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Increasing Precision and Yield in Casting Production by Simulation of the Solidification Process Based on Realistic Material Data Evaluated from Thermal Analysis (Using the ATAS MetStar System)

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Abstract

The conducted work shows and confirms how thermal analysis of grey and ductile iron is an important source for calculating metallurgical data to be used as input to increase the precision in simulation of cooling and solidification of cast iron. The aim with the methodology is to achieve a higher quality in the prediction of macro– and micro porosity in castings. As comparison objects standard type of sampling cups for thermal analysis (solidification module $M \approx 0.6$ cm) is used. The results from thermal analysis elaborated with the ATAS MetStar system are evaluated parallel with the material quality (including tendency to external and internal defects) of the tested specimen. Significant temperatures and calculated quality parameters are evaluated in the ATAS MetStar system and used as input to calibrate the density curve as temperature function in NovaFlow&Solid simulation system. The modified data are imported to the NovaFlow&Solid simulation system and compared with real results.

Keywords: Ductile iron, Simulation and defect prognosis, Density calibration, Thermal analysis

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1. Introduction – Background

It is a common experience for a foundryman to compare the shrinkage defects in castings produced in the foundry and the results from a simulation of the filling and solidification process using a commercial simulation system that they do not always show the same result. The practice most frequently used today, is to take parameter values from literature to use as input for the calculations. The simulated result is in many cases close (but not always) to reality in terms of temperatures, cooling speed and solidification time. However, the prognosis for calculation of shrinkage defects (macro and micro) could show a large discrepancy from the real results. The fact is if the same casting is simulated, using the same material data, in another foundry with a similar metallurgical production process, the simulated results and the actual "real" result could be very different.

The material standard of the cast iron is the same, the same target for chemical composition, the same pouring temperatures and filling times but the "real metallurgical production" in a foundry process show variations caused by the metallurgical conditions, chemical composition holding times and metallurgical treatment methods for magnesium addition. The final quality of the raw casting is also influenced by properties in the mold material. The conclusion is that a metallurgical process has a certain process window, there are metallurgical parameters which show variations from one batch to another and the process window is different from one foundry to another. The differences and variation may not be large, but it could have strong influence on the final casting quality.

For example, the Fe-C binary phase diagram, developed for thermodynamic equilibrium conditions, gives important but only general information about how the variation of the carbon content influences the liquidus temperature and allows to estimate (quantitatively/qualitatively) of the maximum possible precipitated volume of graphite during the solidification process. The total carbon content and the effect on the precipitation of graphite particles are key parameters for grey- and ductile iron to produce a casting free from macro and micro defects, considering the balance of expansion of graphite and contraction of austenite.

The conducted work shows and confirms how thermal analysis of grey and ductile iron could be used as a source for calculating important metallurgical data. The information could be used as input data to increase the precision in simulation of solidification of cast iron and contributes to achieve a higher quality in prediction of macro and micro porosities in the castings.

Standard type of sampling cups for thermal analysis ($M \approx 0.6$ cm) are used for the thermal analysis. The results from thermal analysis elaborated with the ATAS MetStar system are evaluated parallel with the material quality (including tendency to external and internal defects) of the tested ATAS castings.

2. State of art

Limitations and uncertainty of physical data as input for simulations is a challenge to calculate properties with a high precision in cast components. Material data must be adopted to several process types and these processes are described with different models for the calculations and predictions, depending on the brand of commercial simulation program [1]. Many of the commercial systems have a standard set of original data due to high expectations on optimization of the production process and component design, more and precise data is needed. The lack of data to describe the practical conditions in the process and the standard data set is not accurate enough.

There are both commercial and open sources available to collect material data for example Thermocalc, JMatPro, inverse solutions, technical articles, from laboratory and industrial tests. However, some of these data is calculated under equilibrium conditions and information from databases and other data are assessed from tests with specific and local boundary conditions. Nilsson [2] are pointing out that there is a metallurgical variation of the important parameter's which defines the final properties in the castings, both mechanical and physical macro/micro defects (shrinkage). Ignaszak and Popielarski [1] validated several simulation codes and found a difference in data and results of the calculated results. Bertuzzia, G. Scarpab [3] discuss the need for performing practical test and create data for input for the specific metallurgical production of cast iron. Nilsson [2], Stefanescu [4] Sparkman [5] and Tremblay [6,7] have in detail described the role of methods for metallurgical process control based on thermal analysis for collecting and calculating metallurgical data for real industrial conditions.

ATAS MetStar is a metallurgical process control system based on thermal analysis, the system has functions to collect, calculate and analyze process data. The main purpose with the system is to control the metallurgical production process for producing grey- and ductile iron. The system has functions to calculate and export parameters to be employed in the simulation system NovaFlow&Solid.

