Valorisation and Dissemination of Secondary Metallurgy Technology

DissTec

Impact of inclusions formed in steelmaking operations on flow control in continuous casting and defects formation

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Introduction

The large number of European researches on steel cleanliness contributed to the evolution of the concept of “clean steel”, from the original meaning of low contents of impurities to a modern “holistic” vision[*], where steel is defined in terms of global composition, paying big attention to the non-metallic inclusions.

In the modern vision, steel cleanliness requirements are defined in terms of target specifications for the final products.
At the same time steel cleanliness must be controlled to avoid drawbacks in continuous casting.

This presentation shows examples, taken from real industrial cases, of the application of knowledge and tools developed in European researches to improve the continuous casting performance and to control defects.

[*] Jean Pierre Birat, Steel cleanliness and environmental metallurgy, Metall. Res. Technol. 113, 201 (2016)
Plenary presentation to the 9th International Conference on Clean Steel; 8–10 September 2015; Budapest; Hungary

Application of computational thermodynamics to improve castability

Inclusions play a big role on phenomena such as clogging and corrosion of refractory components in continuous casting (stopper rods, submerged nozzles, sliding gates).

An accurate evaluation of the chemical composition of the inclusions in steel is necessary and actions to control inclusion scenario (mass, composition and size of inclusions) must be undertaken: "**inclusion engineering**"

The European research has provided a fundamental contribution in the development and application of powerful computational thermodynamics to inclusion engineering.

Application of computational thermodynamics to improve castability

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 thermodynamic calculations were used to evaluate the effects of various factors on steel composition and inclusion quantity and characteristics.

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

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

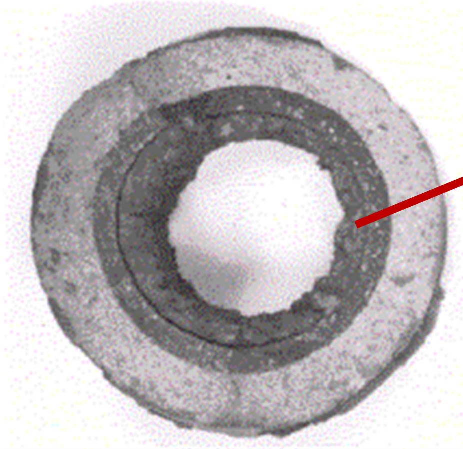
Application of computational thermodynamics to improve castability

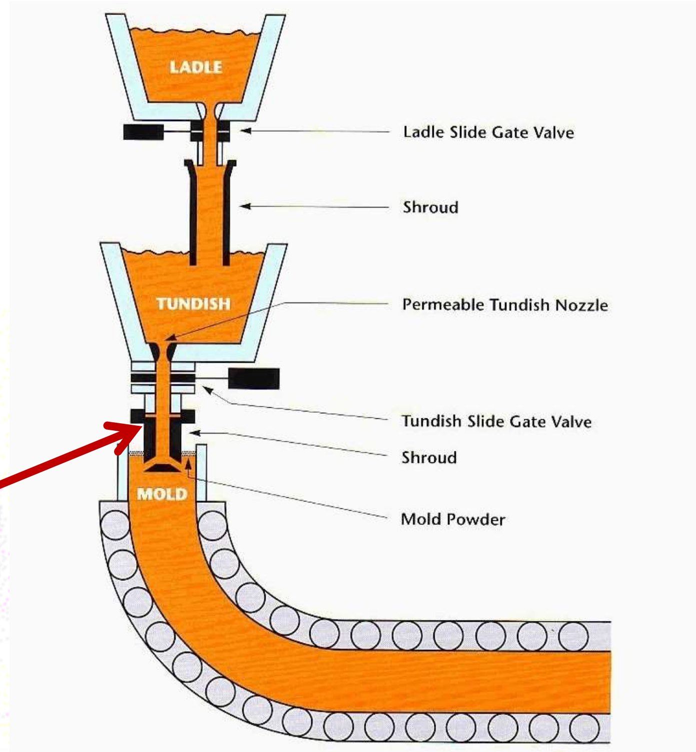
Example: ***Resulfurised steels***

Sulfur content provides the steel with high workability properties.

In resulfurized steel problems of SEN nozzle clogging occurred despite the steel composition was in the required range.
A possible cause could be the formation of undesired inclusions.

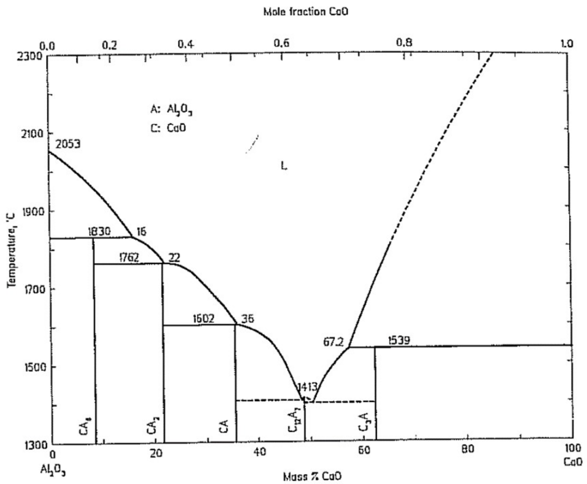
Desired inclusions
Manganese sulfide
formed during solidification
Harmful inclusions:
Solid inclusions (Al_2O_3, CaS)
Formed in ladle and tundish
that may cause tundish nozzle clogging during casting and hinder the formation of MnS



