Valorisation and Dissemination of Secondary Metallurgy Technology

# DissTec

## Designing of operating practice for ultra clean steel

Filippo Cirilli
Michele De Santis
Antonello Di Donato
Patrizia Miceli

# Scope of the presentation

The improvement of steel cleanliness has always been a major objective of the European research activities.

The former C2, and now TGS2 expert group, has been the context where fundamental studies have been carried out and advanced techniques have been developed.
The final objectives being to get knowledge and tools necessary to the industry for producing quality steel at competitive cost.

This presentation shows examples of sophisticated advanced techniques applied to give practical insights for the improvement of operating practices in secondary steelmaking operations obtaining benefits on the product quality.

# Computational thermodynamics and fluid dynamics for modelling operations in ladle

Sophisticated computational techniques have been developed and are available as commercial codes allowing accurate calculations of the influence of operating conditions on steel quality.

In many research projects fluid dynamic and thermodynamic calculations were used to evaluate the effects of various factors on steel composition and inclusion quantity and characteristics.

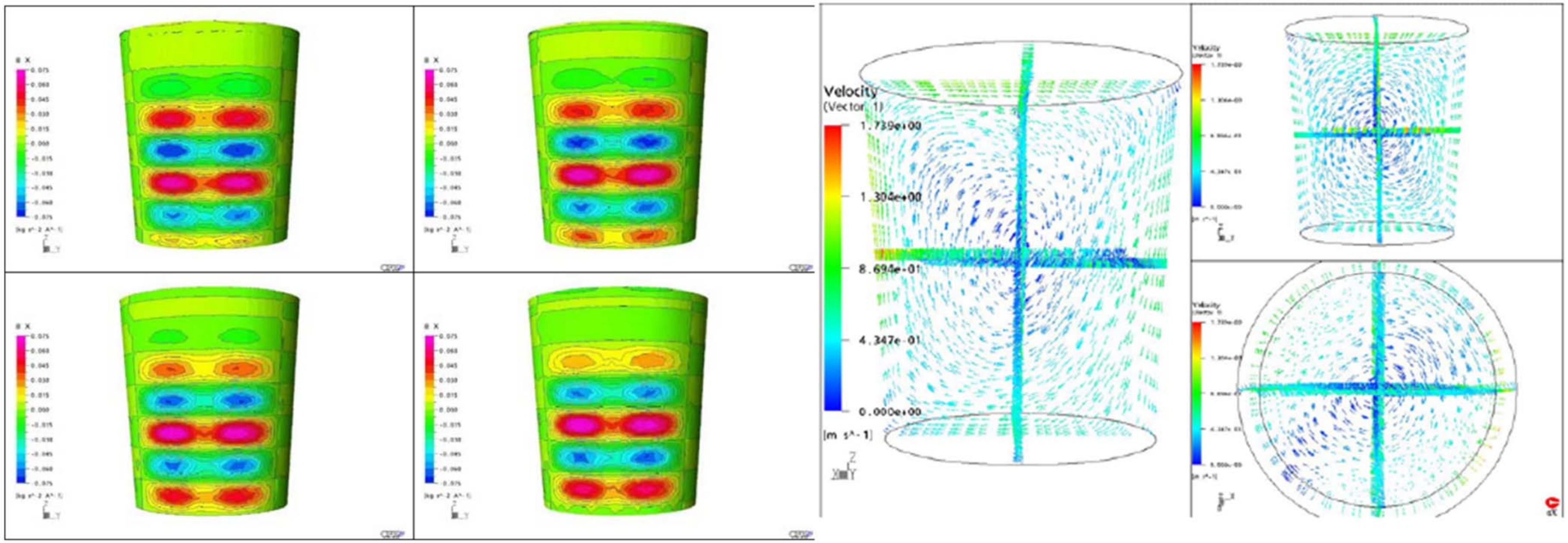
The results of these evaluation gave useful indications and in order to improve the operating practices.

The benefits were assessed in terms of castability and steel cleanliness.

# Computational fluid dynamics for modelling operations in ladle

## Simulation of stirring practices

CFD calculations were used for simulating the effect of both gas and magnetic stirring on steel flow, interaction between slag and steel, inclusions floatation and entrapment in slag.

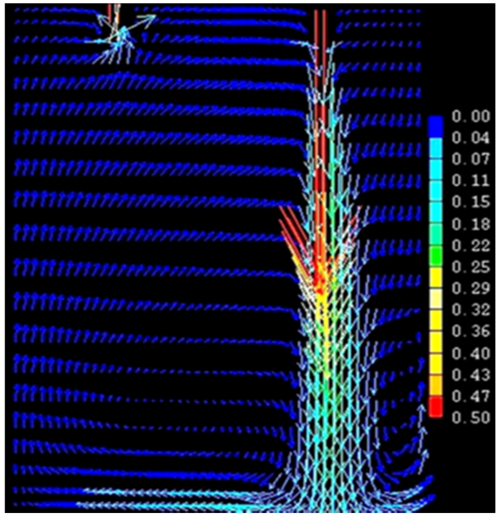


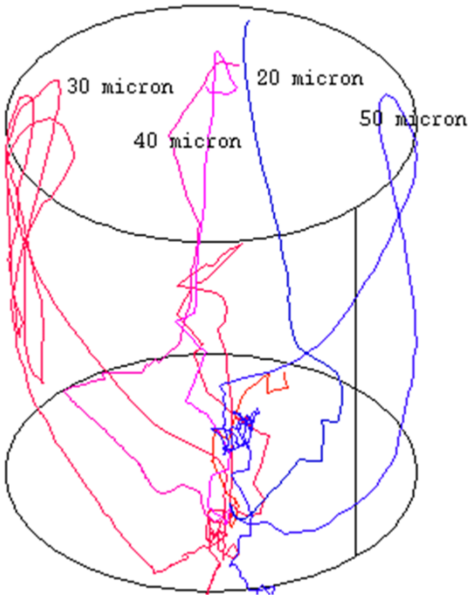

Magnetic field (left) each 0.1 s and resulting velocity field (right) in steel in a 65 t ladle with electromagnetic stirring [1].

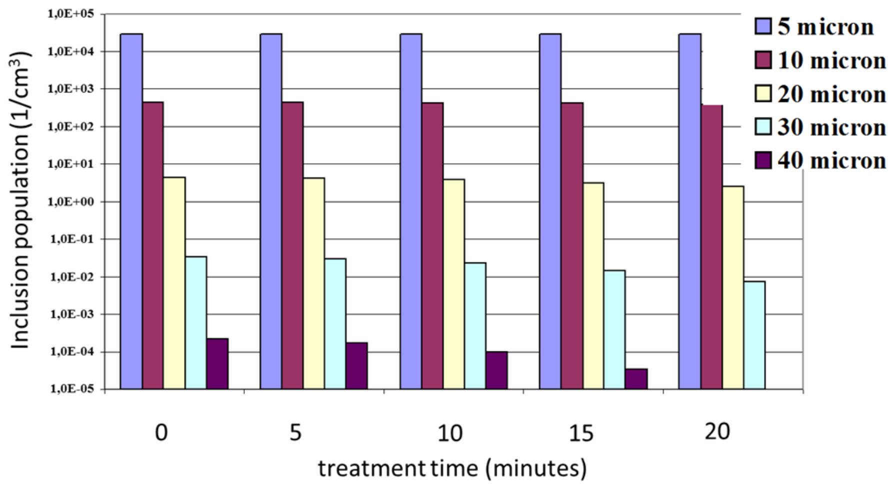
[1] Improved control of inclusion chemistry and steel cleanness in the ladle furnace – EUR 23593 - 2005

