Comparison of casting simulation results and experimental data in heavy section ductile iron production

Today, casting simulation represents a helpful and effective tool for designers to investigate, in advance, the influence of the casting process on material strength. Moreover, this sharing of knowledge between design and manufacturing engineering, usually called Concurrent Engineering, plays a key role in the design of heavy ductile iron casting components, due to their large distribution on microstructure and mechanical properties inside the item itself. Because of the measurement's complexity, only few studies have investigated so far in comparing simulated results and experimental data in the field of long solidification time. In this study, some thermocouples are placed inside a casting to record the cooling curves and several tensile specimens which were core drilled in the area with different cooling conditions. The experimental data were then compared with the results obtained with a solidification and cooling simulation. The comparison shows a good agreement between the experimental and calculated cooling curves, and the mechanical properties.

Introduction

Today, ductile iron is one of the most used materials in critical engineering applications, such as wind turbines, gas and steam turbines, nuclear waste storages, big engine blocks and hydraulic presses, due to its excellent mechanical properties and castability. For heavy and thick items, from few to hundreds of tons, it is critical to provide design engineers with consistent and reliable data on mechanical properties and microstructure, as well as how they change inside the item itself. Typically, casting design is based on average properties from international standards, but, it is well known, they are not homogenous inside the casting due to different manufacturing processing parameters, for example, local solidification and segregation path. It is also acknowledged that the mechanical properties of ductile iron are strictly related to the microstructure. The factors that influence the mechanical properties include chemical composition of the matrix, graphite nodules shape and size, ferrite to perlite ratio, dimension of the ferrite grain and pearlite lamellae spacing. A lot of effort has been made to correlate manufacturing casting parameters to the microstructure and the microstructure to the mechanical properties in order to predict and to map them on the casting.

Unfortunately, there is limited research focused on the prediction of microstructure and mechanical properties in large items, where lengthy solidification time and huge segregation have a strong impact and the established prediction model begins to incur problems. Moreover these studies are focused on specific geometries and it's not easy to transfers the results onto generic commercial items.

In this study we used a generic commercial ductile iron casting to obtain experimental data of the cooling curves, microstructure and mechanical properties inside the castings. A solidification simulation was performed using MAGMAsoft 5.3 and MAGMAiron and the simulated results were compared to the experimental ones.

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Mg
wt %	3.6	2.7	0.2	0.04	0.007	0.1	0.02	0.03	0.0005	0.055

Table 1 - Chemistry composition

Experimental Set-Up

To acquire experimental data on the temperature field during the solidification process and to check the mechanical properties and microstructures analysis inside the casting, an experiment was set up using a commercial ductile iron casting. The material investigated is ferritic ductile iron EN-GJS-400-18 with the chemical composition showed in Table 1, produced in a furanic resin bonded sand.

An appendix added was directly attached to the casting (weight ~ 12000 kg), (Fig. 1). The appendix, was introduced during the sand filling, with a polystyrene pattern removed before assembling the mould box cope and drag, this weighed ~1050 kg with the following dimension 1200mm x 400mm x 320mm (Fig. 2). The appendix was added in order to introduce some thermocouples to record the cooling curve in the middle of the thickness 320mm and to core drill some mechanical specimens. During the moulding 8 thermocouples, type-K Inconel sheath 0.5÷1mm, were located in different areas of the appendix, with their tips on its centre (Fig. 3). The thermocouples were coated with different refractory material in order to withstand up to the shake out of the item. The behavior of the coatings have been investigated in a previous experiment using smaller items and comparing the effects with non-coated thermocouples: the results shown that after an initial transitory interval, due to the heat resistivity of the coating, the cooling curve measured by coated and non-coated thermocouples were almost identical. Since the solidification time in the experimental item is much longer than the initial transitory we assumed the effect of the coating negligible. The data logger to record the cooling curves was an Agilent 34970A.

