Influence of Pouring Technology on Macro-Segregation in AISI 4340 Forgings Products

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Abstract

The analysis objective was to establish the influence of pouring temperature, hot top size and initial mold temperature on A-segregation in order to increase the homogeneity of AISI 4340 forging products manufactured from 50 tons ingots. To this purpose, a mathematical model and the computer program SimCADE v.2.0 have been employed to simulate the solidification process. In these numerical experiments, cooling and solidification rate have been correlated with the criterion value calculated by macro-segregation prediction module of the simulation software. The mathematical model is based on the chemical composition of the steel and the A-segregation mechanism proposed by Suzuki and Miyamoto. The results are useful not only for steel manufacturers but also for semi-manufactured or forging products buyers. Using the manufacturing records as input data for the simulation software, the buyer may choose a forging product with higher homogeneity of mechanical properties.

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-segregations, often found in large steel ingots, present channels enriched by sulfur, carbon, phosphorus and is one of the reasons why the mechanical properties of the final product are anisotropic. A-segregations 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 casting technology, we realized a series of

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numerical simulations, applied the Suzuki and Miyamoto criterion and measured the A-segregations area size. From all parameters that have influence on the segregation process, in this paper, we are focused over the effect of pouring temperature, hot top ratio, and initial mold temperature. Also, we tried to establish a global criterion in order to find out which one from the analyzed manufacturing variables affects most the segregation process.

2 The mathematical model 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:

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

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:

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

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

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 is a lot of methods to include this external source in the heat transfer model. We use the following relation:

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

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:

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

In matriceal form this equation can now be written as follows:

$$K^e_1 \dot{T}^e + (K^e_2 + K^e_3) \cdot T = K^e_4 \qquad (8)$$

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:

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

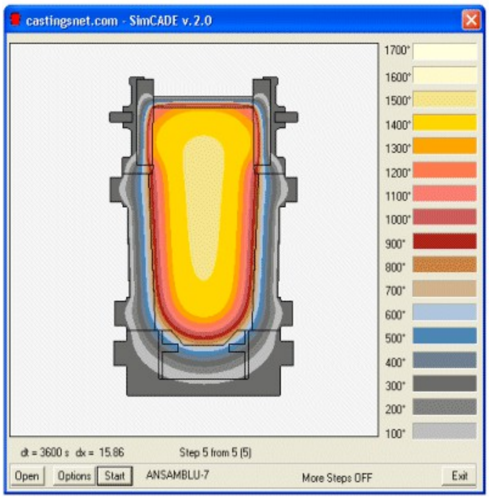
Using the last equation we can compute all temperatures at time t+dt if we know the temperature at time t.

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 equations system is about 60 seconds for a PC computer system.

The successive approximation method with a variable suprarelaxation factor is used to solve the equation system. The software has routines for automeshing 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.

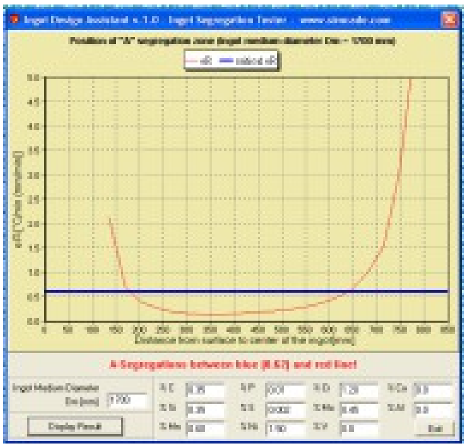
The software has been tested for industrial conditions in slab reheating and casting solidification applications. The results from heat transfer simulation have been close to data taken in industrial conditions.

4 A-segregation Prediction Module

The segregation in the columnar zone is much influenced by the cooling and solidification rate. To define the A-segregations 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):

$$R \cdot V^{1.1} \leq \alpha \qquad (11)$$

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, the value α calculated is 0.63 and is shown in Picture 2. This picture also displays the variation of $R \cdot V^{1.1}$ on the section of an ingot with 1700



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

mm medium diameter. In the area with the $R \cdot V^{1.1}$ values lower then the critical value α, A-segregations will occur.

