Porosity and A-Segregation Prediction in Hollow Ingots for Large Forgings

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Abstract

Macro-segregation in forging ingots has adverse effects on the quality of the final product and is one of the reasons why forgers have to choose the ingot function by both forging part shape and steel type to get a low cost, save time and energy, and improve the internal quality of the part.

The goal of this work is to analyze comparatively axial porosity and A-segregation in carbon and several low alloyed steels poured in conventional and hollow ingots in order to avoid or reduce internal defects in pressure vessel or ring type forgings with high-quality requirements.

An integrated online mold design and the solidification simulation software SimCADE v.2.0 has been utilized to simulate the solidification process and model the porosity and A-segregation appearance. The data from the simulation has been calibrated and validated using sulfur print of cut conventional and hollow ingots with weights between 20 and 140 tons.

The results of the experiments we made show that the material homogeneity of pressure vessels or ring type forgings can be drastically improved if we choose the hollow ingots instead of conventional ingots, no matter the steel type.

Key Words:

segregation, segregation area, segregation intensity, ingot, mold, casting variables, chemical composition, solidification, simulation, SimCADE 2.0, mold design, Ingot Mold Design Assistant v.1.0

1 Introduction

The internal defects that can affect the quality of steel ingots include porosity and, as shown in Figure 1 [1], primary and secondary pipe, positive segregation, negative segregation, V-segregation, and A-segregation. From all these types of defects, our comparative analysis is focused on porosity and A-segregation.

Macrosegregation type, commonly known as A-segregation, presents channels enriched by sulfur, carbon, and phosphorus and is one of the factors that has a critical impact on the mechanical properties of the final forging product and is one of the reasons why the forged product can be rejected at the ultrasonic test.

A-segregation forms in the zone of columnar grains at the regions with structures characterized by the transition from the columnar to large equiaxed grains and is often accompanied by porosity.

This defect occurs due to the shrinkage process during phase transformation combined with a simultaneous redistribution of impurities in the two-phase zone during the solidification process. The main cause of A-segregation is the relative movement of segregated liquid during solidification. Most elements have a lower solubility in solid than in liquid phase, as is shown by phase diagrams. During the solidification process, the solutes are rejected into the liquid phase, leading to a continual enrichment of the liquid and lower concentrations in the primary solid. By this mechanism, the size of A-segregation may be, by solidification conditions and ingot size, from several millimeters to centimeters or even meters as shown in sectioned ingots [2], [3], [4], and Figure 2 [5]. Because of the low diffusion of the solutes in the solid state and the large distances involved, macro segregation cannot be removed after the solidification is completed.

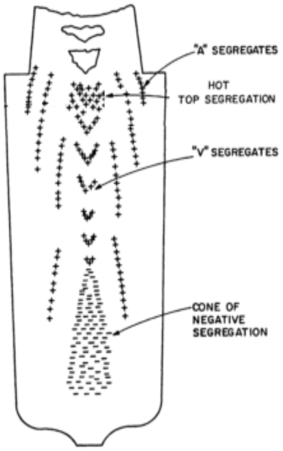


Figure 1: Macrosegregation in steel ingots [1].

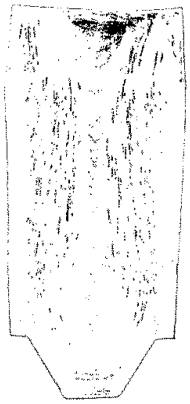


Figure 2: Sulfur print in cut ingots [5]

2 Analysis Tools

In order to comparatively analyze the internal integrity of the ingots, we employed an online tool to design molds for both conventional and hollow ingots, the solidification simulation software SIMCADE v.2.0, to simulate the solidification process and criteria relations to evaluate the conditions at which the porosity and A-segregation begin to occur.

2.1 Ingot and Mold Design

Ingot and Mold Design Assistant v.1.0 [6] is an online tool based on a mathematical model that allows you to design ingot and molds using minimum data such as ingot weight and ingot shape defined by H/D ratio, taper, and number of sides. This tool can generate quickly ingot and mold projects for conventional and hollow ingots having round, rectangular, or polygonal section and makes available instantly 2D drawings and 3D models and prepares the geometrical data needed by SimCADE v.2.0, the solidification simulation software.

In Figure 3, there are several examples of 3D models generated by online Ingot Mold Design Assistant.

