Casting Process Simulation of Compacted Graphite Iron (03-025)

Dipl.-Ing. C. Heisser
MAGMA Foundry Technologies, Inc., Arlington Heights, Illinois

Dr.-Ing. Jörg C. Sturm
MAGMA Giessereitechnologie GmbH, Aachen, Germany

ABSTRACT

The use of Compacted Graphite Iron (CGI) is expanding, especially into newly developed engine block castings. The successful introduction of this relatively new material to the casting designers requires the foundry engineers to provide detailed material property predictions and casting process knowledge. Based on casting trials with detailed microstructure analysis, a new simulation tool has been developed to predict shrinkage behavior and microstructure (i.e. nodularity), which are of importance to the mechanical properties of the casting. This paper will describe the development process of this new casting process simulation tool using comparisons of production castings to simulation results.

INTRODUCTION

Compacted Graphite Iron (CGI) has been known since the nineties as a high-strength casting material (Figure 1). However, applications of this material were limited due to uncertainties with regard to process control and machinability. Presently, the decision of automobile manufacturers to substitute CGI for gray iron engine blocks has lead to an increased use of this material. Casting designers are now asking for clear design rules and tools that support the layout of a casting for successful utilization of CGI. The material properties of pearlitic CGI are strongly dependent on the local graphite nodularity; therefore, they are related to the chosen metallurgy and process control, but also to the geometry of the casting. The designers are uncertain about the actual mechanical properties they can expect. The foundry personnel have questions regarding the castability of CGI, i.e. its specific solidification and feeding behavior. This relates not only to the reproducibility of the graphite morphology, but also its influence on the feeding behavior.

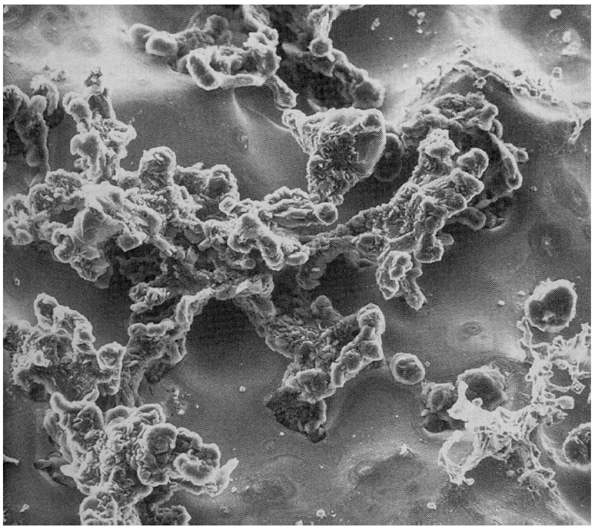

Fig. 1. Typical Microstructure of Compacted Graphite Iron.

Casting process simulation can provide answers to both, the casting designer and the foundry engineer. Therefore, it is important to not only qualify, but to quantify the mechanisms that define the solidification behavior of CGI. This can be accomplished by close cooperation between foundries and material process specialists. As part of an industrial project with recognized cast iron foundries, OEMs and technology partners, the knowledge to model the growth and solidification of CGI as a function of the iron composition, applied metallurgy, and local cooling conditions was developed /1/ /2/.

The metallurgy and graphite morphology in relationship with the solidification conditions of CGI was evaluated based on complex, instrumented experiments. Detailed microstructure analysis, utilizing color etching, provided insight into the growth kinetics of compacted graphite. Thermocouple plots were matched with predicted microstructures that provided the base for building a model to describe the solidification behavior of CGI. These findings were integrated into existing software algorithms used for solidification simulations of iron. Additionally, the models used for the shrinkage defect prediction were expanded by the influence of the local nodularity. These were the first steps made into predicting local nodularity in CGI castings as a function of metallurgy, melt composition, and cooling conditions.

This paper describes the steps that lead to the development of the simulation tool and documents the integration of simulation results into the product development process of automotive castings.

