Optimization of ingot geometry, casting technology and chemical composition of a 20 tons 42CrMo4 ingot to minimize A-segregation and increase material homogeneity

Ovidiu Bogdan,
Industrial Soft, 341-5 Graham
Montreal, QC, H3P 2C7, Canada

Contact
Ovidiu Bogdan
Industrial Soft, 341-5 Graham
Montreal, Quebec, H3P 2C7, Canada
Phone: 514-3425833
Web: www.castingsnet.com
Email: bogdan@castingsnet.com

Abstract

Macrosegregation in forging ingots has adverse effects on the quality of final product and is one of the reasons why the ingot manufacturer has to choose the right technology parameters to get a cost effective product and save time, energy and improve the internal quality of the ingot.

The goal of this work was to choose the optimum ingot geometry, casting technology variables and chemical composition in order to avoid or reduce segregation and increase the homogeneity of a 42CrMo4 20 tons ingot.

An integrated mold design and the solidification simulation software SimCADE v.2.0 has been used to analyze the solidification and put in evidence the influence of ingot geometry (height/diameter ratio, hot top size, ingot taper), casting variables (pouring temperature, exothermic material) and chemical composition (C, Si, Mn, Cr, Mo) on the size and position of A-segregation area.

In the experiments performed, to get the area affected by segregation, cooling and solidification rate have been correlated with the A-segregation critical value calculated by macrosegregation module of the software, module based on the chemical composition of the steel and method proposed by K.Suzuki and T.Miyamoto.

To assess comparatively the influence of the analyzed variables we have defined two quantitative parameters: the A-segregation ratio Rs (ratio between area affected by segregation and the longitudinal section area of the ingot body) and A-segregation intensity Is (measures the difference between minimum value of cooling and solidification rate and A-segregation critical value).

The results of the experiments we made show that in this particular ingot the homogeneity of the material can be improved if we choose an ingot with high height/diameter ratio, low hot top size, low Carbon and Silicon and high Molybdenum content. The experiments done with various pouring temperatures, ingot taper, and various Mn or Cr content have low or no influence on the A-segregation.

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, as shown in Figure 1 [1], include primary and secondary pipe, positive segregation, negative segregation, V-segregation and A-segregation. From all these types of defects, in our analysis, we are focused on A-segregation.

Macrosegregation type commonly known as A-segregation, presents channels enriched by sulfur, carbon, phosphorus and is one of the factors that has a critical impact on the mechanical properties of the final forging product and 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 structure characterized by the transition from the columnar grains 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 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, function 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.

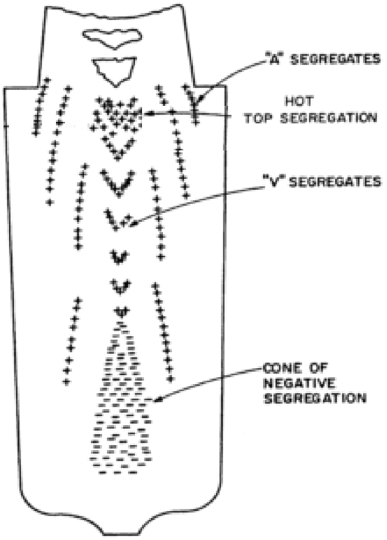


Figure 1 Macrosegregation in steel ingots [1]

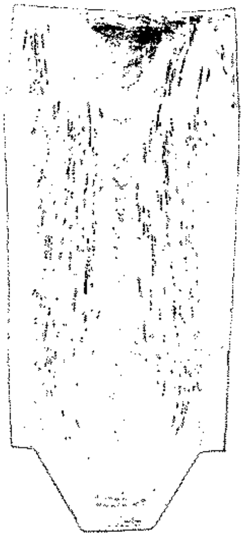


Figure 2 Sulfur print in sectioned ingots [5]

2 Analysis tools

In order to analyze A-segregation and optimize the ingot geometry, casting variables and chemical composition we have developed Ingot Mold Design Assistant v.1.0, the solidification simulation software SIMCADE v.2.0 and a mathematical model to evaluate the critical value at which the A-segregation begin to appear.

2.1 Ingot and mold design

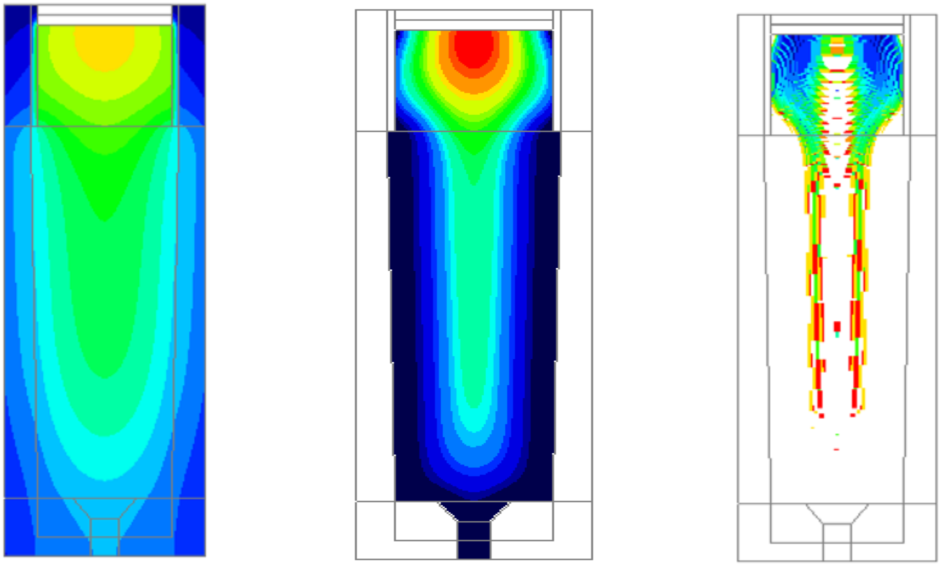
Ingot and Mold Design Assistant v.1.0 [6] is an online tool based on a mathematical model that allows to design both ingot and mold using minimum data such as ingot weight, ingot H/D, ingot taper, number of sides, etc. This tool can generate quickly ingot and mold projects having round, rectangular or polygonal section and makes available instantly 2D drawings, 3D models, and prepare 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.

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, thermo insulation, and exothermic materials.

