# Interfacial Phenomena in Metal-Slag Reactions: Past, Present and Future

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# CONTENT

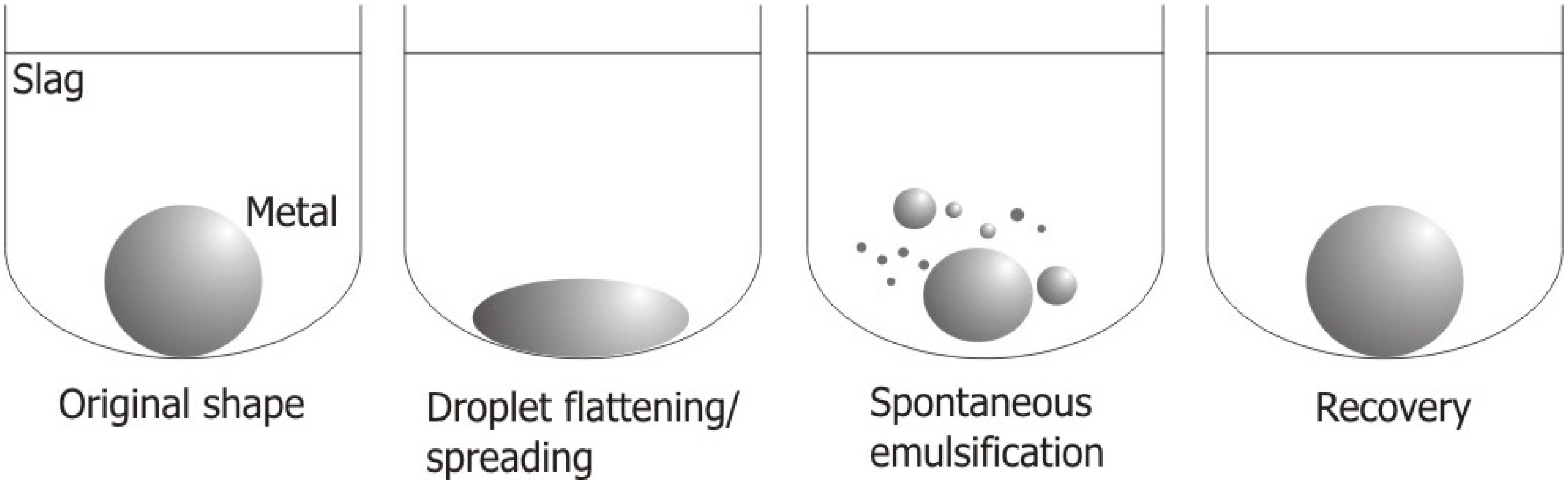

- Introduction
  - Interfacial phenomena and its importance
- Previous Studies on Interfacial Phenomena (Metal-Slag Reactions)
- Challenges
- Current Progress
- Future Directions
- Conclusions

# INTRODUCTION

> Dynamic interfacial phenomena?

"dynamic" → non-equilibrium

> Behaviour of iron-alloy droplet reacting in liquid slag




<u>Observed in</u>

Liquid Fe-Al; Fe-C-S; Fe-Ti; Fe-P; Fe-B; Fe-Cr; Fe-Si alloys reacting in liquid slag