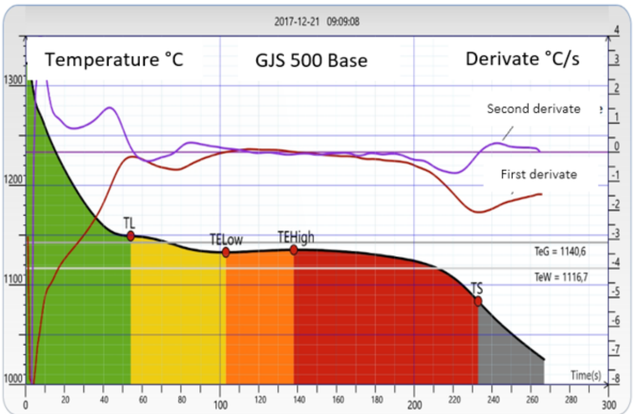


Fig. 1. An example of cooling curve evaluated with ATAS MetStar for a hypoeutectic ductile iron GJS 500 before final inoculation

The objective with this paper is to prove that the adequate connection between DTA system and simulations systems is possible to increase precision in the prediction and optimization of the casting quality.

The data from thermal analysis elaborated with the ATAS MetStar system [8,9] are evaluated (Fig. 1, above) parallel with the internal material quality (including tendency to external and internal defects using X-ray) of the poured ATAS sample. The sample for the ATAS analyses is used as the "casting geometry" for the comparison of real results and simulated results.

3. Problem description

NovaCast Systems develops systems for calculating gating and feeders and simulation of the complete castings process, e.g. mold filling, solidification and residual stresses, using suitable micro/macro models. The systems from NovaCast should be perceived as a tool box for analyzing, stabilizing and optimizing the whole casting process chain.

3.1. Metallurgical conditions in a real foundry environment

Using a metallurgical process control tool based on thermal analysis is one way to document the variation in the metallurgical cast iron quality in a foundry. Figure 2 shows the variation of the liquidus temperature (TL) for a ductile iron GJS 500 after final inoculation.

The variation of the TL value is within the specified minimum and maximum interval, 1140 to 1153 °C (area in green color in the diagram).

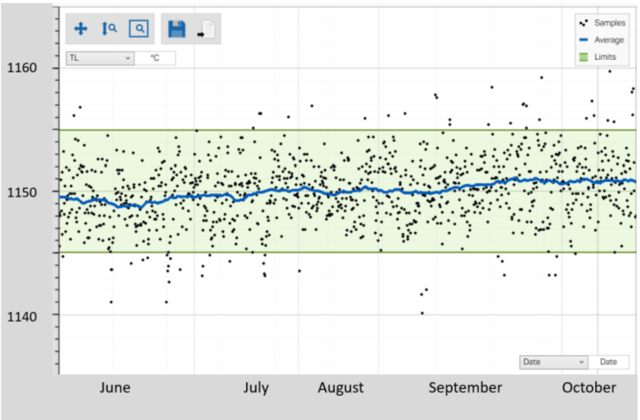


Fig. 2. Variation of the of the liquidus temperature for GJS 500 after final inoculation. The diagram shows the results in production under a period of 6 months (June to November). The defined process window for TL is in this case 1140 – 1153 °C (area in green color). The blue line represents calculated running average

However, there are also values outside the control limits. The variation of TL will be reflected in the metallurgical quality and influence important parameters characterizing cast iron quality. It is important to note that even if the variation is considerable the chemical analysis is consistent and within the standard for the iron.

Significant temperatures and parameters concerning the metallurgical conditions of the melt are calculated from the cooling curves. The Active Carbon Equivalent (ACEL) is evaluated from the Liquidus temperature (TL) and lower eutectic temperature (TELow),

ACEL% = 14.45+ (- 0.0089·TL (°C) + Constant ·TELow (°C))

Figure 3 below shows the ACEL value in the melt calculated from the information in Figure 2. The method used for the calculation is the six σ method for process control and process capability studies. The distribution of ACEL is calculated and graphically presented as a "bell" diagram. The x-axis shows the statistical dispersion (negative and positive) and the height of the column shows the number of values that are calculated to be within each dispersion interval.

The variation in ACEL is considerable and the solidification morphology is sometimes hypoeutectic, eutectic or hypereutectic. The Fe-C binary phase diagram, elaborated years ago in quasi-stationary laboratory conditions and developed for so called thermodynamic equilibrium conditions, gives important but only general information about how the variation of the carbon content influences the liquidus temperature and allows to estimate quantitatively the maximum possible precipitated volume of graphite during the solidification (by progressive crystallization of all possible phases) process. Total carbon content in liquid cast iron and participation in it the precipitation of graphite phase in solid state are key parameters for grey- and ductile iron to produce a casting free from macro and micro defects, considering the balance of austenite contraction and the expansion of graphite.