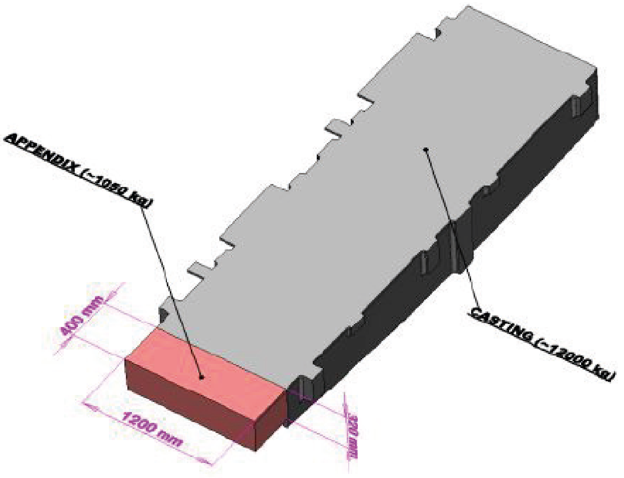


Fig. 1 - Geometry of the casting (gray) and the appendix (red)

Fig. 2 - Geometry of the casting (gray) and the appendix (red)

Fig. 3 - Coated thermocouples during the mould box assembly

Cooling Curves

The cooling curves were recorded from the pouring up to the shake out time. Unfortunately only 2 thermocouples out of 8 gave us reliable results in the solidification field, due to the high aggressive environment they were located. Only one thermocouple recorded data after the solidification down to about 800°C. The measured cooling curves were exported in Microsoft Office Excel, and the first derivative were calculated. The first derivative have been smoothed using a LOESS algorithm to evaluate the end of solidification: in which the minimum of the first derivative was considered the end of solidification and the corresponding time was assumed as the solidification time. In Fig.4 the measured cooling curves

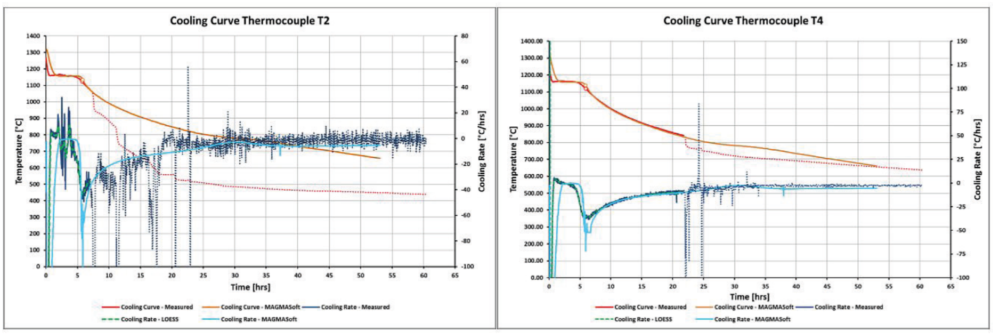


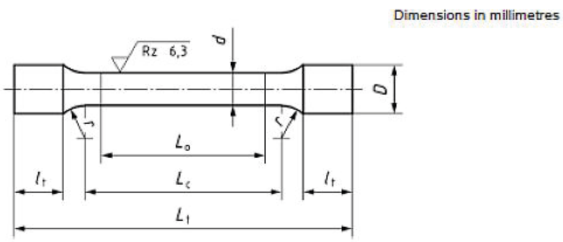
Fig. 4 - Thermocouple T2: cooling curve and cooling rate (left); Thermocouple T4: cooling curve and cooling rate (right)

are shown: the continuous lines represent the cooling curve as recorded (red Temperature vs. Time, blue Cooling Rate vs. Time), while the dotted lines represent the curve where the data recording failed; the green dashed lines represent the LOESS smoothed cooling rate curves.

Mechanical Properties and Microstructure Analysis

After the shake out and fettling the appendix were cut and 7 core drilled specimens were also cut out using a CNC machine tool (Fig. 5). Their position was selected to get solidification time between 1 to 6 hours. Before cutting the appendix, it has been checked using

Fig. 5 - The appendix during the specimens core drilling



d	L_o	L_c min.
5	25	30
7	35	42
10	50	60
14 [a]	70	84
20	100	120

[a] Preferred dimension for 25 mm cast sample diameter.

Fig. 6 - The tensile specimen geometry

UT to avoid developing some traces of refractory coating. Moreover their surfaces were investigated using PT to check the presence of porosities. From the drilled specimens, 14 tensile specimens were extracted with a diameter Ø 10mm (Fig. 6). The specimens have been tested in a Zwick/Roell Z250 to check the tensile properties ($R_{p0.2}$, R_m, and A%).
After the mechanical tests 7 of them have been cut along the main axis, polished and checked with an optical microscope LEICA DM 6000 M. The graphite nodules have been checked using the image analysis software Fiji. For each specimen 800 mm^2 were investigated and the nodule count was recorded. After this the specimens were etched with Nital 2% to check the ferrite to pearlite ratio (Fig. 7).