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# INTRODUCTION

## DYNAMIC INTERFACIAL PHENOMENA:

Spontaneous emulsification, Surface roughening, Droplet flattening

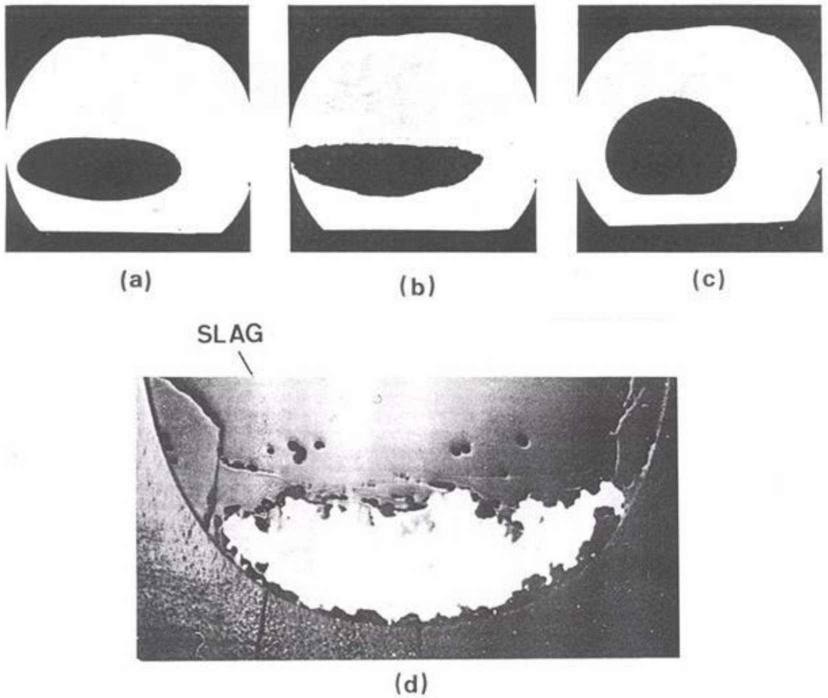
↓

- Spontaneous increase of reacting interface area
- Enhancement of mass transport (several orders)
- Increase in global kinetics

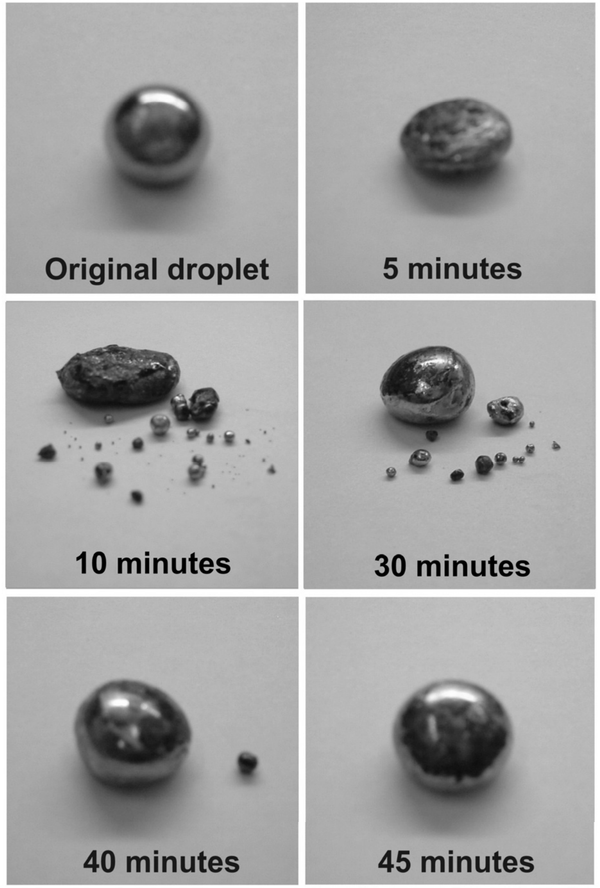
↓

Speed up the processing time

# PREVIOUS STUDIES IN INTERFACIAL PHENOMENA




2.5g Fe-4.45%Al at 1600°C
(a) 7 min; (b) 18 min; (c) 40 min;
(d) polished section of b,
from Riboud and Lucas (1981)




2.35g Fe-4%Al droplet in $CaO$-$SiO_2$-$Al_2O_3$ slag at 1650°C, from Rhamdhani et al (2004)