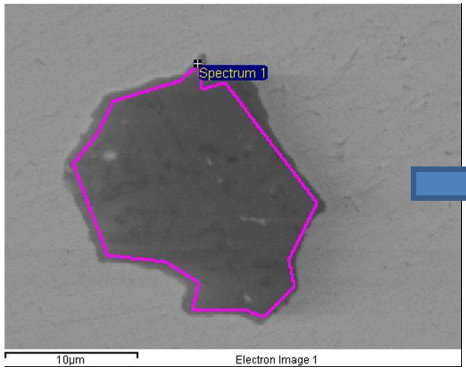


Application of computational thermodynamics to improve castability

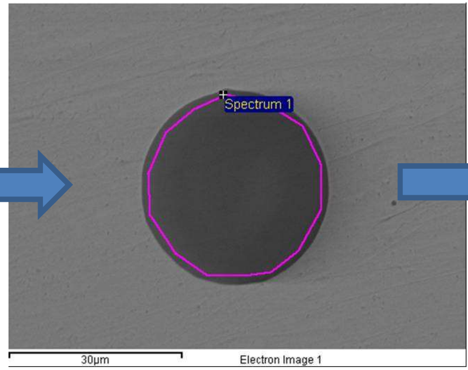
Common practice to avoid solid Al_2O_3 inclusions is to transform them in liquid Ca-aluminates by adding Ca.



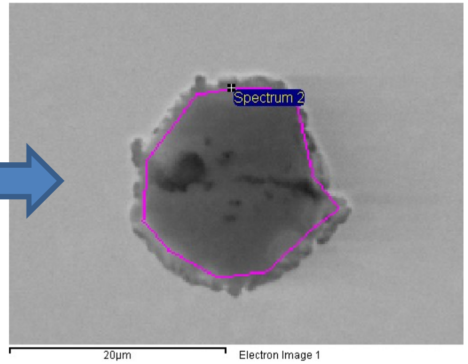
Solid inclusion (Alumina)



Liquid inclusion (Calcium Aluminate)



Example of solid inclusion AlCa with CaS



However, Ca addition can form the harmful solid CaS (possible cause of clogging and hindering MnS formation)

Application of computational thermodynamics to improve castability

Computational thermodynamics has been applied to analyse "*good*" heats (no clogging) and "*bad*" heats (clogging), to individuate the conditions favouring clogging in re-sulfurised steel and to supply practical rules to define the correct amount of calcium to add to the steel avoiding the formation of CaS inclusions, that are the main causes of the clogging events.
Therefore, the content of O_{tot} at the end of LF treatment has been calculated from measurements available on the plant.

Heat	**Mn**	**Si**	**S**	**Al**	**Ca**	**O activity (ppm)**	**T (°C)**	**Calc. Total Oxygen (ppm)**
Good	1.5477	0.2992	0.0336	0.0315	**0.0024**	4.49	1607	**39**
Good	1.5707	0.2628	0.0261	0.0281	**0.0019**	4.75	1611	**34**
Good	1.5446	0.2545	0.0323	0.0334	**0.0016**	5.06	1630	**23**
Good	1.5322	0.2877	0.0334	0.0338	**0.0020**	4.53	1614	**35**
Bad	1.4628	0.3966	0.0282	0.0352	**0.0022**	2.39	1617	**20**
Bad	1.5617	0.3020	0.0283	0.0316	**0.0026**	2.53	1622	**28**
bad	1.3862	0.4099	0.0294	0.0370	**0.0021**	2.27	1624	**19**

Application of computational thermodynamics to improve castability

Thermodynamic calculations have been carried out to individuate the existing fields of the different types of inclusions as a function of calcium and oxygen concentration for each heat.

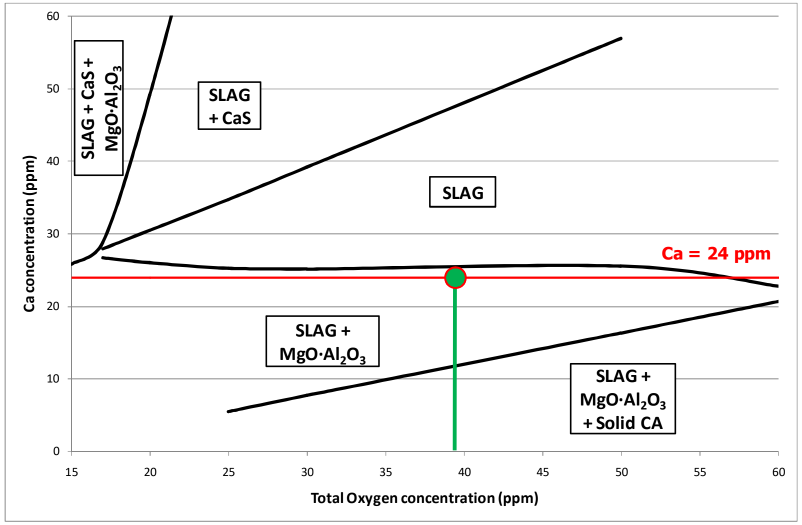
Using the steel chemical analyses before casting, it was possible to identify the type of inclusions actually present in each heat.

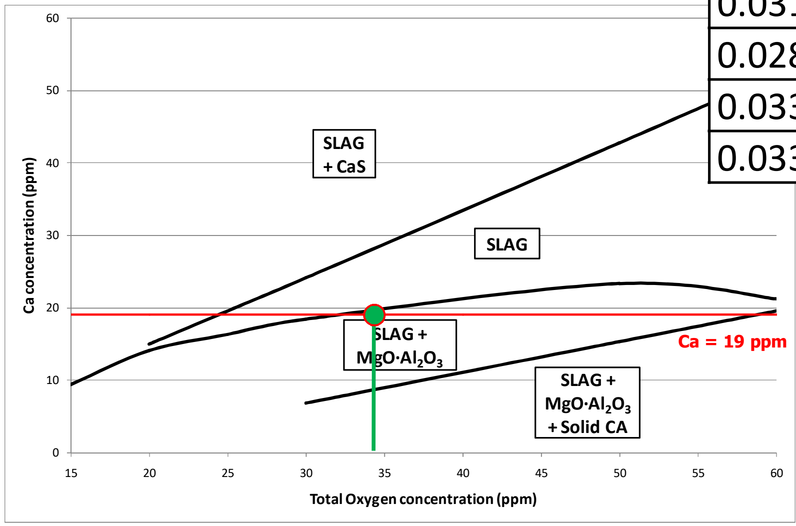
Then the calculations were applied to build maps of inclusions formation - specific for the steel composition of interests - useful to individuate the regions of "safety casting".

