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The Study of chemical Inhomogeneity Formation in Cast Ingots

This paper presents a study of chemical inhomogeneity formation indirect casting of a 6 to ingot, using the AnyCasting software (Var.3.10, 2009). The ingot was obtained from steel with a medium content of carbon alloyed with chromium, molybdenum and vanadium, type 1.2344 (X40CrMoV51) (conf. DIN 17350), using the procedure of ingot mould gravity filling (direct casting). Such an ingot is subsequently subjected to a hot plastic deformation in order to obtain flat semi-finished. The presence of these semi-finished of chemical inhomogeneities influences the behaviour of the ingot deformation.

Key words: *ingot, chemical segregations, gravity casting*

1. Introduction

The quality of the products obtained by hot plastic deformation of the cast steel ingot with a medium content of carbon and alloyed with chromium, molybdenum and vanadium, represents an important problem, being determined by physical and structural inhomogeneities and by chemical inhomogeneities. The obtaining of a homogenous ingot supposes the solving of divers problems regarding the distribution of chemical elements in the volume of the ingot, which together with thermo-physical parameters of mould filling and with the heat transfer coefficients compete in obtaining this structure.

Thus, the study of structure formation, respectively of the chemical inhomogeneities in the entire volume of the 6 to ingot, cast directly from steel, type 1.2344 (H-13, Air Hardening Tool Steel) (Table 1), in a classic ingot mould, obtained by grey cast iron casting is presented. Such an ingot is destined for hot plastic deformation in order to obtain flat semi-finished.

Table 1. Prescribed steel chemical composition 1.2344 [in weight %]

C	Si	Mn	Cr	Mo	V
0.32 - 0.45	0.80 - 1.25	0.20 - 0.60	4.75 - 5.50	1.10 - 1.75	0.80 - 1.00

For this purpose, the study starts from the stage in which the ingot mould is filled in with liquid steel, by gravity flow. In order to study the evolution of crystal-line structure formation, respectively of chemical inhomogeneities a proper simulation program was used - AnyCasting (Var.3.10, 2009).

The studies were theoretically realized by simulation, taking into consideration high temperatures in the development of metallurgic processes, with rigorous time limits, being compared to other studies realized abroad. These studies were made for ingots cast in Romania.

The simulation conditions are the following: casting temperature: 1550°C; mould preheating temperature: 80°C. The coefficients of thermal transfer are automatically set by the software.

The application of the software considers the hydrodynamics of the liquid steel jet and analyzes the behaviour of the metal jet in the mould. In real steel casting conditions the liquid metal jet may deform and even decompose due to an air resistance, the action of gravity forces and the interior forces determined by the turbulent and curved character of liquid flow. Thus the formation of three areas can be observed in the jet: the continuous area, dense and characteristic for the jet stable state; the vibrant area in which the continuity of the jet is turbid; and the decomposition area in which the jet is decomposed into drops.

The theoretical aspects regarding solidification published so far, the apparition of chemical segregation and the laws that govern these phenomena are the following:

- the concentration of chemical elements from the solidification front is fed by description from the surface of the solid phase during the transfer towards the liquid limit is made by diffusion. The reaching of a stationary regime leads to the idea of a layer of maximum concentration in contact with the solid;
- the thickness of the solidification and the diffusions front depends on the temperature gradient, on the cooling speed and on the diffusion coefficient; for a given elements this process is realized by mechanical mix determined by convective currents in the melt;
- in the case of convective homogeneity of liquid concentration in contact to a limited diffusion layer, the value of the effective coefficient of distribution is dependent on the value of equilibrium repartition coefficient, on the mass transfer coefficient, on the cooling rate and on the temperature gradient.

2. The study of chemical segregations formation

For an application of a direct casting procedure for the ingot presented in this study, the software used highlighted the fact the mould filling was realized at a filling speeds of 8m/s.

During the application of this casting variant, it has been proved that there is a great possibility for the formation of casting flaws specific to ingot casting by gravity filling: open pipe and sometimes closed at the superior side of the ingot; micro-

sulphides (pinches) on the thermal axis of the ingot and a high concentration of inclusions and oxides in the entire volume of the casting (Figures 1-2).