Figure 3 Ingot and molds generated by Online Ingot Mold Design Assistant



a. Temperature distribution b. Solidification isotherms c. A-segregation distribution

Figure 4 Data generated by solidification simulation software, SimCADE v.2.0

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 min. to complete one numerical experiment and display results, Figure 4.

2.3 Mathematical model to evaluate the A-segregation appearance

Using laboratory experimental data we have developed a mathematical model to evaluate the solidification conditions and establish the critical conditions at which the A-segregation start 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 to be done to cover other steels.

2.4 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 experimental established and depends strongly by chemical composition.

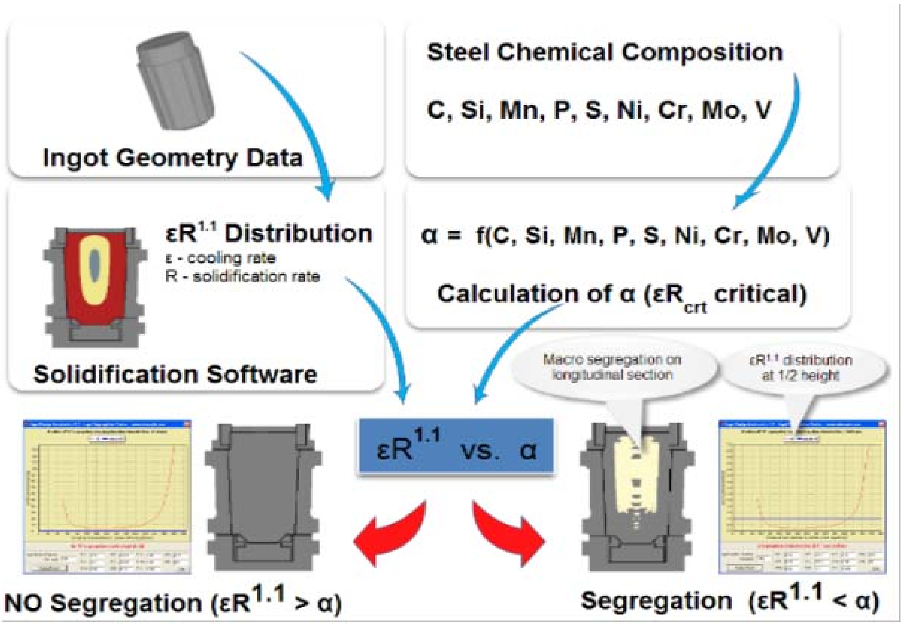


Figure 5 A-segregation prediction technique

In Figure 5 is presented the flowchart of technique we have developed to predict 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 taken from online Ingot and Mold Design Assistant v.1.0, calculates using SimCADE v.2.0 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 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], [11] and by our experiments made with Companhia Siderúrgica Paulista (COSIPA), Brazil and published in [12].

The calculation of critical value α, has been validated using both, data published in various technical papers [13], [14], [15], [16], [17], [18] and in industrial conditions with Doosan-IMGB using the results of ultrasonic test for over 50 ingots with weight between 5 to 220 tones.

In this report, 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.

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

3 Optimization of ingot geometry

To analyze the influence of ingot geometry on A-segregation the pouring temperature considered in these numerical experiments has been 1570°C; the other initial temperatures have been 20°C. The chemical composition of the 42CrMo4 steel that has been taken in consideration is presented in Table 1 and geometry data of the analyzed ingots is in Figure 6 and Table 2.

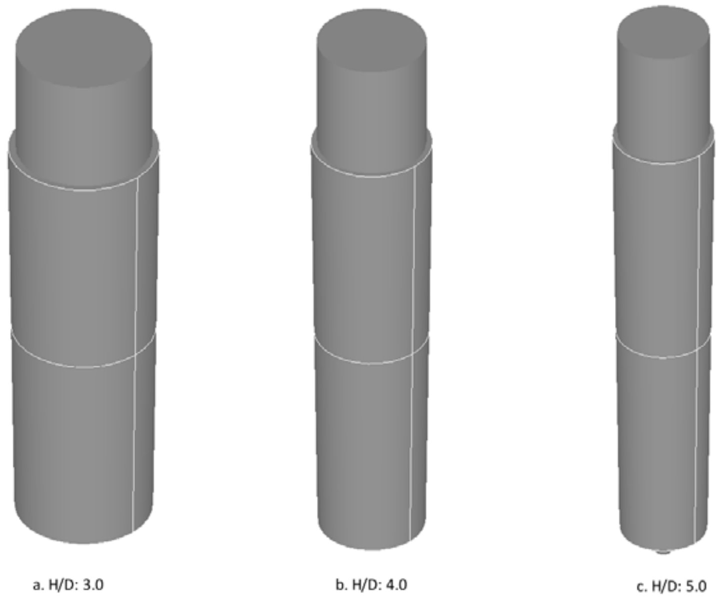


Figure 6 Geometry of the analyzed ingots

	C	Si	Mn	P	S	Cr	Mo
42CrMo4	0.41	0.30	0.70	0.01	0.01	0.80	0.20

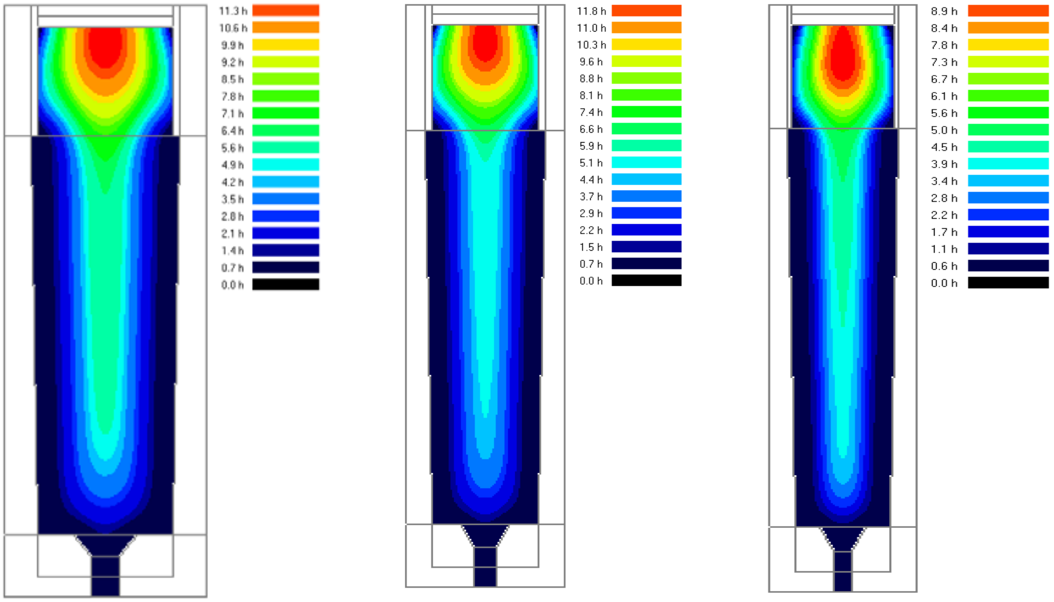
Table 1. Chemical composition of analyzed steel