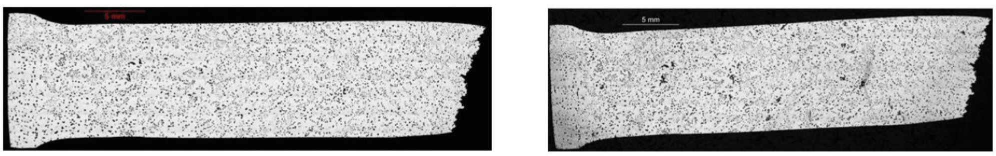


Fig. 7- Microstructure specimen not-etched (left) and Nital 2% etched (right)

Simulation Set-Up

A solidification and cooling simulation was set up using MAGMAsoft 5.3 and MAGMAiron. We decided to skip the filling simulation due to the dimension of the item: since the solidification takes several hours the filling has a negligible impact on it. The mesh counted a total of 2 741 706 elements, 598 542 of which metal cells (Fig. 8). The material used were the GJS400 presents in the MAGMAsoft database with the chemistry changed according to Tab. 1, the chillers and the sand were respectively GJL300 and furan resin bonded according to MAGMAsoft material database.

Fig. 8 - Mesh of the casting

During the pre-processing some “virtual thermocouples” were placed in the same positions as the real thermocouples’ tips and in the centre of the tensile test specimens in order to record the simulated cooling curves and to get the simulated mechanical properties and microstructures results (Fig. 9).

Results and Discussion

Cooling Curves Comparison

For the simulated cooling curve of the thermocouples T2 and T4 the first derivative was calculated as if it was made for the real component. For each thermocouple both the cooling curves and its first derivative were compared (Fig. 10). In the solidification field the simulated results concurred with the experimental results. Only at the beginning, there are some mismatches due to the thermal inertia of the thermocouple coating as discussed previously. Looking at the solidification time we can find that the predicted and actual corresponded perfectly (Table 2).
As mentioned before only Thermocouple T4 was measured after the solidification, but still the simulated curve matches well the experimental data.

a summary is presented: in this case we added a value “Best Fit” where we calculated the max., and mean percentage error choosing for each comparison the closer of the three.

The difference between the calculated and measured values can be due to set-up of the melt treatment in the simulation software that can be tuned to get a better prediction of the microstructure and in the strain hardening behavior of the material. In Fig. 13 an example is shown: since the R_m values are in the area of the flattening of the stress strain curve a small change in the R_m can produce a huge effect on the A%.

Concerning the microstructure we considered the Pearlite content (P%) and the Nodule Count (Nc). The P% calculated was less than 3% for all the specimens in good agreement with the measured values that showed only few percent of Pearlite. The Nc (Fig. 14) is in good agreement for the specimens of the “Int.” series, while for the “Ext.” series the deviations are bigger. As mentioned for A%, probably, the differences are related to the set-up of the melting treatment in the simulation pre-processing. Further investigation in this field are needed in the future to try to improve the prediction.

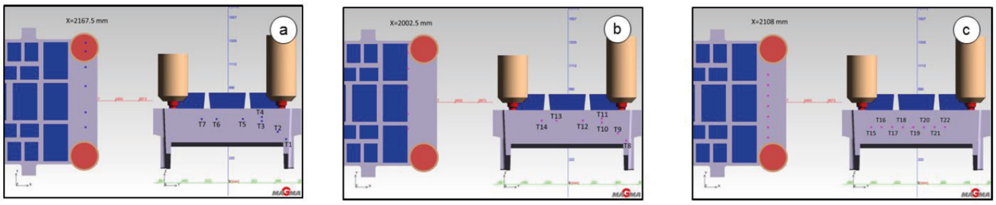


Fig. 9 - “Virtual thermocouples” location: tensile specimens “Int.” (a), tensile specimens “Ext.” (b), actual thermocouples’ tips (c)