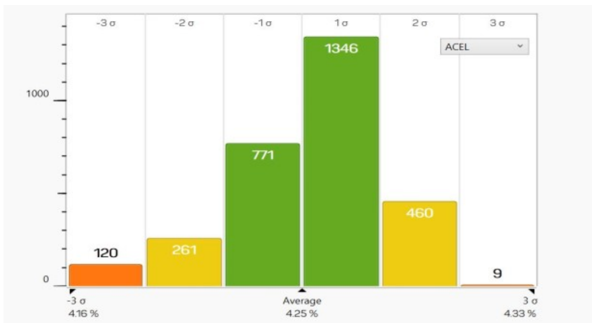


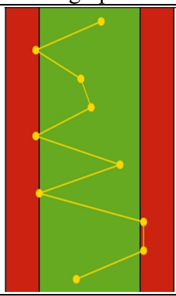
Fig. 3. Example of production statistics analysed using the six σ-method for ACEL final ductile iron after inoculation based on results show in Fig 2. The distribution of ACEL is calculated and graphically presented as a "bell" diagram. The x-axis shows the statistical dispersion (negative and positive) and the height of the column shows the number of values that are calculated to be within each interval. Lower control value is 4.16 % ACEL and the upper control value is 4.33 %. The largest group of ACEL values, 771 + 1346 samples is within -1 σ to +1 σ

The metallurgical quality of the final melt is not consistent. The quality as a variation between charges and each ladle tapped from the furnace. The statistics in Figure 3 shows the variation for ACEL in the final ductile iron after inoculation. The practical conclusion is, for the same type of castings the foundry must prepare and use a "universal" gating and feeding technology that could be successful for all types of solidification morphologies (hypoeutectic, eutectic, or hypereutectic) which in practice is an impossible task.

3.2. Parameters which describes the metallurgical quality of the melt

The significant temperatures which describes the basis of metallurgical quality for the solidification process are evaluated from the DTA cooling curve. To have a higher accuracy in the determination of the temperatures the system uses information from the 1st and 2nd slope, marked in Figure 1. Some of the significant temperatures and important parameters as example, are given and explained in Table 1.

Table 1.
Significant temperatures and parameters evaluated by the ATAS MetStar system. The example is from a hypoeutectic ductile iron. S1 represents the precipitated amount of proeutectic austenite, GRF1 and GRF2 are factors describing the effectiveness of the precipitation of graphite

Indicator	Min	Current	Max	Fingerprint
TL	1140.0	1149.2	1155.0	
TES	1143.0	1141.5	1154.0	
dT/dt TES	-1.00	-0.59	0.00	
S1	20.0	27.7	35.0	
TELow	1138.0	1132.8	1148.0	
R	0.5	2.5	3.0	
GRF1	70	70	100	
GRF2	15	109	40	
dT/dt TS	-5.00	-2.07	-3.00	
TS	1055.4	1083.7	1132.4	

The lower eutectic temperature (TELow) gives important information about the nucleation/phase growth properties in the melt. With the same philosophy as above for TL, the value of TELow is analyzed for a group of melts to determine the nucleation conditions for production of ductile iron.

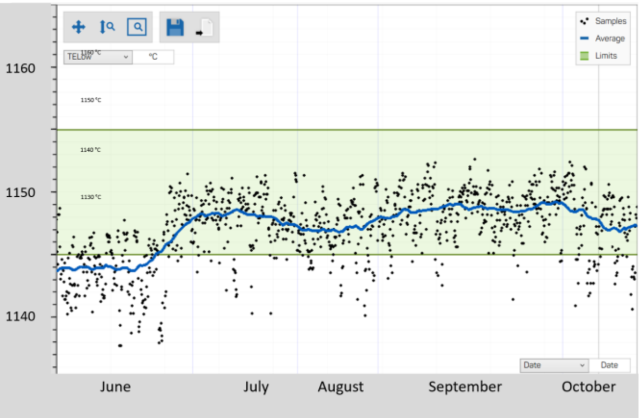


Fig. 4. The lower eutectic temperature, TELow, determined with ATAS MetStar for typical ductile iron production, the same final ductile iron and group of samples as in Figure 2. There are a large scatter and there are both low values, risk for micro porosities and carbides, and high values risk for hypereutectic solidification morphology

It is important to understand the individual value and the variation of TELow between melts are strongly depending on the solidification morphology. If the melt has a hypoeutectic, eutectic or hypereutectic solidification morphology the variation of TELow must be analyzed using the correct (by definition) group.

