A RAPID APPROACH TO ESTIMATE THE MECHANICAL PROPERTIES OF GREY CAST IRON CASTINGS

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Abstract
Grey cast iron is a brittle or quasi-brittle material very sensitive to the microstructure morphology deriving from its solidification kinetics. This is the reason why different zones of a casting, even with the same thickness, may be characterized by different mechanical properties according to the solidification time. The mechanical characterization of the alloy made by following the Standards that refer to values obtained from separately casted samples is insufficient for a designer who needs to know the specific properties of the material in each zone of interest of the casting.
In this work a method is described to predict the mechanical properties of castings made of GH 190 cast iron that correlates the solidification times with the ultimate tensile strength through a master curve, supposed to depend only on alloy chemical composition. This predictive approach was successfully validated with experimental mechanical characterization of a real industrial casting.

Keywords: Grey Iron, Finite Element, Thermal Analysis, Mechanical Properties, GH 190

1 Introduction
Grey cast iron is one of the most widely used ferrous alloys in the world. This is due to its unique technological, physical and mechanical characteristics such as a lower melting point compared to that of the others ferrous alloy, good thermal conductivity, vibration damping ability and good machinability. It is used to produce, by casting, near-net shape components such as diesel engine components, including cylinder heads, cylinder blocks and piston rings. The major drawback of this material is its brittleness mainly due the notching effects induced by the brittle flake graphite morphology that acts as a discontinuity in the relatively tough metallic matrix. The ultimate tensile strength (UTS) is the results of the intimate collaboration between the flake graphite and the primary phases [1], which in turn depends on the cooling rate or the solidification time at each point of the casting. It is an important task to identify the contribution of the different microstructure components to crack formation. Beats [2], for instance, by using the fracture mechanics theory, formulated the UTS of these alloys as a function of half of the maximum graphite flake length. In another work, Ruff and Wallance [3], correlated the primary austenite and the eutectic cell with the UTS in grey cast irons. Finally, Diòszegi et al. [1] proposed a new model to predict the tensile strength of grey cast iron based on interpretation of the stress intensity behaviour in a single eutectic cell prior to fracture.

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Despite the above-described attempts to model the mechanical behaviour of grey cast iron, this issue is not well deepen yet in literature. More in general, if all cast irons families are taken into account, static and fatigue strength of heavy section iron castings are not standardized yet and this is the reason why in recent literature an attempt is made to fulfil this gap [4-8].

Instead of analytical models [1-3], numerical simulation can be used, which is able to predict the mechanical properties of the casting according to the chemical composition of the alloy and process parameters [6].

Jakob Olofsson and Ingvar L Svensson demonstrated [10] that it is possible to predict the mechanical properties of a cast iron component through casting process simulation and stress-strain simulations. A particular simulation strategy called ‘a closed chain of simulations for cast components’ [11], which uses solidification and solid-state transformation models to predict microstructure formation and mechanical behaviour on a local level throughout the component, was proposed. Similarly, two years before, Donlean carried out a model to predict microstructure and mechanical properties of ferritic ductile iron components [12]. The numerical model was applied to a heavy section casting with a satisfactory correlation between numerical and experimental results. In the same year (2000), Italian researches, Calcaterra, Campana and Tomesani, used an artificial neural network-based system to predict the mechanical properties of spheroidal cast iron components according to process parameters [13]. The required input data are chemical composition of the melt, inoculation temperature, time before casting and diameter of the castings. However, due to the limited number of specimens considered, the variation range of tensile strength should be kept below 100 MPa to ensure effectiveness of the prediction. Furthermore, that approach does not take into account geometry variations of a real cast component. Another interesting and recent approach applied for casting mechanical properties evaluation is the rapid estimation of mechanical properties of castings through electrical resistivity measurement [14]. However, even if such approach appears very efficient for a rapid castings diagnostic on the production line, it requires the determination of a regression equation for each cast geometry. Finally, a regression analysis was proposed by Shturmakov and Loper to predict mechanical properties of commercial grey iron [15]. Unfortunately, the results obtained did not take into account process parameters and casting geometry but considered only variations in chemical composition. Mechanical properties of grey cast iron is well studied in literature according to the microstructure variations [16] and cooling rate [17] but only the correlation between hardness and cooling rate was assessed [18] by experiments.

