Influence of Ingot Size and Mold Design on Macro-Segregation in AISI 4340 Forging Products

O.Bogdan[1], *Industrial Soft*
Montreal, Canada
bogdan@castingsnet.com

Abstract

The analysis goal was to find out if the ingot geometry and mold design of a particular 50 tons ingot offers conditions of avoiding of macro-segregation and homogeneous mechanical properties in AISI 4340 steel grade forging products. To this purpose, the solidification software SimCADE v.2.0 has been used to analyze the solidification process of the ingot with the same weight but with variation of height/diameter ratio, ingot taper and mold wall thickness. In all numerical experiments performed, the solidification and cooling rate has been used to calculate the A-segregation criterion value for a particular AISI 4340 steel grade chemical composition. The numerical analysis results show that in the analyzed ingot, the macro-segregation will occur and the material is not homogeneous. The experiments done with a different ingot taper or mold wall thickness show that A-segregation will occur in all these ingots as well. If the ingot height/diameter ratio mold is higher, the ingot will have a lower A-segregation area; ingot taper and mold wall thickness have influence on A-segregation area size but it cannot avoid A-segregation and material heterogeneity completely.

1 Introduction

It is known that one of the most important factors that affect the final quality of forging products is the solidification process. Macro-segregation commonly known as A-segregation, often found in large steel ingots, presents channels enriched by sulfur, carbon, phosphorus and is one of the reasons why the mechanical properties of the final product are anisotropic. A-segregation form in the zone of columnar grains at the regions with structure characterized by the transition from the columnar grains to large equiaxed grains.

Manufacturing a forging product with a high homogeneity of mechanical properties is impossible without a strict control of A-segregation and solidification process variables. In order to better understand how these parameters are influenced by ingot geometry and mold design, we

[1] O.Bogdan has been for ten years with the Research & Design Department, IMGB (Doosan IMGB SA)

performed a series of numerical simulations, applied the Suzuki and Miyamoto criterion and measured the A-segregation area size. From all parameters that have influence on the segregation process, in this paper, we are focused on the effect of ingot height/diameter ratio, ingot taper and mold wall thickness on A-segregation.

2 The mathematical model used to simulate the solidification process

The equation used to describe the heat flow during the solidification process in two coordinates for transient regime is the following:

$$\frac{\partial}{\partial x}[\lambda(T)\frac{\partial T}{\partial x} + \lambda(T)\frac{\partial T}{\partial y}] = \rho C_p \frac{\partial T}{\partial t} \qquad (1)$$

where T represents temperature, λ - conductivity, C - specific heat, t - time and ρ - density. The initial condition (2) and boundary condition (3) attached to Equation (1) to obtain a complete model are:

$$T = T_0,\ t = 0 \qquad (2)$$

$$\lambda(\frac{\partial T}{\partial x}n_x + \frac{\partial T}{\partial y}n_y) + \alpha(T - T_0) = 0,\ \ \forall P(x,y) \in S_\alpha \qquad (3)$$

where T_o represents temperature at initial moment and α is the heat transfer coefficient on the surface S_α.

During the solidification process a significant factor is the latent heat which works like an external source of heat. To obtain a valuable model it is necessary to include this factor in our mathematical model. There are a lot of methods to include this external source in the heat transfer model. We use the following relation:

$$C_1^{'} = C_1 + \frac{L}{\delta T} \qquad (4)$$

where C'_1 represents the specific heat which include the latent heat, C_1 - specific heat without latent heat, L - latent heat and δT - the differences between liquidus and solidus temperatures.

