USING AI MODELS TO MOULD DESIGN, PREDICT SEGREGATION, POROSITY AND CET ZONE IN STEEL INGOTS

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The goal of this work was to describe the AI models employed to design the ingot shape, asses segregation, porosity and CET (columnar to equiaxial transition) zone in steel ingots.

To predict A-segregation, porosity and CET area have been used geometric, analytical and numeric models that take into account the ingot shape, steel chemical composition, material properties, and ingot cooling conditions. The results we obtained by simulation have been compared to sulfur print, cut ingots and laboratory data to calibrate these models and verify the results.

Several examples will show how to use the proposed models in ingot mould design, optimization of steel chemical composition, and analysis of pouring variables that may help both to improve the internal quality of steel ingots and to choose the right ingot size and shape for a particular material.

KEYWORDS: SEGREGATION – POROSITY – CET – INGOT – MOULD – SOLIDIFICATION – IA – AI

AI MODELS EMPLOYED IN INGOT MOULD DESIGN AND SOLIDIFICATION ANALYSIS

Ingot And Mould Design

Ingot and Mold Design Assistant [1] is a software tool based on several geometric models that allow to design ingots and moulds using minimum data such as ingot and hot top weight, height and ingot diameter ratio, ingot taper, number of sides. These models quickly generate ingot and mould projects for round, rectangular, polygonal conventional or hollow ingots and makes available instantly 2D drawings and 3D files. In Fig.1, there are several examples of 3D ingots and moulds generated by AI geometric models.



Fig.1 - Ingot and moulds generated by AI geometric models

A-Segregation Prediction Model

To predict the A-segregation, we developed a model that takes into account the cooling rate, ε and the solidification rate, R calculated by the simulation software [2] and α [3, 4], established experimentally, the critical value at which the A-segregation occurs. The following relation has been used:

$$\varepsilon \bullet R^{1.1} \leq \alpha$$

In this relation, if the first term is bigger than the critical value α, there will be no segregation; if it is lower than the value α, the A-segregation will occur and its intensity depends on the difference between local $\varepsilon \bullet R^{1.1}$ and critical value α. In Figure 2 is presented the flowchart of technique we have developed to model the A-segregation in steel ingots. In this flowchart there are two branches:

- the left branch calculates, by simulation, the cooling and solidification rate. This branch, that has as input data the ingot geometry, material properties and pouring data, calculates the cooling and solidification rate;
- the other branch calculates, using the chemical composition, the critical value α, the value at which the A-segregation will occur.

Then, the software compares the values we obtained from both branches and plots the segregation area in regions that contain values below the critical value. Here, we have two situations:

1. in the first case, if the first term of the relation is bigger than the critical value α, as seen in the bottom left side example, we do not have segregation;
2. in the second one, if the first term is lower than the critical value α, we will have A-segregation and its intensity depends on the difference between local $\varepsilon \bullet R^{1.1}$ and critical value α.

To asses quantitatively the influence of various variables on A-segregation, we have defined the parameter Rs, the ratio between area affected by A-segregation and the longitudinal section area of the ingot body.

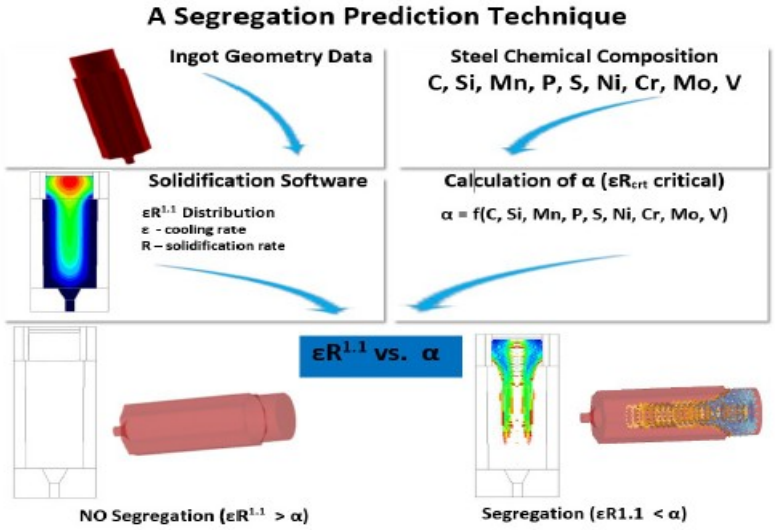


Fig.2 - A-segregation prediction technique

Moreover, because in controlling the A-segregation not only is important the area size of segregation but also the size and distribution of the segregates inside the segregation area. Therefore we defined the parameter Is, Intensity of A-segregation, as the difference between the critical value α and local $\varepsilon \bullet R^{1.1}$.