To quantitatively appreciate the influence of the casting technology variables 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 poured into 50 tons ingot.

5 Numerical experiments

5.1 Initial conditions, boundary conditions and material properties

The chemical composition of AISI 4340 steel is shown in Table1. 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	%P	%S	%Cr	%Mo	%Ni
0.36~ 0.44	0.10~ 00.35	0.45~ 0.70	max 0.040	max 0.035	1.00~ 1.40	0.20~ 0.35	1.30~1. 70

The emissivity value on the outside surfaces of the mold and hot top frame were assumed to be a function of temperature and estimated to be 0.75 - 0.95. The heat transfer convection coefficient on the outside surface of the mold and hot top frame was 15 kcal/m²h°C. The upper surface of hot top has been taken as insulated. The material data of cast iron, brick, steel frame and AISI 4340 steel used in these numerical experiments are in Table 2. The geometry data of the ingot used in simulation is shown in Table 3.

Table 2.Materials and thermal properties used in simulation

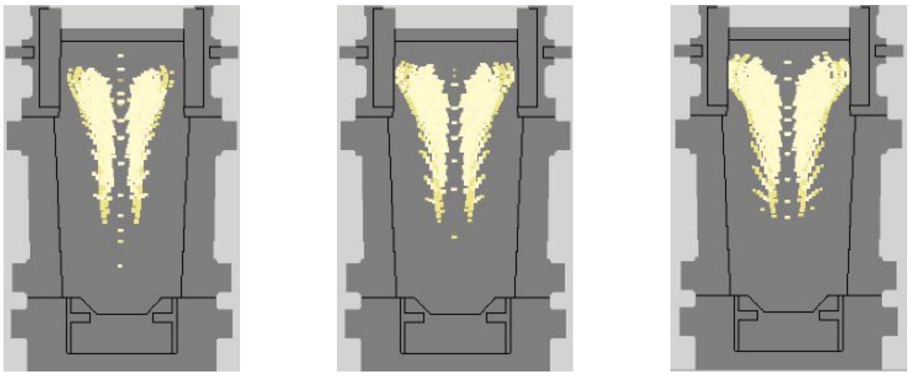
	Conductivity	Specific heat	Latent heat	Density
	W/m°K	J/kg°K	kJ/kg	kg/m³
AISI 4340	33.0	480	267.0	7800
Mold (Grey Iron)	59.0	460	-	7000
Brick	1.31	1000		
Steel Frame	27	480	-	-

Table 3.Size of the ingot taken in simulation

Ingot Weight	Medium Diameter	Body Height	H/D ratio	Taper Ratio
50 tons	1700 mm	2250 mm	1.5	9.0 %

5.2 Influence of pouring temperature on A-segregation area size

To quantify how the pouring temperature affects the segregation zone, a simulation series has been made with the pouring temperature between 1540°C and 1600°C. The results and the influence of pouring temperature on A-segregation zone ratio Rs, are shown in Figure 2 a, b, c and Figure 3.



a.) Pouring temp. = 1540°C b) Pouring temp. = 1570°C c) Pouring temp. = 1600°C

Figure 2. Effect of pouring temperature on A-segregations

As seen from these simulations, the size of segregation zone increases with increasing the pouring temperature. A-segregation zone ratio Rs, varies from 14% for 1540°C to 17% for 1600°C.