Because the analytical equations cannot be used to realize the computer program it is necessary to transform it into an integral model. Knowing the differential equation (1), initial (2) and boundary condition (3) the integral equation for mathematical model is:

$$\pi = \int_V \tfrac{1}{2}[\lambda_T(\frac{\partial T}{\partial x})^2 + \lambda_T(\frac{\partial T}{\partial y})^2]dV + \int_V \rho C_p \frac{\partial T}{\partial x} dV + \int_{S_\alpha} \tfrac{\alpha}{2}(T - T_\alpha)dS \qquad (5)$$

Having in view that the analyzed domain V can be broken into finite elements with quadrilateral shape, using the linear functions we can describe the temperature with the following equation:

$$\hat{T}(x,y,t) = N_1(x,y)T_1(t) + N_2(x,y)T_2(t) + N_3(x,y)T_3(t) + N_4(x,y)T_4(t) \qquad (6)$$

where $N_1(x,y)$, $N_2(x,y)$, $N_3(x,y)$ and $N_4(x,y)$ represents shape functions and $T_1(t)$, $T_2(t)$, $T_3(t)$ and $T_4(t)$ the temperatures in finite element nodes. With this last relation and imposing the stationary conditions for Eqn. (5), we have the following equation:

$$\sum_1^n (\int_{V^e} B^T D B T^e dV + \int_{V^e} \rho C_p \frac{\partial}{\partial t} N dV + \int_{S_\alpha^e} N_{N^T} T^e dS + \int_{S_\alpha^e} \alpha T_\alpha N^T dS = 0 \qquad (7)$$

This equation can now be written as follows:

$$K_1^e \dot{T}^e + (K_2^e + K_3^e) \cdot T = K_4^e \qquad (8)$$

After assembling all elements of analyzed domain we obtain the final equations:

$$K_1 \dot{T} + (K_2 + K_3) \cdot T = K_4 \qquad (9)$$

To obtain the temperatures in transient regime we use finite differences method. The equation which gives the initial temperatures for a new cycle of computing is:

$$(\tfrac{2}{\Delta t} K_1 + K_2 + K_3) \cdot T_{n+1} = (\tfrac{2}{\Delta t} K_1 - K_2 - K_3) \cdot T_n + (K_{4,n+1} + K_{4,n}) \qquad (10)$$

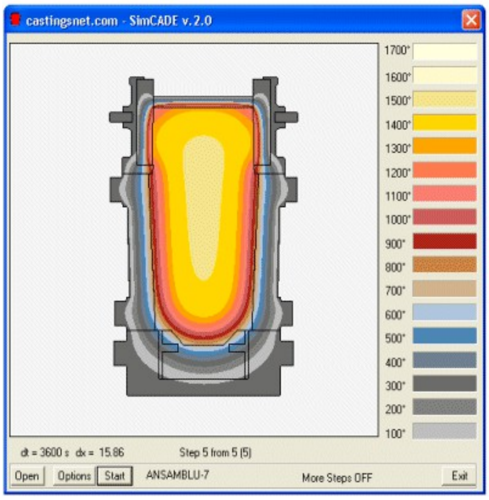
Using the last equation we can compute all temperatures at time t+dt if we know the temperature at time t.

3 The computer program

Using the mathematical model described, we have developed a computer program to simulate the heat transfer during the solidification process. The software simulates cooling and solidification of metal in the mold so that the effects of various manufacturing parameters and environmental conditions upon the solidification process can be examined.

The computer program, shown in Picture 1, written in C++ language, take in account the internal sources and variation of material properties with temperature. The software uses over 450.000 finite elements to obtain an accurate geometrical description of the domain. The necessary time to compose the problem and solve the equation system is about 60 seconds for a PC computer system.

The successive approximation method with a variable supra-relaxation factor is used to solve the equation system. The software has routines for auto-meshing the analyzed geometry and displays results in graphical mode.



Picture 1 SimCADE v.2.0 – software for simulation the solidification process

The main simulation system of the software consists of three processors:
- the pre-processor module for reading the 3D CAD drawing of the analysis model and automatic generation of the finite element mesh,
- a simulator for the solidification process and,
- the post-processor module to display the results.

The software has been tested for industrial conditions in slab reheating and casting solidification applications.