# PREVIOUS STUDIES IN INTERFACIAL PHENOMENA

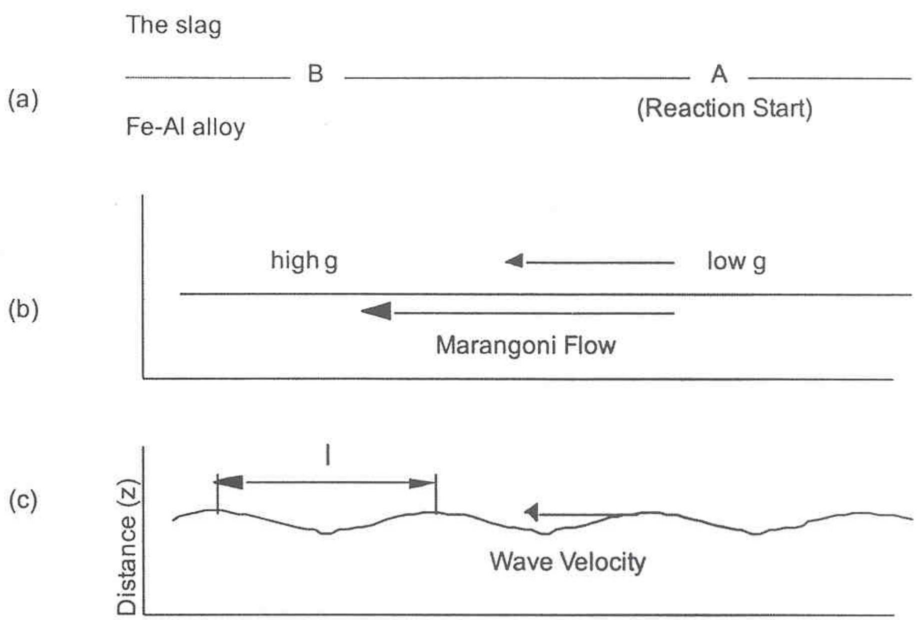
| Researcher | Details |
|---|---|
| Kozakevitch *et al.* (1955) | • Fe-C-S droplets + $CaO\text{-}SiO_2\text{-}Al_2O_3$ slag<br>• Utilized x-ray |
| Deryabin *et al.* (1968) & Saburov *et al.* (1971) | • Fe-S and Fe-C-S + $CaO\text{-}SiO_2\text{-}Al_2O_3$ slag at 1450°C and 1550°C<br>• Fe-Ti droplets (10 - 20wt% of Ti) with the same slag at 1540°C and 1580°C<br>• Fe-Al (5, 10 and 20wt% Al) + $CaO\text{-}Al_2O_3\text{-}TiO_2$ slag<br>• Utilized x-ray |
| Ooi *et al.* (1974) | Observed the phenomena in:<br>• Fe-Al and Fe-Ti + $CaO\text{-}SiO_2\text{-}Al_2O_3$ (40:40:20 in wt%) slag at 1570°C<br>• Kinetic study assuming constant interfacial area<br>• Utilized x-ray |
| Riboud and Lucas (1981) | • Various metal-slag systems; using x-ray<br>Fe-Al + $CaO\text{-}SiO_2$ (or $-Al_2O_3$)<br>Fe-Si + $Cu_2O\text{-}Al_2O_3$<br>Fe-Ti + $CaO\text{-}Al_2O_3\text{-}SiO_2$<br>Fe-B + $CaO\text{-}Al_2O_3\text{-}SiO_2\text{-}Fe_2O_3$<br>Fe + $Cu_2O$<br>Fe-Al + $CaO\text{-}Al_2O_3\text{-}Fe_2O_3$<br>Fe-C-S + $CaO\text{-}Al_2O_3\text{-}SiO_2$<br>Fe-P + $CaO\text{-}Al_2O_3\text{-}Fe_2O_3$<br>Fe-Cr + $CaO\text{-}SiO_2\text{-}FeO$ |