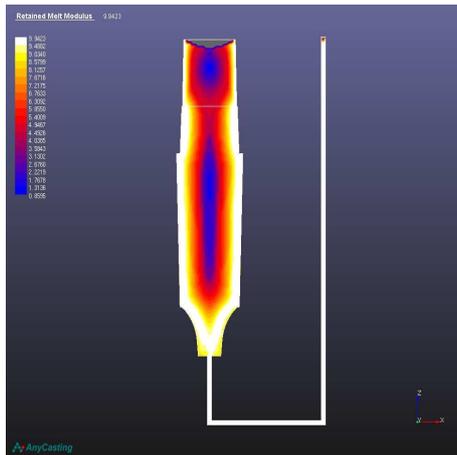


Figure 1. The positioning of casting flaws in the ingot, using the "retained melt modulus" criterion

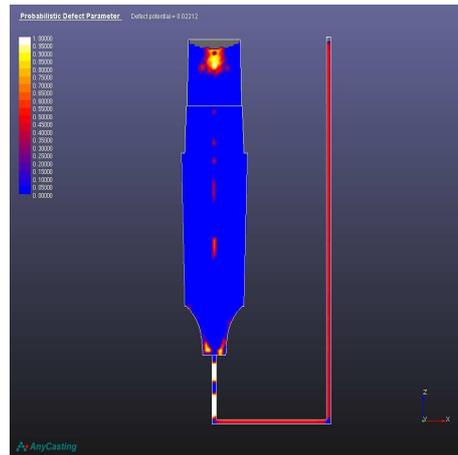


Figure 2. The positioning of casting flaws using the temperature gradient criterion.

These aspects were taken into consideration because the study of the chemical elements segregation will also highlight these structural particularities.

In the analysis of chemical segregations the carbon and chromium segregations will be the ones highlighted, these chemical elements being able to form carbides in the structure and on the segregations of manganese and sulphur, which are inclined to form sulphides (sometimes even complex sulphides, with iron). The study of segregation for the main chemical elements of alloyed steel, cast in ingots, is made in vertical sections of the ingot.

By forming chromium carbides which are separated at grains limits, the chromium concentration in the grain will significantly decrease.

If the final product comes into contact to water, the presence of manganese sulphides may determine the product corrosion by oxidation. Water has an acid character, if it comes from flowing water (from rivers) or if it is industrial water, it is more corrosive due to active impurities present. Thus, it is very important to know the phenomenon of chemical segregation in such ingots.

For starters, the carbon distribution will be analyzed followed by the chromium distribution, and in the end of these discussions regarding the segregation of chemical elements, the segregation of manganese and of sulphur will be presented.

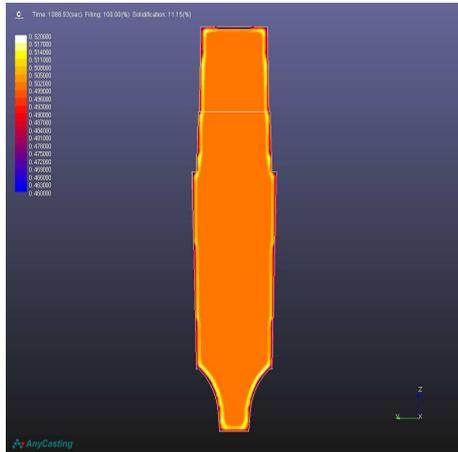


Figure 3. Carbon distribution in the ingot during a solidification of 11.15%, of the steel volume

