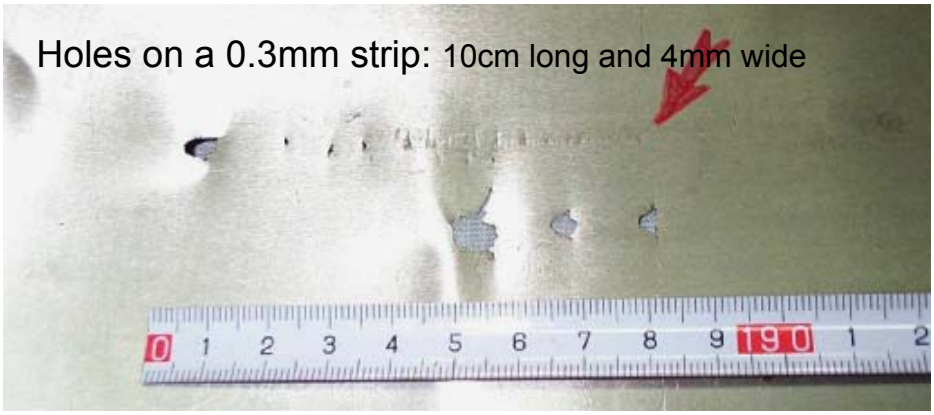
J. Wei, K. Cai, Univ. of Sci. & Tech. Beijing (USTB)
Lifeng Zhang, University of Illinois at Urbana-Champaign
Y. Zhou, Handan Steel, China

Current Study — Thin Slab at Handan Steel, China

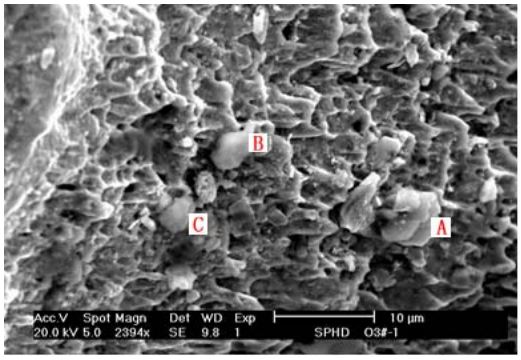
Handan Steel, China
- BOF(110 tonne)→LF→CSP (70mm thick slab)
- Started since 1999
- Current annual tonnage: 2.4 million tonne

Steel grade in the current study	LCAK Steel
Tundish capacity	36tonne, single strand, 1100mm depth
Slab width	1100-1680mm

Severe Defects in Cold Rolled Strips

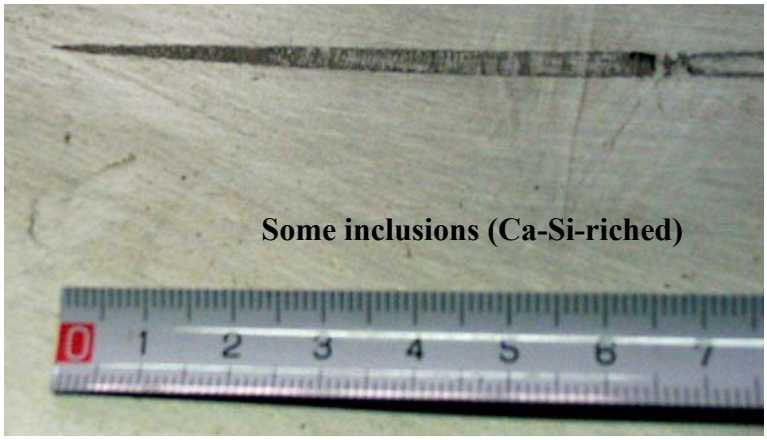


Composition of Inclusions in Severe Defects

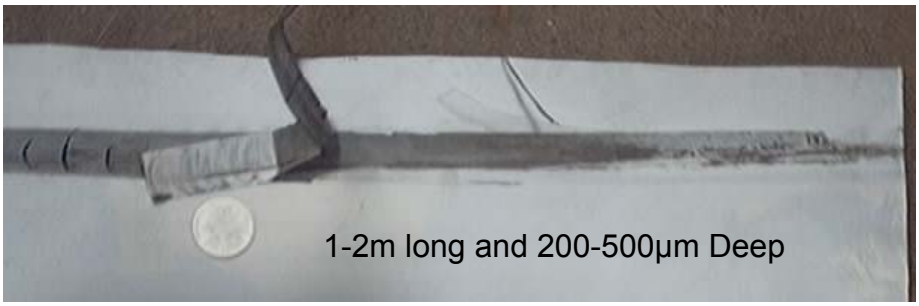


(A): Al: 40.32, Si: 3.35, S: 2.59, K: 0.19, Ca: 12.91, Fe: 40.64;
(B): Si: 19.28, K: 5.26, Ca: 9.38, Fe: 66.08;
(C): Al: 35.03 Ca: 64.9
(from Mold Slag)