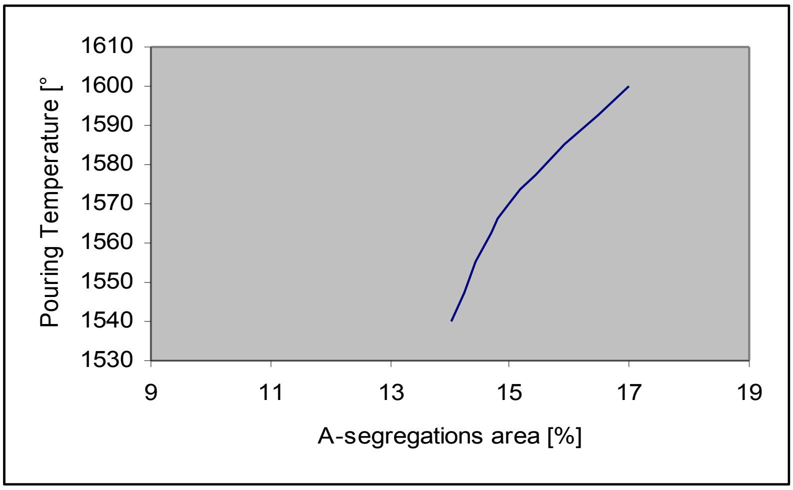
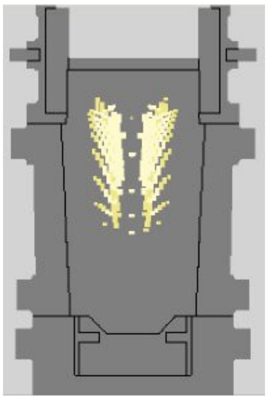


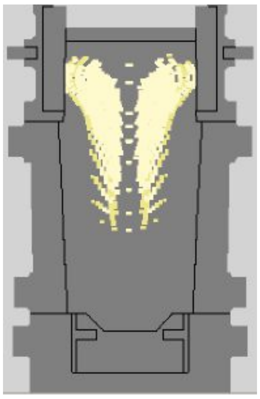
Figure 3. A-segregations zone ratio function by pouring temperature

5.3 Influence of hot top size on the A-segregations

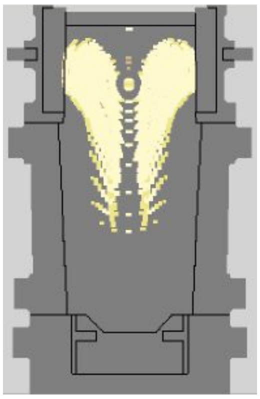
To study how the hot top size has influence on the segregation area, three simulations with the hot top weight ratio between 20% and 40% have been made. Figure 4 a, b, c and Figure 5 show the results of simulation and how the A-segregation zone area Rs is influenced.



a) Hot top ratio = 20%



b) Hot top ratio = 30%



c) Hot top ratio = 40%

Figure 4. Influence of hot top size upon A-segregation area

When using a small hot top, the ratio of segregation zone Rs, may be reduced up to 10%. A bigger hot top will produce an extended segregation area size. In this case, Rs is over 20% if the hot top weight ratio is 40%.

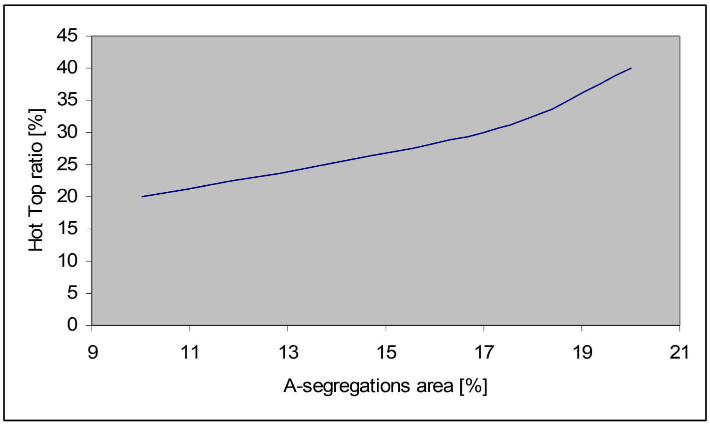
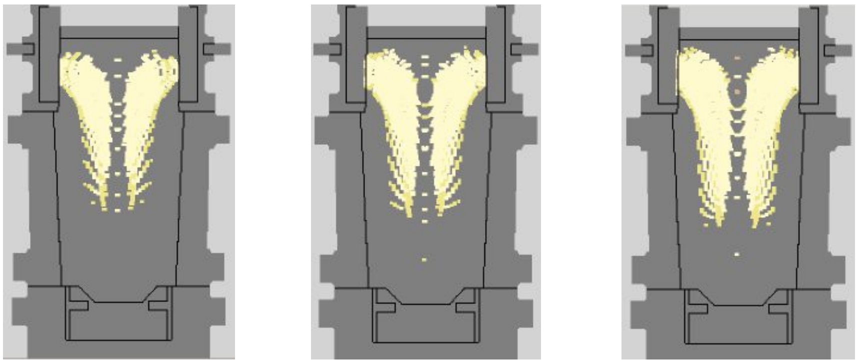