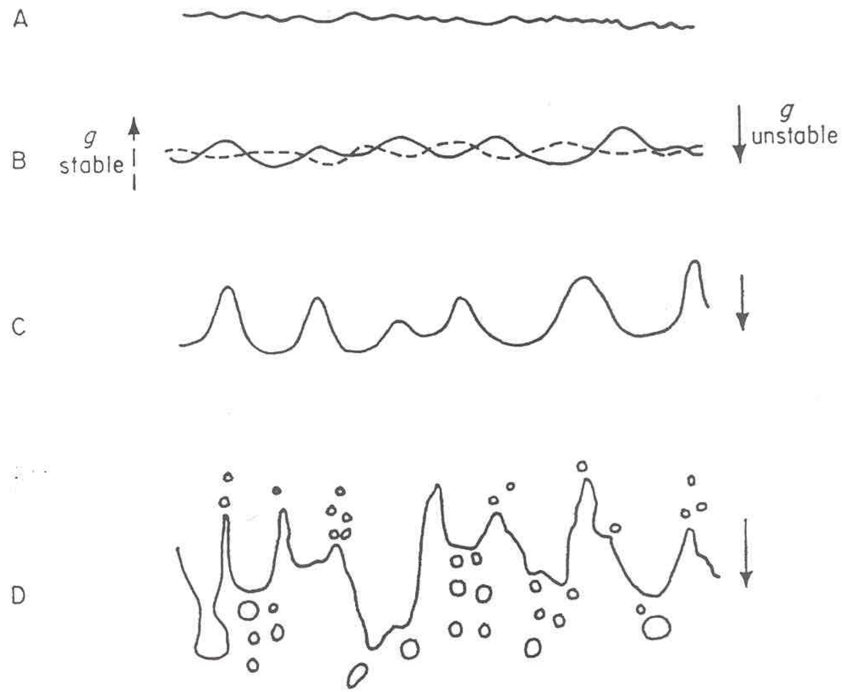
# PREVIOUS STUDIES IN INTERFACIAL PHENOMENA

| Researcher | Details |
|---|---|
| Sharan and Cramb (1995) | • Utilized x-ray<br>• Fe-20Ni-2.39Al + $CaO\text{-}SiO_2\text{-}Al_2O_3$ at 1550°C<br>• Proposed a mechanism for droplet flattening, i.e. due to difference of oxygen chemical potential |
| Chung and Cramb (1998, 2000) | • Utilized x-ray<br>• Optical and Scanning electron microscopy observation of the reacting interface<br>• Fe-Al + $CaO\text{-}SiO_2\text{-}Al_2O_3$ and Fe-Ti + $CaO\text{-}SiO_2\text{-}Al_2O_3$<br>• Reported slag emulsification and evidence of non-uniform reaction<br>• Proposed a mechanism for spontaneous emulsification through Kelvin-Helmholtz instability |

- Previous studies → phenomenological studies
- Lack of experimental data
- Holistic understanding of the phenomena is not yet achieved