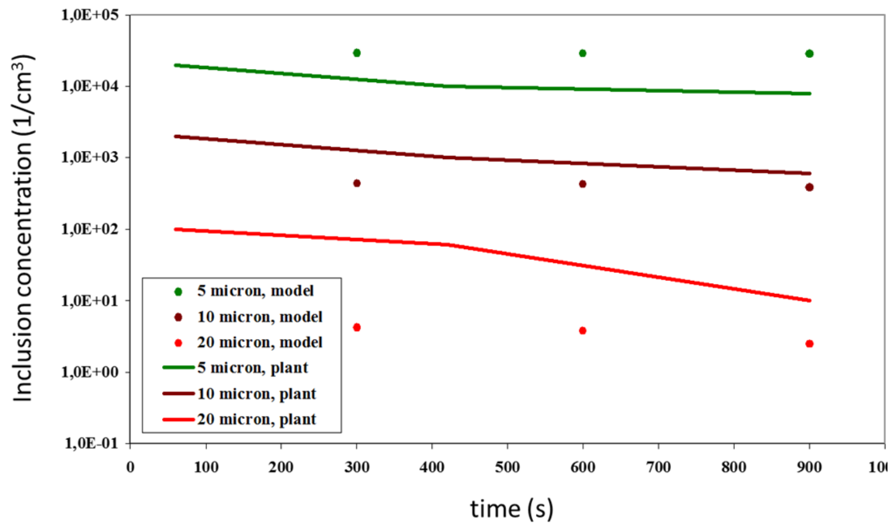
# Computational fluid dynamics for modelling operations in ladle

## CFD for modelling inclusion removal in RH operations



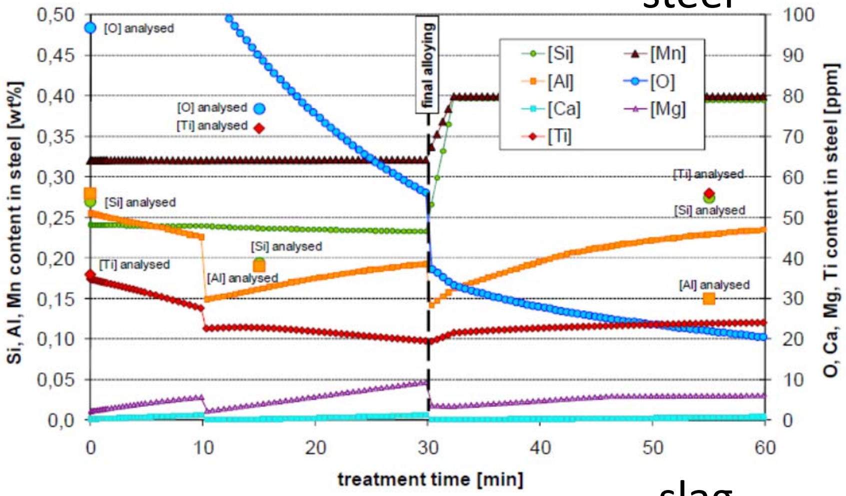

CFD simulations to determine flow field, inclusions paths and coalescence probability of particles dispersed in steel and entrapped in slag. The results were validated wit experimental data [2]

[2] Improvement of inclusion flotation during RH treatment – EUR 22388 – 2004

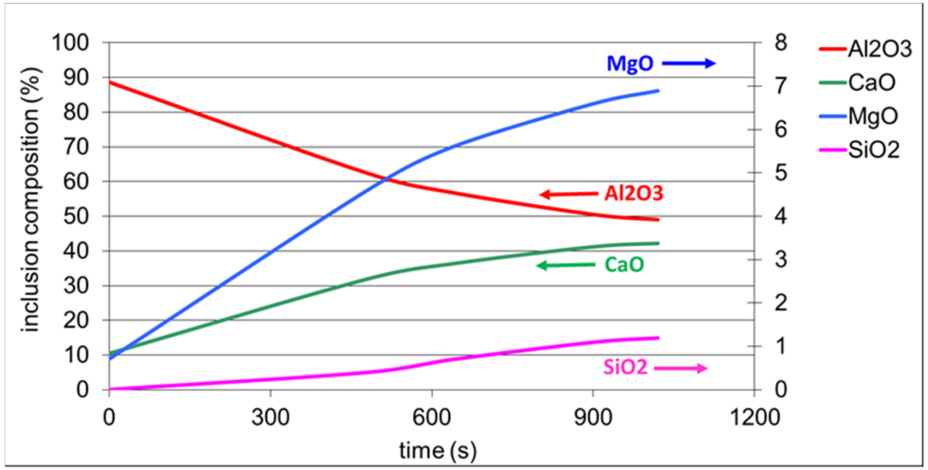
# Computational thermodynamics for modelling operations in ladle

## Thermodynamic simulations of ladle operations

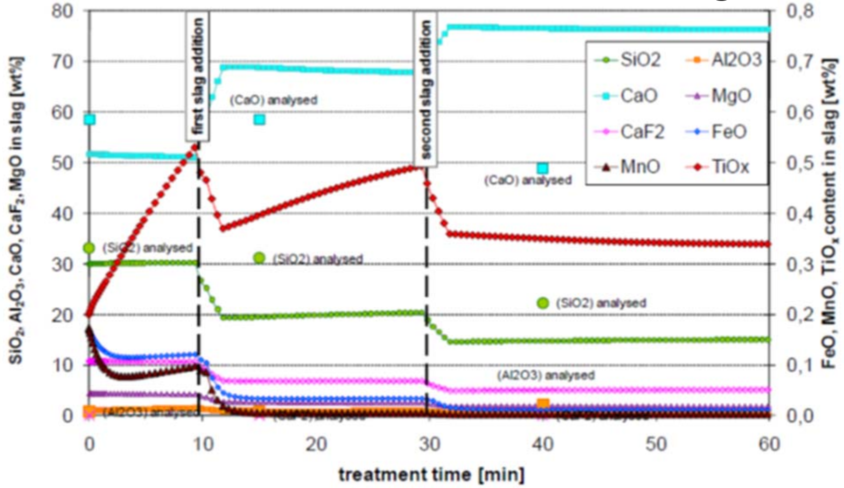
steel




inclusions




slag




Computation thermodynamic has been demonstrated a powerful technique to predict evolution of steel, slag [3] and inclusions composition [4] during ladle operations.

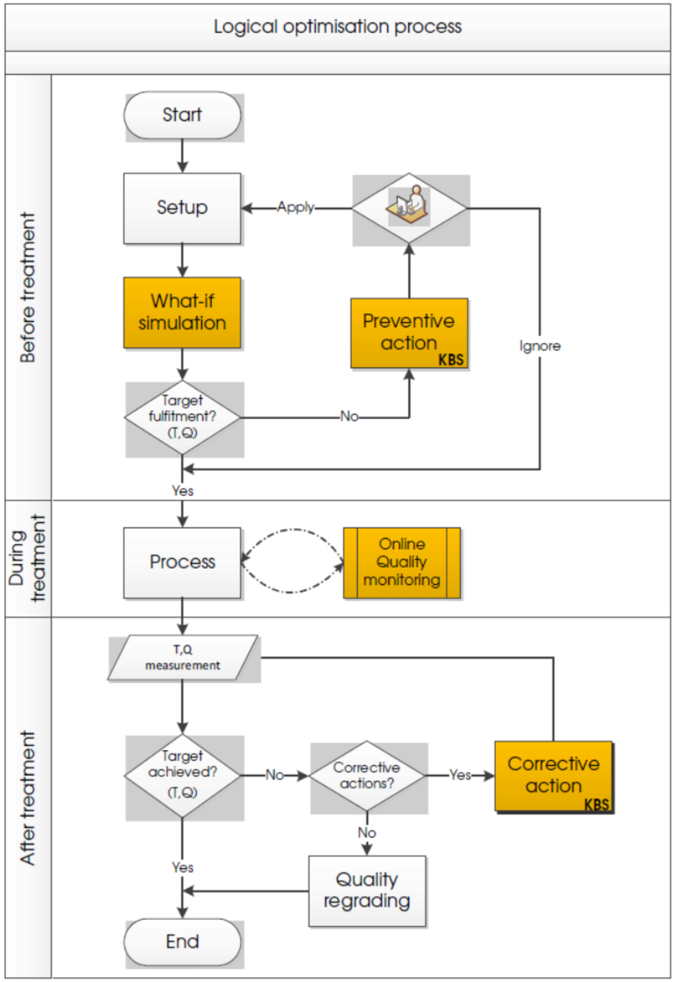

[4] De-oxidation practice and slag ability to trap non metallic inclusions and their influence on the castability and steel cleanliness - 7210-PA/329 - 2005

[3] Development of steel grade-related slag systems with low reoxidation potential in ladle and optimised ladle glaze techniques for improving steel cleanliness (STEELCLEANCONTROL) – EUR 25076 - 2013


BFI MPI Materials Processing Institute Excellence in Materials & Process Innovation CRM GROUP swerea MEFOS CSM Centro Sviluppo Materiali

# Statistics and mathematical techniques

Besides deterministic models, statistics and other advanced mathematical techniques (neural networks, fuzzy logic, Optimization algorithms) have been largely used to model and control secondary steelmaking operations [4,5].
A number of pre-developed model have been integrated and applied in the recent totoptlis project, based on a through-process approach for multi-criteria optimization of the process cycle[6]




Layout of the optimization strategy defined in the totoptlis project and applied in ArcelorMittal


[4] The use of artificial intelligence to control secondary steelmaking practices – EUR 28178 - 2002
[5] Innovative methodology for through process inclusion level forecasting of engineering steel (INCLUSIONS)- EUR 26175 -2013
[6] Multi-criteria through-process optimisation of liquid steelmaking (totoptlis) – EUR 26931 - 2015

# Application of modelling techniques for designing improved operating practices for clean steel

## Examples of improvement of operating practices

The following two examples have been extracted from European projects where mathematical techniques have been applied at the State-of-the-Art and validated with measurements and analysis from plants.