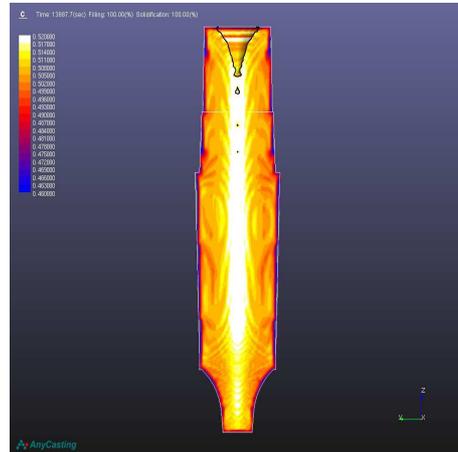


Figure 4. Carbon distribution in the ingot, during a complete solidification

For a solidification of 11.15 %, of the ingot volume (Fig. 3), realized after a period of 1088.93 seconds from the ingot mould filling, immediately after the formation of a solidified rim, regarding the carbon distribution, the following can be observed: a concentration of 0.487%C, close to the surface of the ingot on the walls of the mould (rim); the following layer liquid is increased with 0.514%C and layer decreased to 0.505%C, in the entire volume of liquid steel, in comparison to the buffer liquid layer between the rim and the rest of the liquid, but which is increased in comparison to the rim concentration.

After a complete solidification of the cast steel in the mould realized in 13887,7 seconds, the carbon distribution is the following (Fig. 4): it decreases to 0.475%C in the rim in comparison to the phase in which a solidification of only 11.15% was observed in the ingot volume and reaches a medium of 0.520%C, in the rest of the ingot (an oscillation between 0.514 and 0.520% is observed in the median area of the ingot, vertically), with the exception of the area belonging to a thermal axis, where the carbon concentration has values of 0.520%, in the central area of the ingot and in the inferior side of the feeder. At the base of the ingot a concentration of 0.520%C is presented under the shape of islands, surrounded by a carbon distribution, basket shaped of 0.514% (carbon oscillations concentrations similar to those from the median area of the solidified ingot).

A macropipe is formed in the feeder and a porous area, situated on the thermal axis of the ingot (more accentuated in the superior area of the ingot).

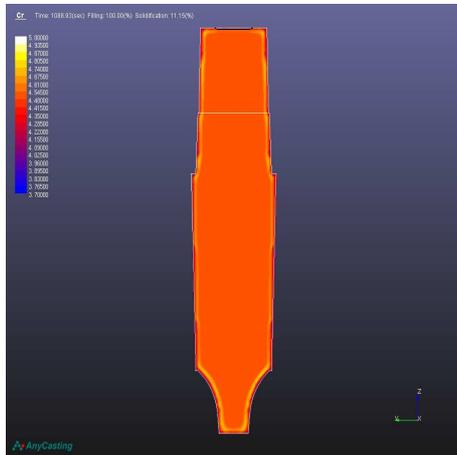


Figure 5. Chromium distribution in the ingot, during a solidification of 11.15%, of the steel volume

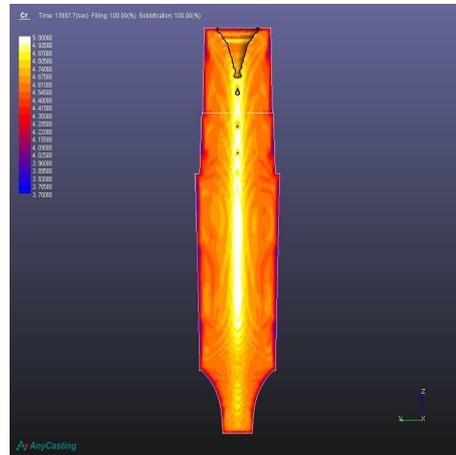


Figure 6. Chromium distribution in the ingot, during a complete solidification

During the stage in which only 11.15% of the total liquid volume solidified (Fig. 5), the chromium distribution in the volume is similar to the carbon distribution: at the mould interface a chromium concentration of 4.285% is observed, which is later increased to 4.745% in the buffer rim liquid solidified – the rest ingot, because in the other liquid layers it is decreased to 4.54% (higher than in the solidified rim). The intermediary layer can be observed where the chromium concentration is of 4.74% and it is thicker at the base of the ingot in comparison to the other area of the ingot.

Regarding the chromium distribution, during complete ingot solidification (fig. 6), the situation is almost the same as in the case of carbon distribution, with the exception of the fact that concentrations fluctuations are more presented than in the case of carbon distributions, but in general, these respect the same distribution rules. Thus, in the rim, the chromium concentration is situated at values of 3.960% (law in comparison to concentration in the ingot volume) so that in the following layer this distribution is increased to 4.285%, alternating to “currents” of concentrations of 4.545%; while in the area close to the ingot thermal axis alternation of chromium concentrations can be observed between 4.740-4.805%. In the central area of the ingot, higher values of chromium concentration of 5.000% can be observed.