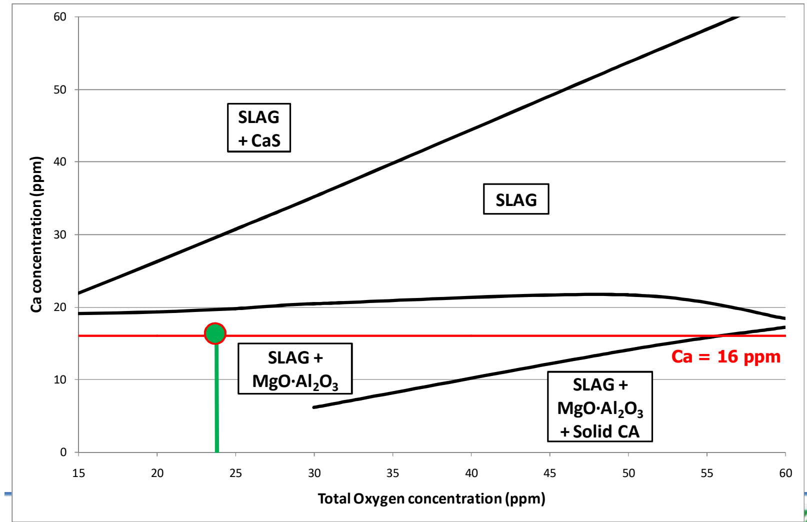
Application of computational thermodynamics to improve castability

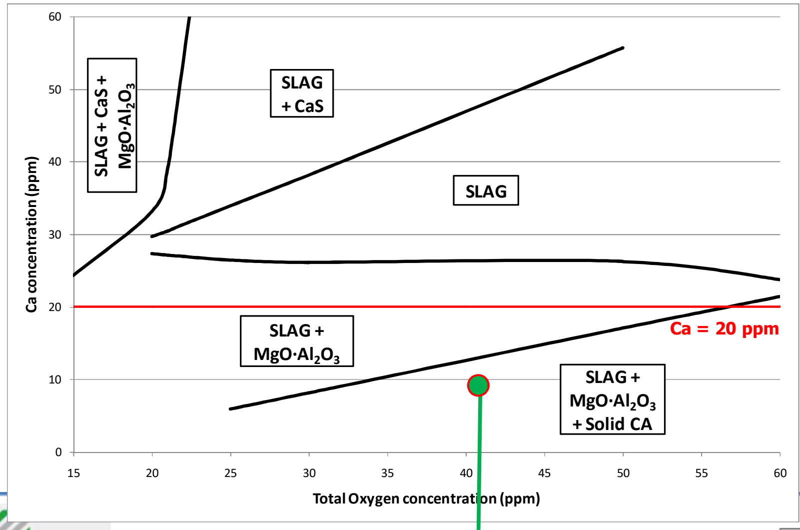
Good casting

Al	Ca	T.O. (ppm)
0.0315	0.0024	39
0.0281	0.0019	34
0.0334	0.0016	23
0.0338	0.0020	35