Among the above suggested approaches present in literature to predict the mechanical properties of a cast iron component, the numerical simulation of the casting process would seem the most promising. However, some drawbacks must to be critically taken into account. Fluid-thermo-mechanical, transient and non-linear computation is time and cost expensive. The high computational cost of a model is often not suitable for industrial applications that require fast and reliable solutions. Model reliability is related to the correctness of input data that are often difficult to find such as metallurgical, thermal and mechanical properties as a function of temperature, thermal resistance at the interface between mould and casting and so on. Another method is based on the mechanical properties evaluation as a function of the section thickness [18] and/or microstructure [19]. In this context, the present work is aimed to propose an approach that exploits the advantages of numerical thermal simulation and overcomes the problems related to the micro- and macro-mechanical computation. The solidification time is first obtained at each point of the casting by means of moulding and thermal numerical

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simulation, which are known to be fast and reliable [20]. Mechanical properties of the component are then calculated by using a master curve (MC) that correlates the ultimate tensile strength (UTS) with the solidification time.

2 Materials and Methods

The material analysed is the GH 190 grey cast iron obtained by using the cupola oven starting from pig iron, steel scarp, returns, tin-sheet, coke and a pouring temperature of 1385 °C. The alloy chemical composition is collected in **Table 1**.

Table 1 Chemical composition of the analysed alloy (wt%)

C	Si	Mn	Cu	Cr	Ni	Mo	Sn	S
3.24	1.83	0.76	0.1	0.2	0.032	0.0078	0.006	0.087

The geometry of the samples was obtained according to both UNI EN 1561 Standard and the work carried out by Behnam et al. [14]. In particular, the thicknesses and the corresponding sample diameters were chosen according to the relevant wall thickness defined in the above-mentioned Standard. **Fig. 1** shows the geometry of the sample used in the experiments.

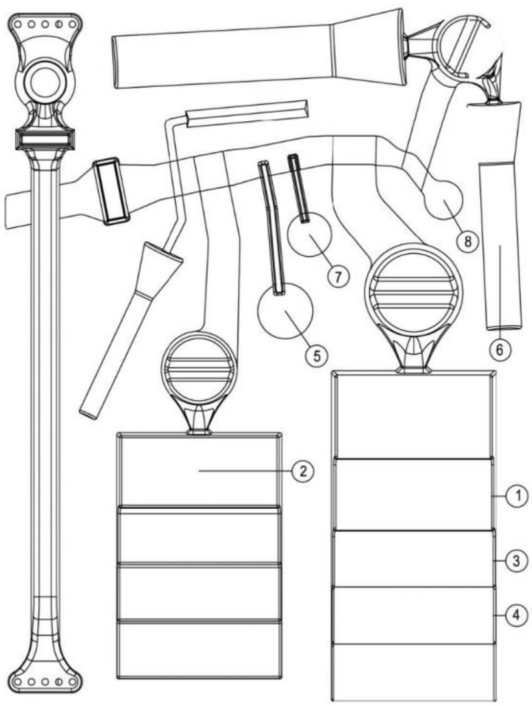

Fig. 1 Sample geometry used in the experiments. Specimens numbered 5, 7 and 8 are vertical cylinders of diameter 47 mm, 32 mm and 17 mm, respectively. The step-shape geometries are indicated with the numbers 1, 2, 3 and 4 and are characterized by thicknesses of 30 mm , 30 mm, 15 mm and 10 mm, respectively.

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The sample casting consists of two step-form samples and different cylindrical specimens with vertical and horizontal orientation. In **Fig. 1** steps 1 and 2 are 30 mm thickened while steps 3 and 4 are 15 mm and 10 mm thickened, respectively. It is noted that, steps 1 and 2, even if characterized by the same thickness value, feature different cooling rate because step 2 is directly ahead the gate compared to step 1 (**Fig. 1**). Furthermore, in order to dampen the bias due to variables of foundry parameters that may occur in different working days, four samples a day were casted in four different days. **Fig. 2** shows a schematic of the sample geometries according to the Standard UNI EN 1561:2011. The diameter value (d) was equal to 8 mm, 12.5 mm or 20 mm according to the zone of the casting where the tensile test sample was taken from.