4 A-segregation Prediction Module

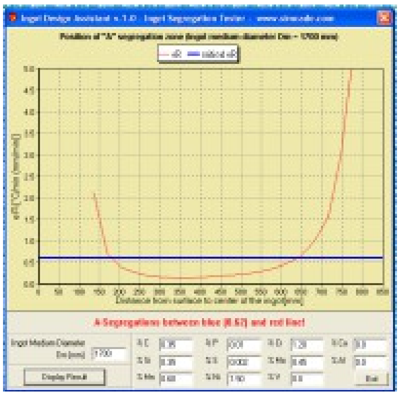
The segregation in the columnar zone is much influenced by the cooling and solidification rate. To define the A-segregates occurring conditions K.Suzuki and T.Miyamoto proposed the following Equation (11), based on solidification rate V (mm/mm) and cooling rate R (°C/min):

$$R \bullet V^{1.1} \leq \alpha \tag{11}$$

K.Suzuki and T.Miyamoto have investigated at Muroran Research Center, The Japan Steel Works Ltd. (JSW) a 0.7 % carbon steel and obtained α = 8.75; however, the value α is depending upon chemical composition. Using the Equation (11), the chemical composition of the analyzed steel, liquid diffusion and solid diffusion equation applied for carbon and Scheil's equation applied for all elements except carbon, we have developed the prediction module attached to the simulation software SimCADE. For AISI 4340 steel with the following chemical composition:

%C	%Si	%Mn	%P	%S	%Cr	%Mo	%Ni
0.40	0.35	0.60	0.01	0.002	1.20	0.25	1.50

the calculated value α is 0.63 and is shown in Picture 2. Because the $R \bullet V^{1.1}$ values (red curve) does intersect critical value α (blue line), the



Picture 2 A-segregation prediction module attached to SimCADE v.2.0

A-segregates will occur in the ingot with the chemical composition given and poured into a 1700mm medium diameter mold.

To quantitatively appreciate the influence of ingot height/diameter ratio, ingot taper and mold wall thickness on A-segregation, we have defined the parameter Rs, the ratio between area affected by segregation and the longitudinal section area of the ingot.

The following numerical experiments will calculate the area affected by segregation, Rs for AISI 4340 steel ingot.

5 Numerical experiments

5.1 Initial conditions, boundary conditions, material properties

The limits of the chemical composition of AISI 4340 steel grade are shown in Table 1. Liquidus and solidus temperature taken in simulation have been 1490°C and 1430°C, respectively.

Table 1. Chemical composition of AISI 4340 steel

%C	%Si	%Mn	%Cr	%Mo	%Ni
0.36~ 0.44	0.10~ 0.35	0.45~ 0.70	1.00~ 1.40	0.20~ 0.35	1.30~ 1.70

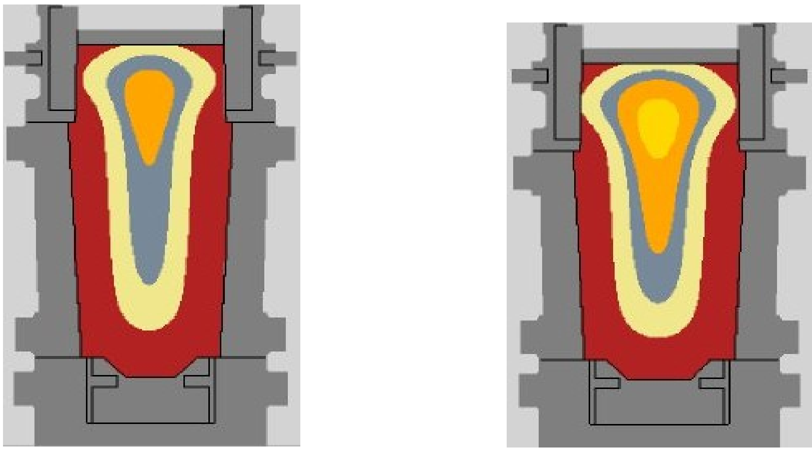
The emissivity values on the outside surface of the mold has been assumed to be a function of temperature and estimated at 0.75 - 0.95. The value of the heat transfer convection coefficient on the outside surface of the mold has been 15 kcal/m²h°C. The upper surface of the ingot has been considered as insulated. The material data of the mold and AISI 4340 steel used in these numerical experiments are given in Table 2. The pouring and initial mold temperature used in these experiments have been 1590°C and 20°C, respectively.