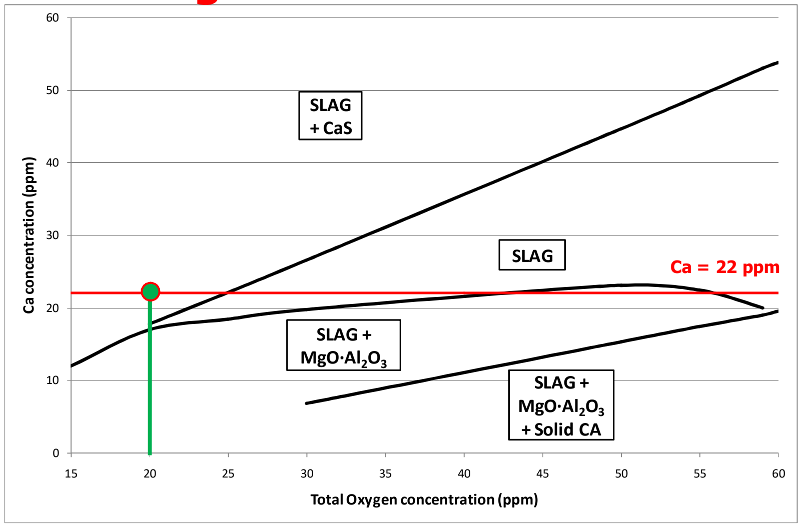


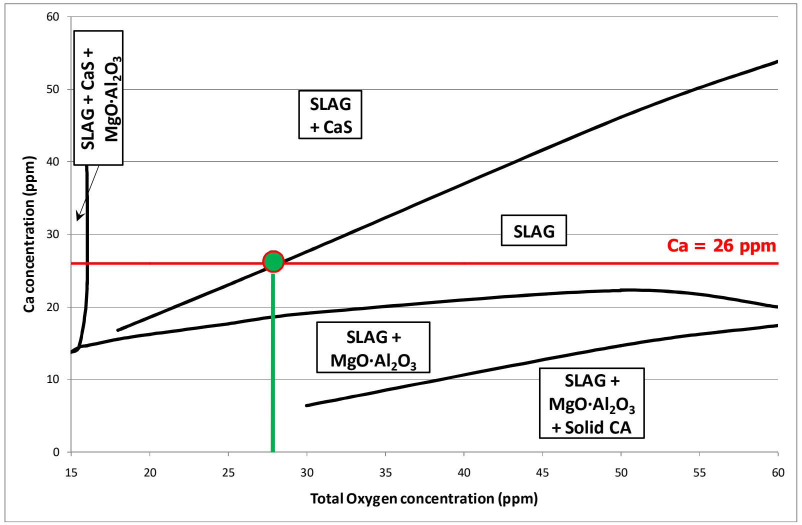


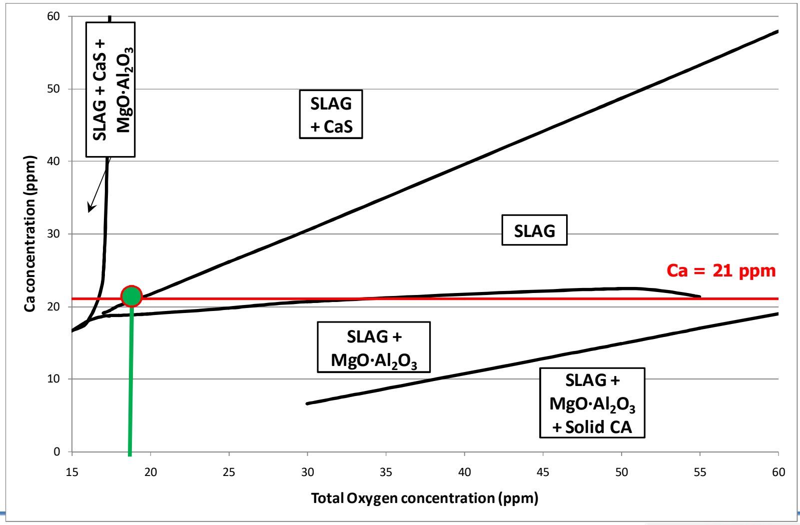
For the content of measured Ca and of calculated O_{tot} the inclusions present in the steel at the measured T are slag (liquid inclusions) and spinel $MgO·Al_2O_3$.

Application of computational thermodynamics to improve castability

Bad casting





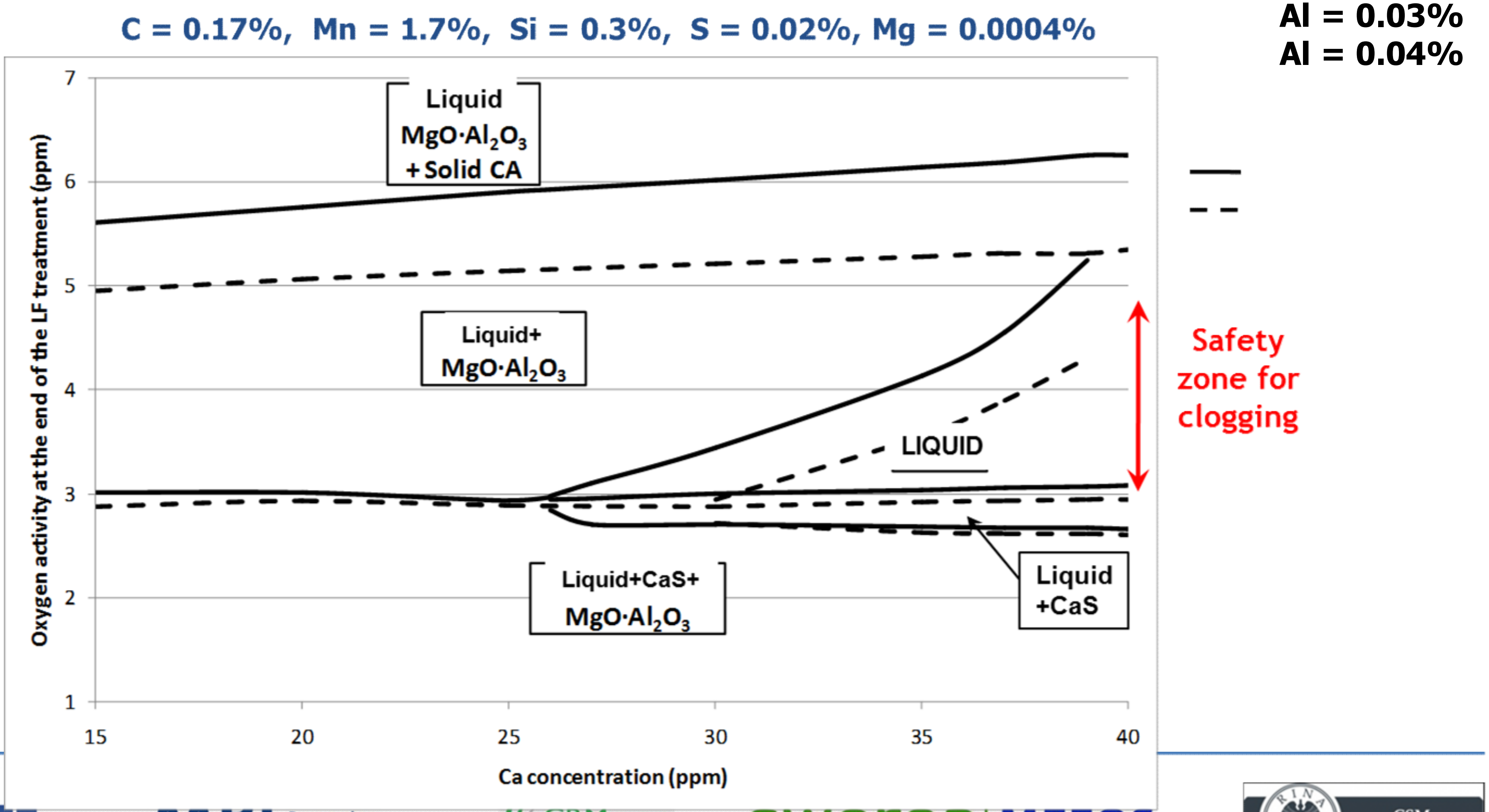


Al	Ca	T.O. (ppm)
0.0352	0.0022	**20**
0.0316	0.0026	**28**
0.0370	0.0021	**19**

For the content of measured Ca and of calculated O_{tot} the inclusions present in the steel at the measured T are slag (liquid inclusions) with CaS.