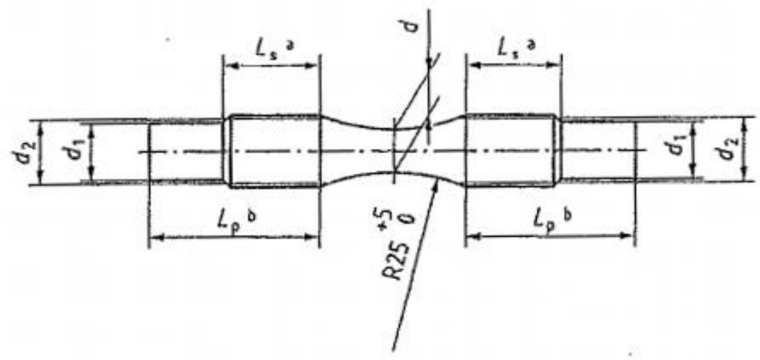

Fig. 2 Tensile test sample geometry (UNI EN 1561:2011)

The testing machine 'MTS Criterion 43' was used for samples of diameter 8 mm and 12.5 mm, while 20 mm diameter samples were tested with the Galdabini PM30 machine. Four to five samples were tested for each analysed conditions. Both optical and scanning electron microscope were used to investigate the microstructure of representative samples while fracture surface analysis was carried out on some samples to study the fracture mechanism.
In order to validate the UTS predictive approach, tensile test samples were also taken from an industrial casting produced with the GH 190 grey cast iron (GCI), a lift housing raw element produced according to the Fiat 52205 Standard. The required Brinell hardness of the casting had to fall in the range between 190 HB and 240 HB while the tensile strength had to be at least 210 MPa. **Fig. 3** shows the geometry of the real casting used to validate the proposed approach and the areas where the samples for tensile tests were taken from.
A numerical model for moulding and solidification simulation was carried out by NovaFlow & Solid. In the proposed approach the simulation is used to calculate the solidification times in the different parts of the casting whose mechanical properties has to be determined.
In order to calibrate the numerical model a temperature measurement was carried out directly inside the casting during the moulding and solidification by means of a K-type thermocouple (K chromel (Ni-Cr)(+)/alumel(Ni-Al)(-)). With the purpose to protect it from the melted alloy, the thermocouple was inserted in a ceramic pipe (Al_2O_3) and locked within, through a subsequent pipe filling with an alumina-based ceramic solution, then dried. The thermocouple was put in the middle of the 30 mm thickness step 1 (**Fig. 1**).

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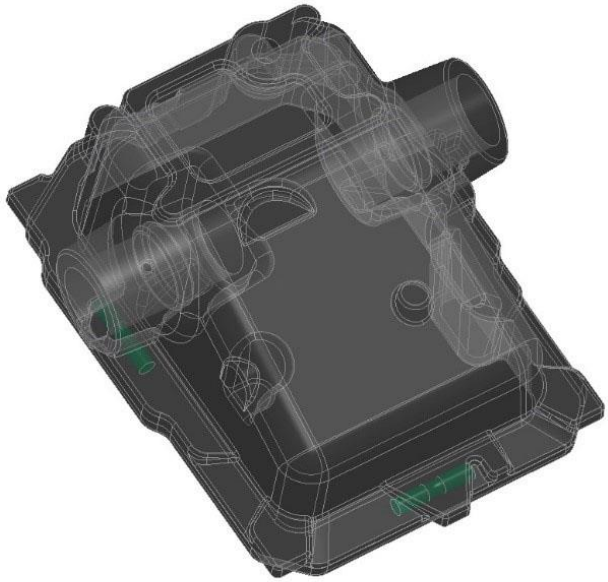

Fig. 3 Lift housing raw element

A convergence analysis, resulting in a 4.7 mm finite element edge, was performed in order to optimize the mesh density and the corresponding computational times. The parameters calibration of the model was obtained by comparing the thermal history measured with the thermocouple and the one resulting from the simulation. Input parameters such as the thermal and physical properties of cast iron and mould were taken from the software data-base and little variations were made necessary in order to overlap the two curves as shown in **Fig. 4**. The alignment between experimental and numerical results assured the calibration of the model parameters. **Fig. 4** shows also the procedure used to calculate the solidification time (Δt_s).