From the collected data significant parameters are calculated by the ATAS MetStar system which characterize the metallurgical quality. These values illustrate how efficient the precipitation of graphite is during the entire solidification process. Based on empirical findings, two parameters, GRF1 (Graphite Factor 1) and GRF2 (Graphite Factor 2) is developed. These factors explain the effectiveness of the precipitation process during the latter part of the eutectic transformation. GRF1 is identified and calculated from the point at the highest eutectic temperature (TEHigh) and forward to the Solidus temperature (TS) which is the point where all melt is consumed (liquid fraction LF= 0), the material is 100 % solid, the value of GRF2 is identified and calculated. Information for these two values and the combination of both, gives valuable supplementary information about the metallurgical quality of the melt and the risk for defects in the castings.

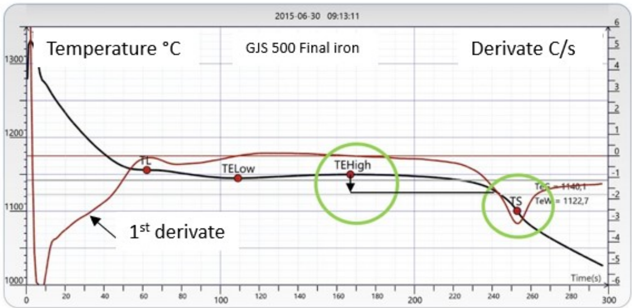


Fig. 5. Example of the cooling curve (black solid line) for determination of GRF1 and GRF2 (the alloy is Ductile cast iron GJS 400). Red line is the first derivative, cooling speed °C/s

3.3. Quantitative calculations of shrinkage behaviour

From the 1st and 2nd derivative it is achievable to detect significant points where changes in the nucleation and growth process of austenite and graphite (sometimes even carbides) is verified. Based on this information the possible amount of graphite is calculated for each phase during the solidification and cooling process in the cup. In Figure 5, one example for a hypo eutectic ferritic ductile iron is shown.

The carbon content (CTL) is calculated based on the liquidus temperature (TL) and the information concerning silica- and phosphorous content evaluated from a spectrometer. The CTL (Carbon content from Liquidus Temperature) value has a high accuracy in comparison with a carbon value evaluated with a spectrometer. In order to have a high precision in the carbon evaluation using a spectrometer, the sample quality have to be completely solidified as white iron in combination with a frequent calibration interval and a high service level of the spectrometer equipment. The calculation of CTL can be compared with the calculation of the ACEL value (Active Carbon Equivalent) which is computed using an equation consisting of liquidus temperature (TL) and lower eutectic temperature (TELow).

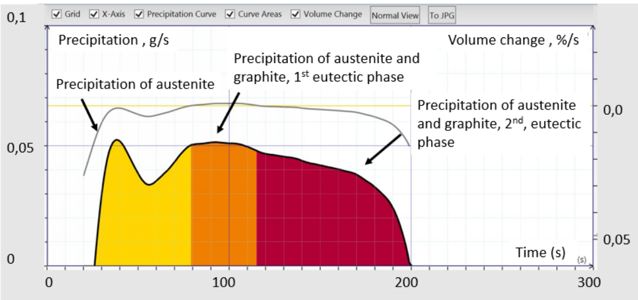


Fig. 6. Diagram showing the precipitation of graphite and austenite for a GJS 400 final ductile iron based on the ATAS MetStar system

In order to estimate the shrinkage, it is necessary to combine this information with the carbon content (CTL) and the target pouring temperature. The amount of shrinkage is calculated for each phase, liquid, semi-solid (during solidification process) and solid to calculate the total shrinkage of the iron.

The conducted work shows and confirms how thermal analysis of grey and ductile iron could be adopted as a source for calculating important metallurgical data. This data can be used as input to modify the chosen database parameters and increase the precision in simulation results of cast iron solidification to achieve a higher quality in prediction of macro and micro porosities in the castings. Thus, the standard type of DTA sampling cups (solidification module M= 0.65 cm) are used for the usual thermal analysis. The results from thermal analysis elaborated with the ATAS MetStar system are evaluated parallel with the material quality (including tendency to external and internal defects) of the tested ATAS castings.

In the quasi-equilibrium model there is a dependence of temperature and liquid phase fraction. This dependence is obtained different for type of castings processes and casting geometries because of the conditions for heat removal., but in the limits of one casting the beginning and end of solidification are the same in all points of the casting.

4. Basic methodology for experimental and virtual tests

The investigated alloy is GJS 500-7. Chemical composition for A1-A2 specimen is presented in Table 2. The ductile iron is produced using a cored wire method. Parallel with the addition of FeSiMg the melt is pre-inoculated using a cored wire inoculant. For the tests a standard measuring cup produced with the “Croning” process (shell sand) for thermal analysis is used, the dimensions of the test body (Figure 7).