Ingot ID	Ingot Weight	Body Weight	Hot Top	Ingot H/D
a	20T	16T	20.0%	3.0
b	20T	16T	20.0%	4.0
c	20T	16T	20.0%	5.0

Table 2. Size of the ingots analyzed

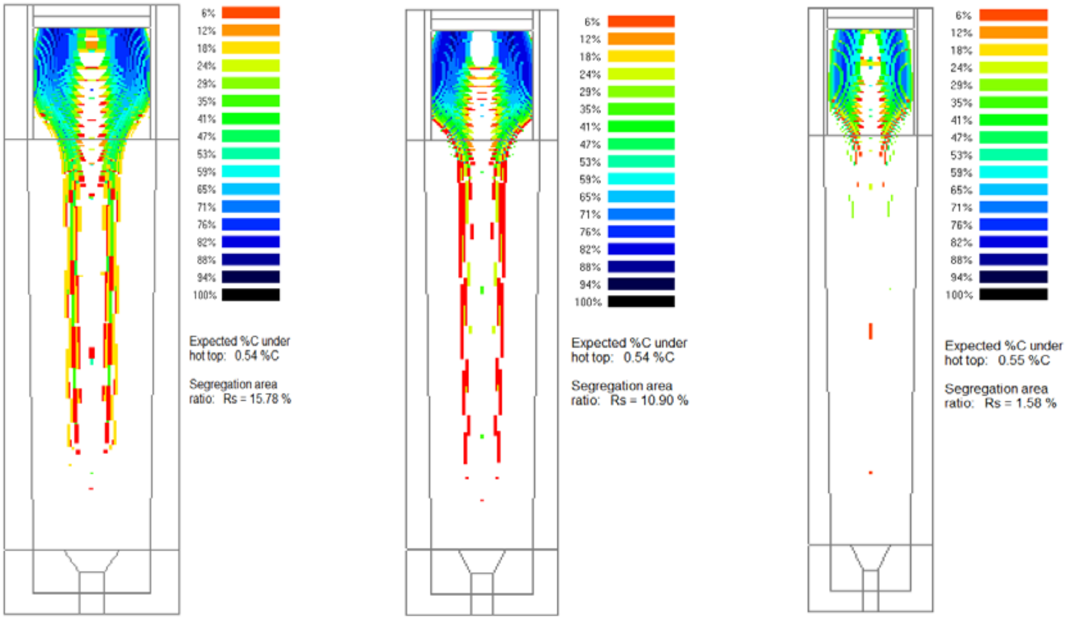
3.1 Influence of H/D ratio on A-segregation

To analyze the influence of ingot height/diameter (H/D) ratio on segregation we made three simulations with ingots having H/D ratio 3.0, 4.0 and 5.0, Figure 6. The solidification isotherms and the segregation distribution in these ingots are presented in Figure 7 and 8.



H/D: 3.0 H/D: 4.0 H/D: 5.0

Figure 7 Solidification isotherms for 3.0, 4.0 and 5.0 H/D ingot ratio



H/D: 3.0 H/D: 4.0 H/D: 5.0

Figure 8 Segregation area function by H/D ratio

In these experiments, the Rs value, the ratio between A-segregation area and ingot body section area, decreases from 15.78% to 10.9% and 1.59%. The value of segregation intensity Is, decreases from around 40% to below 4%. Because the segregation area size is much smaller if the ingot H/D ratio is 5.0 it is highly recommended using this ingot for pouring the 42CrMo4 steel. Indeed, the ingot H/D ratio has been identified by multiple authors [20], [21], [22] as one of the factors that has a very strong influence on the solidification and segregation process.

3.2 Influence of ingot taper on A-segregation

To analyze the influence of ingot taper on segregation, three simulations have been made with ingots having ingot taper of 0.1%, 2.0% and 4.0% and keeping the H/D ratio at 4.0 and all other parameters unchanged. The Figure 9 shows a small increase of Rs from 8.27 to 10.24 with the taper from 0.1% to 4%. The reason of this increase is a lower solidification rate due to a diameter increase near hot top.