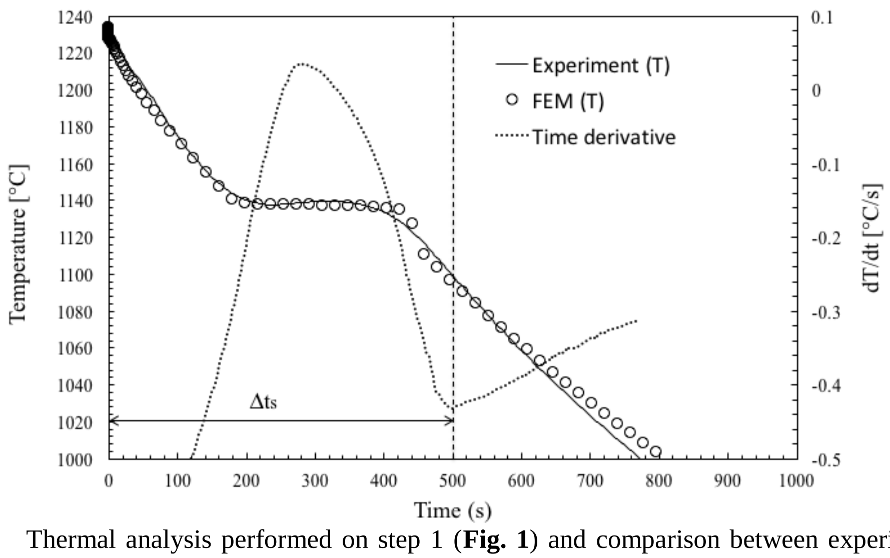

Fig. 4 Thermal analysis performed on step 1 (**Fig. 1**) and comparison between experimental and numerical temperature history evaluation

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3 Results and discussion

3.1 Microstructure and fractography

Fig. 5 shows a SEM micrograph of the analysed material. The flake graphite was surrounded by a thin layer of ferrite in a fully pearlitic matrix. The different graphite morphologies, as a function of the step thickness, are collected in **Fig. 6**. The greater the step thickness, the greater the flake graphite dimensions. Fractographs shown in **Fig. 7**, confirm the brittle fracture behaviour that characterizes the analysed cast iron.

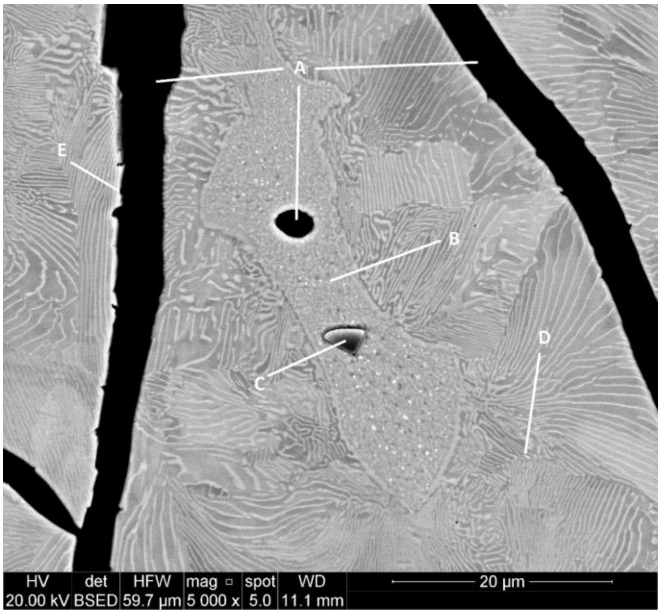

Fig. 5 SEM micrograph of the analysed alloy showing all its constituents detected: flake graphite (A), steadite (B), manganese sulphides (C), pearlite (D), ferrite (E)

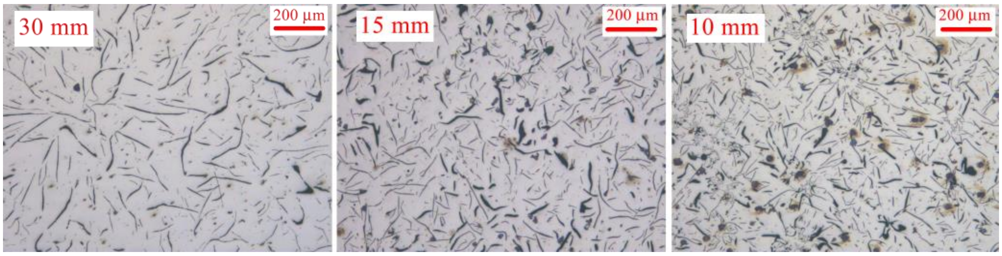

Fig. 6 Graphite morphology as a function of the step thickness.