EXPERIMENTAL PROCEDURE

To achieve a detailed understanding of the solidification behavior of CGI, a test pattern was developed to provide castings for microstructure analysis. The pattern contained castings with several different wall-thickness, which were instrumented with thermocouples to record the solidification of the castings (Figure 2). It also contained castings to evaluate the shrinkage behavior. A 3D-model of the geometry was created for use in the casting process simulations (Figure 3).

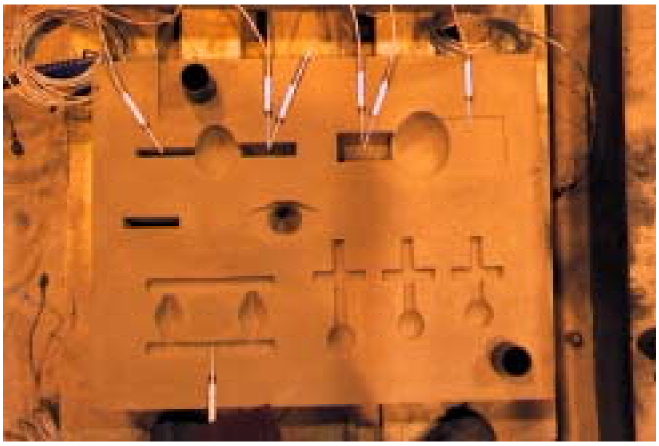

Fig. 2. Layout of experimental pattern.

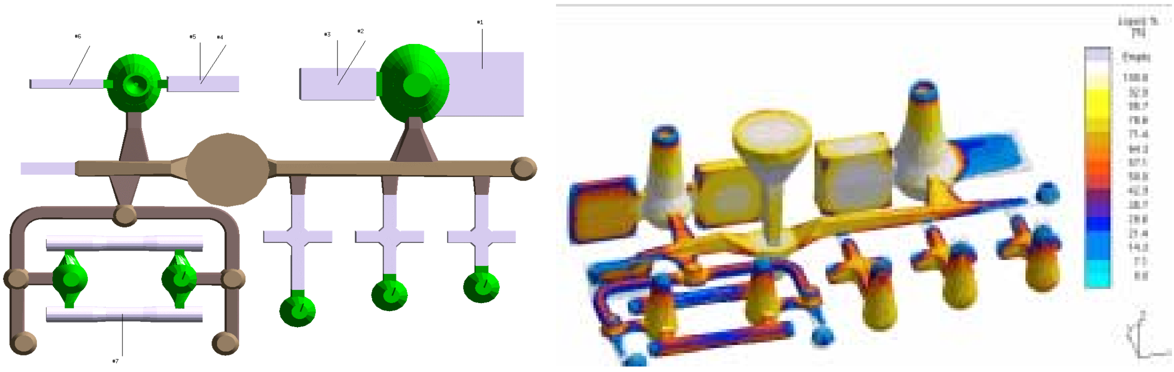

Fig. 3. 3D-model of experimental pattern (a) and fraction solid plot of the casting for a given time during solidification (b).

The experiments were performed in a foundry and the status of the melt was controlled by the Sintercast® process control method /3/. A total of 7 different melts were prepared to investigate the full spectrum of graphite formation (from Gray via Compacted to Nodular Iron), Figure 4.

Prior to casting, the ladles were controlled. If the ladle was not at the targeted modification and inoculation levels, wire additions were made. Once the melt had reached the desired modification and inoculation levels, casting of the instrumented castings began. For every ladle, two castings were made at two different inoculation levels. Between the two castings, a constant addition of inoculant wire was made to the waiting ladle. The first melt was considered as "low inoculation" and the second melt as "normal inoculation".