# MECHANISM FOR THE PHENOMENA



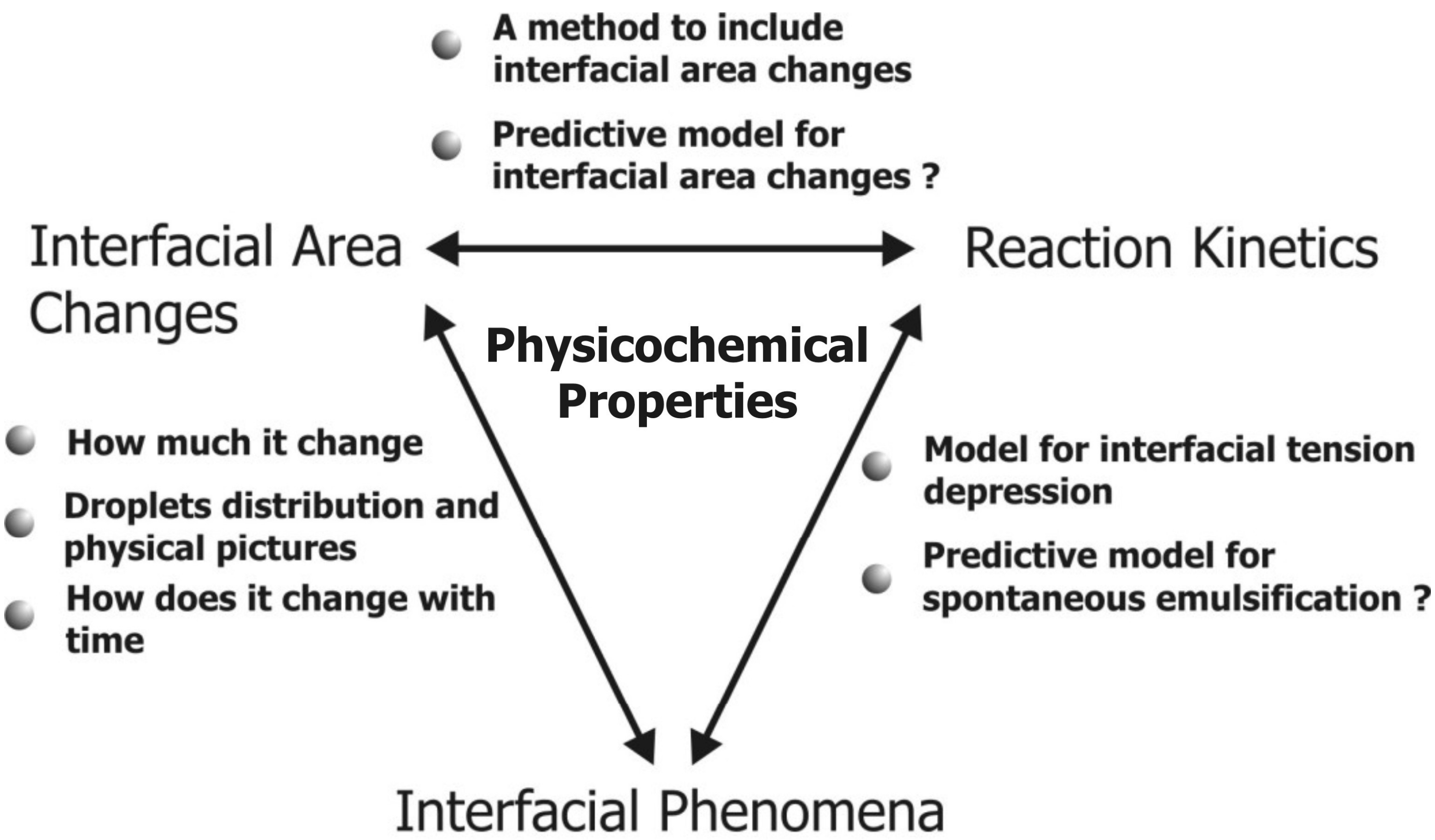




Marangoni flow leading to emulsification via Kelvin-Helmholtz instability (Chung & Cramb, 2000)

## Gradient of interfacial tension

- gradients of temperature (thermocapillarity)
- gradients of electrical potential (electrocapillarity)
- gradients of concentration (solutocapillarity)

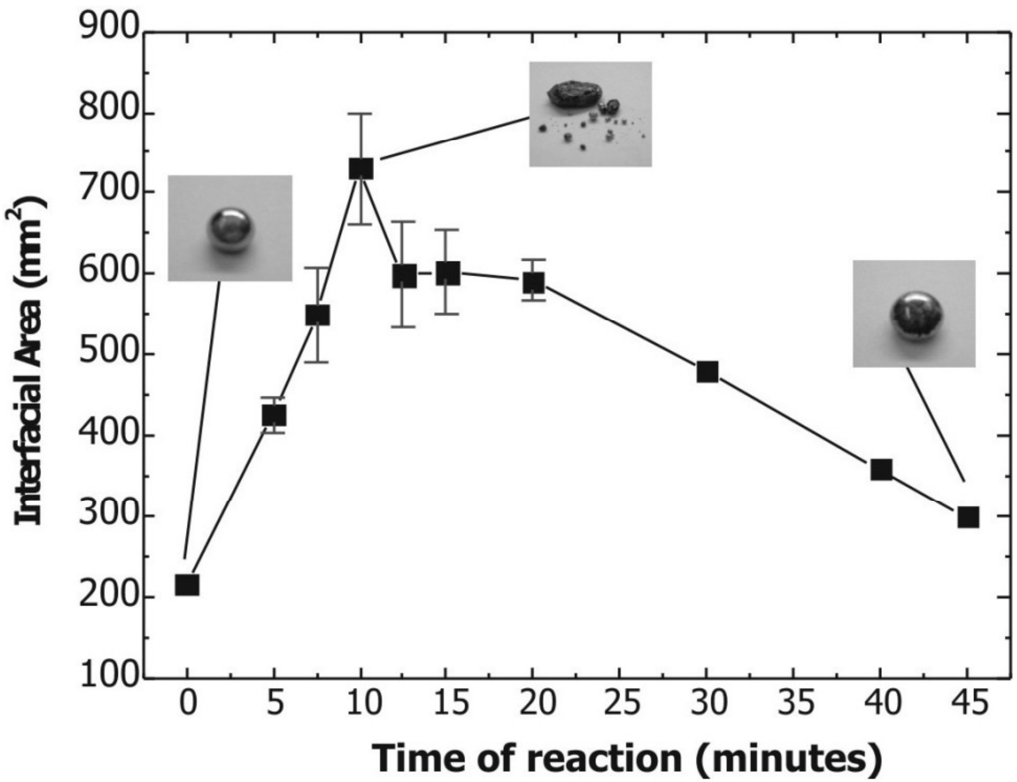
# CHALLENGES


A method to include interfacial area changes
Predictive model for interfacial area changes ?
Interfacial Area Changes
Reaction Kinetics
Physicochemical Properties
How much it change
Droplets distribution and physical pictures
How does it change with time
Model for interfacial tension depression
Predictive model for spontaneous emulsification ?
Interfacial Phenomena