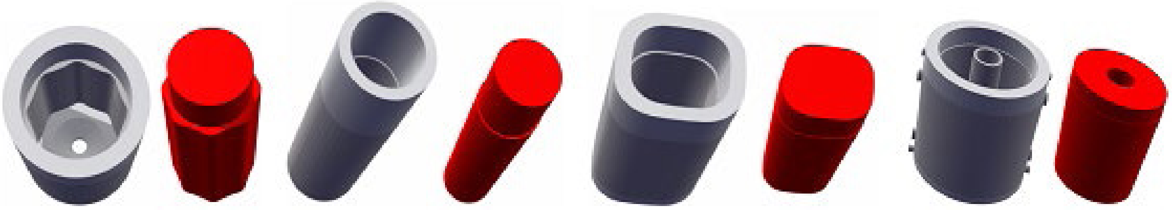


Figure 3: Ingot and molds generated by online Ingot Mold Design Assistant.

2.2 Solidification Simulation Software

The solidification simulation software, SimCADE v.2.0 [7], takes into account the material properties, internal sources and their variation with temperature, heat exchange with the environment, insulation, and exothermic materials.

The software uses over 160,000 finite elements to get an accurate geometrical description of the model. The needed time to compose the problem and get the results is about 30 seconds for one step and around 20 minutes to complete one numerical experiment and display results, see Figure 4.

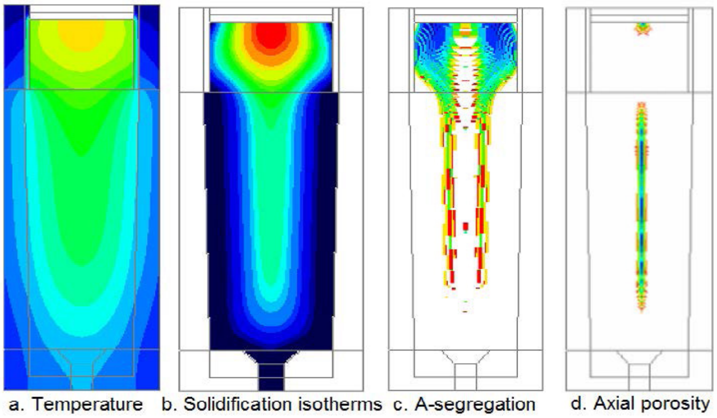


Figure 4: Data generated by simulation software SimCADE v.2.0.

2.3 Segregation Prediction Technique

The segregation in the columnar zone is much influenced by the cooling and solidification rate. To define the A-segregation occurring conditions, K. Suzuki and T. Miyamoto [5] proposed the following equation, based on solidification rate R (mm/mm) and cooling rate ε (°C/min):

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

K. Suzuki and T. Miyamoto have investigated at Muroran Research Center, The Japan Steel Works Ltd., (JSW) a 0.7 % carbon steel and obtained $\alpha = 8.75$, the critical value of A-segregation appearance; the value α is experimentally established and depends strongly on chemical composition.

Using laboratory experimental data we have developed a mathematical model to evaluate and establish the critical value α, the value at which the A-segregation starts to appear. The model takes into account the solidification limits, change in density of solutes at the solidification front, and the chemical composition of the steel (C, Si, Mn, P, S, Ni, Cr, Mo, and V).

At the moment, our mathematical model is applicable to Cr-Mo, Ni-Mo, Ni-Cr-Mo-V, Mn-Ni-Mo, and carbon steels. More experiments must be done to cover other steels.

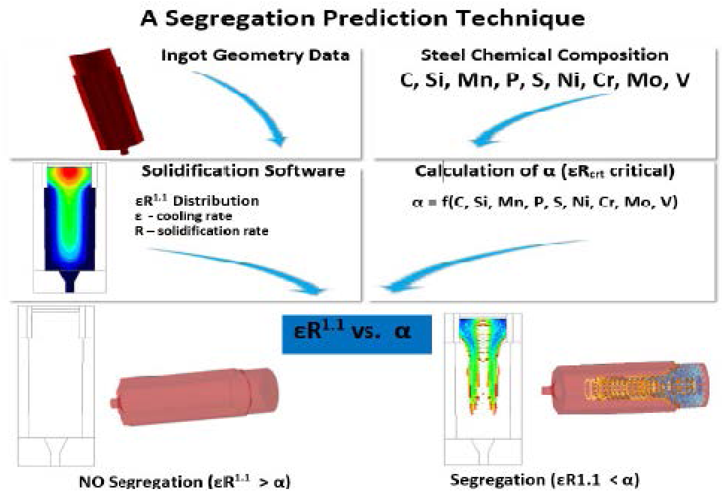


Figure 5: A-segregation prediction technique.