The results were used to give precise indications for the design of operating practices that gave practical benefits in terms of steel quality.

# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Defining stirring practices improving inclusion control

In the project "*Improved control of inclusion chemistry and steel cleanness in the ladle furnace (7210-PR/331)*" the integration of fluid dynamic and thermodynamic calculations was used to evaluate the impact of slag composition and stirring strategy on inclusion mass and composition and inclusion removal.

The results of the modelling were used to define innovative stirring strategy favouring final steel cleanliness

[1] Improved control of inclusion chemistry and steel cleanness in the ladle furnace – EUR 23593 - 2005

# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Defining stirring practices improving inclusion control

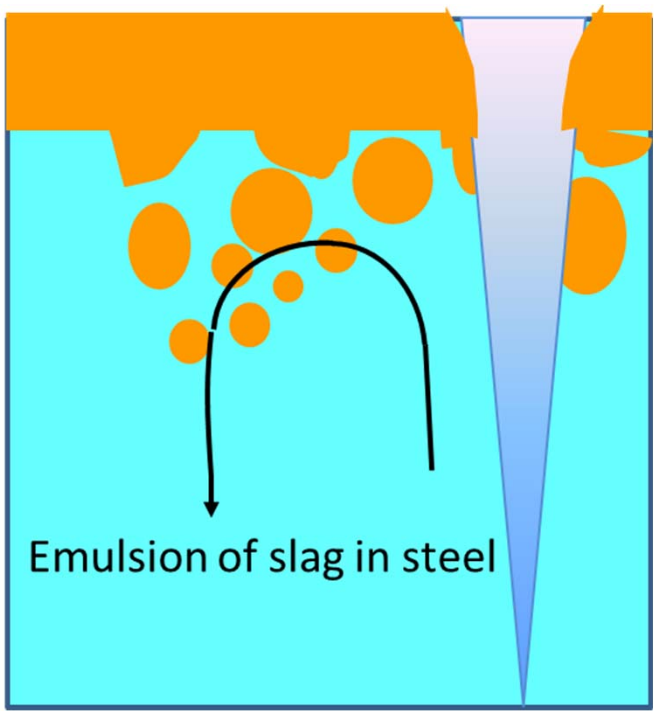
**The concept**

In operations in ladles strong gas or electromagnetic stirring are used for different purposes (e.g. ferroalloys mixing, desulfurization).

The consequent emulsification of slag and steel has a strong impact on concentration of dissolved element in steel (Si, Al, O) and inclusion chemistry.

This phenomenon can be exploited to control steel chemistry and inclusion.

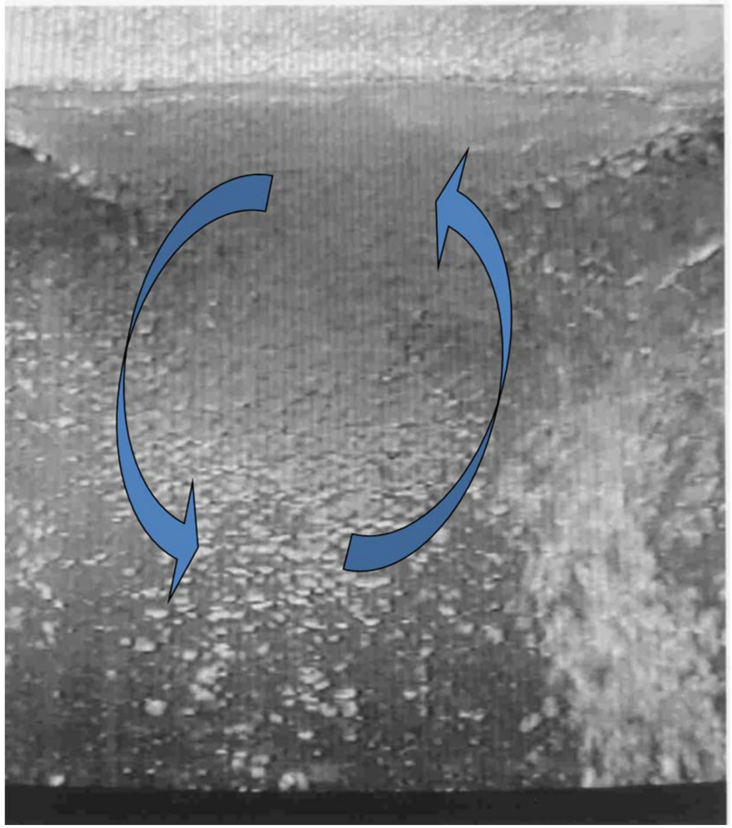
In this example the objective was to reduce the final concentration of dissolved oxygen and total amount of inclusions, measured in terms of concentration of total oxygen.
This result was obtained adjusting the stirring strategy.



# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Effect of stirring practices on steel flow and slag emulsification

The amount of emulsified slag depends on stirring conditions.
The effect of stirring practice on slag emulsification can be studied with both physical and numerical models.

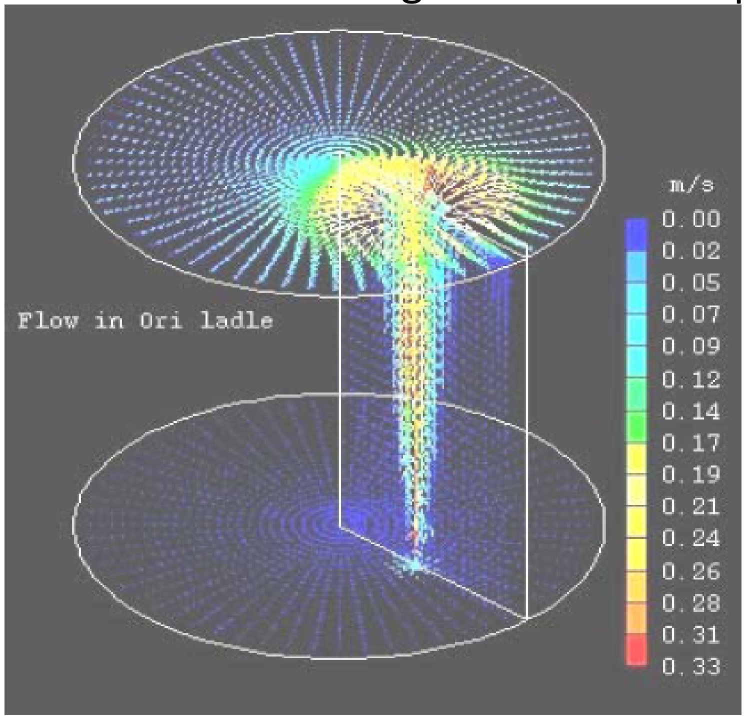


Physical simulation of slag emulsification caused by gas stirring.
Physical model with water and oil