Table 2.Materials and thermal properties used in simulation

	Conductivity	Specific heat	Latent heat	Density
	W/m°K	J/kg°K	kJ/kg	kg/m³
AISI 4340	33.0	480	267.0	7800
Mold (Grey Iron)	59.0	460	-	7000

5.2 Influence of ingot height/diameter ratio on A-segregation

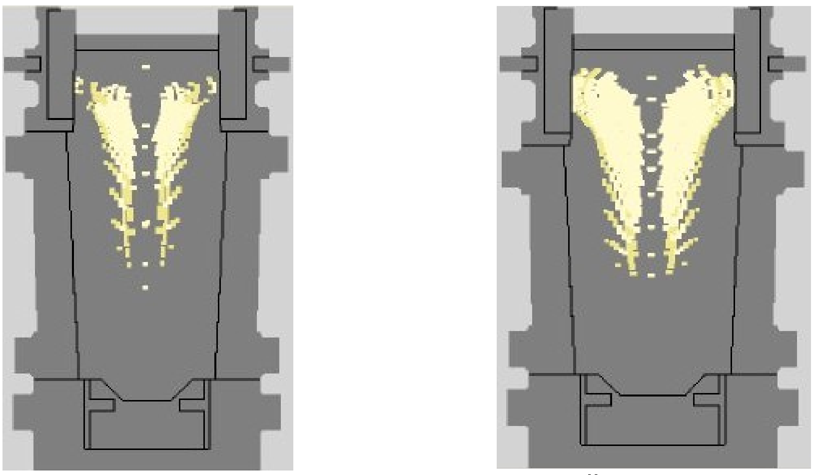
To analyze the influence of ingot height/diameter ratio on A-segregation two simulations have been made. For one of them, the ingot height/diameter ratio value taken into consideration has been 1.5 (1700mm medium diameter). For the second one, the ingot height/diameter ratio has been 2.0 (1500mm medium diameter). The calculated temperatures in transitory regime have been used to calculate solidification and cooling rate. The iso-solidus curves and A-segregation prediction module results are shown in Figure 1 and 2, respectively.



a) Height/diameter ratio = 2.0
(1500mm medium diameter)

b) Height/diameter ratio = 1.5
1700mm diameter ingot)

Fig.1 Iso-solidus curves function by ingot height/diameter ratio



a) Height/diameter ratio = 2.0
(1500mm medium diameter)

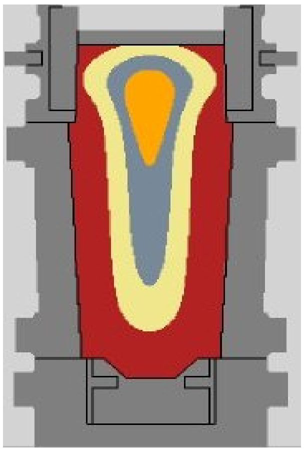
b) Height/diameter ratio = 1.5
(1700mm medium diameter)

Fig.2 A-segregation zone function by ingot height/diameter ratio

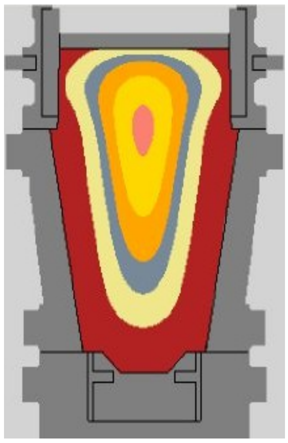
As seen in Figure 2, for 2.0 height/diameter ratio ingot, the Rs value, ratio between A-segregation area size and ingot section area, is 28.0. For the original ingot (height/diameter ratio 1.5) the Rs value is 39.0. In both ingots A-segregation will occur. Also, these results show that the segregation area size is lower in the ingot with higher height/diameter ratio. For this reason, to minimize the segregation area it is recommended using this ingot for pouring AISI 4340 steel.

5.3 Influence of ingot taper on A-segregation

To analyze the influence of ingot taper on A-segregation, two simulations (9.0 and 11.0 ingot taper) have been made using the original medium diameter ingot and the same weight. The iso-solidus curves are shown in Figure 3.