Figure 5 presents a flowchart of the technique we developed to model the A-segregation in steel ingots. In this flowchart, there are two branches. The left branch calculates the cooling and solidification rate via simulation. This branch has as input data the ingot geometry taken from online Ingot and Mold Design Assistant v.1.0 and calculates using SimCADE v.2.0's cooling and solidification rate. Using the chemical composition, the other branch calculates the critical value α, the value at which the A-segregation will appear. Then, the software compares the values we got from both branches and plots the segregation area in regions that contain values below the critical value.

Here, we have two situations: in the first case, if the solidification rate is bigger than the critical value α, as seen in the bottom left side example, we do not have segregation; in the second one, if the solidification rate 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.

The solidification simulation software and the mathematical model for temperature calculation has been validated using experimental data published in [8], [9], [10], and [11].

The calculation of critical value α has been validated using both data published in various technical papers ([13], [14], [15], [16], [17], and [18]) and in industrial conditions with several companies using the results of ultrasonic test for over 50 ingots with weight between 5 to 220 tones. In this analysis, to quantitatively appreciate 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.

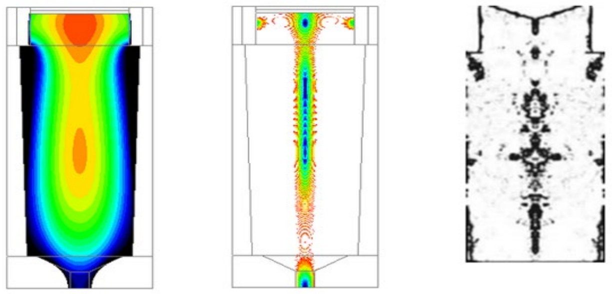
More, as remarked in paper [19], because in controlling the A-segregation not only the area of segregation but also the size and distribution of segregates inside the segregation area is important, we defined the parameter Is, Intensity of A-segregation, as the difference between the critical value α and local $\varepsilon \bullet R^{1.1}$.

2.4 Porosity Prediction Technique

Shrinkage porosity in heavy forging ingots is one of the most common defects and is one of the main reasons, besides macrosegregation, why the manufacturer has to choose the right technology parameters to improve the internal soundness of the ingot.

To predict the porosity area size and its location, we employed the Niyama criterion, the most common criterion for porosity prediction in steel ingots.

The value of Niyama criterion has been calibrated and validated using a cut ingot [20], as seen in the figure below:



a. Solidification isotherms b. Axial porosity c. Axial porosity in cut ingot [20]

Figure 6: Axial porosity comparison between simulation and 8T cut ingot.

3 Results and Discussion

From the parameters that usually have influence on the segregation process in this work, we are focused on the effect of using hollow ingots on A-segregation in ingots having weights between 20 and 140T poured in various steel types.

In order to assess the porosity and A-segregation level in hollow ingots in comparison with conventional ingots, for every series of two experiments we kept the same ingot weight, chemical composition, and all other pouring variables, and we applied Niyama criterion for porosity and Suzuki-Miyamoto criterion for A-segregation to predict the internal quality of the analyzed ingots.

Tables 2 and 3 are the boundary conditions and the thermal data of the materials in all performed experiments.

	Air Temperature °C	*Heat Transfer Coefficient W/m°K*	*Thermal Flux kW/m^2*
Mold	24	45	-
Steel Frame	24	45	-
Hot top insulation	24	45	-
Hot top exothermic	-	-	2600

Table 2: Boundary conditions between mold assembly and environment

Material	*Conductivity W/mK*	*Specific Heat J/kgK*	*Density kg/m^3*	*Latent Heat kJ/kg*
Steel	30.0	680	7800	270
Mold	50.0	695	7100	-
Insulation powder	1.0	900	2200	-
Steel Frame	30.0	680	7800	-
Insulation board	0.2	134	304	-

Table 3: Materials and thermal properties of materials used in simulation.