# CURRENT PROGRESS

## 1. Collection of interfacial area data during reaction

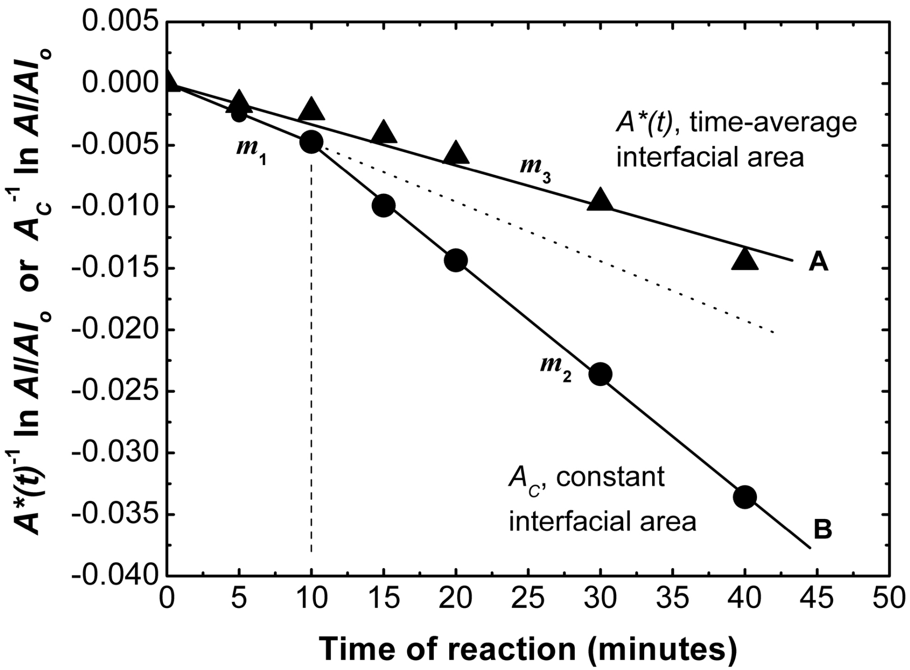
- Allows the development of the transient approach for kinetic analysis
- Interfacial area increase were found to be 300 to 500% (Rhamdhani *et al.*, 2005)




Fe-4%Al reacting in $CaO$-$SiO_2$-$Al_2O_3$ at 1650°C

# CURRENT PROGRESS

## 2. Transient approach for kinetic analysis




- Mass transfer control in metal

$$\frac{V_m}{S}\frac{dC}{dt} = -k_m(C_b - C_i)$$

- Considering time-averaged interfacial area

$$\int_{\%Al_o}^{\%Al} \frac{d(\%Al)}{(\%Al)} = -\frac{k_m}{V_m}\int_0^t S(t)\cdot dt$$