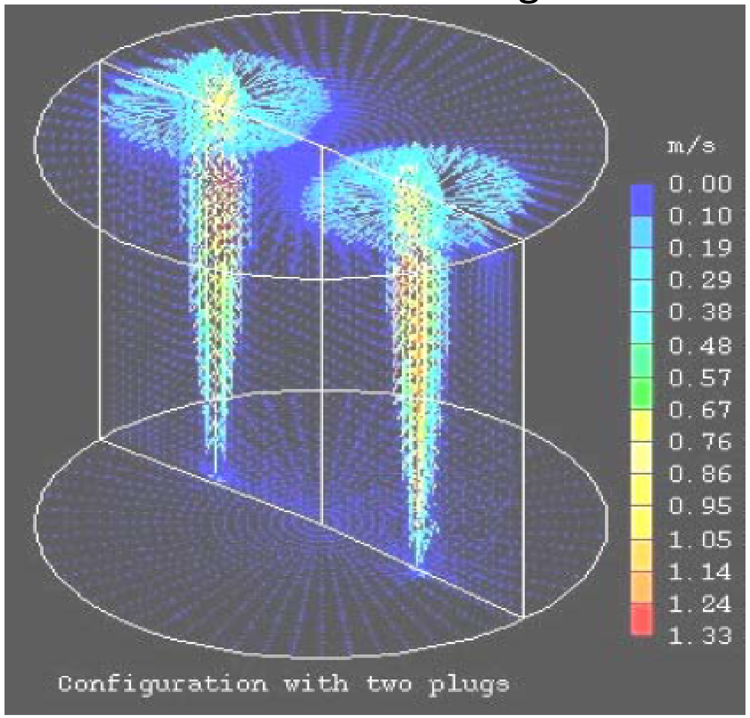
# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Effect of stirring practices on steel flow and slag emulsification

Numerical modelling allows more rapid and more flexible investigation




one eccentric porous plug



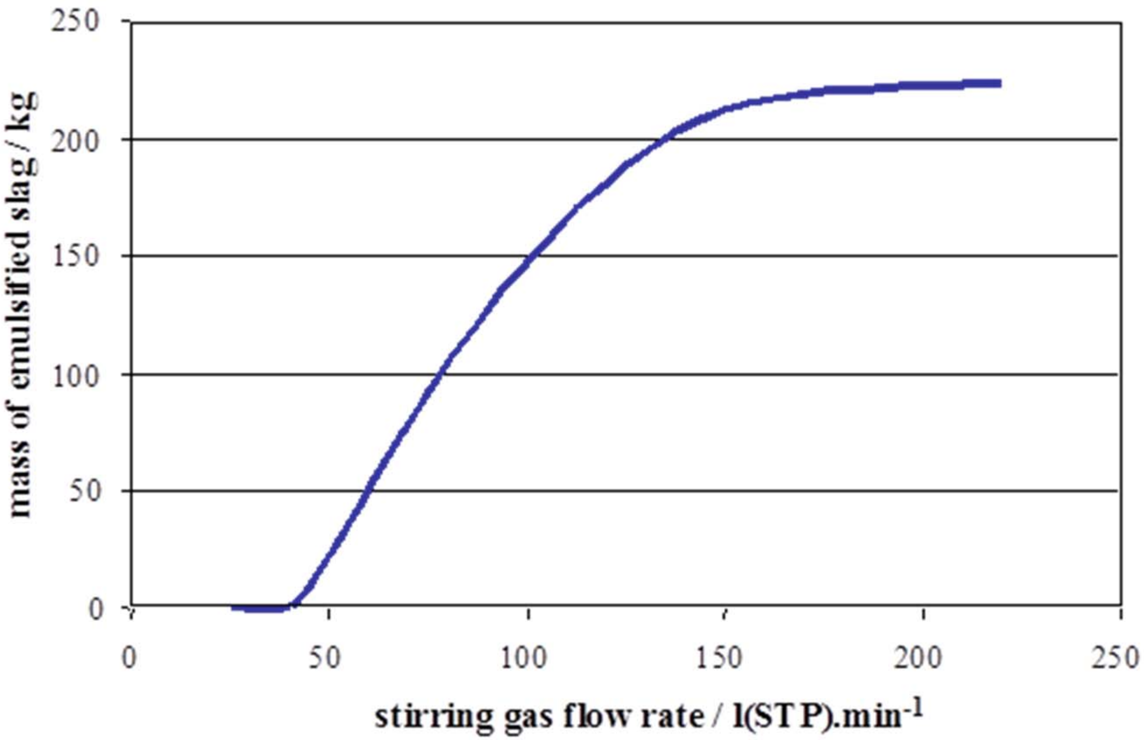

two porous plugs

Velocity fields in steel from CFD-simulations for two different stirring conditions in the same ladle (steel weight 70 t; steel height 2.4 m; ladle diameter 2.4 m).
Gas stirring flow rate: 100L/min.

# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Effect of stirring practices on steel flow and slag emulsification

From the steel velocity at the interface with slag and from the volume of slag occupied by the injected gas the mass of emulsified slag can be estimated.

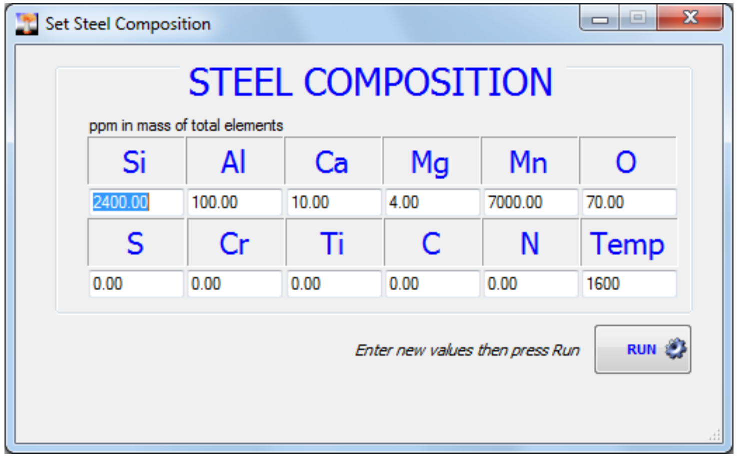


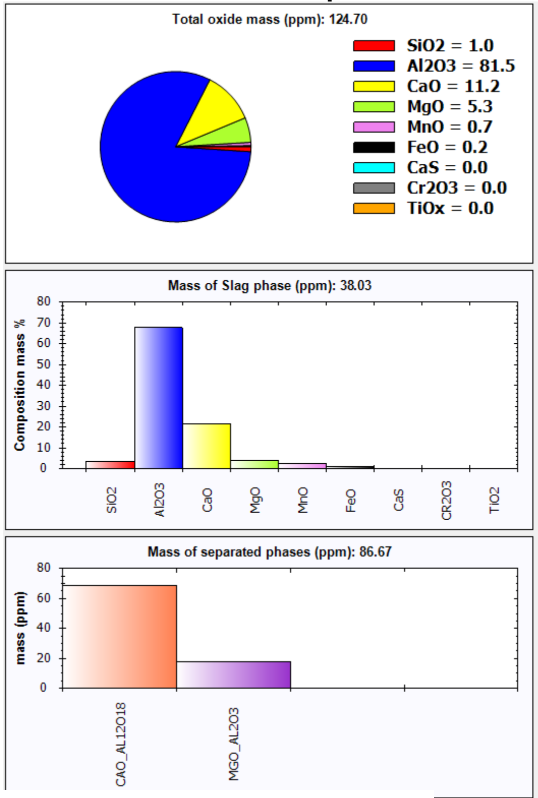

Mass of emulsified slag at steady state as a function of stirring gas total flow

# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Computational thermodynamics to calculate inclusion mass and composition

Computational thermodynamics has been demonstrated an extremely valid technique to evaluate mass and composition of inclusions as a function of steel composition.




From steel composition the thermodynamic model calculates mass and composition of inclusions and concentration of dissolved elements

The resulting concentration of dissolved O is 15 ppm

```
Total Elements (ppm) :Fe=990416 Si=2400 Al=100 Ca=10 Mg=4 Mn=7000 O=70 S=0 Cr=0 Ti=0 C=0 N=0

Dissolv Elements (ppm) :Si=2400 Al=46 Ca=0 Mg=0 Mn=7000 O=15 S=0 Cr=0 Ti=0 C=0 N=0
```

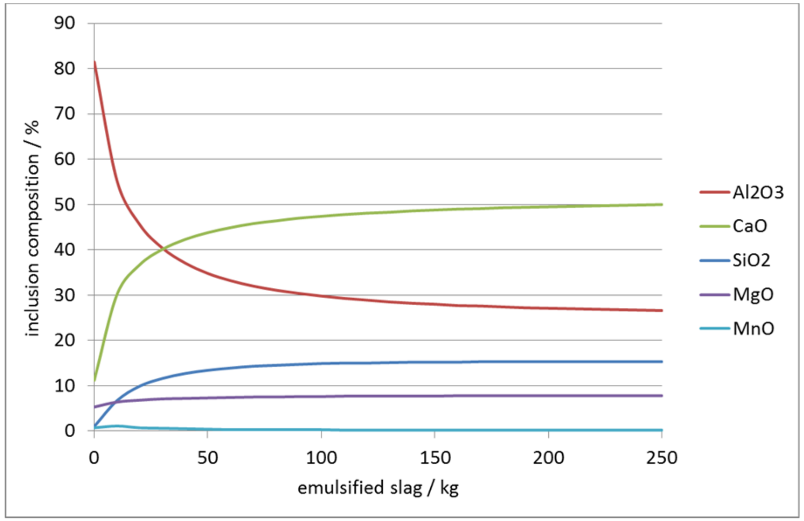
BFI MPI Materials Processing Institute Excellence in Materials & Process Innovation CRM GROUP swerea MEFOS CSM Centro Sviluppo Materiali