3.1 Porosity and A-Segregation in 20T Conventional and Hollow Carbon Steel Ingot

To analyze the effect of using hollow ingots for pouring 20T carbon steel ingots, two experiments have been performed. One experiment considered a conventional 20T H/D ratio 1.5 ingot and the other one a 20T hollow ingot with 500mm core diameter and 1800mm height. The chemical composition of the analyzed steel in both experiments is shown in Table 4.

	C	Si	Mn	P	S
Carbon steel	0.20	0.29	0.96	0.014	0.012

Table 4. Chemical composition of analyzed carbon steel ingot

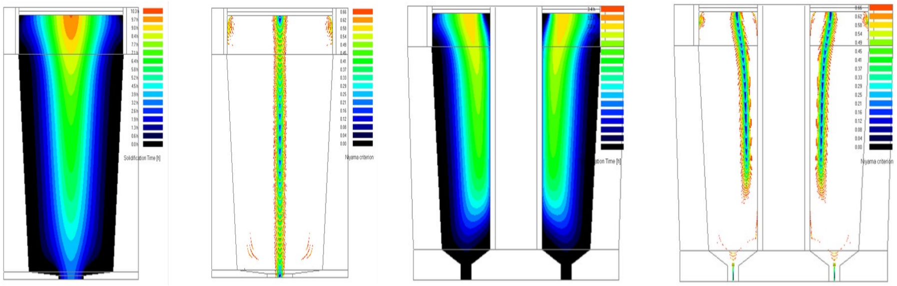
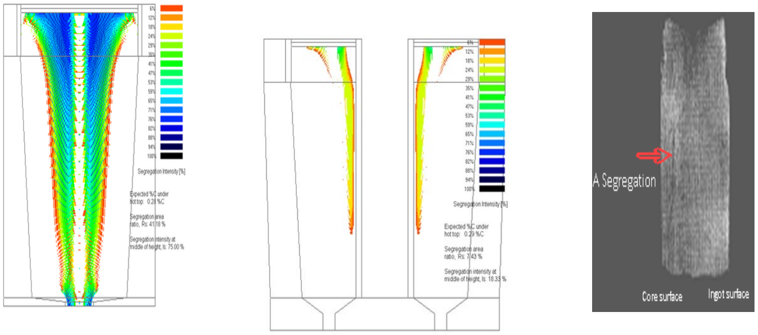

a) Solidification isotherms 20T Conventional ingot
b) Porosity prediction 20T Conventional ingot
c) Solidification isotherms 20T Hollow ingot
d) Porosity prediction 20T Hollow ingot

Figure 7: Axial porosity in 20T carbon steel conventional (a, b) and hollow ingot (c, d).

Solidification isotherms and axial porosity in both experiments are shown in Figure 7. In conventional ingot, the area affected by porosity placed at the center of the ingot is around 11%, and in the hollow ingot the porosity area placed close to the core surface is 13% from the ingot body area.



a) 20T Conventional carbon steel ingot b) 20T Hollow carbon steel ingot c) Sulfur print in 20T cut hollow ingot [21]

Figure 8: A-segregation in 20T carbon steel conventional (a), hollow ingot (b) and cut hollow ingot (c).

The A-segregation distribution in 20T carbon steel conventional and hollow ingot is in Figure 8. As we see there is a net difference between these two ingots in terms of both the A-segregation area size and segregation position. If the area affected by segregation in conventional ingot is around 75% from ingot body area, in hollow ingot the segregation area is just 18%. So, even if the segregation cannot be completely avoided, because the area affected by segregation is much smaller in 20T hollow ingot, a hollow ingot is highly recommended to forge a cylinder type forging. More, by improving the cooling condition in the core area, there are chances to avoid completely the A-segregation in this carbon steel hollow ingot.

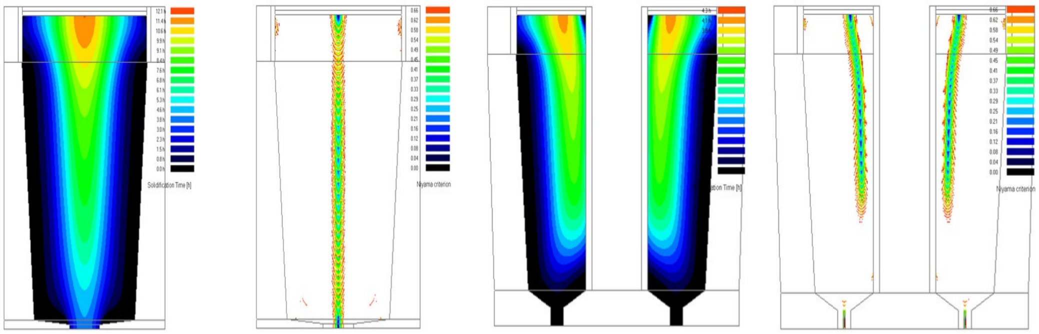
Figure 8c shows the sulfur print [21] of a 20T cut hollow ingot with the same size and chemical composition as the carbon steel hollow ingot in our experiment. Comparing the A-segregation position and size in the cut ingot with modeled A-segregation, Figure 8b, we notice a good agreement between simulation and experimental data.