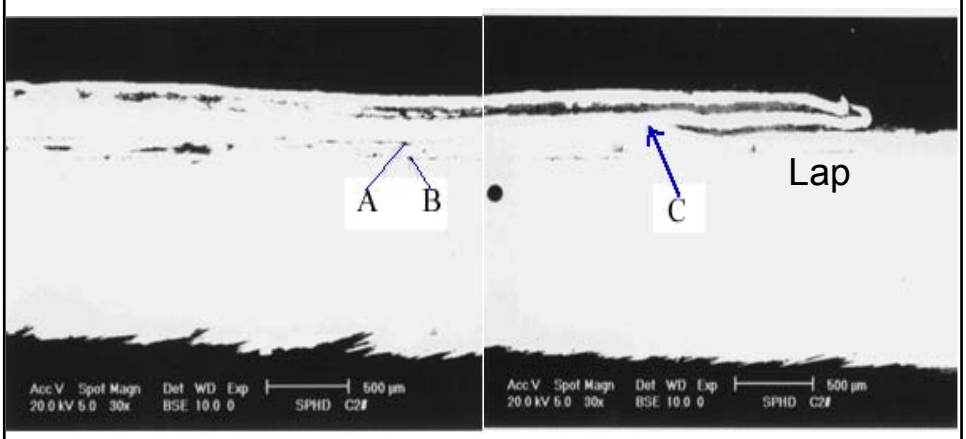
Slivers on Cold Rolled Strips



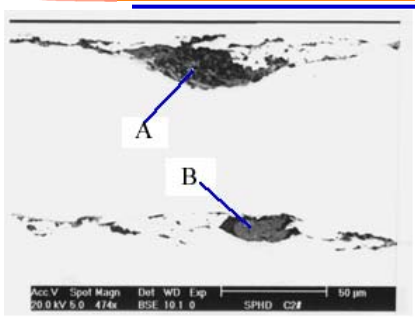
Lap on Cold Rolled Strips

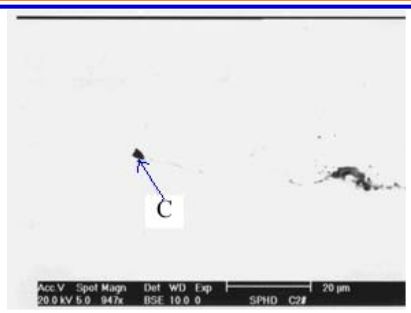


Lap on Cold Rolled Strips



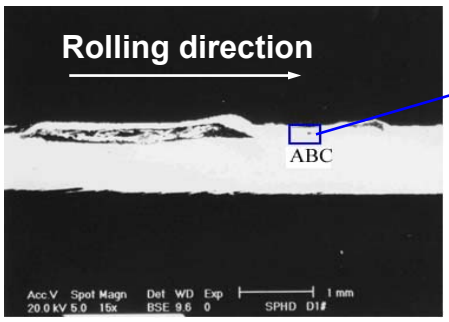
Lap on Cold Rolled Strips

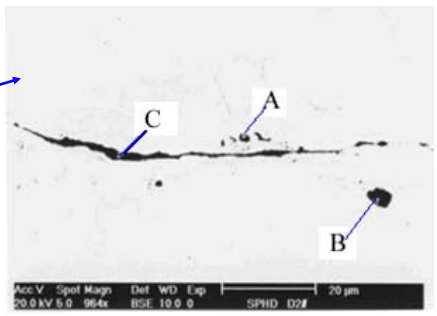




	Al_2O_3	CaO	SiO_2	MgO	K_2O	Na_2O
A	7.83	38.13	29.63	4.68	1.24	3.70
B	78.24	4.23	1.28	0.12	0	0.17
C	53.96	34.12	5.30	0	2.38	0

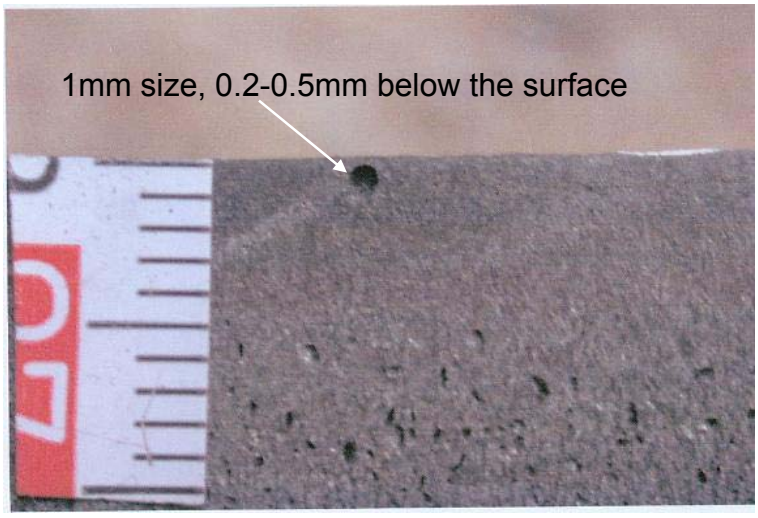
Small "Mountain" along Rolling Direction on Cold Rolled Strips



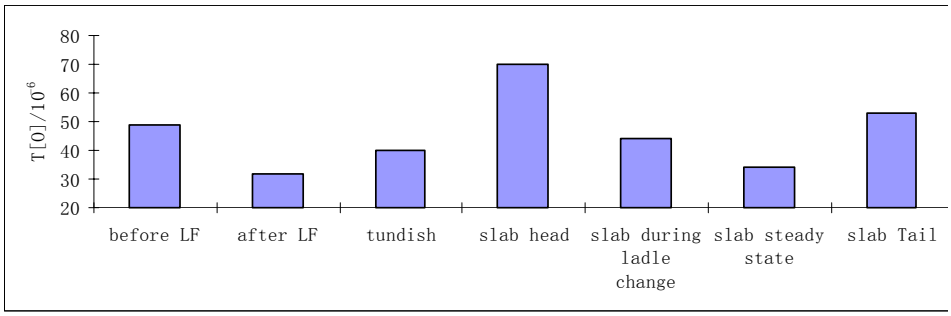


	Al_2O_3	CaO	SiO_2	MgO	K_2O	Na_2O
A	47.15	35.02	0.63	3.89	0	0
B	4.35	38.56	36.74	0.47	4.37	2.98
C	2.83	37.38	41.11	0	1.85	6.54

Bubbles in CSP Thin Slab (No EMBr)



Total Oxygen (No EMBr)