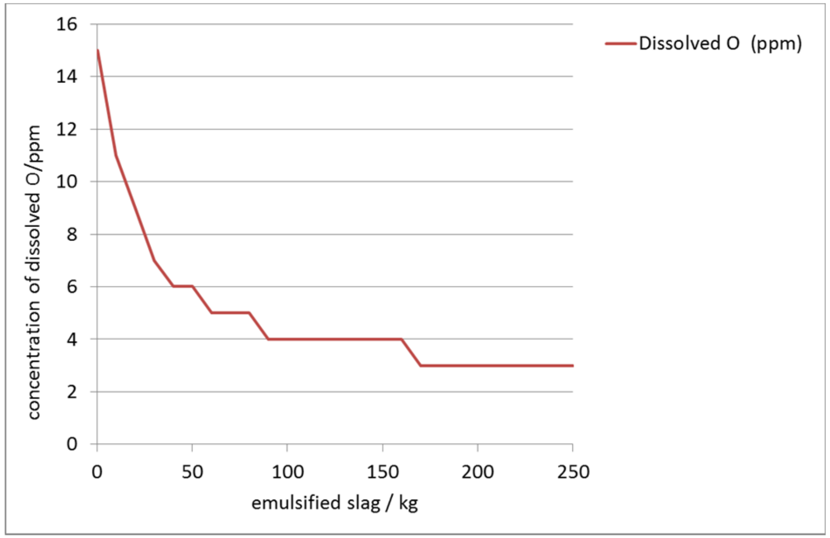
# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Effect interaction between slag and steel

The chemical interaction between slag and steel changes both steel and inclusions. Thermodynamic calculations were used to evaluate the effect of emulsified slag on steel and inclusion chemistry.

| Steel composition ppm | | Slag composition % | |
|---|---|---|---|
| Si | 2400 | SiO2 | 15 |
| Al | 100 | Al2O3 | 25 |
| Ca | 10 | CaO | 52 |
| Mg | 4 | MgO | 8 |
| Mn | 7000 | MnO | 0.1 |
| O | 70 | | |



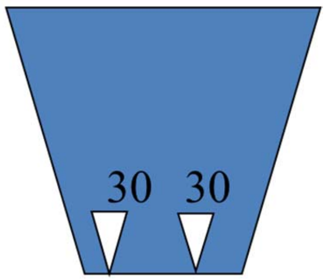



# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Definition of best stirring strategy

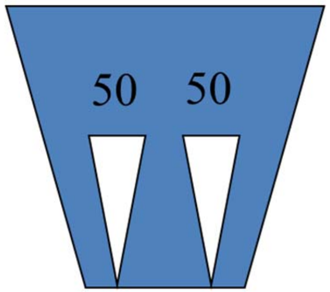
The fluid dynamic model of the ladle was used to study the effect of different stirring practices on mass of emulsified slag

A



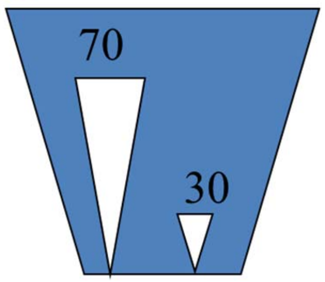

Stirring condition A
Low stirring
Two porous plugs
(30 L/min + 30 L/min)
Constant values
for 20 minutes

B



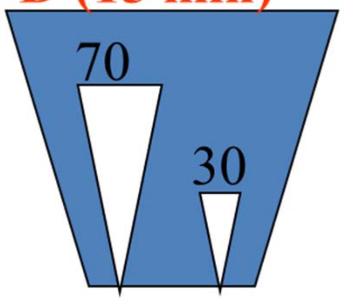

Stirring condition B
High stirring
Two porous plugs
(50 L/min + 50 L/min)
Constant values
for 20 minutes

C

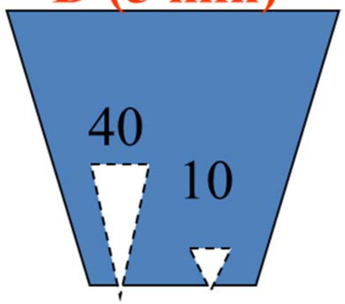



Stirring condition C
High stirring
asymmetric
Two porous plugs
(30 L/min + 30 L/min)
Constant values
for 20 minutes

D (15 min)




D (5 min)

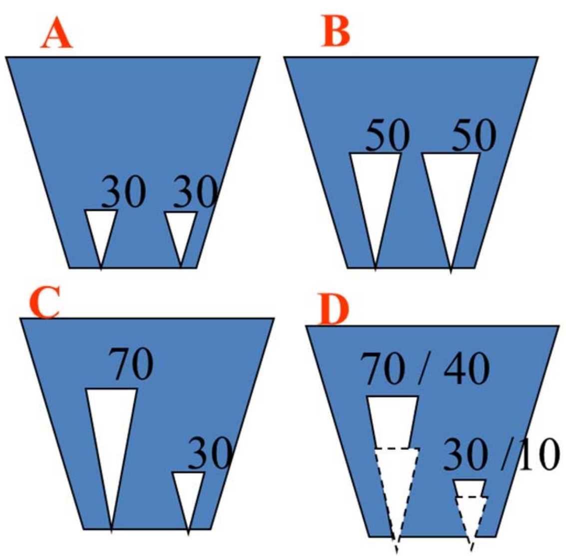


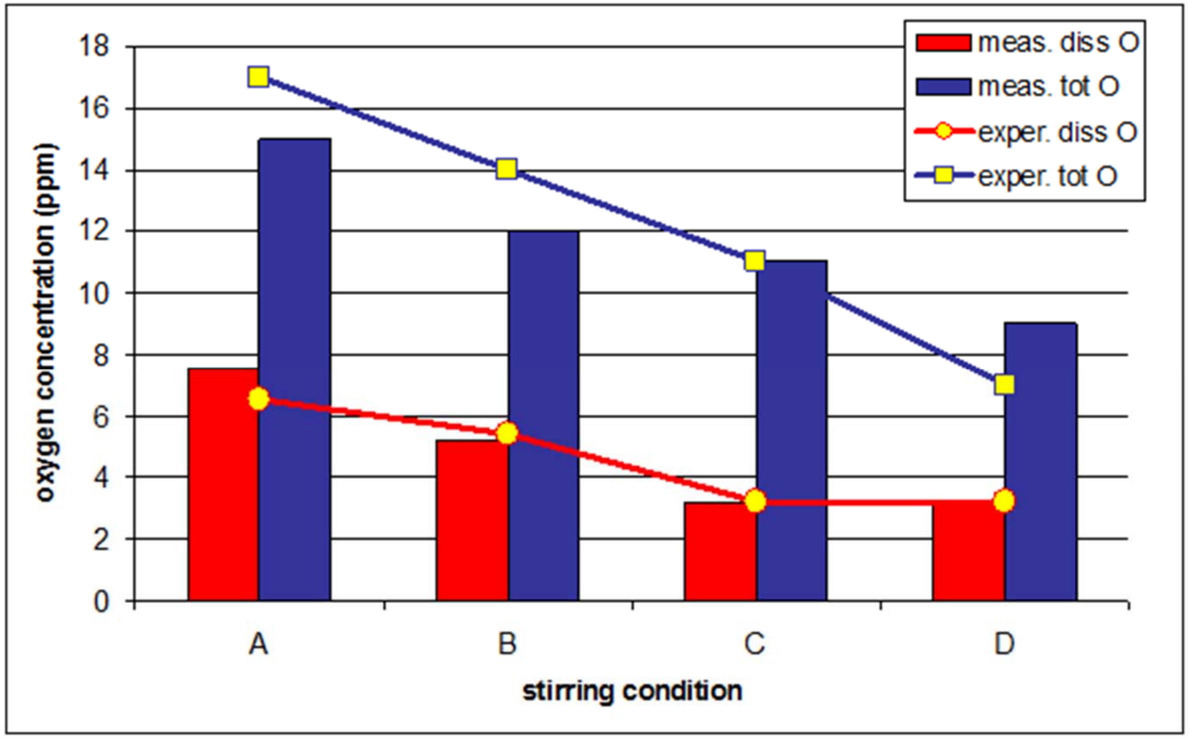

Stirring condition D
High stirring
asymmetric
**variable in time**
Two porous plugs
70 L/min + 30L/min
for 15 minutes
40 L/min + 10L/min
for 5 minutes

# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Definition of best stirring strategy

The different stirring practices, corresponded to different average emulsified slag amounts. Using these amounts in the thermodynamic calculations different amounts of inclusions and different concentration of dissolved oxygen resulted. Confirmed with measurements.