Series	5 mm		10 mm		20 mm		40 mm	
	Flake %	Nod %	Flake %	Nod %	Flake %	Nod %	Flake %	Nod %
A1	100	1.1	100	1.45	100	0.43	100	0.74
A2	100	0.18	100	0.24	100	0.26	100	0.14
B1		69		75		51		54
B2		81		85		79		68
C1	-	-	-	-	-	-	-	-
C2		63		38	25	6	10	6
D1		43		29		21		23
D2		43		41		33		31
E1		62		39	2	10	5	9
E2		46		41	20	5	2	8
F1		66		33		10		3
F2		59		31		16		11
G1		40		23		11		7
G2		47		23		19		12

Fig. 4. Matrix of experiments. The different columns descibe the graphite structure for the plate castings at different wall thickness respectively correspondent cooling rates during solidification.

MICROSTRUCTURES

After casting of the molds, extensive evaluation and documentation work was performed. The plates, tensile test bars, T-sections and the feeders were separated from the gating system and each part was marked and weighed. Samples for microstructure analysis were taken from each plate close to the position of the thermocouple tips. The samples were ground and polished to reveal the graphite morphology. A wide variation in microstructures, from a fully gray structure to a fully nodular structure, was shown. The effects of Mg-treatment and inoculation were well described in the microstructures.

The cross-shaped castings were used to evaluate the impact of casting process parameter changes on the shrinkage defect distribution (Figures 5).

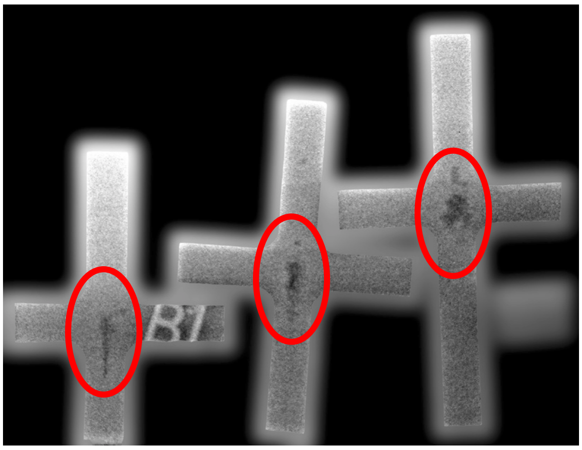

Fig. 5. Shrinkage distribution in cross-shaped castings taken from X-ray investigation by automatic image analysis.

COLOR ETCHING TO REVEAL SOLIDIFICATION STRUCTURE

A major concern in this project was to find out how CGI solidifies which is a prerequisite to build models for use in deterministic modeling software. Data was needed regarding growth morphology as well as how many cells (or equivalent) are growing. This information was not found in published literature; therefore, a special color etching technique was used. This technique reveals the segregation pattern which provided information about the growth morphology, for details see also Ref. /4/.

One example of microstructures in a color-etched sample is shown in Figure 6. In general, the light blue areas represent regions that have solidified early during the solidification sequence. Therefore, the austenite dendrites are usually easy to distinguish. It is interesting to see that the CGI-cells consist of rather large aggregates of “graphite worms”.

From the color-etched pictures, it was possible to evaluate the number of growing CGI-cells in different plates. This information was then coupled with the information from the cooling curves to establish a nucleation law for CGI.

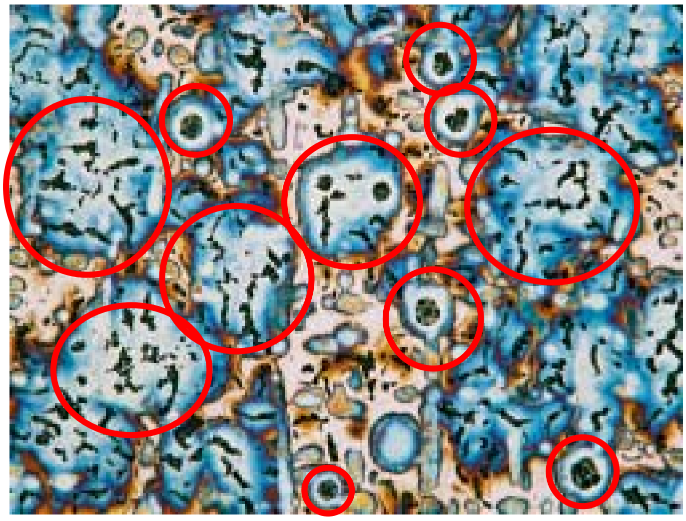

Fig. 6. Color etching provides detailed insight into cell size of CGI.