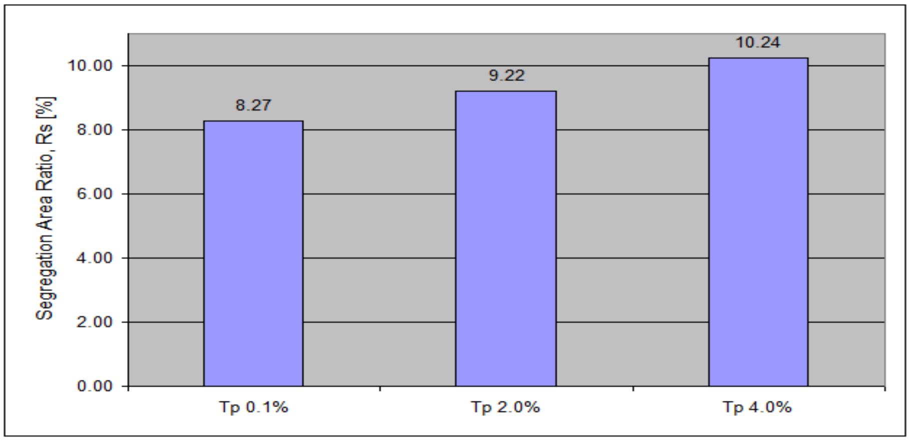
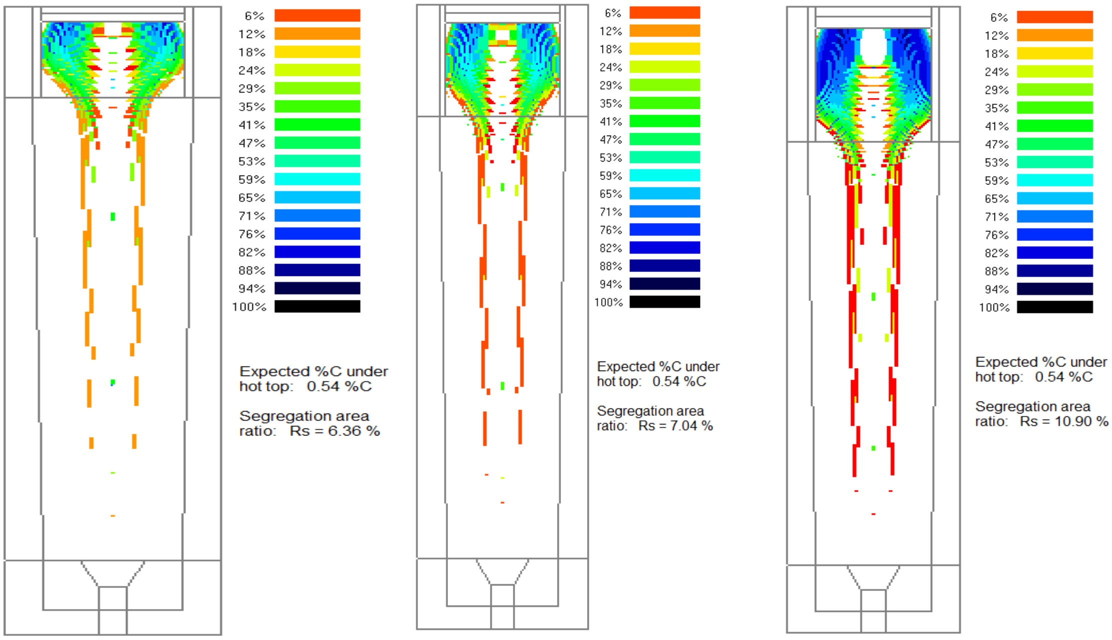


Figure 9 Influence of ingot taper on A-segregation

3.3 Influence of hot hop size on A-segregation

To analyze the influence of hot top size on A-segregation, three simulations have been made keeping the same ingot body weight and H/D ratio at 4.0 and changing the hot top size from 13.5% to 16.7% and 20.0%. The segregation area, Rs and segregation intensity, Is are shown in Figure 10.



Hot Top: 13.5% Hot Top: 16.7% Hot Top: 20.0%

Figure 10 Segregation area ratio function by hot top ratio

These experiments show that the segregation area increases from 6.36% to 10.90% with the increase of hot top size from 13.5% to 20.0%. The reason of this increase is a low solidification rate due to a bigger hot top size. Having in view both, the beneficial effect of a small hot top on A-segregation and the economic reasons we can choose the small hot top.

3.4 Choosing the ingot geometry to minimize A-segregation

The summary of previous experiments are in Figure 11. From the analyzed factors the only variables that have a significant influence on A-segregation are H/D and hot top ratio. To minimize A-segregation we must choose an ingot with H/D ratio 5.0 and a hot top lower than 13.5%. The ingot taper has low influence and we can choose a value that helps extraction of ingot from mold.

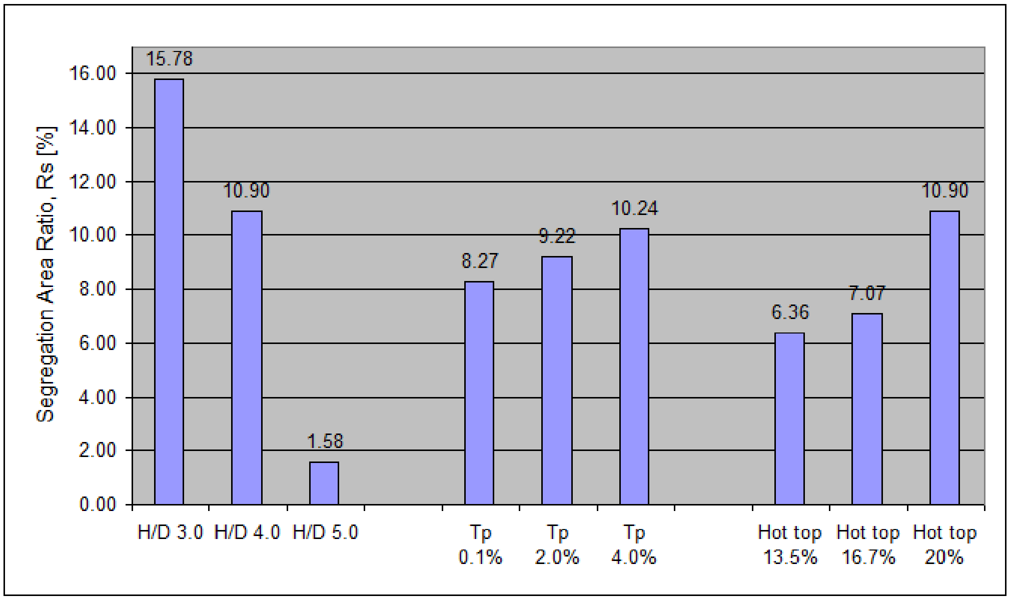


Figure 11 Influence of H/D ratio, ingot taper and hot top on segregation area

4 Optimization of casting technology

To analyze influence of pouring temperature and exothermic material on A-segregation, the steel with composition done in Table 1 and the ingot size and H/D ratio done in Table 4 has been considered.

Ingot Weight	***Ingot Body Weight***	***Hot Top ratio***	***Ingot H/D***
20T	16T	20.0%	4.0

Table 4 Ingot size of analyzed ingot

4.1 Influence of pouring temperature on A-segregation

To quantify how the pouring temperature affects the segregation, a simulation series with pouring temperature between 1540°C and 1600°C has been made. The results we got by simulation are shown in Figure 12. These experiments show that the size of segregation area increases from 9.25% to 10.0% and 11.13% with increasing of pouring temperature from 1540°C, 1570°C and 1600°C respectively. Having in view the low influence of pouring temperature on A-segregation, we can choose a value that helps deoxidation products removal and reduces porosity of the ingot [24].