By observing variations of chromium and carbon, we may sustain that in the area where the chromium and carbon concentrations are lower in comparison to the rest of the ingot, there is a possibility for pure chromium carbides formation ($Cr_{23}C_6$), but the possibility of complex carbides formation of iron, manganese and

chromium cannot be excluded $[(Cr, Mn, Fe)_{23}C_6]$. The areas are: the ingot rim, in which carbides prevail and in the area close to the vertical axis of the ingot, because in the thermal axis this process is greatly diminished.

This affirmation regarding the formation of complex carbides is also based on the study of carbon distribution and the ingot (Fig. 7÷10).

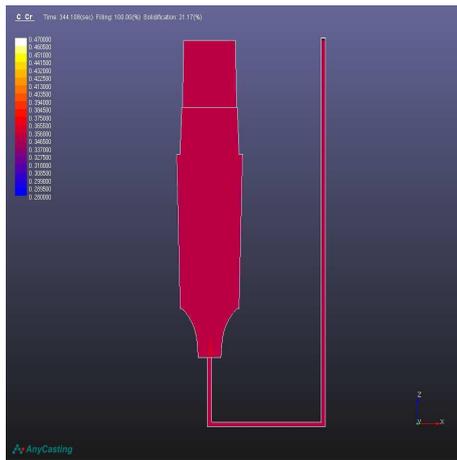


Figure 7. Carbon distribution on chromium carbides during a solidification of 21.17%, of the steel volume

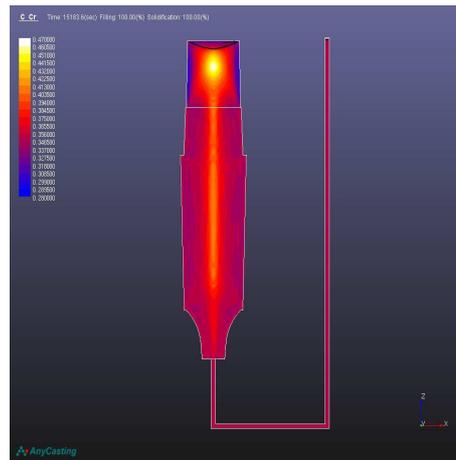


Figure 8. Carbon distribution in carbides during a complete solidification

Unlike the cases in which the carbon and chromium distributions were studied, during a solidification of 11.15%, when distributions of the two elements begin to be clearly observed in the solidified rim and in the volume of the liquid steel, during the study of carbon distribution in carbides the following conclusion was obtained; after a period of 344.108 seconds, for a solidification of 21.17% of the alloyed liquid steel (Fig. 7), the formation of chromium carbides is not highlighted, thus there is no clear clarification on carbon distribution in carbides.

During a complete solidification of the cast alloyed steel in the mould, the carbon distribution in carbides is presented in the following manner (Fig. 9): in the exterior of the ingot, the carbon distribution in carbides decreases from 0.337% to 0.3275%; in the following layer, with a greater thickness that varies 0.375% to 0.3845%; in the thermal axis of the ingot the situation regarding the carbon repartition in carbides presents an increase from 0.4135 to 0.422%, because in the same axis of the feeder is has a greater concentration of carbon in carbides, from 0.4415 to 0.451%.

Taking into consideration the conditions for the formation of manganese sulrims, respectively complex iron and manganese sulrims, the manganese sulphur distributions will be analyzed in figures 9÷12.