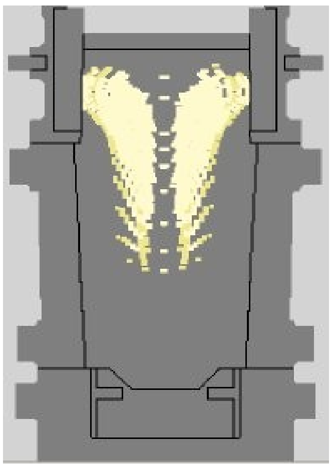


a) Ingot Taper = 9.0

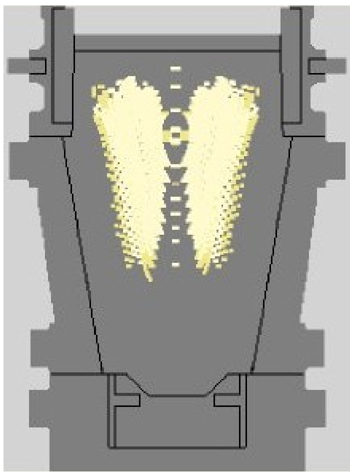


b) Ingot Taper = 11.0

Fig.3 Iso-solidus curves function by ingot taper



a) Ingot Taper = 9.0



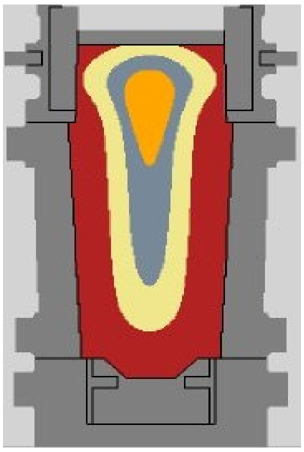
b) Ingot Taper = 11.0

Fig.4 A-segregation area function by ingot taper

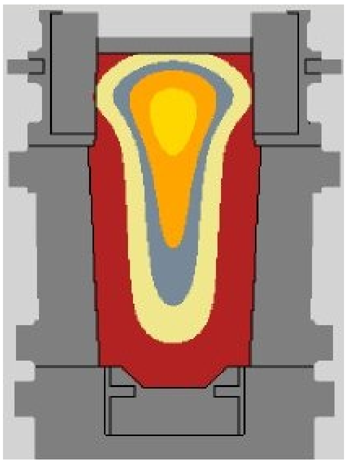
Figure 4 shows the A-segregation prediction module results: in 1700mm medium diameter ingot the A-segregation will occur. For 9.0 taper ingot, the Rs value, the ratio between the A-segregation area and ingot section area, is 35.0%. For the other ingot, the Rs value is 44.0%. The numerical experiment suggests that for AISI 4340 steel a higher value of ingot taper may increase the A-segregation area size.

5.4 Influence of mold wall thickness on A-segregation

To analyze the influence of mold wall thickness on A-segregation two simulations have been made with the original ingot (1700mm medium diameter). For one of the simulation has been considered the original wall thickness. For the other one, the wall thickness size has been increased with 100mm at both ends. The iso-solidus curves are shown in Figure 5.

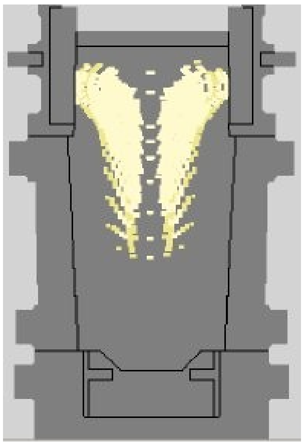


a) Original mold wall thickness

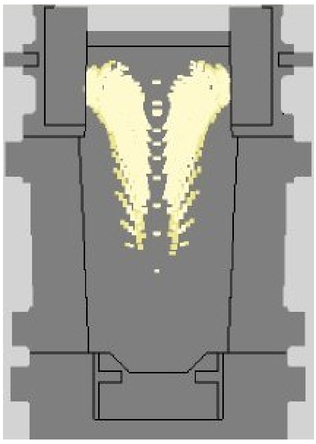


b) Increased mold wall thickness (100mm)