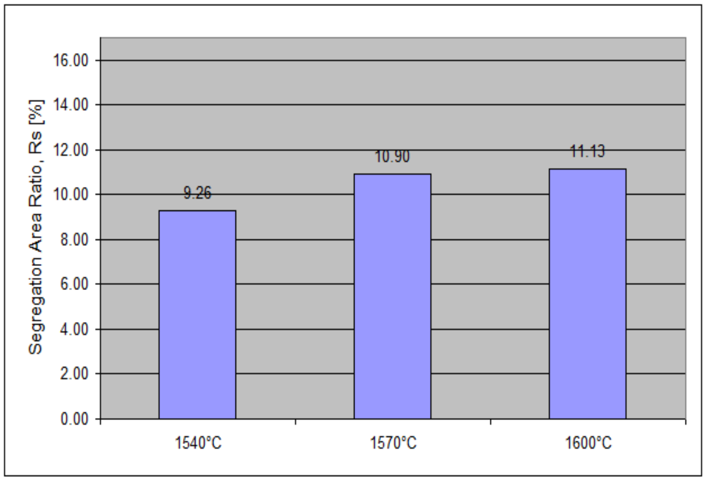


Figure 12 Segregation area size function by pouring temperature

4.2 Influence of exothermic material on A-segregation

To analyze the influence of exothermic material on A-segregation, three simulations have been made using an ingot with H/D ratio 4.0. For one of them has not been added exothermic material, for the second one the exothermic material has been 2 kg/tone and for the last one 4 kg/tone. The Rs value, the segregation ratio in these experiments, shown in Figure 13, is practically unchanged. Having in view the beneficial effect of the exothermic material on the axial porosity, the exothermic material must be as recommended by supplier.

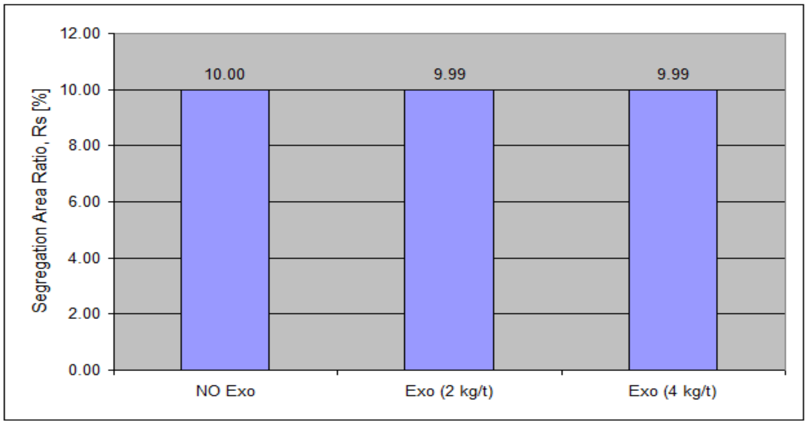
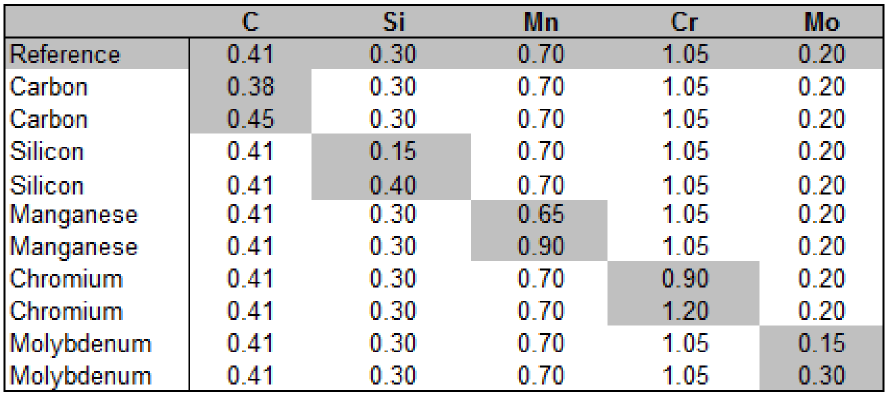


Figure 13 Segregation area ratio Rs function by exothermic material

5 Optimization of chemical composition

The chemical composition that has been taken into account in this analysis is in Table 5 and the ingot size and geometry as done in Table 4. In all experiments the pouring temperature has been 1570°C.



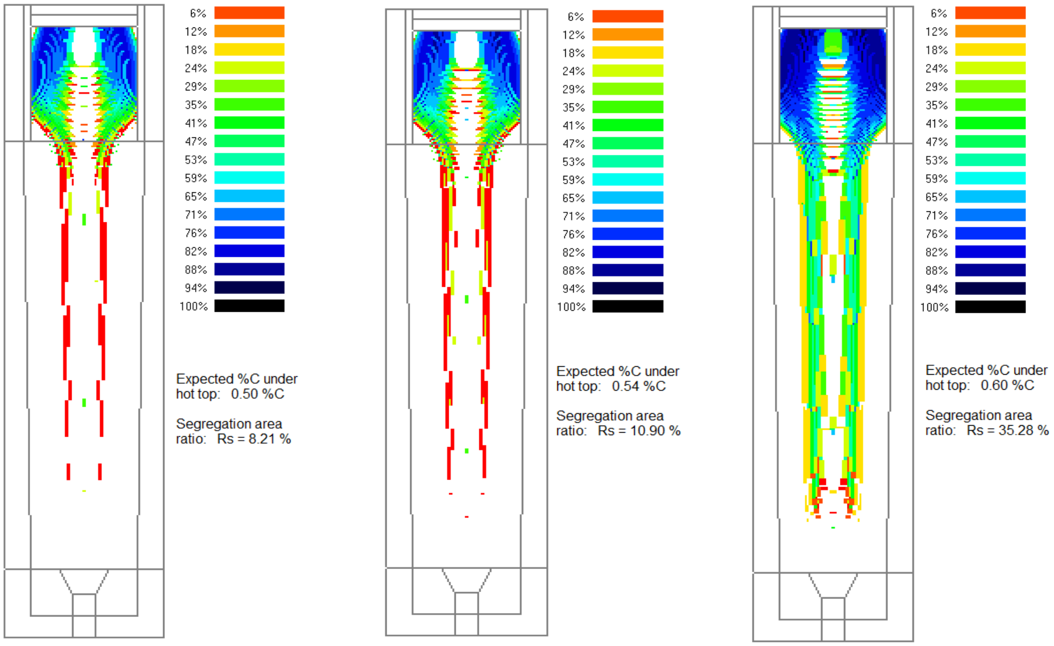
	C	Si	Mn	Cr	Mo
Reference	0.41	0.30	0.70	1.05	0.20
Carbon	0.38	0.30	0.70	1.05	0.20
Carbon	0.45	0.30	0.70	1.05	0.20
Silicon	0.41	0.15	0.70	1.05	0.20
Silicon	0.41	0.40	0.70	1.05	0.20
Manganese	0.41	0.30	0.65	1.05	0.20
Manganese	0.41	0.30	0.90	1.05	0.20
Chromium	0.41	0.30	0.70	0.90	0.20
Chromium	0.41	0.30	0.70	1.20	0.20
Molybdenum	0.41	0.30	0.70	1.05	0.15
Molybdenum	0.41	0.30	0.70	1.05	0.30