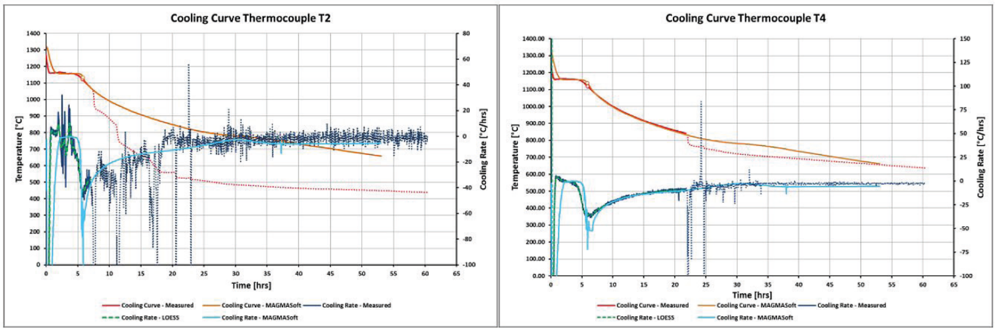


Fig. 10 - Measured vs. calculated cooling curve and cooling rate thermocouple T2 (left) and thermocouple T4 (right)

Thermocouple	Solidification Time Measured [hrs]	Solidification Time Calculated [hrs]	Delta (Measured – Calculated) [hrs]	Percentage Error [%]
T2	5.75	5.78	-0.03	~ - 0.5 %
T4	5.92	5.88	+0.04	~ 0.7 %

Fig. 9 - “Virtual thermocouples” location: tensile specimens “Int.” (a), tensile specimens “Ext.” (b), actual thermocouples’ tips (c)

Mechanical Properties and Microstructure Analysis Comparison

The mechanical properties and microstructure have been predicted using MAGMAiron: we simulated 0.2% Proof Strength ($R_{p0.2}$), tensile Strength (R_m) and Elongation (A%). MAGMAiron supplies for each of the mentioned properties, three values: minimum, medium and maximum. In Fig. 11 the measured vs. calculated values of $R_{p0.2}$ and of R_m are respectively shown. For both the two properties we considered only the minimum value since it matches the measured value the best, while both mean and maximum values were skipped since they are not aligned to the usual values we see in standard production. In Table 3 a summary of the maximum and mean percentage errors are reported for both the two values.

For A%, instead, all the three supplied values (min., mean, max.) were considered since there was not a clear trend in choosing one of them (Fig. 12). In Table 4

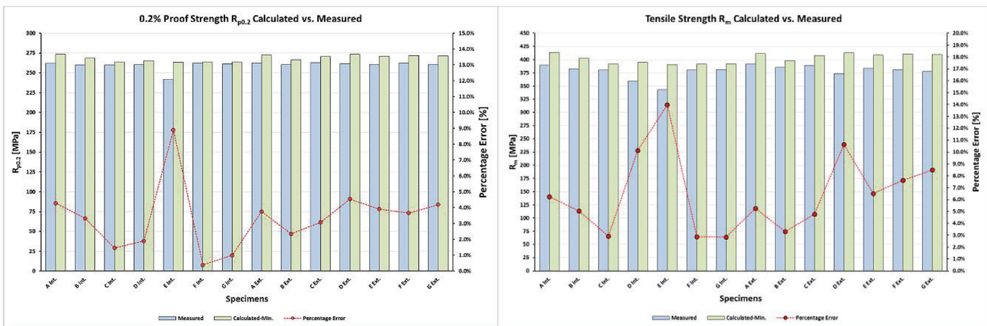


Fig. 11 - Measured vs. calculated Rp0.2 (left) and Rm (right)

	Max. Percentage Error [%]	Mean Percentage Error [%]
$R_{p0.2}$ – Min.	8.9 %	3.3 %
$R_{p0.2}$ – Mean	--	--
$R_{p0.2}$ – Max.	--	--

	Max. Percentage Error [%]	Mean Percentage Error [%]
R_m – Min.	14 %	6.5 %
R_m – Mean	--	--
R_m – Max.	--	--

Table 3 - max. and mean percentage error for Rp0.2 (left); max. and mean percentage error Rm (Right)