COOLING CURVES AND THERMAL ANALYSIS

The temperature measurements were made simultaneously in all molds, using a total of 96 thermocouples.

In Figure 7, the cooling curves from the center thermocouples in the 20 mm plates are shown for all modification degrees at high inoculation. The curves have been displaced on the time axis so that they appear in order of increasing nodularity, thereby facilitating a comparison. The nodularity values and the amount of flake patches (if existing) are shown adjacent to each curve. When increasing the nodularity, the flake patches are reduced, thus changing the solidification sequence as shown in the changes of the cooling curves.

Data from the cooling curves was used for thermal analysis on different levels. On the most basic level, the temperatures from the start to the end of solidification, or other phase transformations, can be found from the derivative with respect to time on the temperature curve. On a more refined level, the transformation rates and fraction-transformed phase were calculated.

Based on this information, the calculated solidification rate could be coupled with the microstructure and growth mode, which enables the calculation of the growth rate of the CGI-cells as well as the kinetic constants in the growth models.

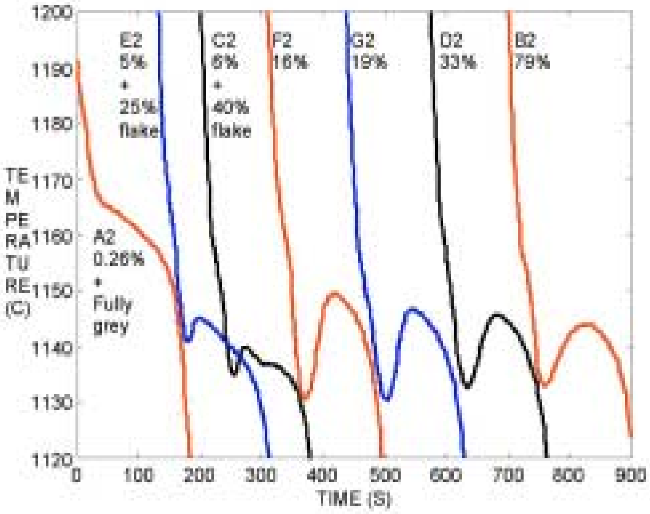

Figure 7: Suite of thermocouple readings for different melts taken from the same 20 mm plate location

MODELING AND SIMULATION

As stated above, the results from the evaluation were used to establish a nucleation and growth law for CGI-cells. These models were implemented in an existing micro modeling module of the simulation code to make it possible to have two different simultaneous cast iron graphite morphologies, nodular graphite and compacted graphite growing in competition with each other. This project did not address the risk for the formation of lamellar graphite.

The main output files from the simulation concerning CGI are:

Nodularity (influenced by % Mg, inoculation and cooling conditions)
Porosity (influenced by % Mg, inoculation and cooling conditions)

To verify the sensitivity of the model, different cases were simulated, where the Mg content as well as the inoculation efficiency was varied:

0.007 % Mg and 50 % inoculation efficiency
0.007 % Mg and 200 % inoculation efficiency
0.021 % Mg and 50 % inoculation efficiency
0.021 % Mg and 200 % inoculation efficiency

Figure 8 shows the affects of different inoculation levels on the simulated cooling curves. Figure 9 demonstrates how the cooling curves change when increasing the Mg content for the same inoculation. The simulation predicts that the recalescence, as well as the recalescence rate, increases when the nodularity is decreased, in accordance with the experiments.