Table 5 Chemical composition of analyzed steels

5.1 Influence of Carbon content on A-segregation

To analyze the influence of carbon on A-segregation, three series of simulations have been made with the carbon content of 0.38C, 0.41C and 0.45C as given in Table 5. The experiment results, done in Figure 14, show that there is a strong increase of the segregation area from 8.21% to 35.20% with the increase of the carbon content from 0.38C to 0.45C; even a small increase of Carbon content gives a big increase of both, the segregation area and segregation intensity.

The main reason of this increase is the increase of the solidification range which has a strong influence on the segregation spots. The size of these spots is function by staying time in solid-liquid zone [5]. To minimize the A-segregation area, a low carbon value is recommended.



Expected %C under hot top: 0.50 %C

Segregation area ratio: Rs = 8.21 %

Expected %C under hot top: 0.54 %C

Segregation area ratio: Rs = 10.90 %

Expected %C under hot top: 0.60 %C

Segregation area ratio: Rs = 35.28 %

0.38 %C 0.41 %C 0.45 %C

Figure 14 Segregation area ratio function by Carbon content

5.2 Influence of Manganese content on A-segregation

To analyze the influence of Mn content on A-segregation, three simulations with 0.65Mn, 0.70Mn and 0.90Mn have been made. The other elements taken into account are in Table 5.

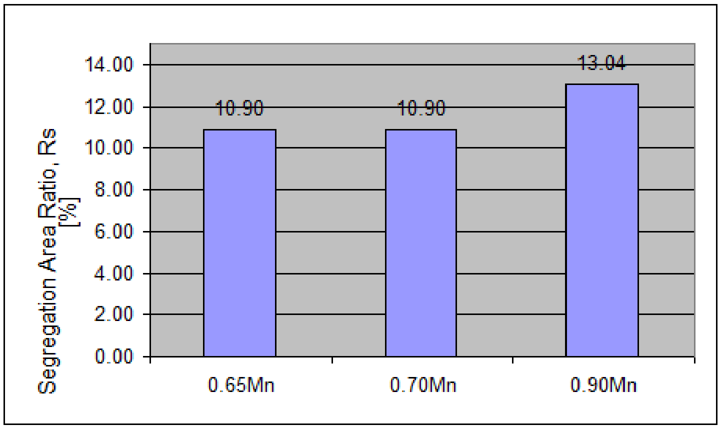


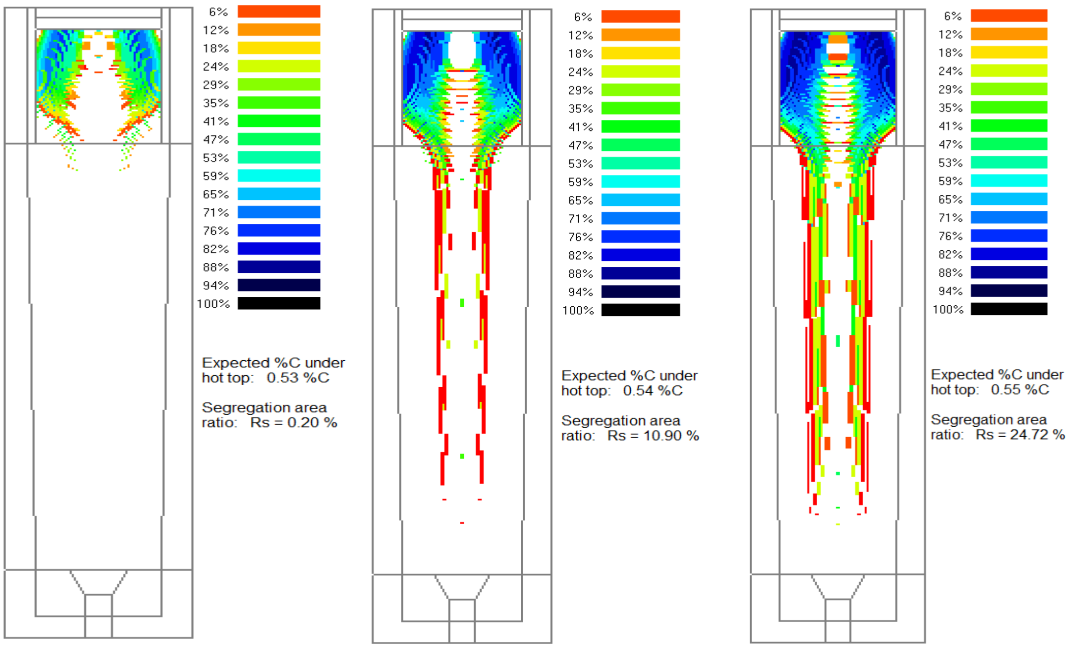
Figure 15 Segregation area ratio function by Mn content

The results of experiments presented in Figure 15 show that the Rs changes little from 13.04% to 10.90% by changing the Mn content from 0.90Mn to 0.65Mn. So, we can conclude that the Mn content has a low influence on A-segregation and we can choose a Mn value that helps the deoxidation process.

5.3 Influence of Silicon content on A-segregation

The influence of Silicon content on A-segregation has been analyzed for 0.15Si, 0.30Si and 0.40Si as done in Table 5. In these experiments, Figure 16, the segregation area ratio increases strongly from 0.20% to 10.90% and 24.72% with the Si content increasing from 0.15Si to 0.30Si and 0.40Si. The reason of this increase is that the steel with high Si content has a coarser structure than the steel with low Si [15], [17], [18]; a coarse grain structure support the expulsion of segregates at the solidification front.

To minimize A-segregation, a low Si content is recommended but a 0.15Si value may have a practical interest only if the steel is poured using VCD technology (vacuum carbon deoxidation).