Figure 5. A-segregations zone ratio function by hot top size

5.4 Influence of initial mold temperature on A-segregation area

In these numerical experiments, the initial mold temperature has been between 20°C and 400°C. The results of simulations and the ratio of A-segregation zone Rs, are shown in Figure 6 a, b, c and Figure 7.



a) Tmold = 20°C b) Tmold = 200°C c) Tmold = 400°C

Figure 6. Influence of mold temperature upon A-segregations

With mold at the environment temperature, the area having A-segregations Rs, is around 16%. If the mold temperature is 400°C, the surface with segregation increases to 22%.

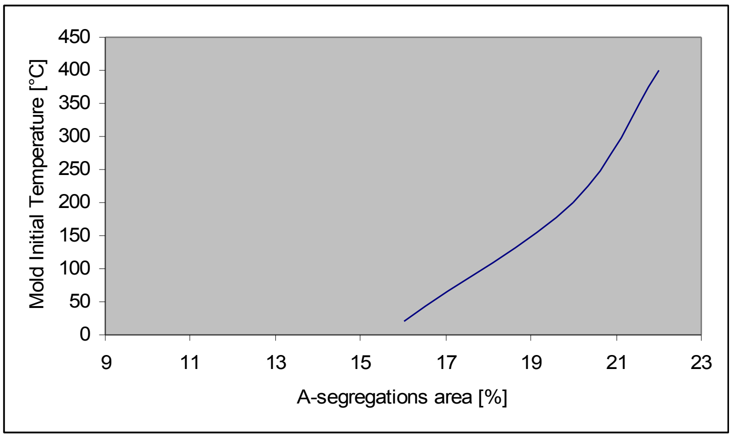


Figure 7. A-segregations area ratio function by initial mold temperature

6 Conclusions

Influence of pouring temperature, hot top size and initial mold temperature on the segregation process 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 AISI 4340 forging products. The following results were obtained:

(1) Minimizing the pouring temperature to an acceptable value, the area with A-segregations may be reduced with only 3%;

(2) It is not recommended to heat the mold before pouring. This will reduce the cooling rate during the solidification process and creates conditions for an extended segregation zone;

(3) From the analyzed parameters, the hot top size has the biggest influence on the segregation process. A small hot top size is recommended.

(4) Using the proposed ingot shape and size, it is not possible to have an AISI 4340 steel ingot free of A-segregations and have a forging product with mechanical properties homogenous only by changing the initial mold temperature, pouring temperature or hot top size;

(5) To obtain AISI 4340 forgings from 50 tons ingots free of segregation, the manufacturer has to find out other ways to increase the solidification rate. For example, changing the ingot shape and size or lower the critical value α, through the chemical composition of the steel, may be some of the solutions that can solve the problem;

(6) Using the simulation software to analyze the solidification conditions before the ingot is poured, the manufacturer can evaluate the casting technology before committing to expensive tooling and may make better decisions, save time, energy and improves the internal quality of the ingot;

(7) With the manufacturing records as data input for the simulation software, the buyer can know if the forging product is free of A-segregation and if the mechanical properties of the forging product will be homogenous or not. More, the simulation software can give information about the segregation position on the section of the ingot

(8) To appreciate quantitatively the A-segregation area, we have defined the parameter Rs, the ratio between area affected by segregation and the longitudinal section area of the ingot. This parameter may serve as global parameter to unify the influence of different technological variables on the ingot homogeneity.

As above-mentioned, this paper has clarified the influence of some of the casting technology variables on the A-segregation process and internal quality of forging products.

Through application of the results presented in this paper, it is possible to manufacture AISI 4340 forgings with increased homogeneity of mechanical properties.

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