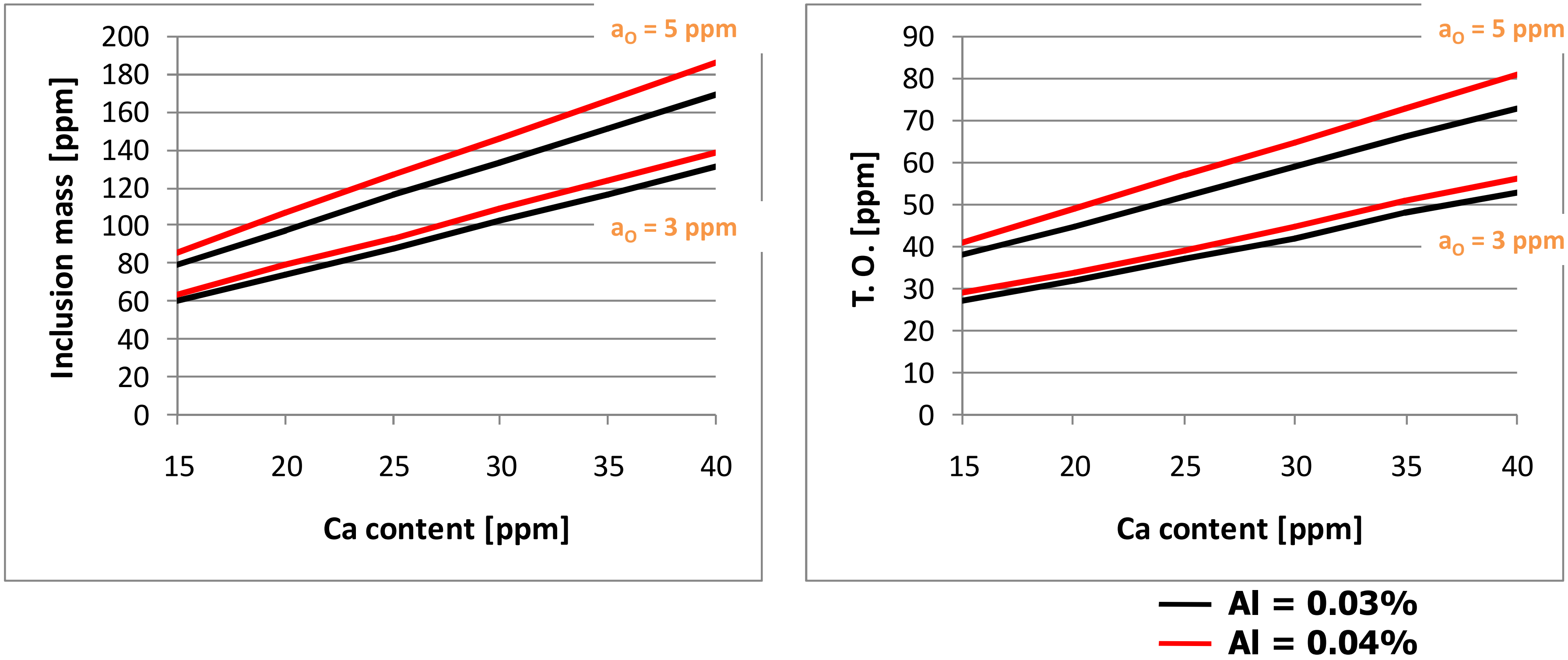
Application of computational thermodynamics to improve castability

Maps of adequate Ca addition as a function of concentration of dissolved O measured in liquid steel to avoid CaS formation have been calculated.



Application of computational thermodynamics to improve castability

In the graphs below the inclusion mass and the total oxygen concentration are calculated at increasing values of Ca content for a_O = 3 ppm and a_O = 5 ppm (range of safety to prevent clogging) and for total Al = 0.03 % and 0.04 %.



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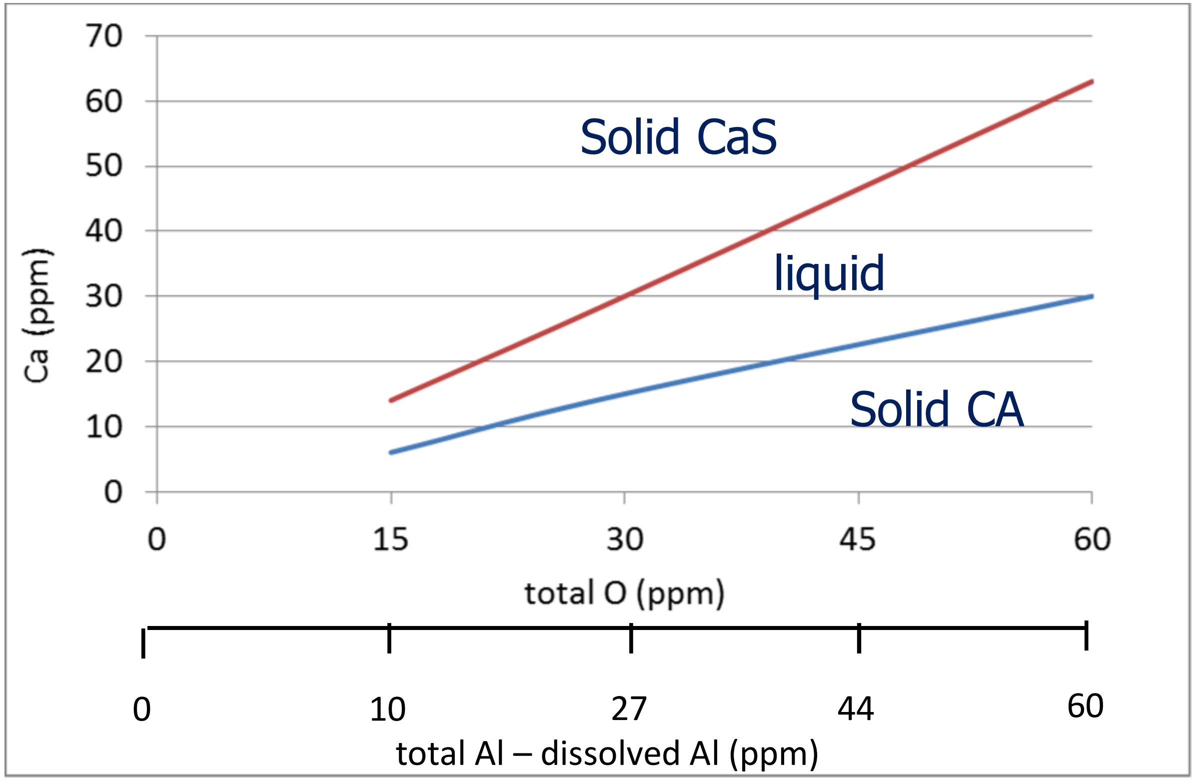
Application of computational thermodynamics to improve castability