The calculation of critical value α, has been validated using both data published in various technical papers [5, 6, 7, 8] and in industrial conditions with several companies using the results of ultrasonic test for over 50 ingots with weights between 5 to 220 tones. The validation of segregation prediction technique has been made with the sulphur print of a 20 tone carbon steel cut hollow ingot [9, 15], as well.

Porosity Prediction Model

Shrinkage porosity in forging ingots is one of the most common defects in steel ingots and one of the reasons, besides A-segregation, why the manufacturer has to choose the right ingot size, shape and technology to improve the internal soundness of the ingot.

A porosity distribution map will help the technology designer to choose the right casting parameters to avoid shrinkage defects in steel forging ingots. The most employed method to predict the porosity area size and its location is the following Niyama criterion:

$$Ny = \frac{G}{\sqrt{\varepsilon}} < 1$$

Ny - Niyama value
G - thermal gradient
ε - cooling rate

Based on this relation, we have developed the porosity prediction technique presented in Fig.3. In this figure there are two branches:

- the left branch calculates by simulation the temperature gradient and cooling rate; it has as input data pouring parameters, the material properties and ingot geometry taken from ingot mold design software;
- in the right branch is the Niyama critical value (established experimentally) at which the porosity occurs; for low alloyed steels this critical value is 1.0.

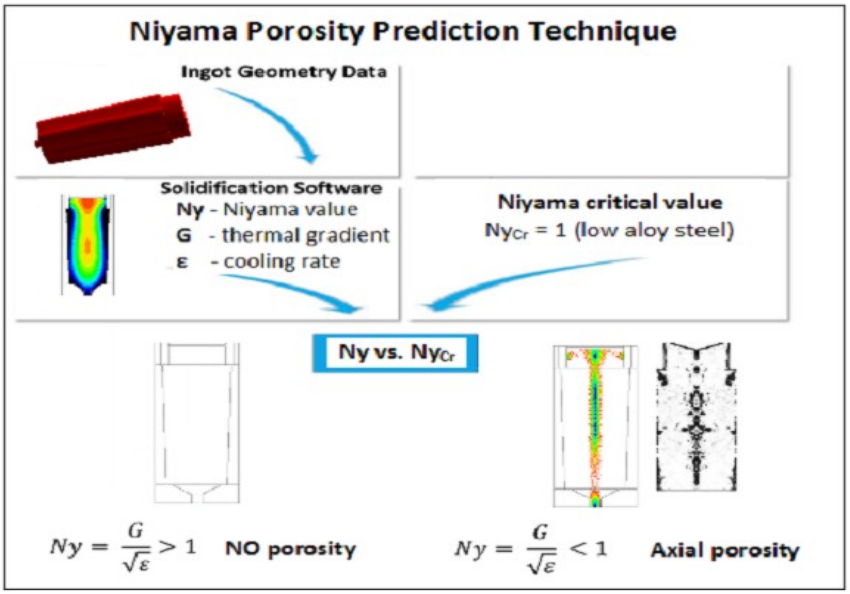


Fig.3 - Porosity prediction technique

Then, the analysis software compares the values from both branches and plots the area where shrinkage porosity occurs. Here, there are two situations:

1. in the first case, if the first term of equation is lower than the Ny critical value, there will not be porosity;
2. in the second one, if the first term is bigger than the Ny critical value, the shrinkage porosity occurs.

To quantitatively appreciate the influence of various variables on porosity, we use in solidification analysis the parameter Rp (porosity area ratio), the ratio between area affected by porosity and the longitudinal section area of the ingot body. The simulation software has been validated using our experimental data and results published in [5, 6, 7]. The value of Niyama criterion and porosity module of the software have been calibrated and validated using a cut ingot [10].