3.2 Porosity and A-Segregation in 20T Conventional and Hollow Cr-Mo Steel Ingot

To put in evidence the effect of hollow ingots on porosity and A-segregation in Cr-Mo steel ingots, we conducted two experiments using ingots with the same size and pouring conditions as in the first series of experiments, changing only the poured material from carbon to Cr-Mo steel. The chemical composition of the analyzed steel taken into consideration in these experiments is displayed in Table 5.

	C	Si	Mn	P	S	Cr	Mo
Cr-Mo steel	0.29	0.30	0.38	0.011	0.004	2.05	0.96

Table 5: Chemical composition of analyzed Cr-Mo steel.



a) Solidification isotherms
20T Cr-Mo Conventional ingot

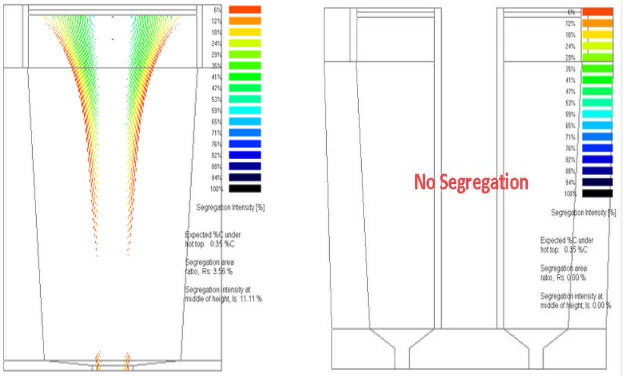
b) Porosity prediction
20T Cr-Mo Conventional ingot

c) Solidification isotherms
20T Cr-Mo Hollow ingot

d) Porosity prediction
20TCr-Mo Hollow ingot

Figure 9: Axial porosity in 20T Cr-Mo conventional (a, b) and hollow ingot (c, d).

As we see in Figure 9, there are very small differences, in terms of axial porosity, from the first series of simulations. In the conventional ingot, the area affected by porosity is around 9% (11% in first series of simulations) and around 11% in the hollow ingot (13% in previous experiments).



a) 20T Conventional ingot b) 20T Hollow ingot

Figure 10: A-segregation in 20T Cr-Mo steel conventional (a), hollow ingot (b).

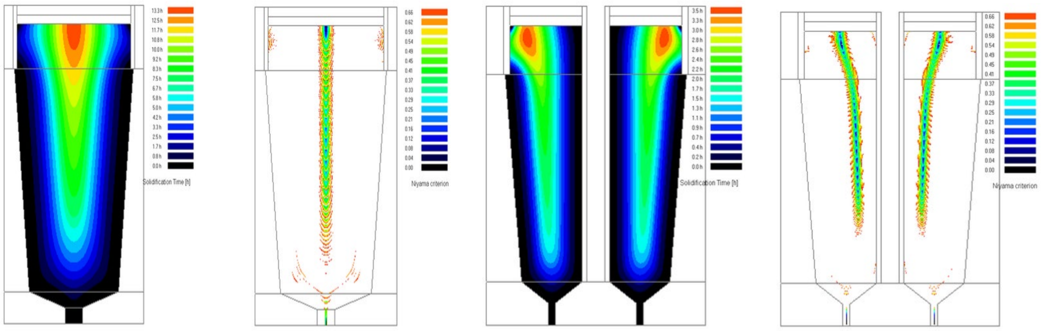
By changing the chemical composition of the steel from carbon to Cr-Mo steel, the segregation level is much smaller in both conventional and hollow Cr-Mo steel ingot than in the carbon steel ingot. Indeed, as we see in Figure 10, the area affected by A-segregation changes to 11% in conventional ingot (from 75.0% in carbon steel experiments) and to 0.0%—no segregation—(from 11% in first series of experiments). So, due mainly to the high Mo content and cooling conditions in the core area, the A-segregation in 20T Cr-Mo hollow ingot is completely avoided and the cylinder type forging will be free of A-segregation.