The metric dimensions of the cup cavity, A= 40 mm, B= 37 mm, C= 32 mm. Position of the thermocouple, D= 20 mm

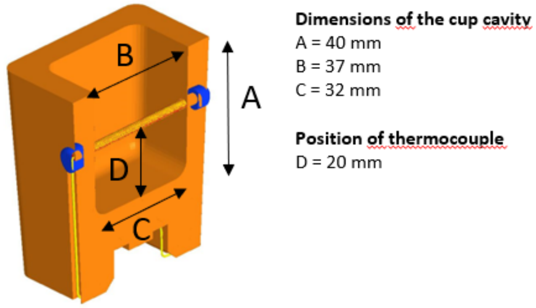


Fig. 7. The classic design of a measuring cup for thermal analysis (CAD model)

The sampling of the TA specimen was made in running production. Samples without any inoculation and inoculated samples were poured parallel. The inoculated samples were inoculated with 0.06 % (0.2 g), Inolate® inoculant. The inoculant, which is carefully weighed to a precise amount, was added at the bottom of the measuring cups before pouring. A total of 15 series, inoculated/not inoculated, were poured [10].

4.1. Experiment methodology

The metallurgical quality of the cast iron sample was analyzed with ATAS MetStar and after cooling and cleaning the samples were analyzed with X-ray, 3D-image and finally prepared for microstructure analysis.

4.2. Simulation analysis in NovaFlow&Solid model

A 3D description of the experimental measurement set up in *.stp format, TA cup and test body, was imported to the process simulation system NovaFlow&Solid 6.3. The parameters describing the boundary/initial conditions, such as surrounding air temperature, radiation, sand mold data, chemical composition and the analyzed metallurgical quality modified based on the results from thermal analysis were set as input data for the simulation study. The sensibility of the NF&S system for changes of modification of major database parameters: density as a function of temperature ρ = f (T), values of critical liquid fraction CLF (upper and lower for feeding phenomena) and liquid fraction curve between TL and TS were evaluated.

5. Results and discussion

5.1. Chemical composition

The chemical composition was analyzed with a spectrometer. The results are tabled in table 2. The Sulphur level after treatment has the highest content in A1/A2 (0.0186 %).

Table 2.
The chemical composition for specimen A1 and A2

Test ID	C	Si	Mn	P
A1/A2	3.65	2.16	0.708	0.0233
S	Cu	Mg	CE	SC
0.0186	0.1203	0.0498	4.31	1.01

5.2. NDT measurements

The results of the X-ray investigation by GE Phoenix v x s 240 machine (confirmed by visual testing after cutting) were rated according to the morphology and the size of shrinkage defect. The rating is shown in Table 3 and examples of the defects is presented in Figure 8. The rating is a proposal from NovaCast Systems.

Table 3.
Conventional rating of the shrinkage defects in DTA samples. The rating is a proposal from NovaCast Systems

Porosity type/morphology	Rating
No, or minor porosity	1A
Small "mushy" porosity below element	2B
Small "mushy" porosity above element	3C
Large "Mushy" porosity around thermocouple	4D
Large hollow porosity below thermocouple	5B
Large hollow porosity above thermocouple	5C
Large hollow porosity surrounding thermocouple	5D

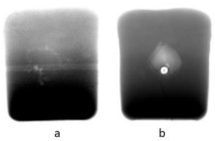


Fig. 8. Examples of X-ray photos and rated quality. Figure a, sample E1 (inoculated), has rating 3C, small mushy porosity above thermocouple. Sample in figure b, sample E2 (no inoculation) has quality rating 5D, Large hollow porosity above thermocouple

Table 4.
Results of the shrinkage evaluation from the X-ray tests, the rating is according to the proposal from NovaCast Systems AB (Table 3).

Test ID	Date	Porosity rating sample A1 inoculated	Porosity rating sample A2 NOT inoculated
A1-A2	2017-12-21 09:09	1A	5D

The thermocouple and glass tube (which is "cast in" in the test body) is marked with arrows in Figure 9. Some test bodies show an angle on the upper surface, the surface is oblique (e g sample in Figure 9 b). The measuring cup has most likely been positioned with a small angle to the sampling stand before the cup was poured. The examples in Figure 9 are for sample A1 and A2, are to demonstrate a typical morphology of the shrinkage defect and how the outer surface of the body has changed during solidification and cooling. In three poured tests the quality in the inoculated sample and the not inoculated sample have the same rating, namely, G1/G2, J1/J2 and K1/K2. One of the inoculated samples had the worst rating, K1/K2. However, three inoculated samples have rating 3 and 4.

From the test series sample A1 and A2 were chosen to be more thoroughly examined. The results presented in Figure 10 is from sample A1 and sample A2. The position of the shrinkage defects is in the center close to the thermocouple.