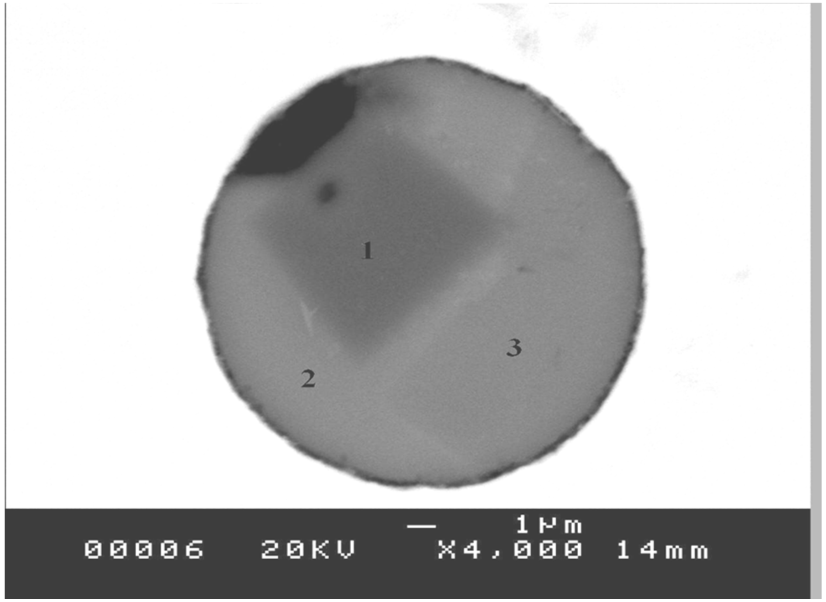


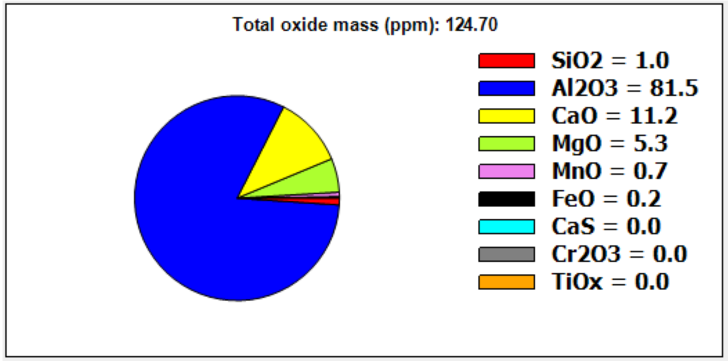
# Computational thermodynamics and fluid dynamics for modelling operations in ladle

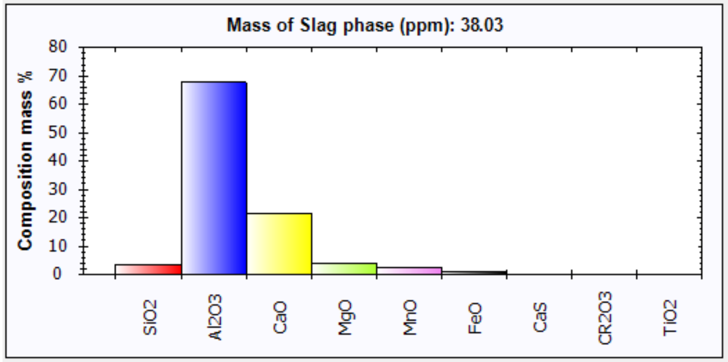
## Effect of interaction between slag and steel

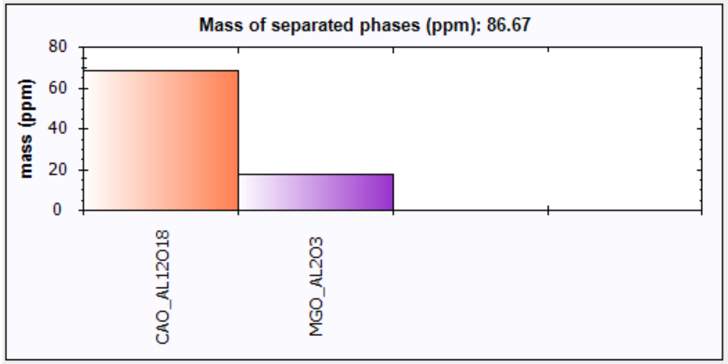
Before emulsification inclusion rich of solid phases are in equilibrium with steel




Inclusion analysis (SEM/EDS):
Point 1: ($Al_2O_3 \cdot MgO$)
Point 2,3: $(CaO) \cdot (Al_2O_3)_x$



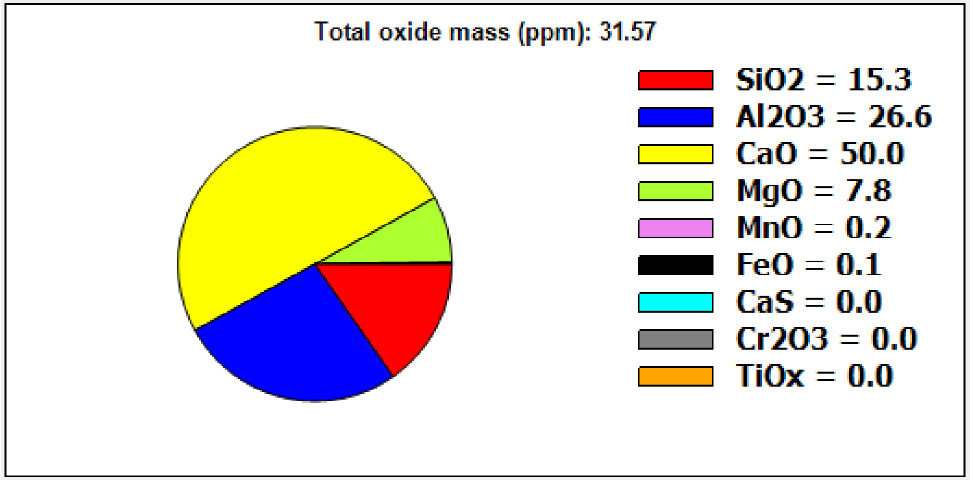



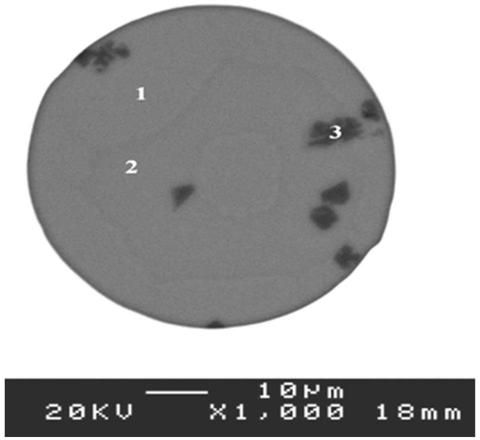
# Computational thermodynamics and fluid dynamics for modelling operations in ladle

## Effect of interaction between slag and steel

After emulsification the inclusions are transformed in liquid inclusions, easily to remove, and dissolved oxygen decreases from 15 ppm down to 3 ppm




Inclusion analysis (SEM/EDS):
$SiO_2$ 12%; $Al_2O_3$ 30%; CaO 50%; MgO 8%



# Computational thermodynamics and fluid dynamics for modelling operations in ladle

The integration of fluid dynamic and thermodynamic model allows to predict the effect of both slag composition and stirring practice on inclusion chemistry and ability of inclusion removal.