Columnar to Equiaxial Transition - CET Prediction

To predict the columnar to equiaxial transition (CET) structure distribution, the following rewritten Hunt criteria for CET prediction has been employed:

$$\alpha_1 < G/V^{0.5} < \alpha_2 \qquad \alpha_1 = \beta_1 N_o^{1/3} C_o \left\{ \frac{8m(k-1)\Gamma}{D} \right\}$$

β_1 = constant for columnar structure

β_2 = constant for equiaxed structure $\qquad \alpha_2 = \beta_2 N_o^{1/3} C_o \left\{ \frac{8m(k-1)\Gamma}{D} \right\}$

V = dendrite velocity, No = nuclei density,
G = temperature gradient, k = distribution coefficient,
Co = alloy composition, D = liquid diffusion coefficient and
m = liquidus slope, Γ = Gibbs-Thomson parameter.

Based on these relations, we have developed the CET prediction technique presented in Fig.4. In this figure there are two branches:

- the left branch calculates by simulation the temperature gradient and solidification rate, and has as input data pouring variables, material properties and ingot geometry taken from ingot design software [1];
- the right branch calculates, using the chemical composition, the critical values α1 and α2 at which the columnar to equiaxial transition starts and ends, respectively.

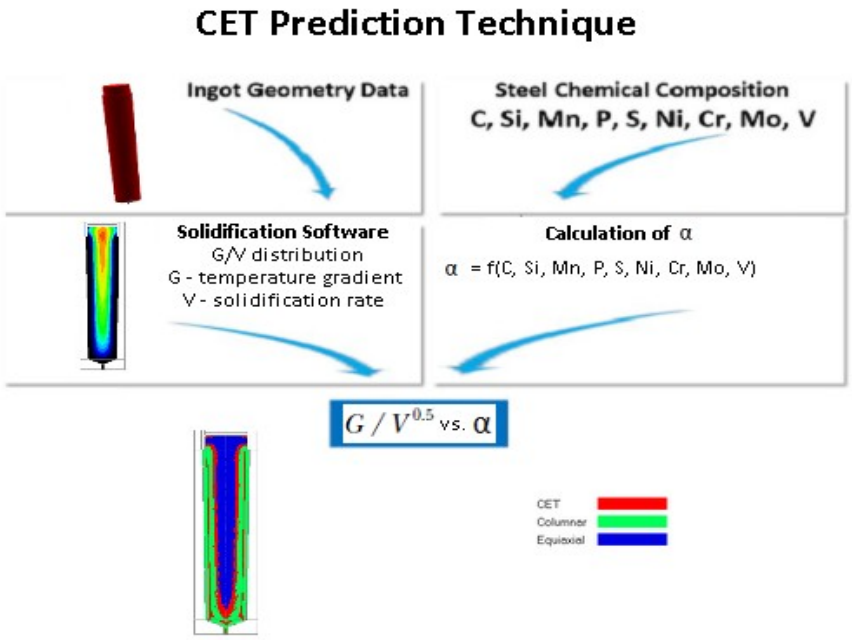


Fig.4 - CET zone prediction technique

Then, the analysis software compares the values from both branches and plots the columnar, equiaxed and CET area. Here, there are three regions:

1. in the first case, if the solidification rate is lower than the critical value α1, the columnar structure will occur;
2. in the second one, if the solidification rate is bigger than the critical value α2, there will be equiaxed structure;
3. if the solidification rate is between critical value α1 and α2, the CET structure will occur.

To quantitatively appreciate the influence of various variables on CET position, we use in our analysis the parameter DCET, the distance from the ingot surface at which the CET zone starts.

To assess the constant values in our CET prediction model, the results published in [11] for a 100kg experimental ingot have been used. The validation of the CET prediction technique has been made with the results published in [12] for a roll ingot.

EXAMPLES OF USING AI MODELS IN MOULD DESIGN AND TECHNOLOGY OPTIMIZATION

Ingot and mould shape optimization

Choosing Ingot H/D Ratio

In Fig.5 is shown the effect of ingot H/D (Height/Diameter) ratio on A-segregation in a 20T 4340 steel ingot. In this case, if we choose an ingot with high H/D ratio, the A-segregation is avoided.