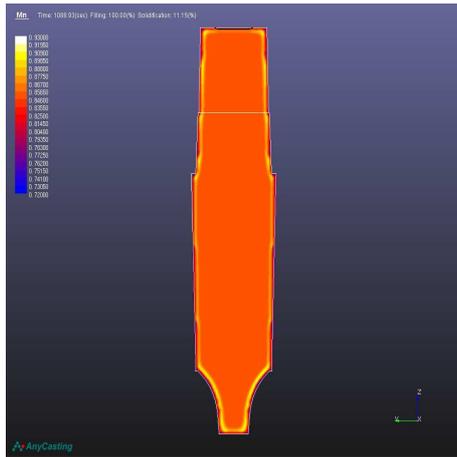


Figure 9. Manganese distribution in the ingot during a solidification of 11.15%, of the steel volume

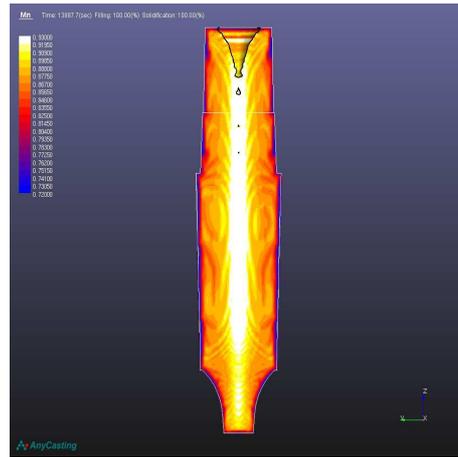


Figure 10. Manganese distribution in the ingot during a complete solidification

After a solidification of 11.15% of the cast liquid steel in the mould, in the rim formed, the manganese concentration (Fig. 9) is of 0.804% (more accentuated at the base and in the superior side of the ingot), and in the following layer is increased 0.888%,; in the entire volume of liquid steel a concentration of 0.867% is kept.

After a complete solidification of the cast ingot, the situation of manganese segregation in the vertical section of the ingot is presented in the following manner (Fig. 10): starting with the exterior layer, where the manganese is tuition at a concentration of 0.741%, following that in the next layer towards the exterior of the casting to alternate between 0.8355 and 0.867%, 0.8985%, and in the middle of the ingot it can reach a concentration 0.93%.

Studying the sulphur distribution on a vertical section in the liquid steel, cast in a mould, and on the vertical section of the ingot (Fig. 11-12), it can be observed that after the formation of a solidified rim at the contact with the mould (11.15%) and in the rest of liquid steel in the mould the sulphur concentration is kept at 0.236%.

After a complete solidification in the steel cast in a mould, the sulphur distribution, on a vertical section of the ingot, varies little in comparison to other chemical elements studied. Thus, in a thicker layer of the ingot, towards the exterior, the

sulphur has a concentration of 0.2325%, so that in the thermal axis of the ingot, this is increased to 0.236%.

Analyzing the manganese and the sulphur on the vertical section of the ingot, it may be considered that there are sections in the ingot where the sulphur is found in a free state, but there are also areas where the sulphur is found as MnS, FeS or even FeMnS.

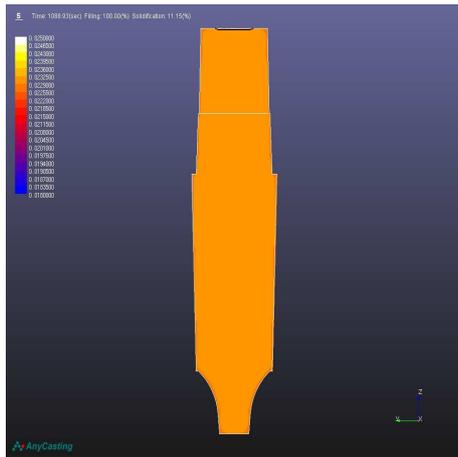


Figure 11. Sulphur distribution in the ingot during a solidification of 11.15%, of the steel volume

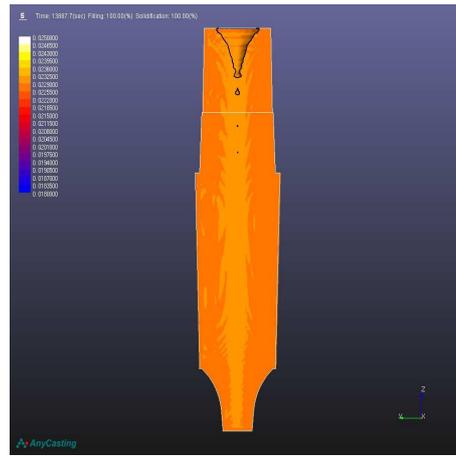


Figure 12. Sulphur distribution in the ingot during complete solidification

3. Discussion

The diffusion and the distribution of chemical elements in the volume of the cast ingot may be also analyzed by studying the particularities of physical properties (viscosity, density) of cast steel and the evolution regarding the formation and development of phases and metallographic constituents during the cooling process of the liquid steel, of the liquid-solid transformation and the cooling of solidified castings. Thus:

- The variation of steel flowing rate: the liquid steel flowing rate decreases rapidly at temperatures of 1550-1500°C (duration: 50 sec.), it slowly decreases at temperatures of 1500-1490°C (duration: 200 sec.), and under the temperature of 1490°C it decreases very fast (≈ 1200 seconds, until the complete formation of the solid fraction);

- The variation of liquid steel density presents an anomaly: for temperatures of 1550-1520°C, the density of liquid steel it is slowly increased from 6.85 g/cm³ to 6.90 g/cm³, and it subsequently decreases at 6.8 g/cm³, at temperatures of 1520-

1400°C. One with another, at the same time the liquid steel is cooled, by decreasing the temperature of 1520°C to 1450 °C, a sudden increase of the density is obtained from 6.9 to 7.15 g/cm³ correlated to the gradual increase of steel density during the liquid-solid transformation and during the cooling of the solidified steel, so that at a complete cooling the value reached is of 7.75 g/cm³;

- On the other side, the viscosity variation of cast steel in the ingot mould presents a predictable evolution. Thus, at the same time with a decrease in temperature from 1500°C to 1180°C we can observe a slight decrease of steel viscosity from 5.5 MPa·s to 8 MPa·s, and in a small interval of temperature (1180-1160°C) a rapid increase to 10000 MPa·s is observed and later at 100000 MPa·s, by lowering the temperature at 1040°C;

- The variation of chemical elements content during the cooling process of the liquid steel, during the liquid-solid transformation and subsequently during the process of solid cooling is presented as follows: chromium is slightly decreased in the liquid, but significantly decreased when the solid fraction is over 0.65 (65%, of the cast steel volume); molybdenum is slightly increased in the liquid, but it begins to significantly increase during the formation of 57.5% solid phase; carbon has an almost insignificant evolution even if it seems to present a slight increase during the process of solid fraction formation in volume.

* The analysis of chemical segregations formations has underlined a unanimous recognition that: the formation of a porous area (micropipes) on the thermal axis of the ingot gravity cast and solidified in the mould.

* The existence of many anomalies regarding the ingot chemical homogeneity.

* The possibility and unequal formation and distribution of chromium carbides in the structure with an influence on the resistance to cavitation erosion and corrosion.

* The existence of inter-granular areas that contain chromium carbides in the ingot structure, respectively in the structure of final products leads to the generation of internal tensions concentrators.

* The formation of structural micro-areas in which simple and complex sultrims of iron and manganese can concentrate and have an unfavourable influence on mechanical properties of restored castings, at normal and high temperatures.

4. Conclusion

In this study regarding steel type 1.2344 (X40CrMoV15) solidification and the distribution of chemical elements in the structure using the AnyCasting software - Var.3.10.2009, the fact that the structure of the directly cast ingot (gravity casting) underlines the structural areas with massive chemical on sections and in the entire volume. Thus, significant areas were observed, where the concentration of basic chemical elements and alloys is situated in higher concentrations than at the superior limit prescribed for steel types. This phenomenon supposes the existence of bordering areas significantly poorer in those chemical elements. Such a distribution

is difficult to observe, at a simple analysis of the distribution colours, the software considering that these nuances are very adjacent.

The unequal distribution of chemical elements in the structure may be caused by an unequal diffusion of chemical elements, by their speeds in different sections of the liquid steel jet, by the currents of the alloy jet and by the cooling rate insured by the mould.

Taking into consideration these structural aspects, the processing by plastic deformation and the processing of ingot gravity cast from steel alloyed with chromium and molybdenum doesn't allow the production of various casting, as a result of chemical and structural inhomogeneities.

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