$$\frac{1}{S^*(t)}\ln\frac{(\%Al)}{(\%Al)_o} = -\frac{k_m}{V_m}\cdot t$$

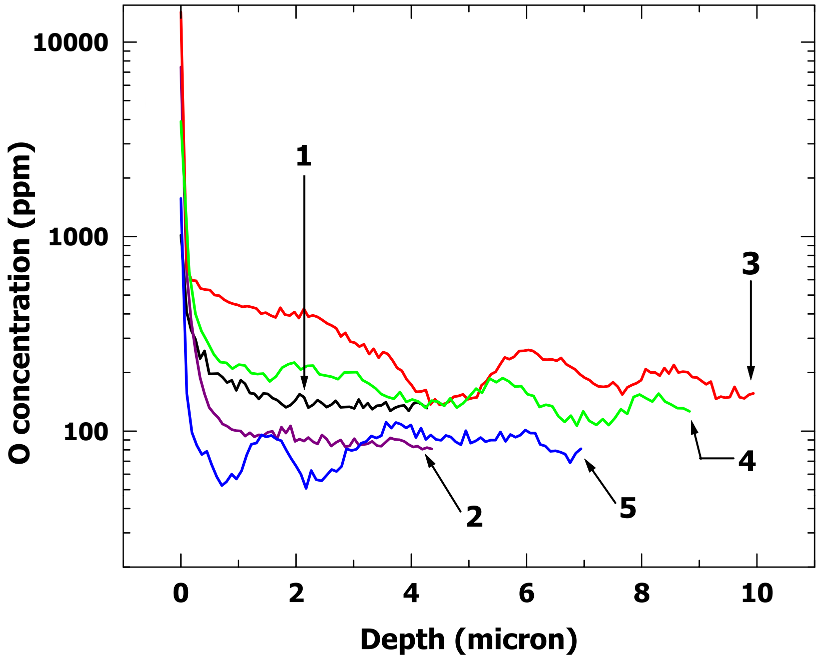
**Considering time-averaged interfacial area** → **Fit in a single straight line**

where

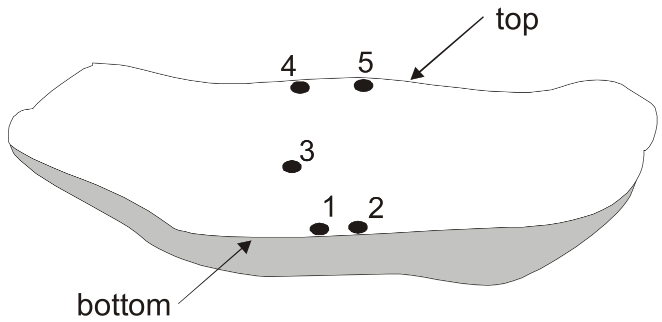
$$S^*(t) = \frac{1}{t}\cdot\int_0^t S(t)\cdot dt$$