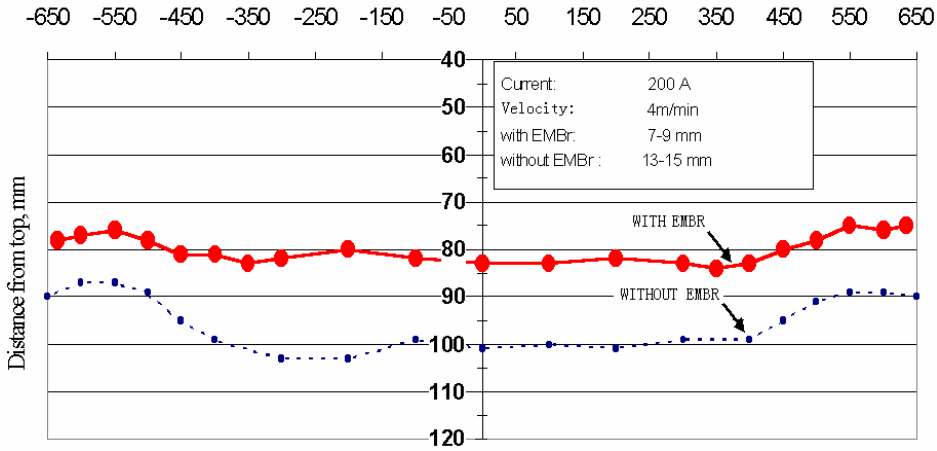
- 7.5ppm T.O. increasing from ladle to tundish (reoxidation)
- Slab T.O. during steady state: 34ppm, 6 ppm lower than tundish T.O. (15% inclusion removal from tundish to slab)
- More inclusions at transient casting period (air absorption and slag entrainment)

Wave Shape of the Top Surface

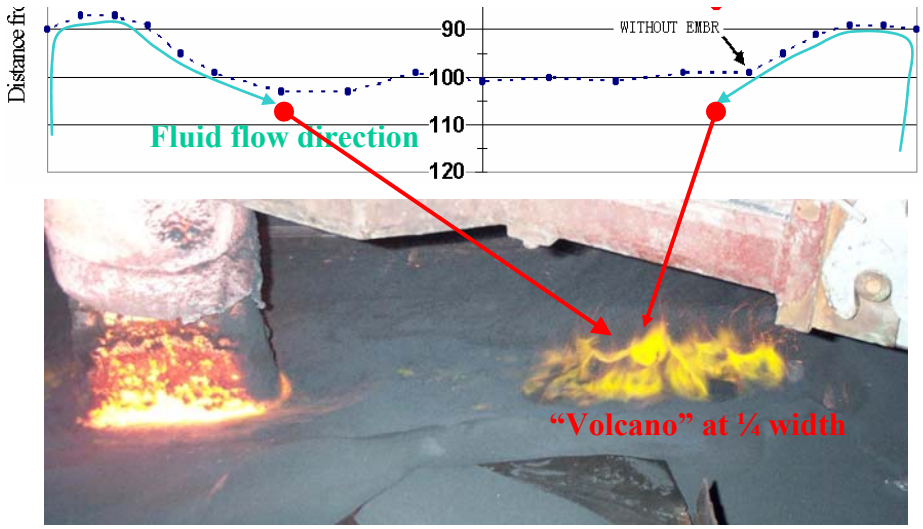
No EMBr

With EMBr

Wave Shape of the Top Surface



Wave Shape of the Top Surface (no EMBr)



Level Fluctuation (Measured)

No EMBr:

±2mm at steady state

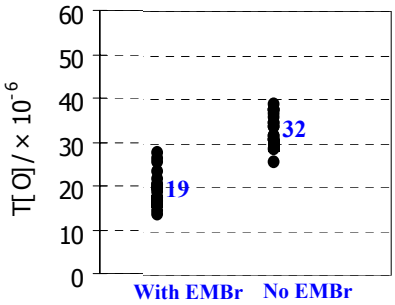
±3~7mm at transient state

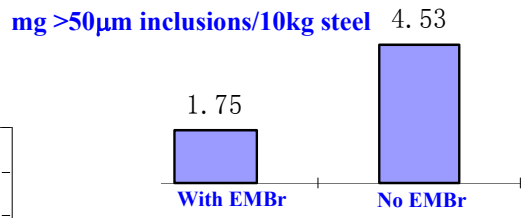
With EMBr:

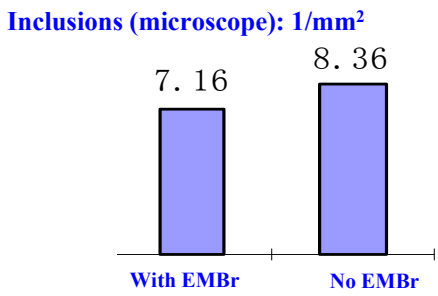
±1mm at steady state

±2~5mm at transient state

Steel Cleanliness of Slabs







Thin Slab with EMBr Has Similar Cleanliness as Conventional CC Slab

	T.O. (ppm)	<50μm inclusions (#/mm²)	>50μm inclusions (mg/10kg steel)
Thin slab (**no EMBr**)	31.9	8.36	4.53
Thin slab (**with EMBr**)	19.2	7.16	1.75
Conventional slab	18.5	6.55	1.99

Conventional CC process: BOF (250t)→LF refining →Vertical bending conventional slab casting (210mm×1350mm) (no EMBr)

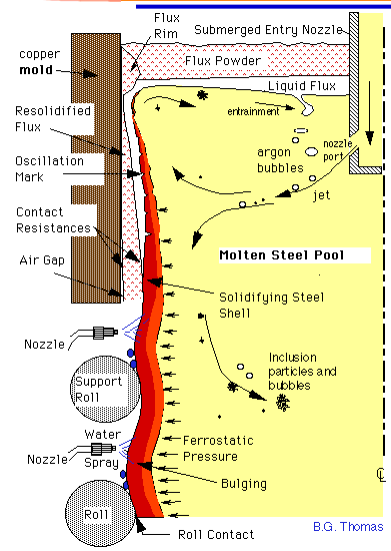
Thin slab CC process: BOF(110 tonne)→LF→CSP (70mm ×1100~1680mm)

Main Conclusions

- Mold flux entrainment is the main source of inclusions in thin slabs and defects on cold-rolled strips.
- Without EMBr, the steel cleanliness of thin slabs is far worse than that of conventional slabs.
- Thin slab with EMBr imposed has a similar cleanliness as that of the conventional slab.