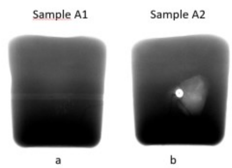


Fig. 9. Result of shrinkage size and position figure 9 a , for sample A1 (inoculated)and figure 9 b, sample A2 (not inoculated).The position of the thermocouple is indicated with white arrows. There is a clear tendency to form a "waist" on the A1 sample, the waist is indicated with black arrows. The indication on "top" of figure b shows the angle of the upper surface

Sample A1 and A2 were cut with a 90° angle to the thermocouple. The samples were polished, and the porosities are documented.in Figure 10.

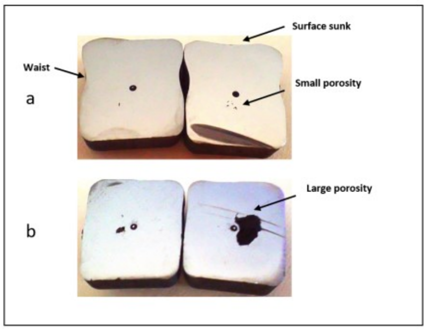


Fig. 10. The specimen cut and polished shows the result of shrinkage size and position for samples A1 (inoculated) figure 10 a and figure 10 b A2 (not inoculated). There is a clear tendency to form a "waist" and surface sunk on the sample, indicated with black arrows

5.3. 3D analysis

The outer dimensions of the sample were analyzed with a 3D scanning apparatus (ATOS Compact Scan 2M, GOM company).

Figure 11 gives information about the how outer surface is deformed during the cooling and solidification process.

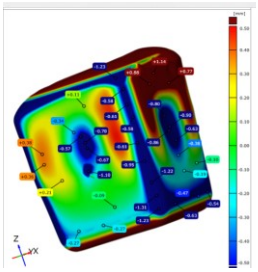


Fig. 11. Results of 3D analysis made on one of the samples. Dark blue colored areas represent a depression (negative deformation) of the surface and deep red color shows a positive deformation of the outer surface

To calculate a "waist" or" surface shrinkage" it is necessary to make a calculation which could describe the plastic deformation of the test body. The "waist" is more pronounced in the inoculated samples.

5.4. Microstructure

The microstructure has a high nodularity in sample A1 (inoculated sample). In A2, (without inoculation) the sample shows a degenerated graphite structure, a low nodule count and low nodularity.

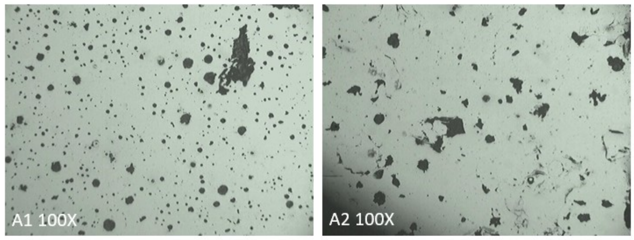


Fig. 12. Evaluated microstructure, polished specimen. Sample A1 to the left has nodules within the correct specification for roundness. The nodule count meets the requirement however the size distribution of the nodules is uneven. Sample A2 has degenerated nodules, an uneven size distribution and low nodule/particle count

5.5. Significant temperatures and parameters evaluated with ATAS MetStar

Based on the results from the thermal analysis the metallurgical parameters are evaluated and calculated to be used as import data to calibrate the simulation parameters. The significant temperatures and quality parameters calculated by ATAS MetStar are shown in table 5 and the cooling curves for both variants in are shown in Figure 13.

Table 5.
Significant temperatures and metallurgical parameters for A1 (inoculated) and A2 (not inoculated) sample.

Test ID	TL	TELow	TEHigh	TES	TS	dT/dt TS	R	GRF1	GRF2	S1	ACEL	Primary austenite
A1	1147.4	1143.8	1144.6	1146.3	1104.4	-3.48	0.8	87	32	24.05	4.24	1,27
A2	1149.2	1132.8	1135.3	1141.5	1083.7	-2.07	2.5	70	109	27.71	4.22	6,00

5.6. Simulation results

In most foundry simulation codes, the density curve (for a macro model) is based on the chemical data from spectrometer. The "start" density of the alloy is calculated and based on the content of the chemical elements in the actual melt. In the investigation the chemical composition is evaluated with a spectrometer and combined with calculation of carbon (CTL) from the thermal analysis. To make a more precise comparison with the experimental results, data calculated with ATAS MetStar describing how the density changes from TL (start of solidification) to TS (end of solidification) is imported to the NovaFlow&Solid system. The ACEL, Active Carbon Equivalent, which gives essential information about the solidification characteristic (hypo/eutectic or hyper eutectic morphology) is important to evaluate accurately. The calculated data includes the effect of the contraction of primary austenite and the volume increase of the precipitated graphite during the first and second eutectic solidification process. Significant temperatures where there is a shift in the density curve are very important to be evaluated correctly, liquidus temperature (TL), lower eutectic temperature (TELow), higher eutectic temperature (TEHigh) and the solidus temperature (TS). is needed to be correctly evaluated order to calculate the CLFU (dendrite coherency point) and CLFD (percolation threshold factor).