3.3 Porosity and A-Segregation in 45T Conventional and Hollow Ni-Cr-Mo Steel Ingot

In the following two experiments we analyze porosity and A-segregation in conventional and hollow SA508 Gr4N ingots, a common Ni-Cr-Mo steel employed to forge pressure vessels for nuclear components. One of the experiments considered a 45T conventional ingot and the other a 45T hollow ingot with 700mm core diameter and 2800mm height. The chemical composition of Ni-Cr-Mo steel taken as input data in these experiments is shown in Table 6.

Steel	C	Si	Mn	P	S	Ni	Cr	Mo
Ni-Cr-Mo	0.19	0.3	0.33	0.015	0.015	3.48	1.7	0.3

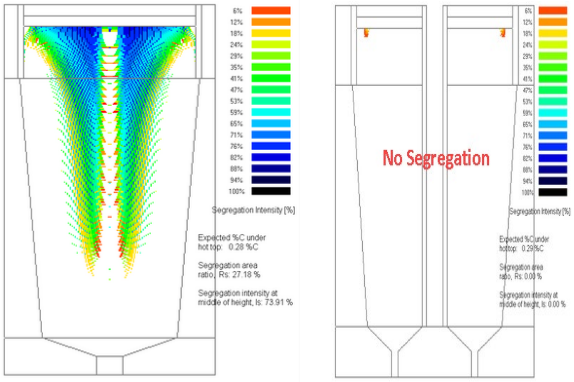
Table 6: Chemical composition of Ni-Cr-Mo analyzed steel.



a) Solidification isotherms 45T Conventional ingot
b) Porosity prediction 45T Conventional ingot
c) Solidification isotherms 45T Hollow ingot
d) Porosity prediction 45T Hollow ingot

Figure 11: Axial porosity in 45T Ni-Cr-Mo conventional (a, b) and hollow ingot (c, d).

The area covered by axial porosity does not change much by using hollow ingots. Indeed, there is a small increase of the area affected by porosity, from 8% in conventional ingot to 11% in the hollow ingot, as seen in Figure 11b and Figure 11d.



a) 45T Conventional ingot

b) 45T Hollow ingot

Figure 12: A-segregation in 45T Ni-Cr-Mo steel conventional (a) and hollow ingot (b).

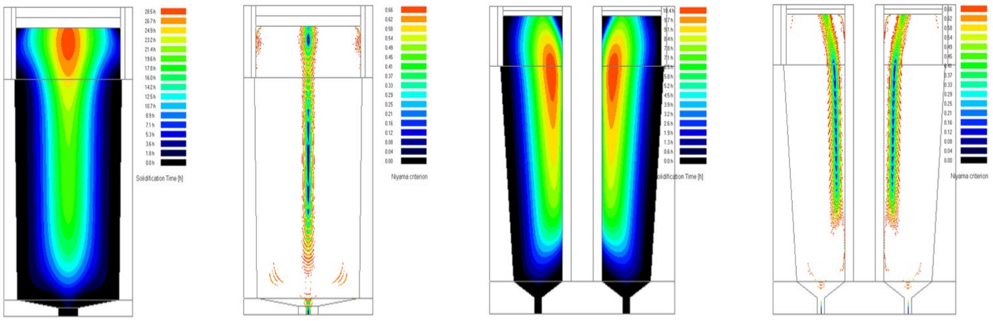
In terms of A-segregation, the area affected by segregation in 45T Ni-Cr-Mo conventional ingot is more than 27%, Figure 12a. Due to the low carbon, high molybdenum content and an increase of the solidification rate in the core area, the A-segregation in hollow ingot is avoided completely, Figure 12b.

3.4 Porosity and A-Segregation in 140T Conventional and Hollow Mn-Ni-Mo Steel Ingot

In the following two experiments, we assess the porosity and A-segregation in Mn-Ni-Mo steel ingots, another type of steel utilized to forge pressure vessels for nuclear components. One of the experiments considered a 140T conventional ingot and the other a 140T hollow ingot with 700mm core diameter and 3400mm height. The chemical composition of the Ni-Cr-Mo steel in these experiments is shown in Table 7.