Different and non-conventional operating conditions can be simulated and those most appropriate for the specific ladle conditions applied, with benefits in terms of final cleanliness.

# Application of statistical techniques and model of inclusion transformation for rapid decision making

The idea of the INCLUSION project [5] was to develop a method allowing foreseeing - in a relatively quick and cheap way - the probability of occurrence of not acceptable defects produced in given rolling operations directly from analysis on liquid steel (or at least in as cast products).

On the basis of this information the steelmaker can decide a different rolling procedure, changing the final destination of the product, in order to reduce the probability of downgrading the product.

**The project was in line with the strategic development of intelligent manufacturing techniques**

[5] Innovative methodology for through process inclusion level forecasting of engineering steel (INCLUSIONS)- EUR 26175 -2013

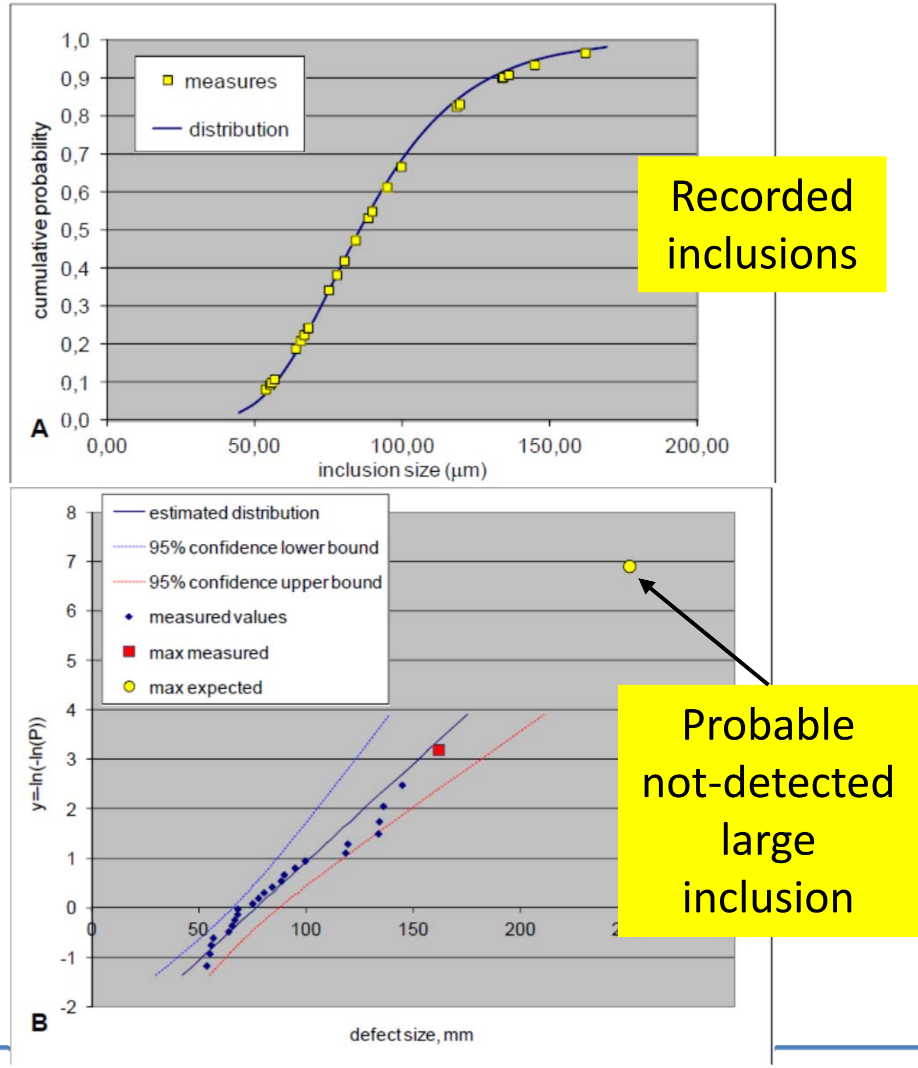
# Application of statistical techniques and model of inclusion transformation for rapid decision making

## Extreme Values Analysis (EVA) – A statistical technique of rare events

Despite the huge and successful effort performed to improve steel cleanliness, large inclusions – causing defect on the product – can be still present at the end of the secondary steelmaking cycle.

The rarity of these events make difficult their individuation and actuation of countermeasures.

EVA is a statistical techniques able to determine the probability of not-detected large inclusions from analysis of recorded inclusions (in lollipop or in as cast product samples)



# Application of statistical techniques and model of inclusion transformation for rapid decision making

## Evolution of inclusions in defects

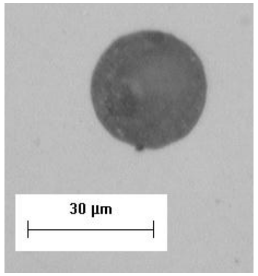
During rolling inclusions present in the final liquid and as cast products, are transformed in defects.

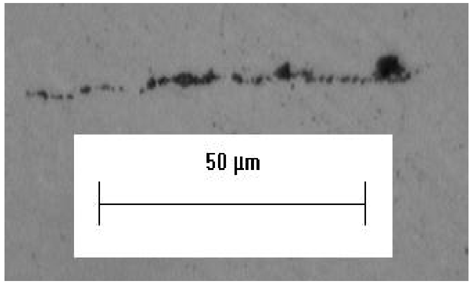
Different types of inclusions generate different defects (which are classified in the standard methods for defects classification and evaluation).

As cast

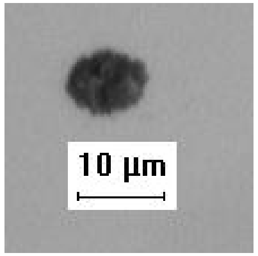
Rolled

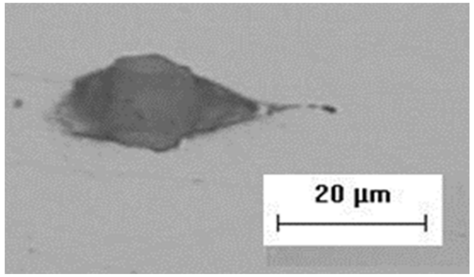
Plastic inclusion:
Liquid inclusions
SiO2-MnO rich
Re-oxidation products



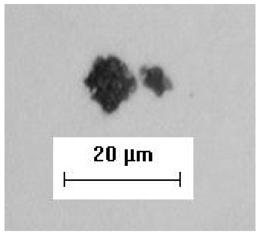



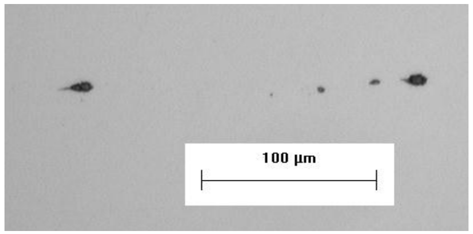

Multiphasic inclusions:
with solid phases like
MgO·Al2O3, CaS precipitates




Rigid inclusion:
clusters of Al2O3 small
particles



# Application of statistical techniques and model of inclusion transformation for rapid decision making

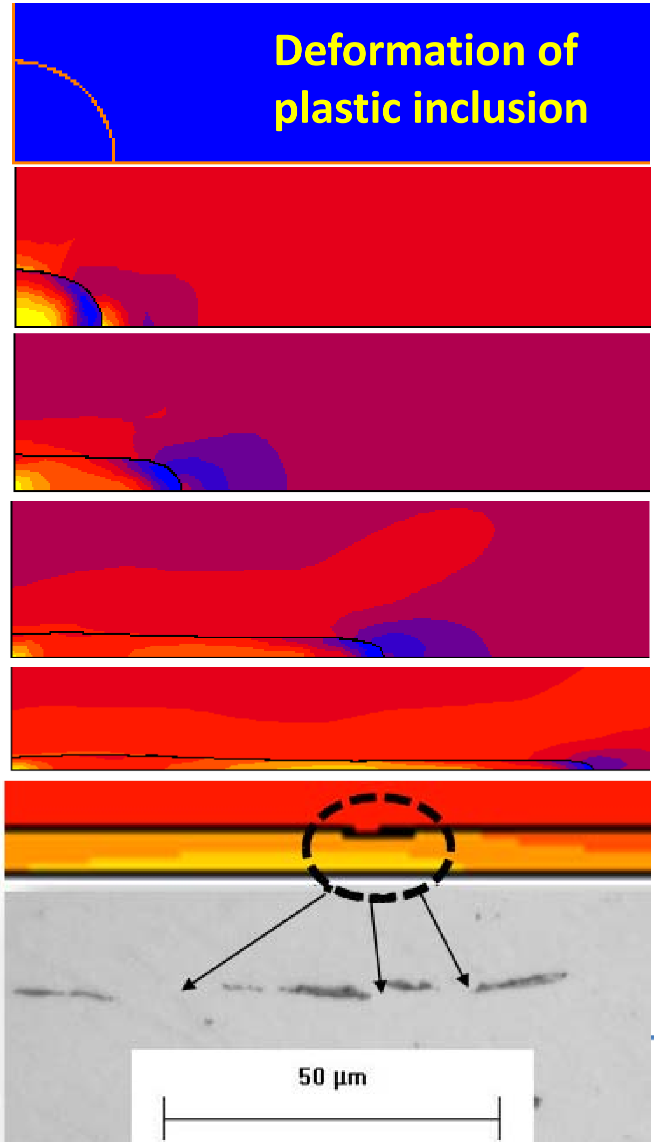
## Model of inclusion transformation during rolling