3.2 Tensile tests

Fig. 8 summarizes the tensile test results (in terms of UTS) as a function of the thickness (or diameter) of the sample where specimens were taken from (**Fig. 1**). It is noted that despite the physiological scattering of the results, typical of the analysed brittle material, an inverse relation is found between thickness/diameter of the sample and its UTS value. The greater the thickness/diameter, the lower the tensile strength. However, this relation does not seem to be true for samples taken from 10 mm steps. This behaviour is due to a not-significant variation of

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the microstructure between 15 mm and 10 mm thick steps **(Fig. 6)**. It is worth mentioning that the scattering of results is also due to the different microstructure that characterize specimens taken from the same step thickness but with different solidification time. For the same reason, the microstructure, and thus the mechanical properties, of specimens coming from step and cylindrical form samples will be different. This is the main reason why the UTS should be related to the solidification time rather than the casting thickness or diameter.

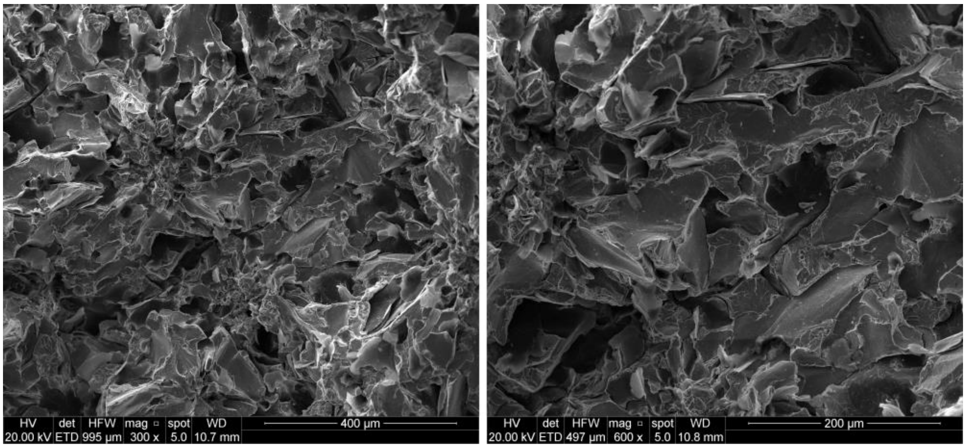

Fig. 7 SEM micrographs of fracture surface of sample taken from 15 mm thick step

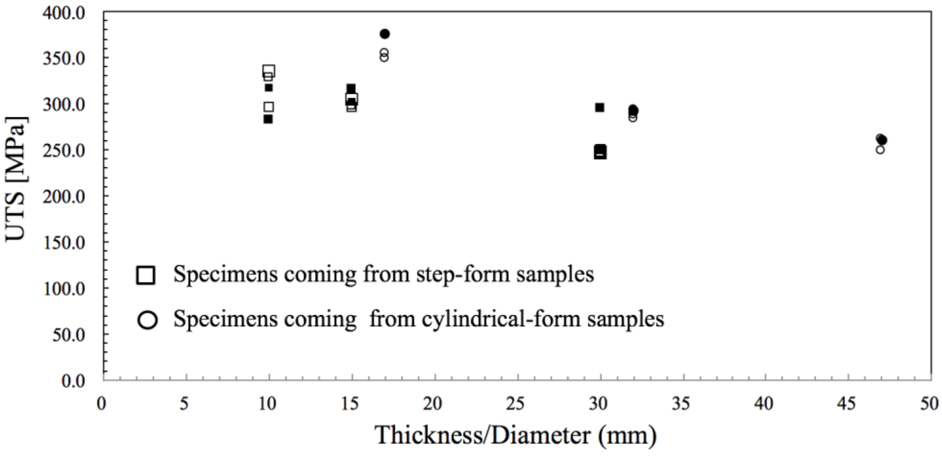

Fig. 8 UTS of GH 190 GCI as a function of sample thickness/diameter

The solidification time that characterizes the microstructure of each specimen was calculated by numerical simulation. By using UTS values coming only from step-form samples, **Fig. 8** was converted in a more convenient plot (named master curve (MC)), i.e., UTS versus solidification time (**Fig. 9**). Data were statistically elaborated by using a lognormal distribution. In particular, the upper and the lower curves refer to a survival probability of 50%, and 95 %, respectively.