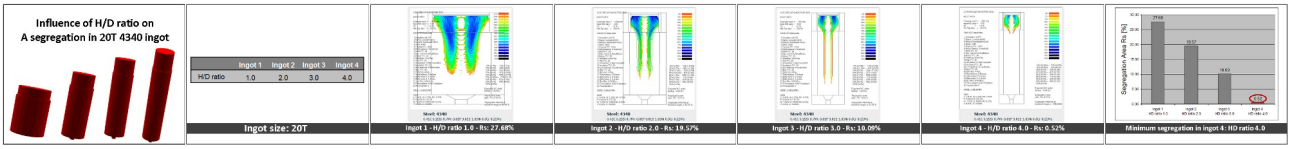


Fig.5 - Effect of H/D ratio on A-segregation

Conventional or hollow ingot

If we need a ring type final product, the A-segregation can be avoided by choosing a hollow ingot as seen in Fig.6. In the same figure is shown the axial porosity as well.

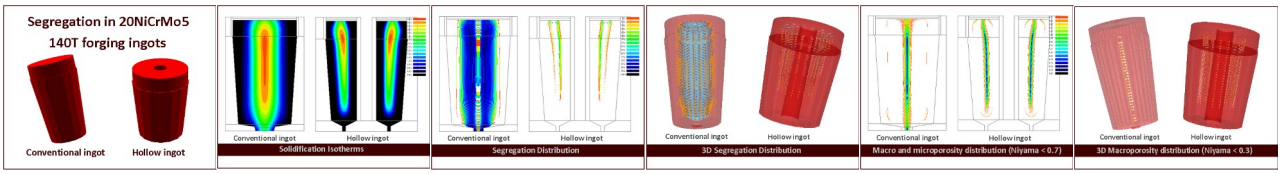


Fig.6 - A-segregation and axial porosity in conventional and hollow ingots

Polygonal or flat ingots

A comparison between A-segregation in 20T 42CrMo4 steel polygonal and flat ingots is shown in Fig.7. The A-segregation can be avoided if we choose a flat ingot with sides ratio 2.0.

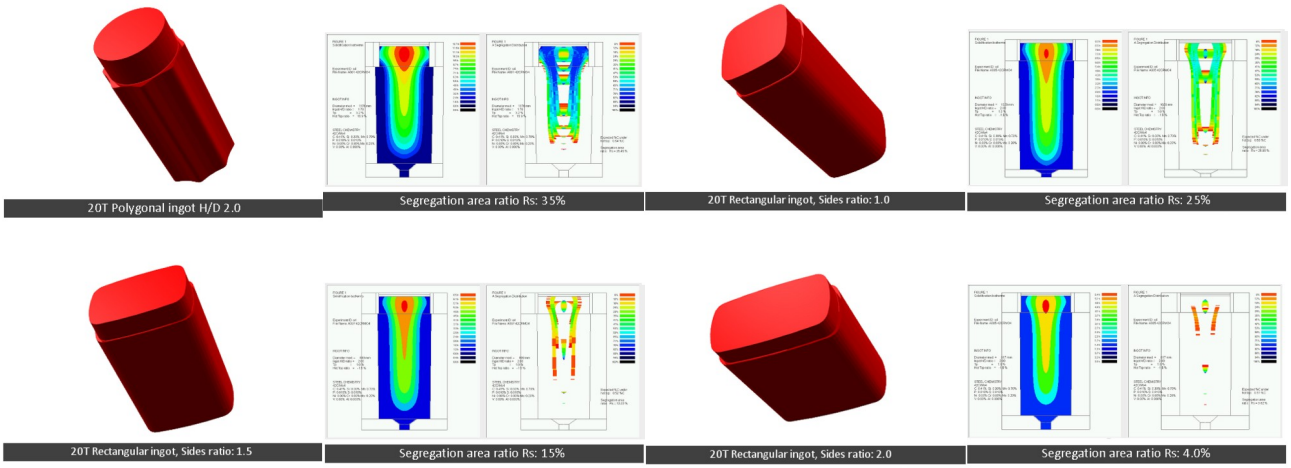


Fig.7 - A-segregation in 20T 42CrMo4 polygonal, rectangular and flat ingots

Optimization of chemical composition

Choosing Carbon content

In Fig.8 is shown the effect of %C content on A-segregation in a 60T 4340 steel ingot. This figure shows that the segregation area is slightly lower in the ingot with lower %C content [13].