Part III: Inclusion Removal by Bubble Flotation in Continuous Casting Mold

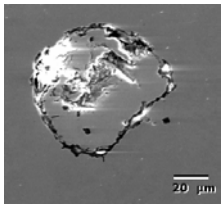
Schematic of Phenomena in Continuous Casting (CC) Mold

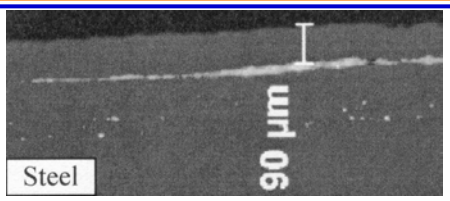


Inclusion destinations in CC Mold:

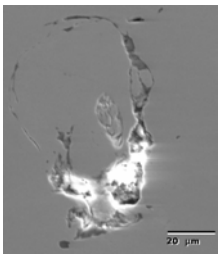
1. Removed to top surface by fluid flow transport;
2. Re-Entrained to the molten steel from the interface between the slag and the molten steel
3. Captured by the solidified shell
4. Recirculating in the molten steel
5. Attached to bubble surface, and bubble with inclusions either being removed to the top surface or captured by the shell

Bubble-Related Inclusions and Defects

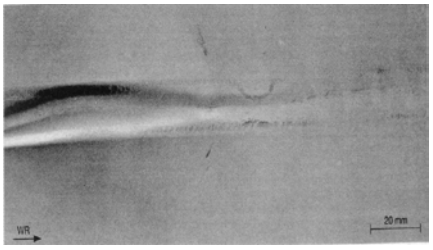




Inclusion sliver (H. Yin et al. in ISSTech2003, pp.217)

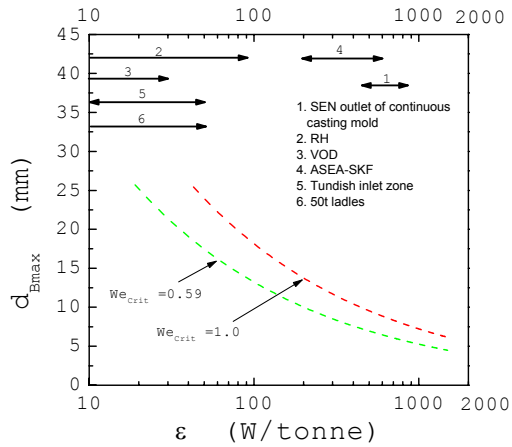


Bubbles with inclusions



Pencil blister(Gass et al. in ISSTech2003,2003, p.3-18)

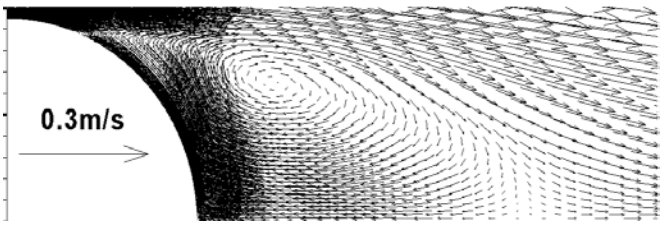
Ar Bubble Size in the Molten Steel



Bubbles in the CC mold: < 5mm
Bubbles in the steel refining: >15mm

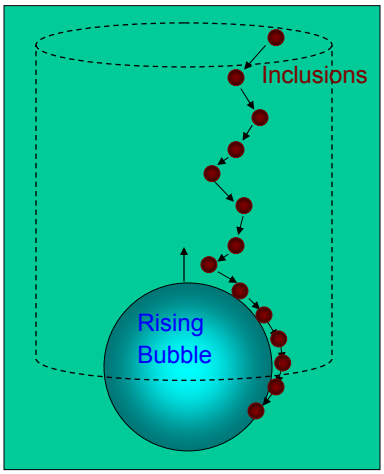
Fluid Flow Validation behind a Rigid Sphere in Water

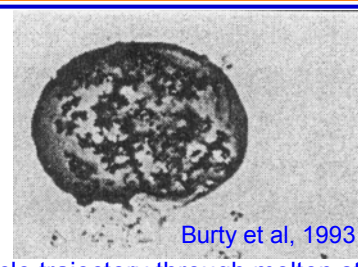
Water photo, Clift et al, 1975



1.5mm diameter rigid particle in water

Attachment Probability: Steps in Inclusion attachment to Bubble





Particle trajectory through molten steel

1. Collision / oscillation
2. Sliding (time for film drainage)
3. Stable attachment

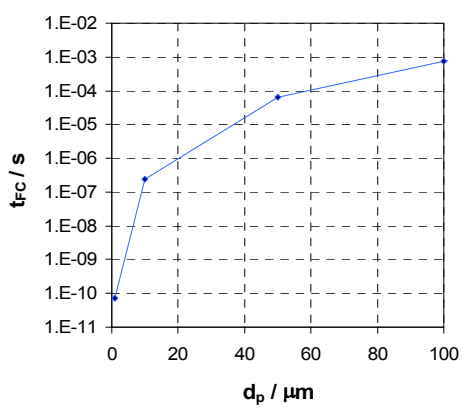
Attachment probability, P_C

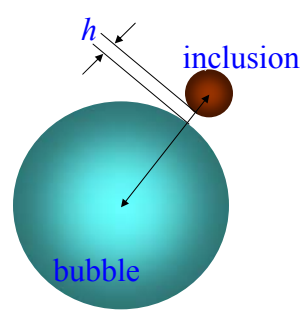
$$P_C = \frac{\#\ particles\ attached}{\#\ particles\ in\ column}$$