Fig.5 Iso-solidus curves function by mold wall thickness



a) Original mold wall thickness



b) Increased mold wall thickness (100mm)

Figure 6. A-segregation zone function by mold wall thickness

Figure 6 shows the results of the segregation prediction module. The Rs value for 1700mm medium diameter ingot (1.5 height/diameter ratio) is 35.0%. For the ingot poured using a mold wall thickness increased with 100mm, the Rs value is 36.0%. This experiment shows that a higher value of mold wall thickness does not have influence on the A-segregation in this particular ingot size.

6 Conclusions

Influence of height/diameter ratio, ingot taper and mold wall thickness have been analyzed in order to check if there are conditions of A-segregation occurring in 50 tons AISI 4340 ingots and if this ingot offers conditions to have a homogeneous mechanical properties of the forging products. The following results have been obtained:

(1) Because the critical value α calculated using the chemical composition of AISI 4340 steel is higher then the solidification rate of 1700mm diameter ingot (1.5 height/diameter ratio), the A-segregation will occur in this particular ingot and the material is not homogeneous;

(2) The experiments done with a different ingot taper or mold wall thickness show that the segregation cannot be avoided in any of the 1700mm medium diameter ingots if the material poured is AISI 4340 steel grade and the mechanical properties of the forgings will not be homogenous;

(3) The ingot height/diameter ratio has a strong influence on A-segregation area size. The low height/diameter ratio ingot develops an extended A-segregation area;

(4) The mold wall thickness and ingot taper have a low influence on A-segregation zone size for this particular steel and ingot size;

(5) If the ingot height/diameter ratio mold is higher, the ingot will have a lower A-segregation area; ingot taper and mold wall thickness have influence on A-segregation area size but it cannot avoid A-segregation and material heterogeneity completely;

(6) Using geometrical variables as ingot height/diameter ratio, ingot taper and mold wall thickness, the mold designer can control the intensity of macro-segregation process and material homogeneity of forging products.

Using the simulation software to analyze the mold design and ingot size, the manufacturer has a useful tool to choose the ingot weight and mold according to the steel grade and minimize A-segregation and mechanical properties heterogeneity in forging products.

References

1. *Influence of Ingot Shape and Chemical Composition on the Inverse-V Segregation In Killed Steel Ingots* - Yutaka Tsuchida, Masayuki Nakada, Yasunobu Kunisada and Toshio Teshima

2. *Critical Conditions for the Formation of "A" Segregation In Forging Ingots* - Hitohisa Yamada, Takashi Sakurai and Tomoo Takenouchi

3. *Estimation of Forming Condition of Center Porosity In Forging Ingot - Hitohisa* Yamada, Takashi Sakurai, Tomoo Takenouchi and Yoshiyuki Iwanami

4. *Estimation of the Formation of A-Segregation In Steel Ingot In Terms of the Chemical Composition of Steel* - Osamu Haida, Shinobu Okano, Toshihiko Emi, and Goro Kasai

5. *Appearance of "A" Segregation In Forging Ingots and Influencing Factors* - Hitohisa Yamada, Takashi Sakurai and Tomoo Takenouchi

6. *The Development of a Chill Mold for Tool Steels Using Numerical Modeling* - Razvoj Kokile, Martin Balcar, MTAEC9, 42(4)183(2008)

7. *Influence of Mold Design on the Solidification and Soundness of Heavy Forging Ingots* - by Koichi Tashio, Shiro Watanabe, Ikujiro Kitagawa and Itaru Tamura

8. *Computer-aided Casting Design and Simulation* – by Dr. B. Ravi, Professor Mechanical Engineering, Indian Institute of Technology, Bombay

9. *Studies on the Solidification and Segregation of Large Steel Ingots* - Heishiro Morikawa, Shinsaku Onodera and Yutaka Arakida

10. *Heat Transfer Simulation during the Solidification Process* - Bogdan, O., Bratu, C., - Machines Construction, 44, 1992, No. 11-12, P.48-52