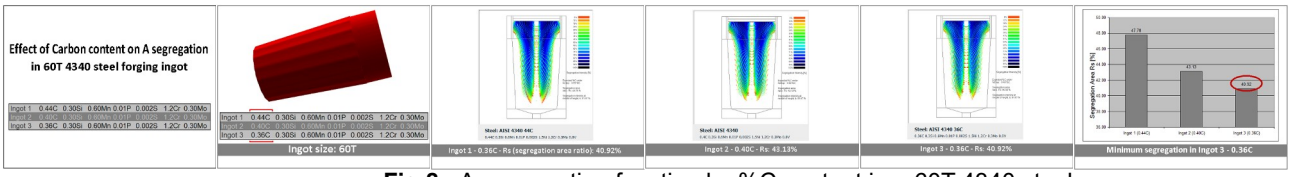


Fig.8 - A-segregation function by %C content in a 60T 4340 steel

Silicon content

The effect of %Si on A-segregation in a 60T 4340 steel ingot is shown in Fig.9. The area affected by segregation decreases significantly by lowering %Si content. Therefore, using a steel with a low Si content, the material will be more homogeneous [13].

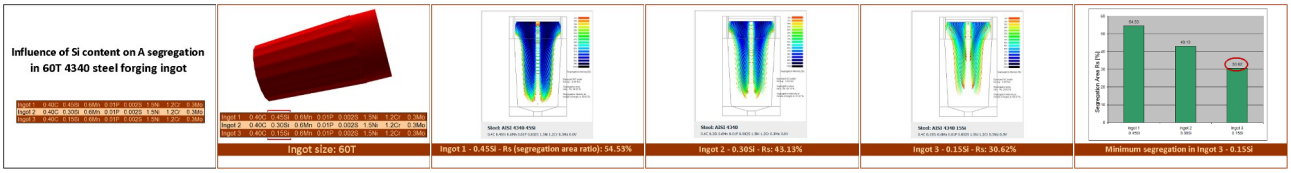


Fig.9 - A-segregation function by %Si content in a 60T 4340 steel

Molybdenum content

Fig.10 shows how the %Mo content affects the A-segregation distribution in a 60T 4340 steel ingot. As we see in this figure, the segregation area is lower in ingots with high %Mo content (13).

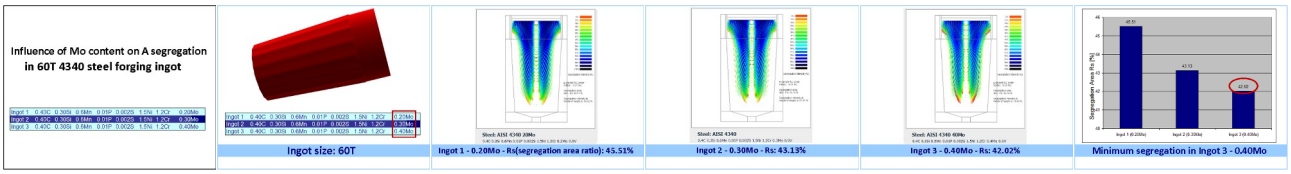


Fig.10 - A-segregation function by %Mo content in a 60T 4340 steel

Optimization of pouring variables

Pouring temperature

Effect of pouring temperature on A-segregation in a 20T 42CrMo4 steel ingot is in Fig.11. This figure shows that a low pouring temperature has a limited effect on A-segregation but a high pouring temperature may help inclusions removal [14].