The map can be built using different combination of input, depending on the measurements available on the plant. In this case (different steel grade and steel plant) the difference between total and dissolved Al concentration is used.
This difference is representative of the concentration of total inclusion.

Steel: Si 0.45%; Mn 1.5%; Al 300 ppm; S 100 ppm; Temp 1600 °C



This diagram indicates the windows available for a proper transformation of alumina inclusions into fully liquid aluminates without CaS precipitation in liquid steel.
It is evident that for low concentration of oxygen the window is narrow.

Little amount of inclusions implies more precise amount of Calcium.

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Concluding remarks

Formation of undesired CaS inclusions is a common problem for steels containing sulfur.
Computational thermodynamics is an important technique for inclusion engineering and can be successfully used to solve the problem.

The big advantage in comparison with conventional simplified systems (such as binary or ternary diagrams) is that the most of the species present in the steel (often all the relevant species) can be taken into account, individuating precisely the good composition regions for the steel of interest.

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

Inclusion formed during steelmaking operations in ladle and tundish and during solidification are transformed in defects after rolling operations.

The prediction of occurrence, size and harmfulness of defects, using information from the ladle and tundish is difficult, also because fatal defects can be caused by rare large inclusions, not easy to detect.

The ability to get information during steelmaking operations, and before rolling, on the probability to generate defects would give an added value to the inclusion analysis from steel samples, giving the opportunity to rate the quality of a particular heat and to make decisions consequently.

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

The idea of the INCLUSION project [*] 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

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

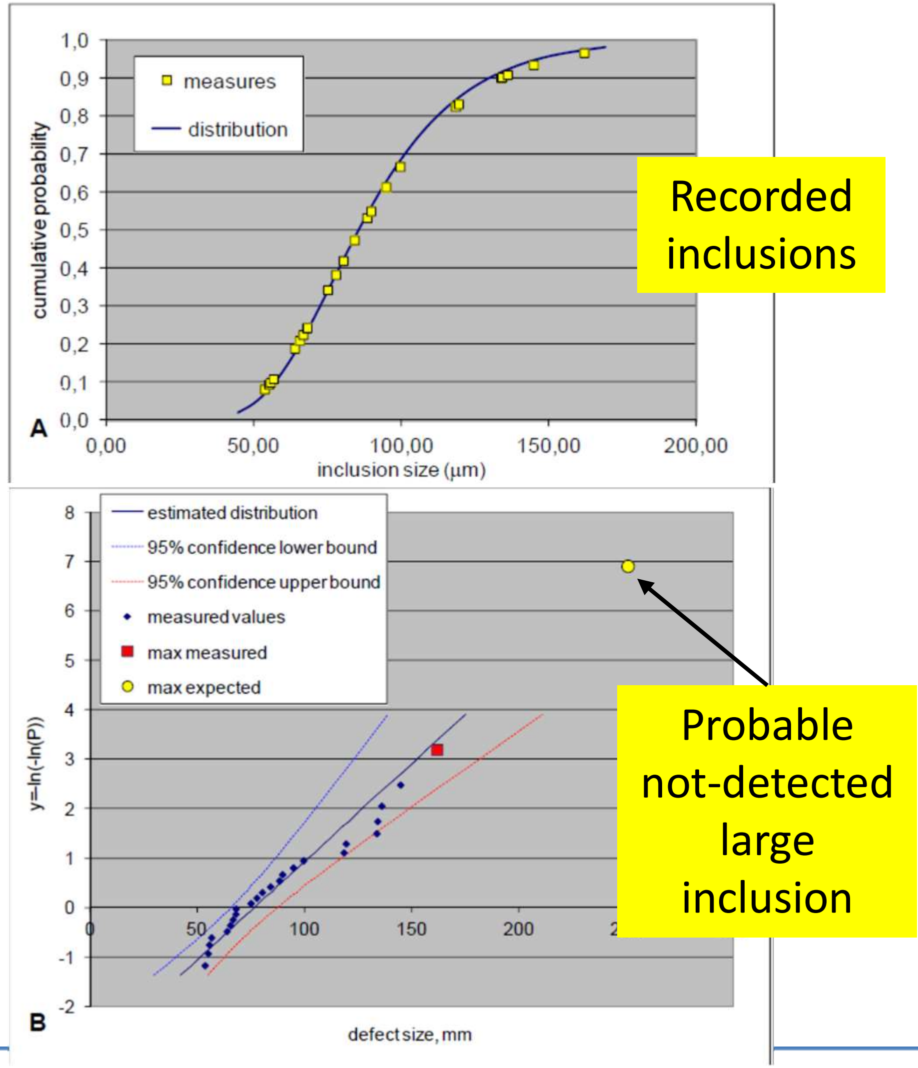
Application of statistical techniques and model of inclusion transformation for rapid decision making

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

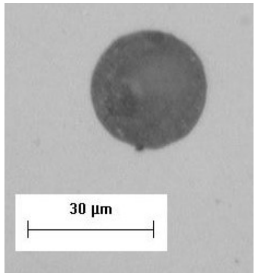
Evolution of inclusions in defects

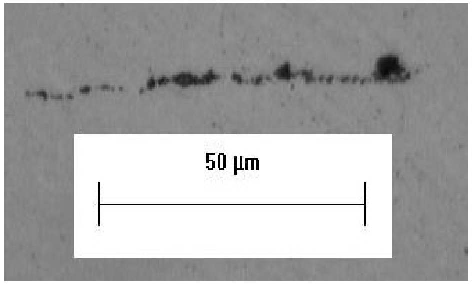
During rolling inclusions present in the final liquid and as cast products, are transformed in defects.