The last data is an empirical macro data describing the mold stability (rigidity) in George Fischer units (+GF+ units).

The results from the simulations compared with the X-ray for the calibrated data is shown in Figure 15 and 16.

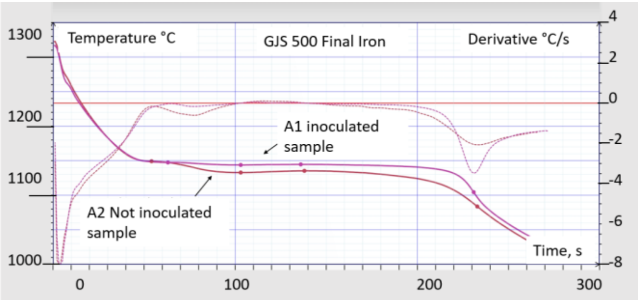


Fig. 13. Cooling curves for inoculated A1 and not inoculated A2 samples. The inoculation has a positive effect on the value of TELow, TEHigh, recalescence (R), TS, GR21 and GRF2. This is also shown in the calculation for the density curves below in Figure 14 b and c

Data from Table 5 in combination with the data concerning the graphite precipitation process were used as input for the calculation of a new density curve for A1 and A2 sample, the density curves in the solidification interval are plotted and compared to a "standard" density curve in Figure 14.

a)

b)

c)

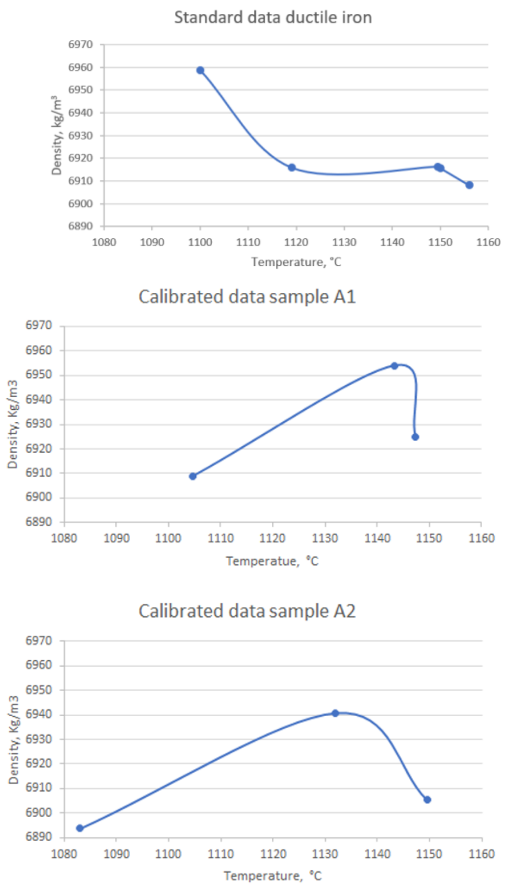


Fig. 14. Comparison of density data in NovaFlow&Solid for the simulations for 3 cases (a) standard curve, b) for sample A1 and c) for sample A2), the density is calculated for the solidification interval from TL (Start of solidification) to TS (100 % solidified)

The standard data is valid for general ductile iron 500 (typical chemical composition) at TL and TS. The data shows a continuous contraction from TELow and forward. Compare with the calibrated data A1 and A2 which shows different significant temperatures and the density is calculated based on the specific cooling and solidification conditions in the ATAS MetStar samples. In both cases, the calibrated data shows an expansion after TELow.

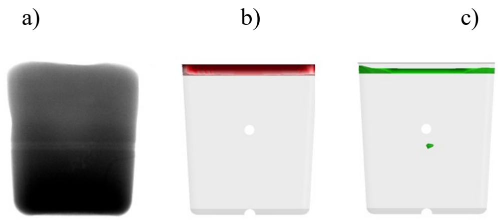


Fig. 15. X-ray results a) and prediction of shrinkage porosity b) Niyama c) for sample A1 with inoculation

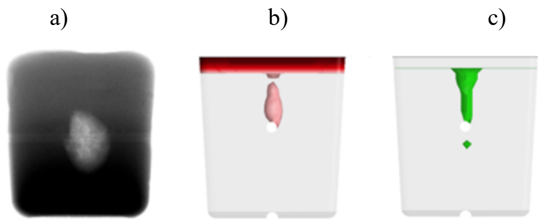


Fig. 16. X-ray results a) and prediction of shrinkage porosity b) Niyama c) for sample A2 without inoculation

The X-ray indicates large porosity. The position is on the right-hand side of the thermocouple. Most likely the cup was positioned slightly with an angle to the sampling stand and the effect of gravity played a role in this "asymmetric" position. The simulation studies are taking the filling of the cup into account however the variation in analyzed pouring temperatures does not have any larger influence on the position of the porosity.