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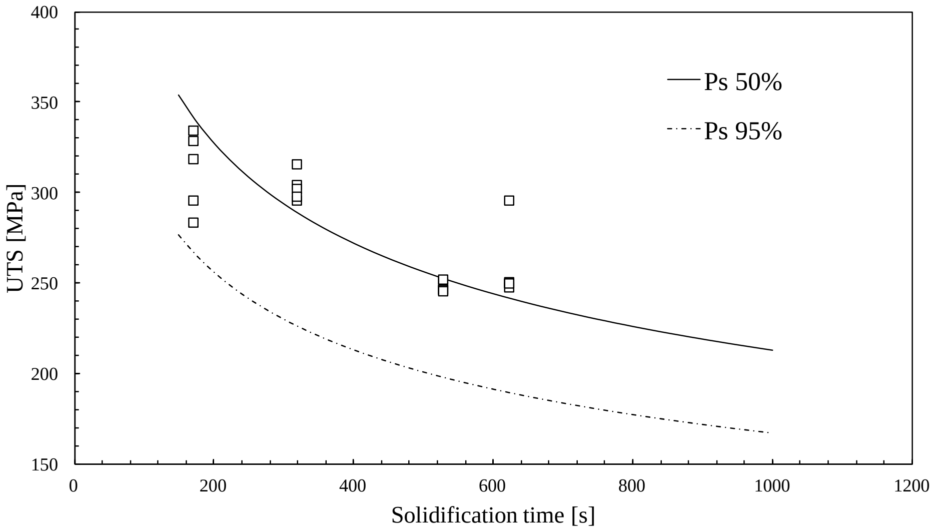

Fig. 9 UTS versus solidification time, Master curve of GH 190 cast iron

The UTS of the different parts of a casting are estimated by using the obtained MC (**Fig. 9**). As a matter of fact, by means of thermal simulation of moulding and solidification, it is quite easy to calculate the solidification times in the points of interest of the casting (**Fig. 3**). It is assumed that a sound casting without relevant macro defects is obtained. By using **Fig. 9** and the calculated solidification times of the zones of interest of the Lift housing raw element shown in **Fig. 3**, the estimated UTS values with a survival probability of 50% were 270 MPa and 236 MPa, respectively. If the real UTS values obtained by means of tensile tests are now plotted over the MC, it is observed that they fall between the survival probability values of 95% and 50%. The same results were obtained for the mechanical properties of the cylindrical-form samples, as shown in **Fig. 10**.

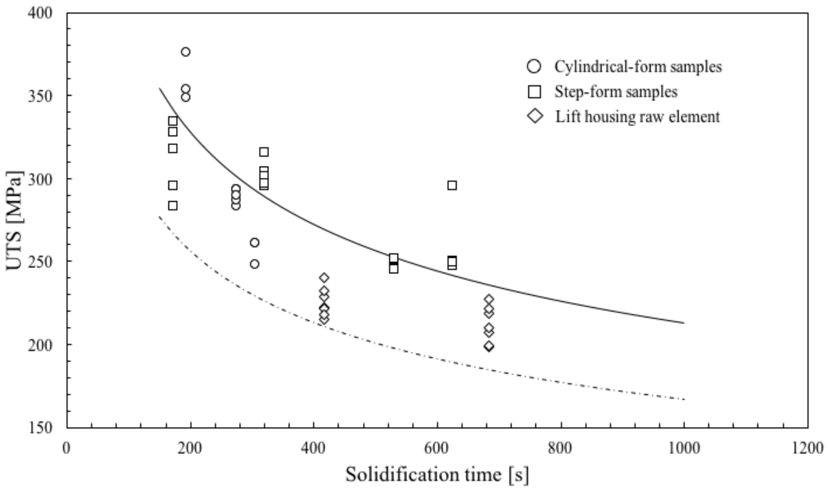

Fig. 10 Comparison between predicted and experimental UTS values as a function of the solidification time

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4 Conclusions

A method was described for a rapid mechanical properties estimation of different zones of a casting made of GH 190 grey cast iron. The proposed approach is based on the intrinsic relation between microstructure-solidification time and mechanical properties. A master curve, describing the tensile property as a function of the solidification time, can be calculated by means of tensile tests performed with specimens taken from step-form samples and moulding-solidification numerical simulation. It is assumed that, for sound castings without relevant solidification defects, the master curve depends only on the chemical composition of the analysed alloy. It was demonstrated that with a rapid numerical calculation of the solidification times of the zones of interest of an industrial casting, the master curve is able to rapidly estimate the ultimate tensile strength of such zones within the scatter band typical of such a brittle material.

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