Steel	*C*	*Si*	*Mn*	*P*	*S*	Ni	*Cr*	*Mo*
Mn-Ni-Mo	0.2	0.25	1.43	0.005	0.002	0.75	0.12	0.50

Table 7: Chemical composition of Mn-Ni-Mo analyzed steel.



a) Solidification isotherms 140T Conventional ingot

b) Porosity prediction 140T Conventional ingot

c) Solidification isotherms 140T Hollow ingot

d) Porosity prediction 140T Hollow ingot

Figure 13: Axial porosity in 140T Mn-Ni-Mo conventional (a, b) and hollow ingot (c, d).

In 140T Mn-Ni-Mo conventional ingot, the axial porosity area ratio is around 8%, Figure 13b, and 45% in the hollow ingot, Figure 13d.

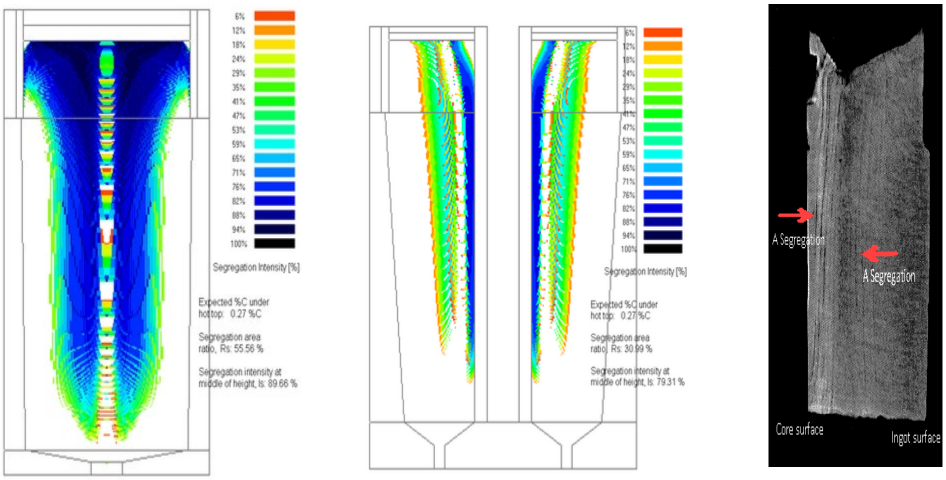


Figure 14: A segregation in 140T Mn-Ni-Mo conventional (a), hollow ingot (b) and cut hollow ingot (c).

Figure 14a and 14b show the result of A-segregation modeling in 140T Mn-Ni-Mo for both conventional and hollow ingots. In the conventional ingot, even if the Mo content is relatively high due to the size of the ingot, the A-segregation covers over 56% from the ingot body area. Due to the cooling conditions offered by the axial core, the A-segregation in hollow ingot is reduced to 31%. Figure 14c shows the A-segregation in a cut 140T Mn-Ni-Mo hollow ingot [20] with the same chemical composition and dimensions as in our experiment. We notice a good agreement between A-segregation prediction, Figure 14b, and the segregation observed in the hollow cut ingot.

4 Conclusions

The effect of hollow ingot on porosity and A-segregation in several ingot sizes and steel types has been analyzed in comparison with conventional ingots in order to assess the soundness of the cylinder type forgings. Figure 15 is a summary of axial porosity in all performed experiments and Figure 16 is the summary of A-segregation results.