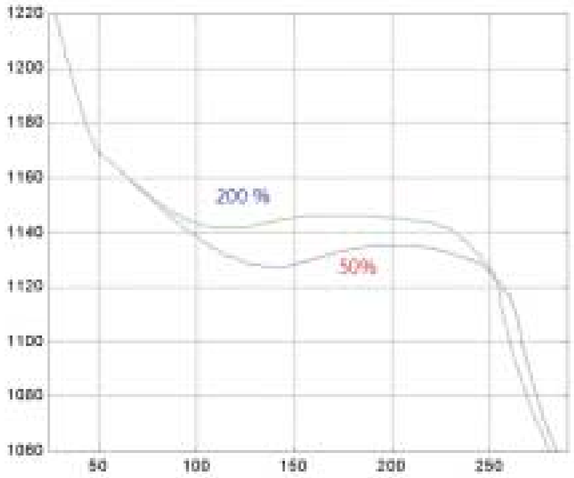

Figure 8: Simulated cooling curves demonstrating the effect of different inoculation levels for CGI

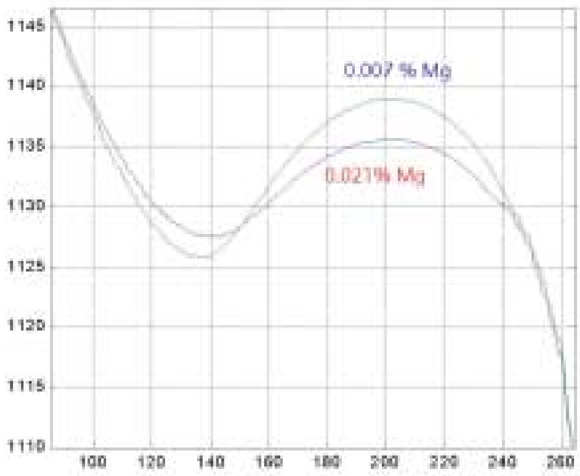

Figure 9: Simulation cooling curves demonstrating the effect of changing effective Mg level

Figure 10 shows the simulated nodularity distribution in the whole casting and in the parting plane; hence, in the plane where the thermocouples were located in the experiments, and where the evaluation of the nodularity was made. The agreement with the experiments is seen to be satisfactory.

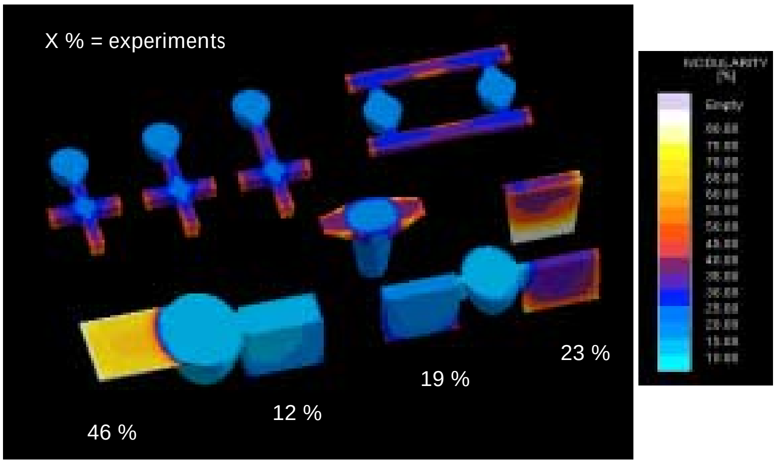

Fig. 10. Simulated nodularity values are compared with measured nodularity found in the test castings

The simulation results showed a very close correlation to the nodularity values and shrinkage defect distribution found in the test castings. The next step was to apply the new simulation tool on a CGI engine block casting.

APPLICATION AND VERIFICATION TO A CGI ENGINE BLOCK CASTING

Apart from the described project, the simulation models were further evaluated based on comprehensive experiments performed by a cast iron foundry together with an automotive company /5/.