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

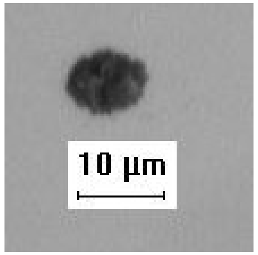
As cast | Rolled

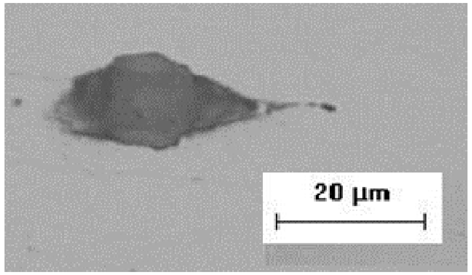
Plastic inclusion:
Liquid inclusions
SiO_2-MnO rich
Re-oxidation products



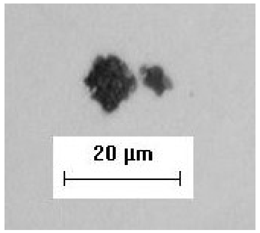


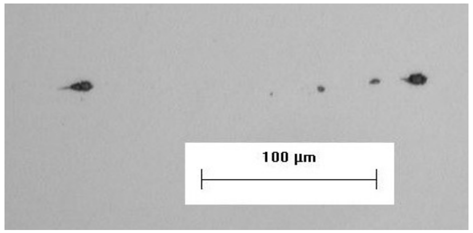
Multiphasic inclusions:
with solid phases like
MgO·Al_2O_3, CaS precipitates





Rigid inclusion:
clusters of Al_2O_3 small particles





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Model of inclusion transformation during rolling

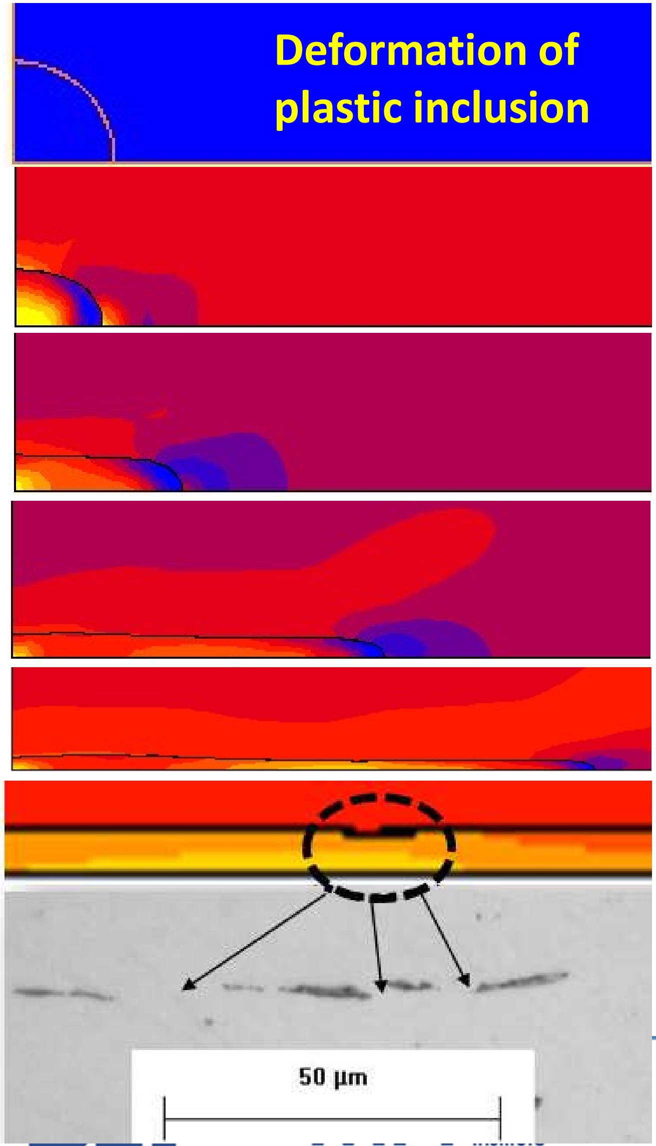
A mathematical model of the model of the deformation of the inclusion during the rolling of the steel product has been developed, based on the rheological properties of steel and inclusion and rolling conditions.