Inclusion Attachment on Bubbles

Film rupture time $t_f = f(d_p, U_B, \rho_p, \sigma, \theta)$

Critical thickness of the thin film $h_{Cr} = f(\sigma, \theta)$





Attachment condition: $t_s > t_f$

(Collaborating with Jun Aoki at Univ. of Illinois)

Parameters in the Current Study

Density of the molten steel: ρ=7020 kg/m^3,

Density of inclusions: ρ_P=2800 kg/m^3,

Density of gas bubbles: ρ_g=1.6228kg/m^3,

Surface tension of the molten steel: σ=1.40 N/m,

Contact angle of inclusions: θ=112°,

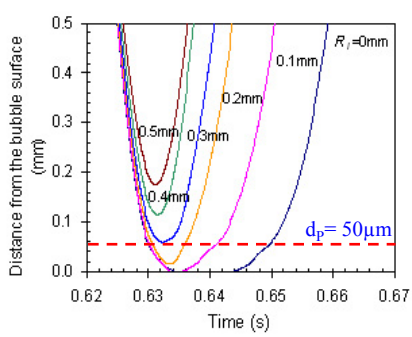
Steel viscosity: μ=0.0067 kg/m-s,

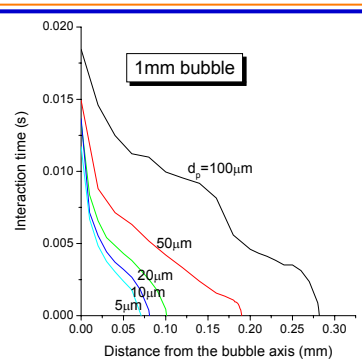
Inclusion size (diameter): d_p=1-100μm,

Bubble size (diameter): d_B=1-10mm

Turbulent energy: *k* = <10^{-2} m^2/s^2 (10W/tonne)

Attachment Probability by Turbulent Trajectory Calculation



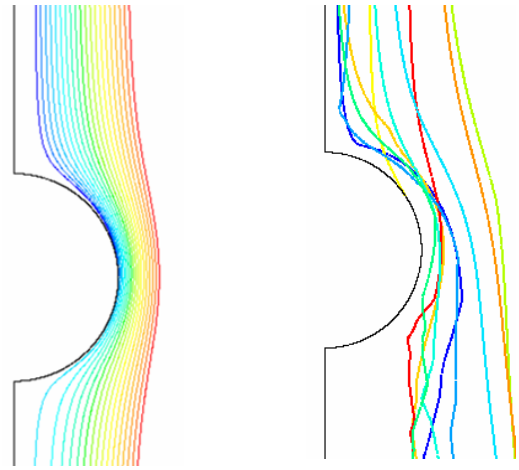


The normal distance from the center of 100μm inclusions to the surface of a 1mm bubble (left), and the interaction time of inclusions on a 1mm bubble (right)

Attachment more likely for smaller bubbles & larger inclusions.

(Collaborating with Jun Aoki at Univ. of Illinois)

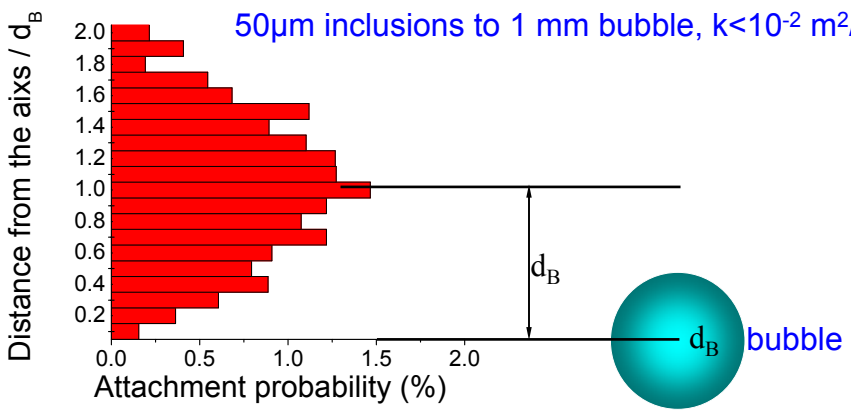
Effect of Turbulence on Inclusion Trajectories around a 5 mm Bubble



Non-Stochastic Stochastic

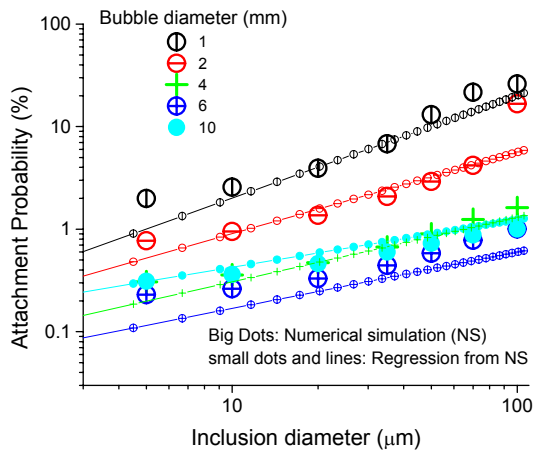
Effect of Turbulence on the Attachment of Inclusion to Bubble

50μm inclusions to 1 mm bubble, $k<10^{-2}$ m^2/s^2



Stochastic model: collision diameter 4mm, 16.5% attachment in total
Non-Stochastic model: collision diameter 0.34mm,11.6% attachment in total