An in-line, four-cylinder, engine block casting was chosen to evaluate the validity of the new simulation tool on production castings. Several castings were sectioned. Nodularity and shrinkage defect distributions were evaluated and compared to the distributions predicted by the casting process simulation. A good correlation was found in comparing the inspected and the simulated nodularity values found in the castings, Figure 11.

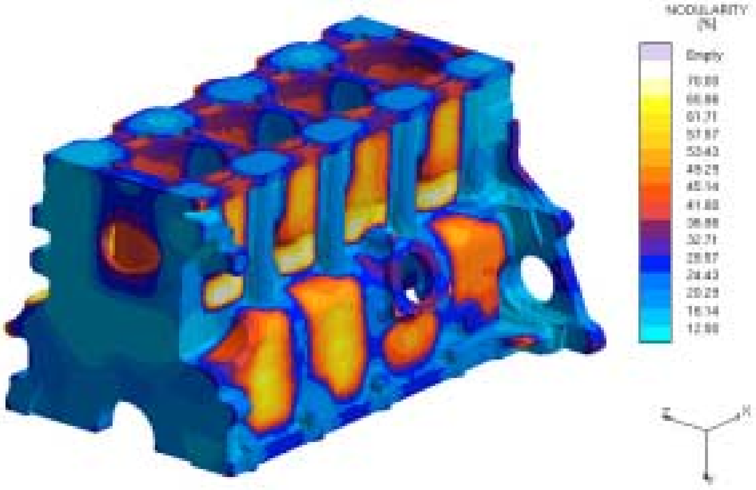

Fig. 11. Simulated nodularity values for an engine block. The comparison with experimental data showed very good correlation /6/

Furthermore an extensive study has been performed to compare the predicted shrinkage defect distribution versus the actual defect distribution found in the castings. Here as well, a very good correlation was found. Details to the experimental and simulation work will be shown in /6/.

Overall, the results given by the new simulation tool showed a very close correlation to the nodularity values and defects found in the casting.

SUMMARY

The increased use of compacted graphite iron, especially in high production automotive engine blocks demanded the expansion of casting process simulation tool capabilities to consider the specific solidification behavior of this relatively new material. Casting process simulation is widely used in cast iron foundries that work very closely with the casting designers in the automotive industry. Until recently, it was not possible to make reliable nodularity and shrinkage defect distribution predictions in CGI castings. This paper describes the process of developing a new casting process simulation tool, which will allow designers to obtain reliable information with regard to nodularity and shrinkage defect distribution in complex castings. It will also allow foundry personnel to define a process parameter window to reliably produce quality CGI castings. After validating the new software on simple test castings, the tool was applied on a complex, thin-walled, in-line, four-cylinder engine block casting. The simulation results showed a very close correlation for nodularity values and shrinkage distribution with the findings in the actual castings.

In can be concluded that for the first time, a casting process simulation tool is now available to reliably predict the specific solidification behavior of compacted graphite iron castings. This will support casting designers and foundry engineers to optimize casting designs and their production for this still relatively new material.

ACKNOWLEDGEMENTS

The result of this work was gathered from a project financed by a European consortium of Cast Iron Foundries (Eisenwerk Brühl Germany, Fagor Spain, Halberg Guß, Germany, Teksid, Italy), two Automotive companies (Ford Research Center, Germany and Scania, Sweden) and two technology vendors (Elkem, Norway and Sintercast, UK). MAGMA and its research partners MAGMA Technology Denmark, Foundrysoft Sweden and University of Jönköping Sweden gratefully acknowledge the interest and commitment of its partners to realize this project. MAGMA is also grateful for the ongoing comprehensive contributions of Ford Research Center and Eisenwerk Brühl to realize the validation work on a real CGI engine block. MAGMA also likes to thank Tupy Fundiçoes Tupy, Brazil for experimental information provided in the further course of development of the simulation models.

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