0.15 %Si 0.30 %Si 0.40 %Si

Figure 16 Segregation area ratio function by Si content

5.4 Influence of Chrome content on A-segregation

As in the previous experiments we made three simulations, with steels having Chrome content of 0.90Cr, 1.05Cr and 1.20Cr. In Table 5 is the complete chemical composition of the analyzed steels.

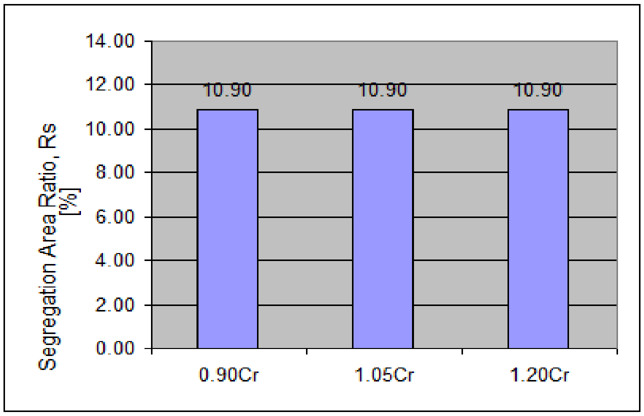


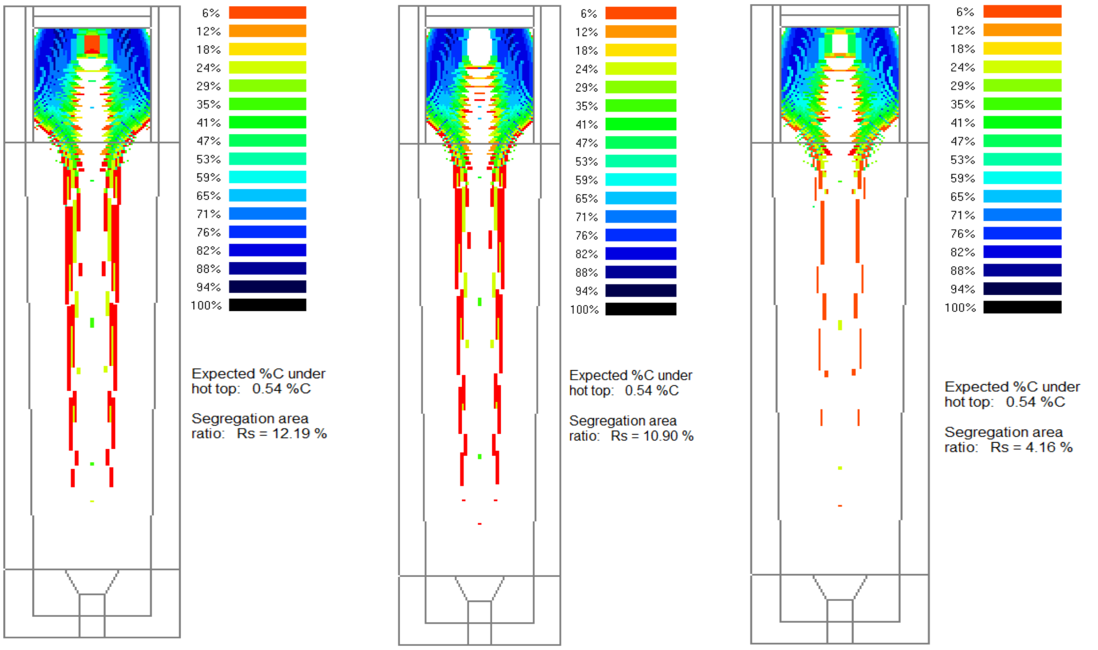
Figure 17 Segregation area ratio function by Cr content

The Figure 17 shows that the segregation area ratio does not change with the change of Cr content from 0.9Cr to 1.20Cr and we can conclude that the Cr content does not have influence on A-segregation; see also [14].

5.5 Influence of Molybdenum content on A-segregation

In the following experiments, the Mo content taken into account is between 0.15Mo and 0.30Mo. The other elements are done in Table 5. Figure 18 shows the results of these simulations.

The segregation area decreases from 12.19% to 10.90% and 4.16% with the increase of the Mo content from 0.15M0 to 0.20Mo and 0.30Mo. Because the decrease of segregation area is so significant with the variation of Mo in the limits of steel we can conclude that for 42CrMo4 steel Mo is an element by which we can control the A-segregation.



0.15 %Mo 0.20 %Mo 0.30 %Mo

Figure 18. Segregation area ratio function by Mo content

The reason of the A-segregation reduction is the solidification fraction that does not allow solute enrichment and segregation formation at the solidification front [14], [18].

In Figure 19 is a summary of the influence of chemical elements on A-segregation.

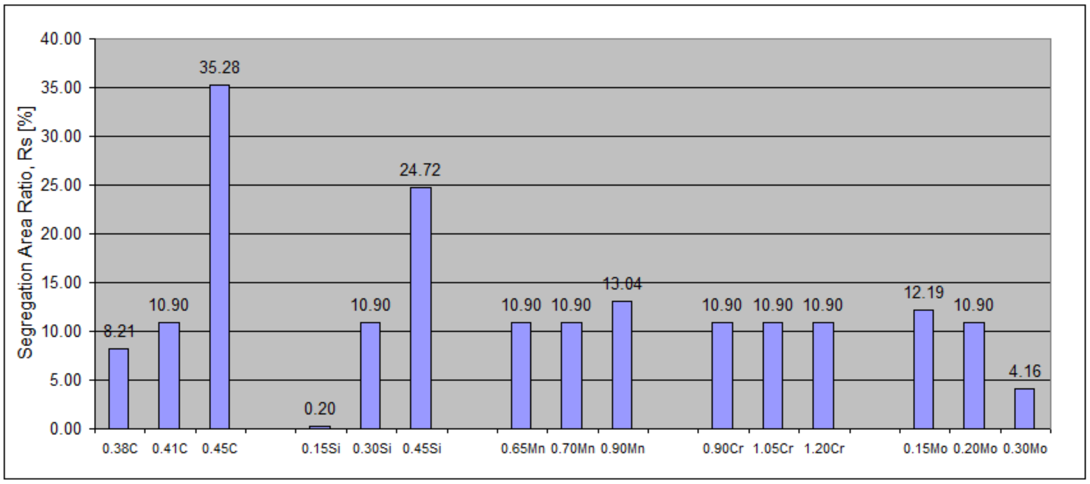


Figure 19 Segregation area ratio function by chemical element

Conclusions

Influence of H/D ratio, hot top size, ingot taper, pouring temperature, exothermic material and the chemical composition have been analyzed in order to establish the values that would decrease the segregation area size and increase the homogeneity of the mechanical properties for 42CrMo4 forging products. Having in view the results of the experiments and the solidification analysis, we can conclude the following:

- ingot H/D ratio has a strong influence on the segregation area size. Using an ingot with 5.0 H/D, the segregation area can be reduced from 15.78% to 1.58%; to minimize A-segregation, an ingot with 5.0 H/D (805mm medium diameter) is highly recommended;
- decreasing the hot top ratio from 20% to 13.5% reduces the segregation area from 10.90% to 6.36%. More, taking into consideration the economic factors, a small hot top size is recommended;
- the experiments show that the ingot taper has low influence on the segregation area size and its value has to be chosen in order to allow an easy extraction of the ingot;
- an increase of pouring temperature from 1540°C to 1600°C has as effect a small increase of the segregation area size but because a higher pouring temperature offers better conditions for inclusion removal, a pouring temperature of 1570°C may be beneficial;
- the exothermic material has effect only on hot top function; it does not have influence on A-segregation area size;
- a high carbon content increases the segregation area size strongly; even a small increase of the carbon content has as effect a strong increase of the segregation area;
- A-segregation area strongly increases with the increase of Si content as well. To reduce the segregation, a low Si content is recommended but when choosing the minimum limit we have to take into account the beneficial effect of Si on the deoxidation process;
- Mn content has low influence on A-segregation and can be established having in view technological reasons;
- Mo reduces the segregation area size and increases the homogeneity of a 42CroMo4 forging products;
- Cr content has a low influence on the segregation process and if there is not another reason to keep their values high, a low content may be taken in consideration.

Finally, having in view the A-segregation, the 42CrMo4 20tons ingot is considered optimized if its H/D ratio is around 5.0, the hot top ratio is lower than 14% and the ingot is poured with the low C and Si and high Mo content.

References

[1] Flemings, M.C.: Our Understanding of Macrosegregation: Past and Present, ISIJ International, Vol. 40 (2000), No. 9, pp. 833–841, 2000

[2] Delorme, J.; Laubin, M., Maas H.; Solidification of Large Forging Ingots, Casting and Solidification of Steel vol.1, ECSC Luxembourg 1977

[3] Lesoult G.: Macrosegregation in steel strands and ingots: Characterization, formation and consequences, Mater. Sci. Eng. A, 413-414 (2005), pp. 19-29.

[4] Kajikawa K., Suzuki S.: Development of 650-ton-class ingot for turbine rotor shaft forging application, ICRF, 2012

[5] Suzuki, K.; Miyamoto, T.: Formation Condition of “A” Segregation, Tetsu-to-Hagane. 63. 53-62, 1977

[6] Industrial Soft: Online Ingot Mold Design Assistant v.1.0, www.simcade.com

[7] Industrial Soft: SIMCADE v.2.0, Solidification Simulation Software; www.simcade.com

[8] Pola A., Gelfi M., La Vecchia G.M.: Comprehensive Numerical Simulation of Filling and Solidification of Steel Ingots, Materials 2016, 9(9), 769;

[9] Combeau H, Kumar A., Založnik M., et al.; Macrosegregation Prediction in a 65 ton Steel Ingot, ICRF 2012

[10] Jaouen O., Costes F., Lasne P.: Ingot casting simulation with Thercast, Casting Plant & Technology 4/2012

[11] Onodera S., Arakida Y.: Studies on the Solidification and Segregation of Larger Steel Ingots I, Tetsu-to-Hagane 1958 Volume 44 Issue 1 Pages 9-14

[12] Gorni, A.; G., Formica, V.B.; Bogdan, O.: Comparaçäo preliminar entre abordagens para o modelmento matemático do perfil térmico de placas durante seu reaquecimento; Revista Escola de Minas - REM, 53:3, Julho-Setembro, 2000, p. 203-209

[13] Yamada, H.; Sakurai T.; Takenouchi, T.: Critical Conditions for the Formation of A-Segregation in Forging Ingots; ISIJ, 1989, p.92-104

[14] Suzuki, K.; Miyamoto, T.: Influence of Alloying Elements on the Formation of A-Segregates In Steel Ingots, Tetsu-to-Hagane, 1979 Volume 65 Issue 10 Pages 1571-1580

[15] Yamada H., Sakurai T., Takenouchi T.: Appearance of "A" Segregation in Forging Ingots and Influencing Factors, 1989 Volume 75 Issue 1 Pages 105-112

[16] Iida Y. et al.: Development of Hollow Ingot for Large Forging, Tetsu-to-Hagane 1980 Volume 66 Issue 2 Pages 211-220

[17] Haida, O.; Okano, S.; Emi, T.; Kasai, G.: Estimation of the Formation of A-Segregation in Steel Ingot in Terms of the Chemical Composition of Steel; ISIJ, 1981, p.954-958

[18] Suzuki K., Taniguchi K.: The Elimination Mechanism of A-Segregates of Steel Ingot, 1979 Volume 65 Issue 10 Pages 1581-1588

[19] Dmitrii Rutskii et al.: A Study of the Development of Chemical Heterogeneity in Large Forging Ingots: Depending Upon the Configuration and Thermophysical Conditions of Casting, Metallurgical and Materials Transactions A · December 2014

[20] Phillips S., Price S., Tomlinson M., Talamantes-Silva J.: Design and Development of Solid and Hollow Ingots for the High Integrity Forging Market, ICRF 2012

[21] Tsuchida, Y.; Nakada, M.; Kunisada, Y.; Teshima, T.: Influence of Ingot Shape and Chemical Composition on the Inverse-V Segregation in Killed Steel Ingots; ISIJ, 1987, p.1125-1132

[22] Tashio, K.; Watanabe, S.; Kitagawa I.; Tamura, I.: Influence of Mold Design on the Solidification and Soundness of Heavy Forging Ingots; ISIJ, 1983, p.312–21

[23] Sang B. G., Kang X. H., Liu D. R. and Li D. Z.: Study on Macrosegregation in Heavy Steel Ingots, International Journal of Cast Metals Research 2010 VOL 23 NO 4 205

[24] Zhang, C., Bao, Y., Wang M.: Influence on Casting Parameters on Shrinkage Porosity of a 19 Ton Steel Ingot, La Metallurgia Italiana - n. 1 2016