Attachment Probability by Turbulent Trajectory Calculation



$$P = A d_p^B$$

$$A = 0.268 - 0.0737 d_B + 0.0615 d_B^2$$

$$B = 1.077 d_B^{-0.334}$$

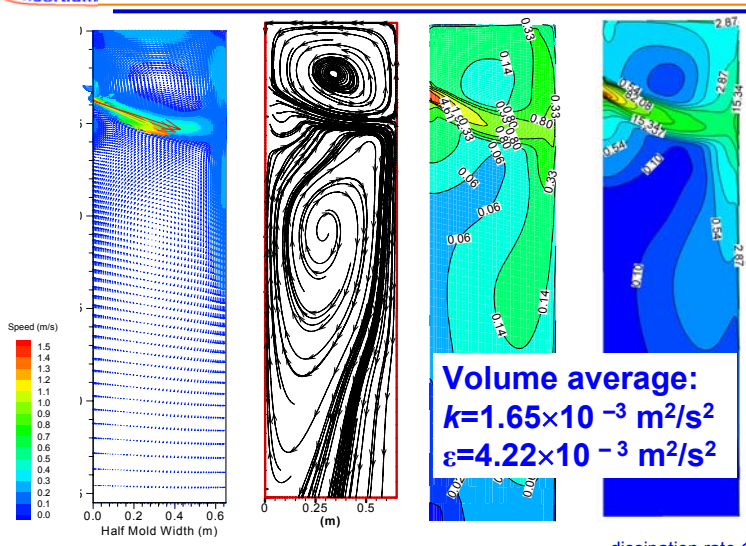
P: %
d_B: mm
d_p: μm.

(Turbulent energy $k<10^{-2}$ m^2/s^2)

Attachment more likely for smaller bubbles & larger inclusions.

(Collaborating with Jun Aoki at Univ. of Illinois)

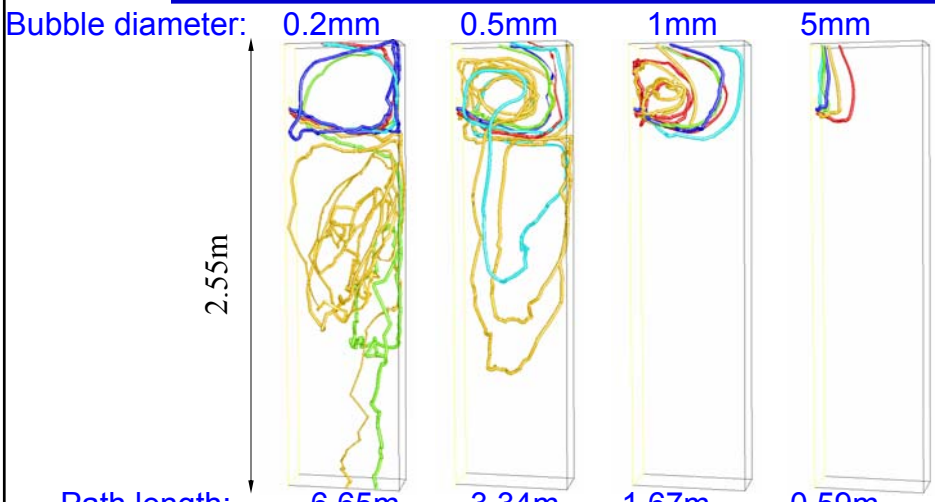
Fluid Flow in the CC Strand



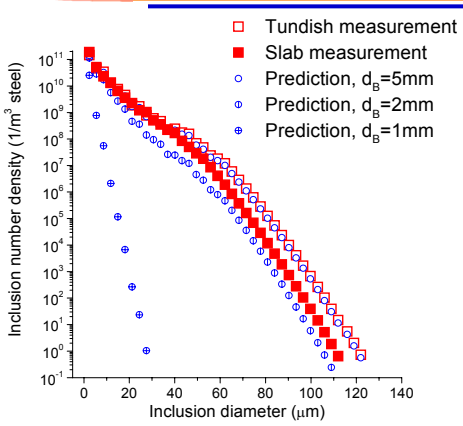
Volume average:
***k*=1.65×10 $^{-3}$ m²/s²**
ε=4.22×10 $^{-3}$ m²/s²

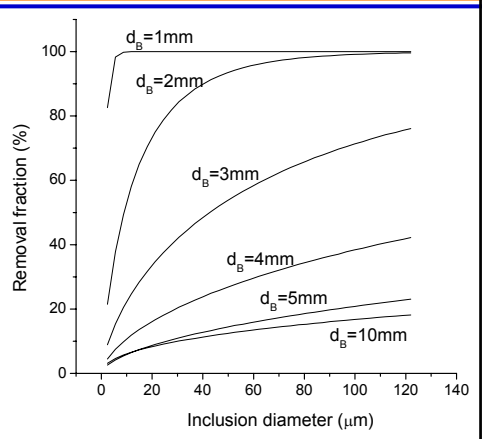
velocity vectors | streamline | turbulent energy 100k | dissipation rate 1000ε

Bubble Trajectories in the Half Mold



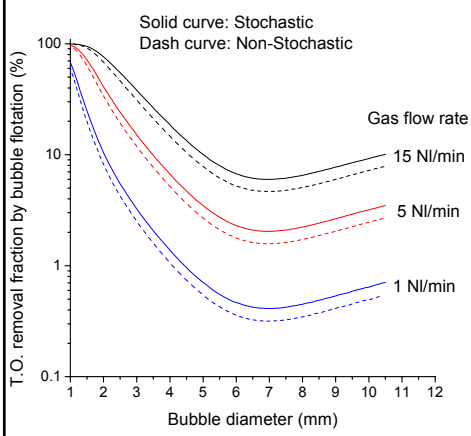
Inclusion Removal by Bubble Flotation





- Smaller bubbles removes more inclusions for the same gas flow rate, but more easily entrapped to the shell;
- There should be an optimum bubble size