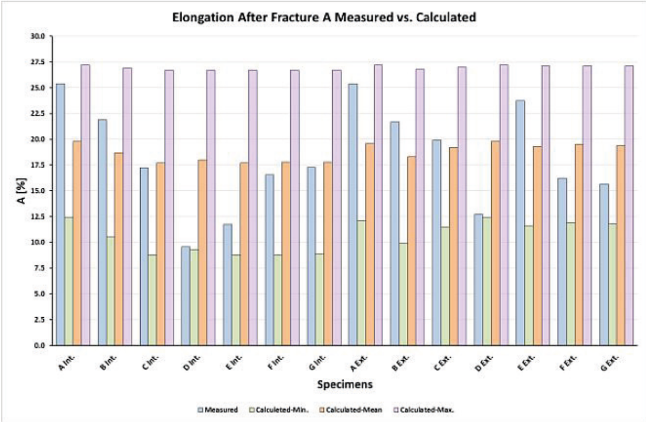


Fig. 12 - Measured vs. calculated A%

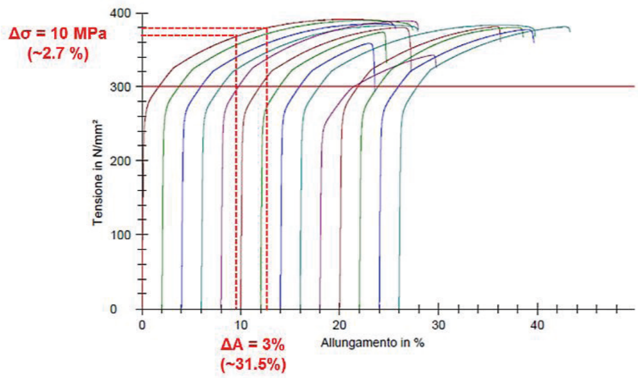


Fig. 13 - strain hardening phenomena and the effect on A%

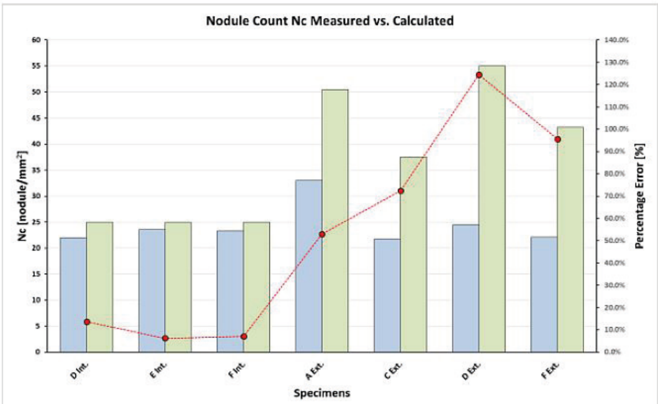


Figure 14: measured vs. calculated Nc.

Conclusions

In this article we present a comparison between simulated and measured cooling curves, mechanical properties and microstructure characteristics in a commercial heavy section ductile iron casting.

The cooling curves measured and calculated in the centre of a section 320mm thick correlate well as does the cooling rate. For the solidification time there is no difference between the measured and calculated values. Concerning the temperature field and its development over the time we can assume MAGMAsoft can predict it correctly for large ductile iron items.

	Max. Percentage Error [%]	Mean Percentage Error [%]
A – Min.	-54.3 %	-37.8 %
A – Mean	88.3 %	24.9 %
A – Max.	179.3 %	60.1 %
Best Fit	25.2%	10.7%

Table 4 -Max. and mean percentage error for A% (min., mean and max.) and best fit

Concerning the mechanical properties the $R_{p0.2}$ and R_m values are in agreement if we compare the minimum values supplied by MAGMAiron. The A% shows some differences probably due to the stress-strain cast iron behaviour and the need to set-up the melt treatment properly in the simulation step.

For the microstructure the P% is predicted correctly for all the specimens, while the Nc is subjected to some variation: also in this case we consider them due to a not perfect set-up of the melt treatment.

Acknowledgements

The Authors want to thank "Fonderia Ariotti SpA" and the "Interdepartmental Center for Industrial Research on Advanced Applications in Mechanical Engineering and Materials Technology CIRI-MAM" of the University of Bologna for the support in the experimental steps.

Giacomo Bertuzzi, SACMI Imola
Giampietro Scarpa, EnginSoft

The Company

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