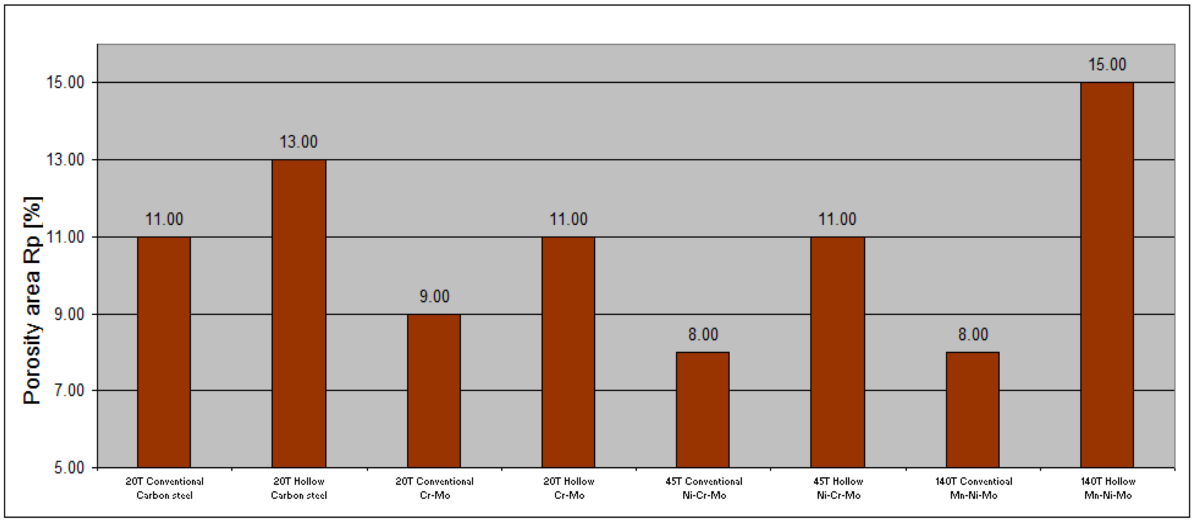


Figure 15: Summary of porosity area ratio in all performed experiments.

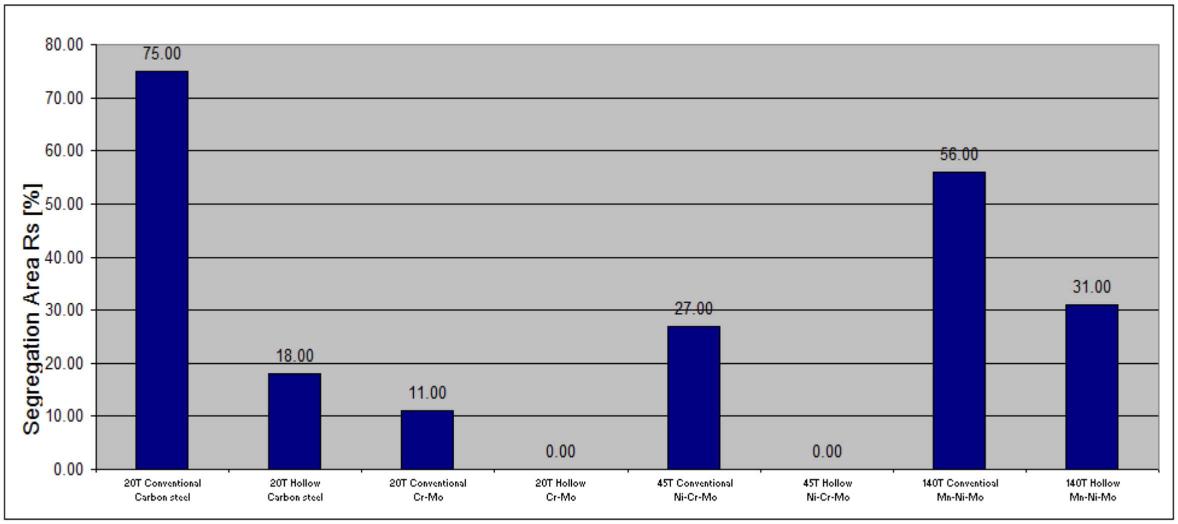


Figure 16: Summary of A-segregation area ratio in performed experiments.

With these results, we conclude the following:

- In conventional ingots, the area affected by porosity, placed at the center of the ingot, is between 8% and 11%; in hollow ingots the porosity area, placed close to the core surface, is between 11% and 15%; the porosity area is slightly bigger in hollow ingots
- In terms of both A-segregation area and segregation position, there is a net difference between conventional and hollow ingots. If the area affected by segregation in conventional ingots is between 75% and 18% for carbon steel and Cr-Mo steel, respectively, in the case of hollow ingots, the segregation area ratio is between 31% and 0% function by steel type and ingot size
- Due mainly to the high Mo content and cooling conditions in the core area, the A-segregation in hollow ingots can be reduced substantially in 20T carbon steel and 140T Mn-Ni-Mo ingots and completely avoided in 20T Cr-Mo and 45T Ni-Cr-Mo ingots

Finally, if there are requirements for high-quality cylinder type forgings, using hollow ingot is a better solution to minimize or avoid the A-segregation type defect than the conventional ingots.

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