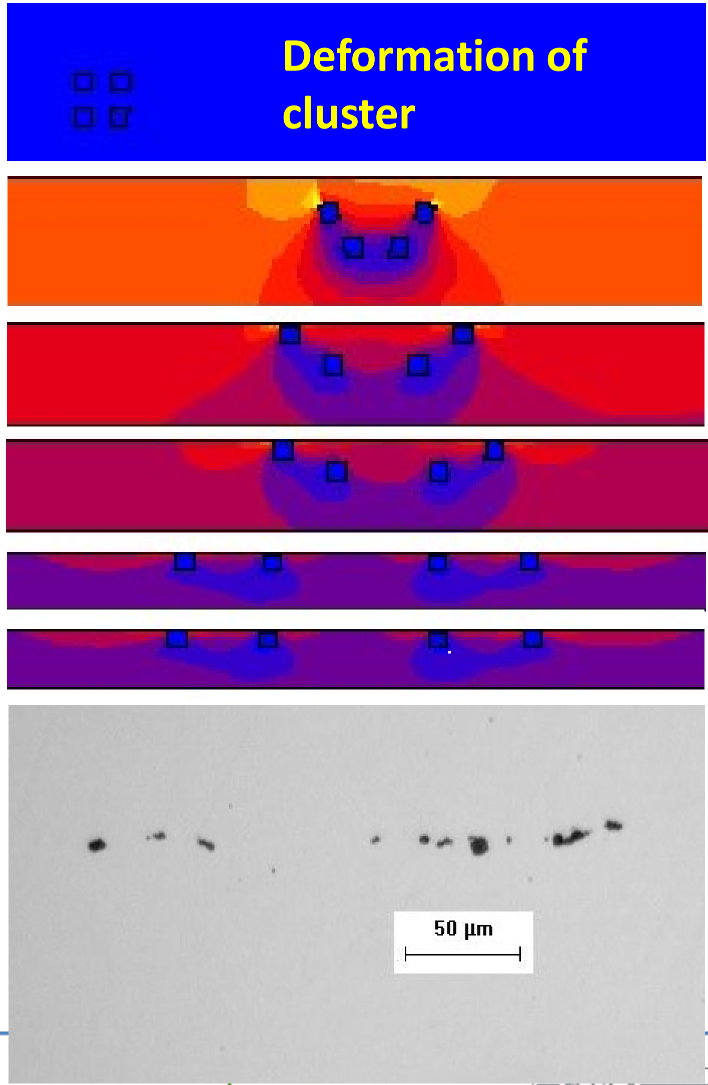
The model predicts the size of the final defects from the characteristics of the original inclusion

Fragmentation during elongation (CAS)

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

Model of inclusion transformation during rolling

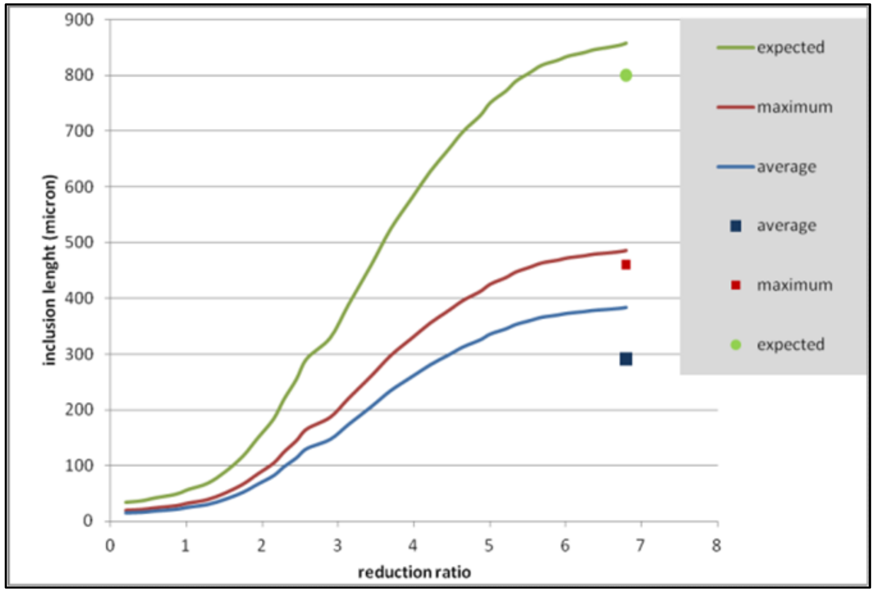


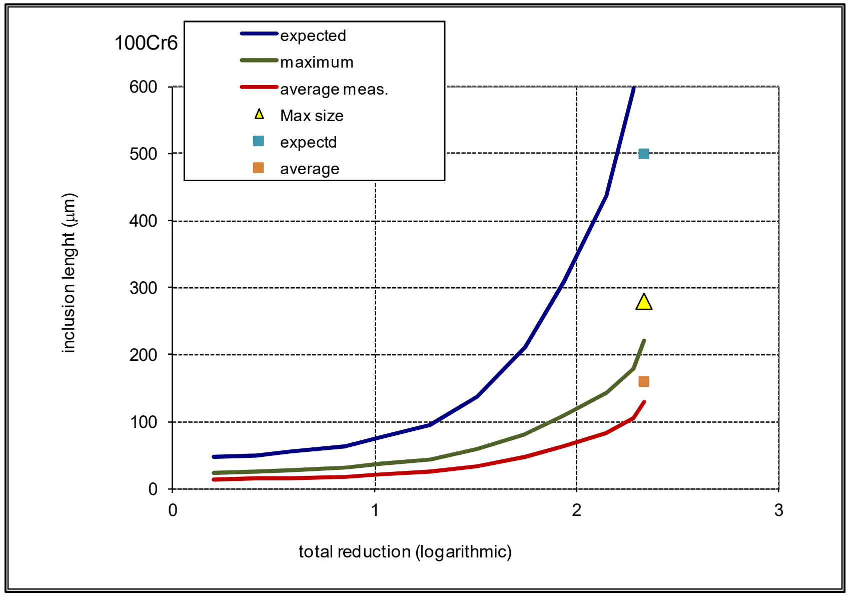


Application of statistical techniques and model of inclusion transformation for rapid decision making

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 defects 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 statistics allows to individuate probable big inclusions, causing big defects, using relatively rapid analysis of 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.

Conclusions

- In the European steel industry there is an increase of the production of quality steel, at more and more stringent requirements, and an enlargement of the spectrum of produced steel grades, together with the increase of the variability of raw materials.
- The consequence is that the control of cleanliness must be continuously re-tailored, taking into account needs of productivity and product quality, which can vary drastically for different steel grades and from heat to heat, in a flexible way and with an integrated vision. This requires the application of modern and powerful tools to understand complex situation in a rapid way.
- The large number and the quality of the European researches on secondary steelmaking technology made available a huge knowledge and validated mathematical techniques.
- A further effort is still necessary to consolidate these achievements in industrial routine applications and to continue the improvement to win the future challenge for the European steel industry.

Thank you

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