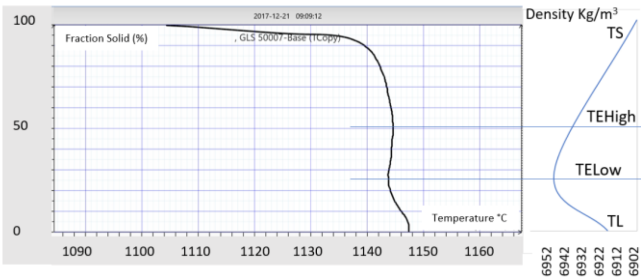


Fig. 17. Calculated fraction solid (ATAS MetStar) and suggested density curve to use as input data for the simulation for calibrated alloy sample A1

The calculated fraction solid and the suggestion for a density curve for sample A1. In Figure 17 the density curve shows a "flatter appearance" in the first part during the precipitation of austenite in comparison with the fraction solid curve for sample

A2, in Figure 18. The amount of pro eutectic austenite is 1.27 % in comparison with 6.0 % for sample A2.

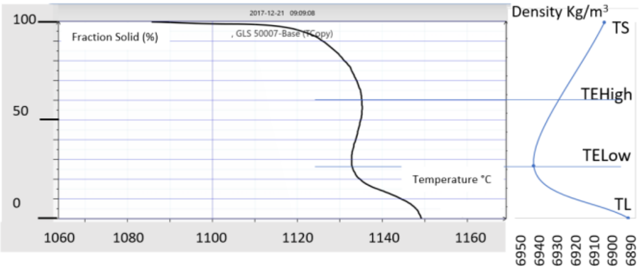


Fig. 18. Calculated fraction solid (ATAS MetStar) and suggested density curve (NovaFlow&Solid) to use as input data for the simulations for calibrated alloy sample A2

The solid fraction curve for the A2 sample without inoculation is shown in Figure 18. The first part of the solid fraction curve is "deeper" and shows a higher contraction (see density curve) because the larger amount of pro eutectic austenite which is precipitated in the beginning of the solidification process.

5.7. Discussion

ATAS MetStar gives a possibility to document the metallurgical process to evaluate significant temperatures and to calculate parameters describing the metallurgical quality in cast iron. The system is based on thermal analysis, it is a well-known analysis method. If the system is calibrated and quality measuring cups are used it gives a high accuracy and repeatability in the data. One weakness is the manual pouring of the cups, it is of greatest importance that the operators are well instructed and educated to make this process in an appropriate way.

The formation of defects in a measuring cup for thermal analysis could be different in comparison with defect formation in a real casting. The cup is "open" to air and the effect of the graphite expansion during the solidification process may be stronger (easier to form inner porosities) in comparison with the cooling and solidification in a closed mold. The result in this article shows that inner defects, small and large porosities and outer surface defects are formed during cooling and solidification in the sample. These types of defects are quite common to experience in a practical foundry environment.

The ATAS MetStar system analyzes the cooling and solidification process and calculates the first order of data which is the significant temperatures and arrest points for the different phases during solidification process. Based on these data the system calculates metallurgical parameters (e.g. Primary Austenite, GRF1, GRF2) which, together with the temperatures, describes the metallurgical quality of the melt. After combining this data with information about chemical composition the system calculates data about how the graphite precipitation takes part in the solidification process and the amount of possible graphite which is precipitated during the complete solidification process.

NovaFlow&Solid is a casting process simulation system based on the control volume method (modified finite difference method). The system has an open database with standard data and possibilities for the user to give external data as input. To calibrate the density curve for a sample the data from ATAS MetStar is exported to NovaFlow&Solid. The thermal and metallurgical data is combined with chemical data for the alloy.

The system defines the significant temperatures in the solidification interval and calculates a new density curve based on the amount of precipitated volume of graphite from TL to TS. Parallel with adjustment of factors

6. Summary

A metallurgical production has fluctuations in the metallurgical quality. These variations have strong influence on the result concerning the formation of shrinkage defects in the castings.

The process fluctuations in metallurgical quality can be analyzed using ATAS MetStar, a metallurgical Process Control system based on thermal analysis. The results from the evaluation of significant temperatures and parameters can be used as input to NovaFlow&Solid to calibrate the density curve.

The article confirms that, using the method above, to combine "real" process data gives more realistic results and higher precision for simulation of castings.

A further development and to increase the quality of the calculations is to develop a non-equilibrium model and with the same strategy to calibrate the growth coefficients for graphite and the austenite phase.

Calibration of density- algorithm, diagram of sensibility for new formula on the density/temperature curve. Introduction of correction coefficients to modify the density/temperature curve.

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