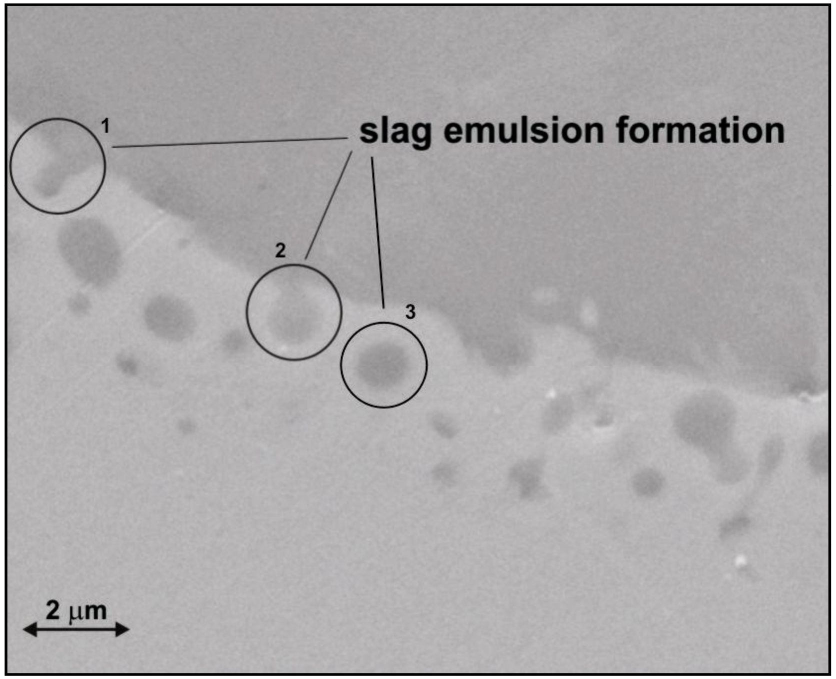
# CURRENT PROGRESS

## 3. Interface characterization and solute oxygen analysis

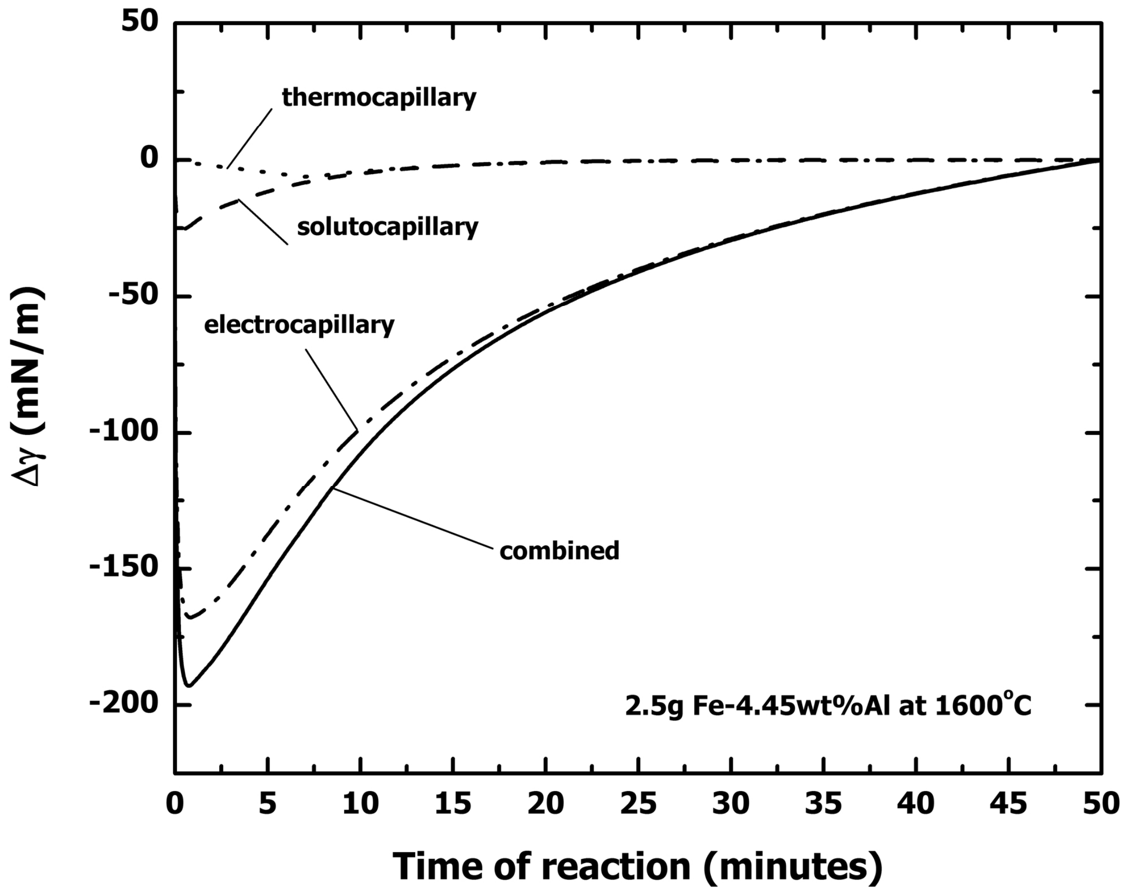



Dynamic SIMS Oxygen Depth Profile
Fe-4.45%Al + $CaO$-$SiO_2$-$Al_2O_3$
2.5g at 1600°C



## 4. Evaluation of the electro-, thermo- and solutocapillary effects




> Adopting the local equilibrium concept and the utilization of the developed kinetic approach
  - Determination of local *T*, $\eta$, and $a_O$ (by using the kinetic information) and their contribution to the lowering of interfacial tension

# FUTURE DIRECTIONS

> Systematic experimental study to provide new data (interfacial tension, interfacial area, chemistry changes)

> Development of predictive model for interfacial area changes

> Understanding of the kinetics of electrochemical reactions and its relation to interfacial phenomena

> Computational fluid modelling of interfacial instability and spontaneous emulsification

## CONCLUDING REMARKS

- There are currently insufficient data to accurately determine the factors resulting the spontaneous emulsification
- The studies up to date have provided a first base understanding of interfacial phenomena
- Understanding the phenomena (including the ability to control them) is important for:
  - Improvement of existing technology → more energy efficient processes
  - Development of new processes

Thank you for your attention!