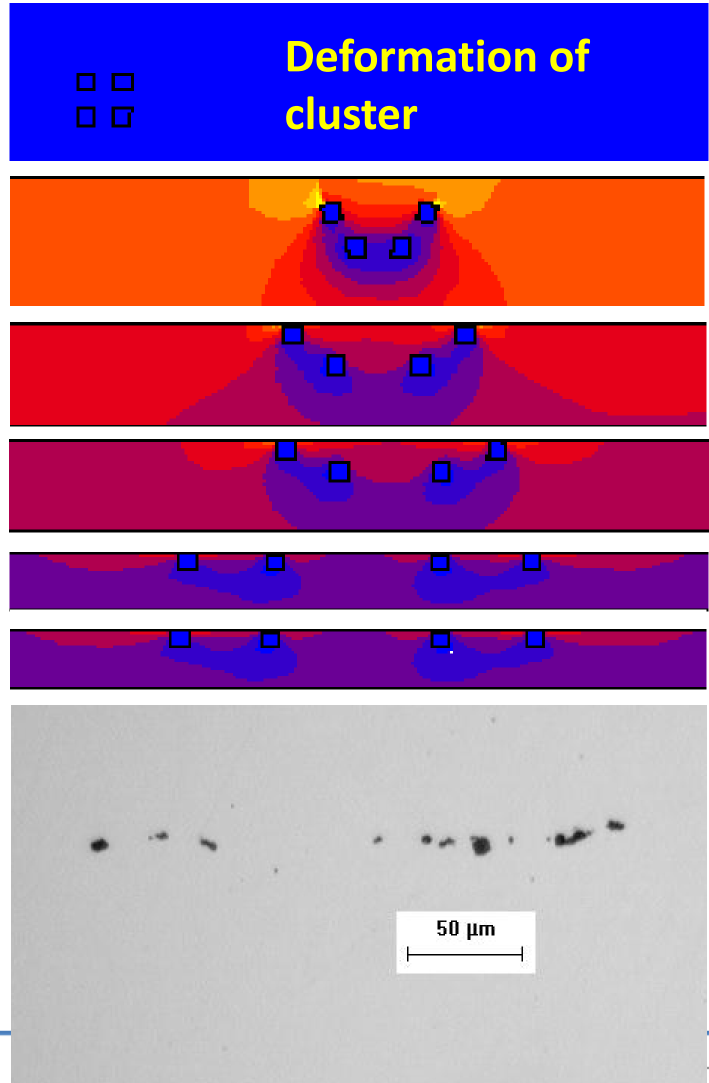
A mathematical model of the model of the deformation of the inclusion during the rolling of the steel product has been developed, based on the  rheological properties of steel and inclusion and rolling conditions.

The model predicts the size of the final defects from the characteristics of the original inclusion

# Application of statistical techniques and model of inclusion transformation for rapid decision making

## Model of inclusion transformation during rolling

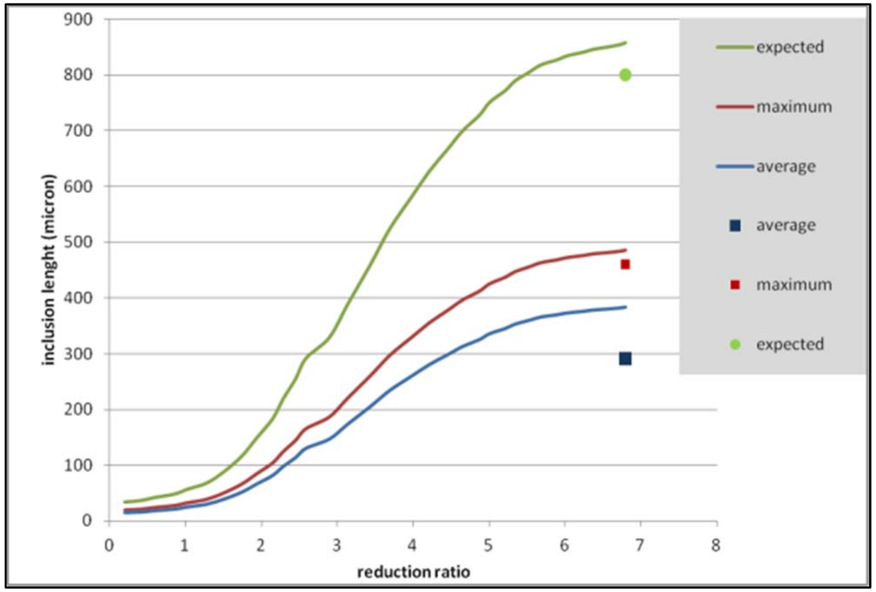


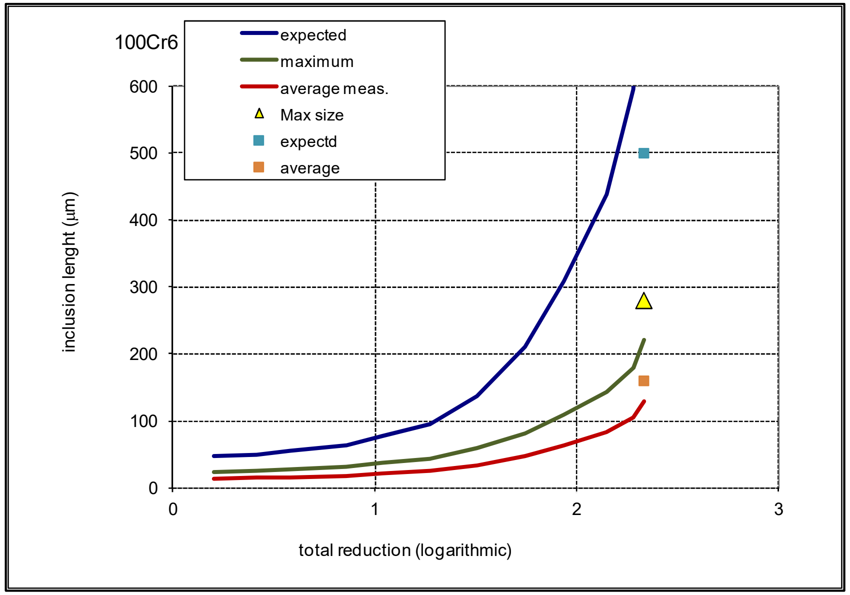



# Application of statistical techniques and model of inclusion transformation for rapid decision making

## Model of inclusion transformation during rolling

The deformation inclusion model has been applied to calculate the defect size expected from probable inclusions estimated with EVA from recorded inclusions, but not actually detected. The predictions of the combination of EVA statistics and inclusion transformation were in agreement with defect found in real products




Comparison between defect size calculated from deformation of inclusion measured and estimated from EVA and defect actually found in products in Cogne (left) and Sidenor (right)

# Application of statistical techniques and model of inclusion transformation for rapid decision making

## Industrial application

The EVA statics allows to individuate probable big inclusions, causing big defects, from with a relatively rapid analysis from a single sample.

This information can be exploited real-time for making decision on rolling strategy and product selection, reducing down-grading problems

The same information can be used to adjust operations in ladle (and tundish) to reduce the occurrence of the problem.

Thank you