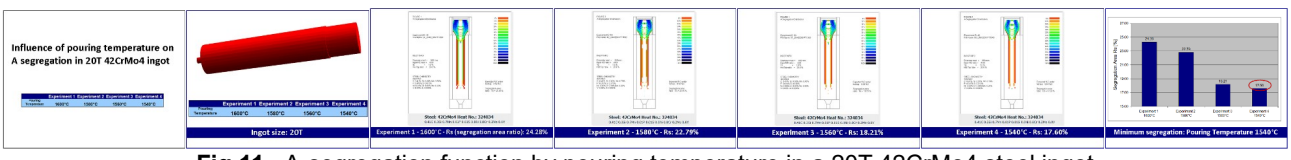


Fig.11 - A-segregation function by pouring temperature in a 20T 42CrMo4 steel ingot

Hot top size

Fig.12 shows the influence of hot top size on A-segregation in a 20T 42CrMo4 ingot. As we see in this figure, by using a small hot top, the A-segregation area will be smaller. Moreover, a small hot top size comes with lower energy and material consumption [14].



Fig.12 - A-segregation function by hot top size in a 20T 42CrMo4 steel ingot

Exothermic material

Influence of hot top exothermic material on A-segregation in 20T 42CrMo4 steel ingot is in Fig.13. This figure shows that the exothermic material has effect only on hot top function; it does not have influence on A-segregation area size [14].

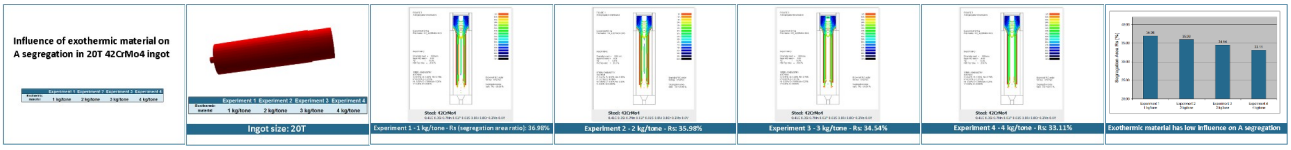


Fig.13 - A-segregation function by hot top exothermic material in a 20T 42CrMo4 steel ingot

Columnar to Equiaxial Transition (CET) Structure Prediction

An example of using the CET structure prediction model for a 100kg experimental steel ingot is in Fig.14.

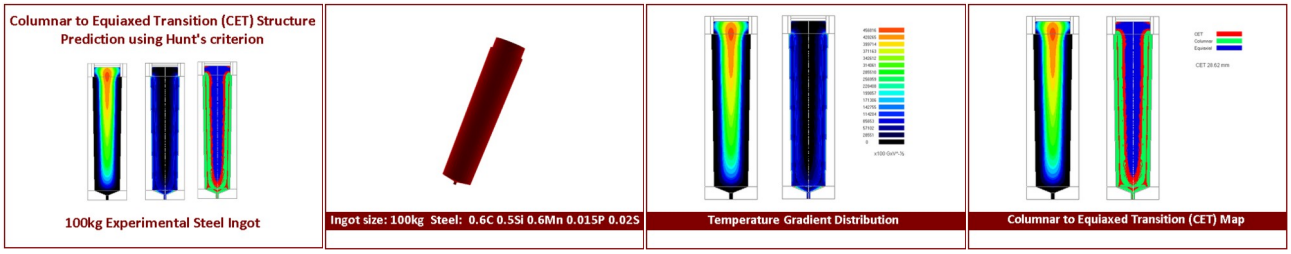


Fig.14 - Solidification isotherms, temperature gradient and CET prediction in a 100kg steel ingot

Using AI Models to Generate Handbooks and Catalogues

In Fig.15 is an example of a handbook generated by the AI models presented in this paper. This handbook comes with over 200 short solidification analysis reports that show solidification isotherms, A-segregation maps, axial porosity maps and Carbon segregation in the V-segregation area [16].



Fig.15 - Handbook of Steel Ingot Solidification generated by AI models

CONCLUSIONS

Using these models may help with avoiding the A-segregation by choosing an ingot with high HD ratio, a hollow or a flat ingot function by the final product shape, size and steel grade.

If the A-segregation can not be avoided, the models may help to increase the steel homogeneity by optimizing the Si and Mo content.

Also, these models can be useful to reduce materials and energy consumption by optimizing, for example, the hot top size and pouring temperature or reducing the time needed to prepare a new project or improve an existing technology.

Very soon a very big solidification reports database will be available to AI developers to generate handbooks, catalogues or create applications to answer questions concerning the ingot manufacturing process or to choose a supplier for a particular ingot size or steel grade.

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