Inclusion Removal by Bubble Flotation in CC Strand



- For >5mm bubbles, <10% inclusions are removed by bubble flotation at the gas flow rate of 15 Nl/min (~ 3ppm T.O. decrease);
- Larger gas flow rate removes more inclusions;
- Considering turbulent Stochastic motion slightly increases the inclusion removal by bubble flotation. (Turbulent energy: $k = <10^{-2}\ m^2/s^2$)

Inclusion Removal Summary

~10% by bubble flotation (current work 15 Nl/min)

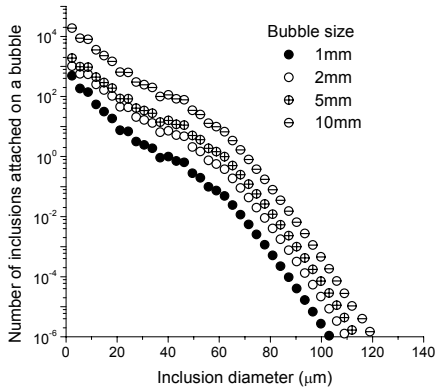
~8% to top surface by flow transport (Zhang et al, ISSTech 2003)

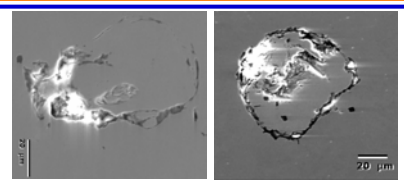
~4% entrapped on SEN walls to cause clogging (estimated)

~22% Total removal in mold **measured**

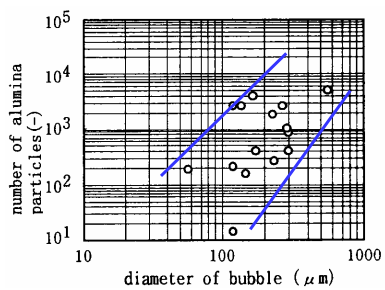
How Many Inclusions Attached to a Bubble?

Increases with larger bubbles and smaller particles





Photos, Zhang et al, 2004



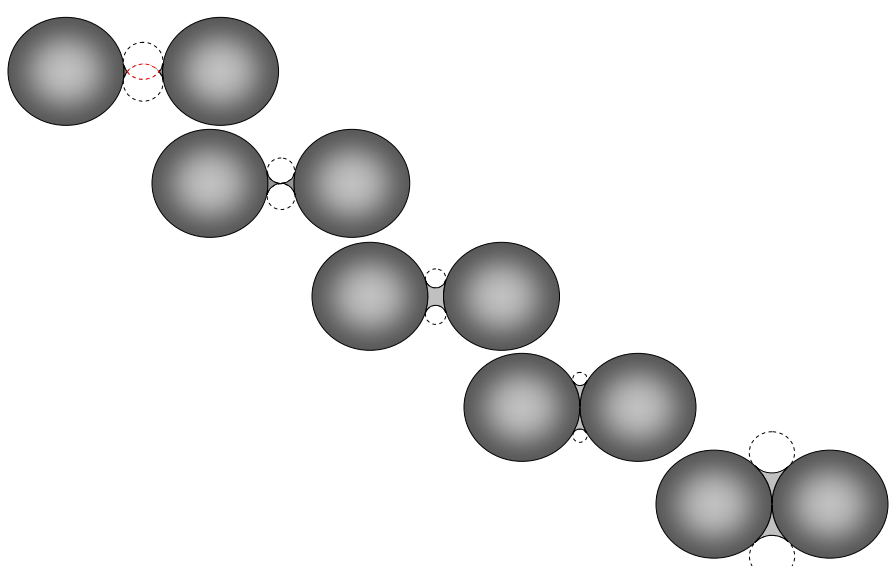
Measurements, Kiriha et al, ISIJ, 2004

Conclusions

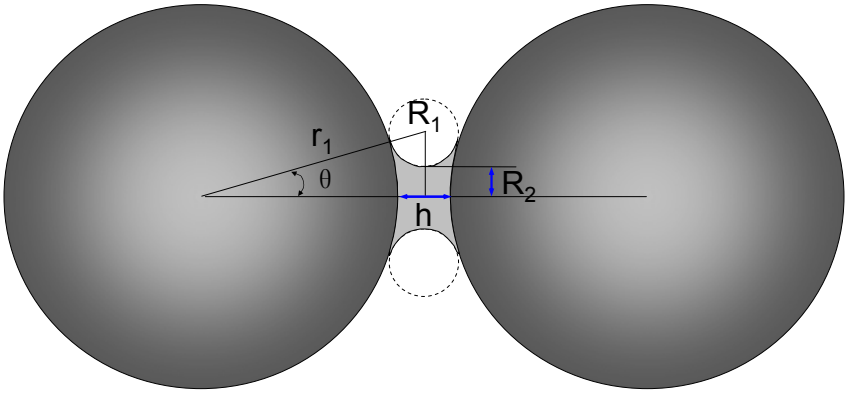
- Smaller bubbles and larger inclusions have larger attachment probabilities. The stochastic effect of turbulence ($k<10^{-2}m^2/s^2$) slightly increases the attachment rate .
- For ~ 5mm bubbles in the strand, ~10% of the inclusions are predicted to be removed by bubble flotation (~3ppm T.O. decrease). ~ 8% inclusion removal by flow transport, ~4 by entrapment to SEN walls.
- Large gas flow rate and smaller bubbles are more efficient at inclusion removal by bubble flotation, so long as they are not entrapped in the solidifying shell. (There should an optimum bubble size)

Part IV: Inclusion Nucleation and Growth and Removal in Molten Steel Systems

Interaction Between Two Spherical Inclusions in Steel



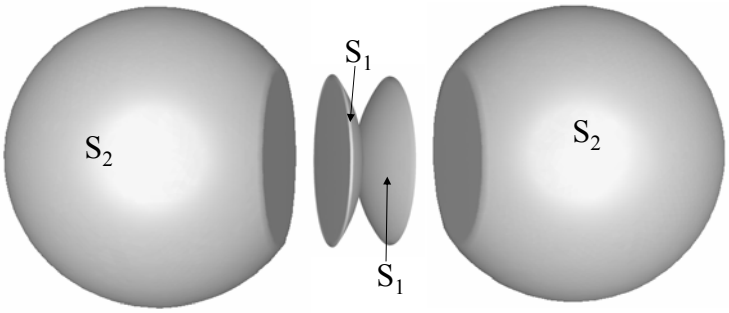
Energy between Two Spherical Inclusions

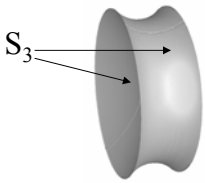


$$dE/dR_2 = 0$$ → Stable neck is reached

$\theta = f(\sigma_{LS}, \sigma_L, \sigma_S) = f(\text{contact angle})$

Total Surface Energy between Two Spherical Inclusions





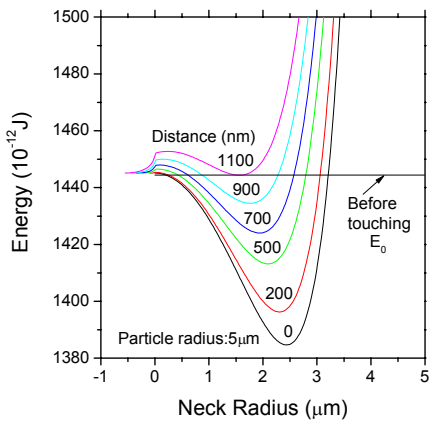
Energy of 2 separate particles

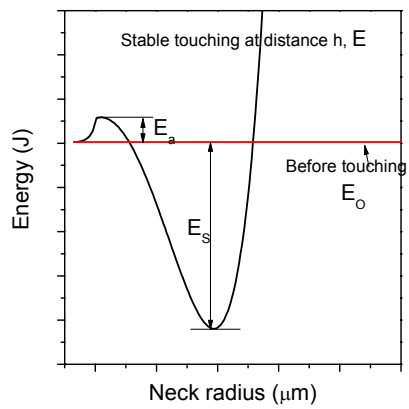
$$E_o = 2\sigma_{LS}(S_1 + S_2)$$

Energy after film rupture

$$E = 2\sigma_{LS}S_2 + 2\sigma_S S_1 + \sigma_L S_3$$

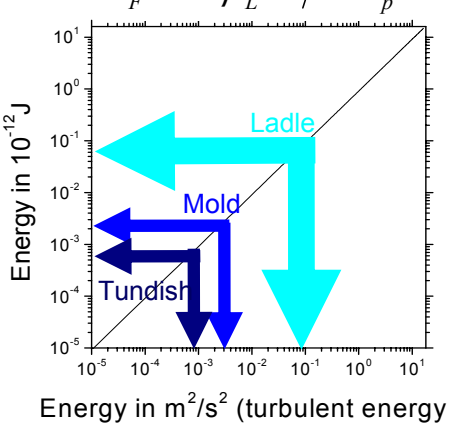
Energy between Two 5μm Al_2O_3 Inclusions in Steel

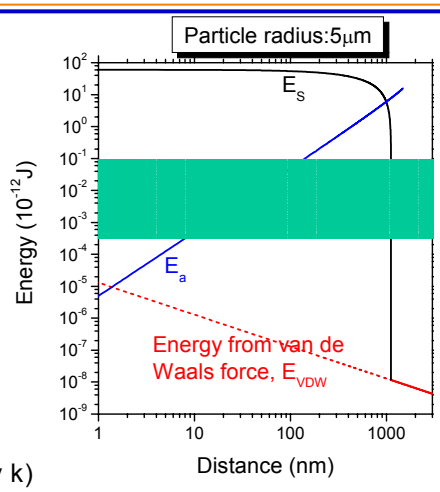




Stability of Inclusion Aggregates in Fluid Flow of Molten Steel

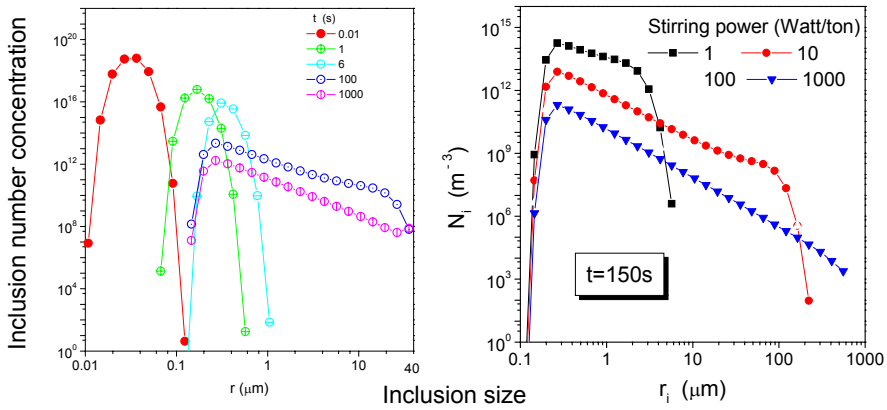
$$E_F = 2k\rho_L \times 1/6\,\pi d_p^3$$





- Fluid flow energy can not break 5μm alumina aggregates
- Attachment occurs if the distance between 2 inclusions is <100nm.

Inclusion Size Distribution Evolution



Conditions:

- Al-killed LC steel steel during ASEA-SKF ladle refining;
- Turbulent energy dissipation rate 0.01224 m^2/s^3
- T.O before deoxidation: 300ppm; Free oxygen at equilibrium: 3ppm

Comments and Questions !!