Processing Thickness Window for As-cast Ausferritic Castings

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ABSTRACT

A process to obtain ausferritic as-cast microstructures through engineered cooling after solidification (without heat treatment) was developed in previous studies for a single alloy and for a specific casting (steering knuckle). However, many automotive castings that are candidates for this technology present geometries with significant thickness variations and consequently with different cooling rates. These differences can complicate or even make impossible the production of fully ausferritic as-cast parts by engineered cooling.

The aim of this work is to develop an experimental model that defines the thickness window in which an ausferritic as-cast microstructure can be achieved without the use of conventional austempering heat treatment, by chemical composition adjustments. Castings with different thermal moduli between 0.4 and 1.5 cm, and three chemical compositions (in the range 3.0-5.0% Ni; 0-0.2% Mo and 0.1-1.0% Cu by weight) were produced through engineered cooling after solidification. The mechanical properties of these castings were related to their different thicknesses, thermal moduli and/or cooling rates, ensuring that they can meet the requirements of the ASTM A897/A897M-06 (2011) and UNE-EN 1564-12 standards. A shakeout temperature window has been defined taking into account the different thermal moduli of a given casting. A transformation temperature range has also been defined where fully ausferritic microstructures could be achieved. The Excel spreadsheet model calculates the transformation temperature of the different sections of the casting and establishes if they are within the correct range.

Keywords: Ausferrite, as-cast, thermal modulus, thickness window, engineered cooling.

INTRODUCTION

The prospect of replacing some steel applications led to the development of a new process for the production of ductile iron with an ausferritic matrix (ADI). Its excellent strength/toughness ratio, allows replacing cast or forged steel, and even aluminum castings, by this new material, offering to the market components with a higher strength-to-weight ratio and lower price [1-4].

The conventional process to produce this microstructure consists in a heat treatment called austempering [5-10]. A process based on engineered cooling that does not require heat treatment was also proposed [11-14]. Ausferritic castings can be produced in as-cast conditions through this method. The engineered cooling reduces the energy required to produce a component and improves the added value of the parts. It also reduces the lead time and the entire life-cycle-energy.

The process variables that must be controlled to achieve the as-cast ausferritic microstructures include the chemical composition of the metal and the cooling rates of the different sections of the casting. The length of the solidification process, the parameters of the eutectoid transformation and of the isothermal transformation must also be included in the analysis.

One of the key points to achieve these as-cast ausferritic microstructures is to define the minimum cooling rate required to avoid the pearlitic nose of the alloy. Continuous Cooling Transformation (CCT) diagrams were developed for three different alloys with chemistry in the range of 3.0-5.0 % Ni; 0.0-0.2 % Mo and 0.1-1.0 % Cu by weight. The change of the minimum cooling rate to prevent the formation of pearlite was linked to the content of the main alloying elements (Ni, Mo and Cu).

Shakeout and isothermal transformation temperatures have a major influence on the final microstructure. Different thicknesses in the same casting involve different processing temperatures. This methodology must provide a fully ausferritic microstructure in all the sections of a casting or at least in the sections defined by the designing engineer. For this reason, the thickness window where completely as-cast ausferritic microstructures are obtainable must be clearly defined.

The present paper presents an experimental model, able to define the thickness window where the as-cast ausferritic microstructures can be guaranteed.

Additionally, the model was validated in a semi-industrial process for the chemical composition range defined earlier. When the thermal moduli of a casting are in the range of the processing thickness window, the model defines the optimum processing parameters with the aim of obtaining mechanical properties (ultimate tensile strength and hardness) that meet the requirements of the ADI materials.

EXPERIMENTAL PROCEDURE

The melts were prepared in a 100 kg medium frequency induction furnace (250 Hz, 100 kW). All the chemical compositions will be expressed as weight %. The metallic charge was made up of low alloyed steel scrap (0.007 % C, 0.002 % Si; 0.17 % Mn, 0.003 % P, 0.006 % S), high purity nickel (99 % min.), FeMo (64.25 % Mo, 2.05 % Si, 0.019 % C, 0.042 % S, 0.030 % P) and copper (99 % min.), graphite (99 % min; <0.03 % S, <0.04 % H, <0.01 % N), and FeSi75 (74.6 % Si, 0.83 % Al, 0.12 % C). Once the raw materials were melted, the chemical composition was checked and adjusted to achieve the required carbon, silicon, nickel, copper and molybdenum contents.

The tapping process from the furnace to the ladle was carried out at a temperature in the range 1510-1530ºC (2750-2786F). The spheroidization treatment was performed through sandwich method, adding 1.2 % of the total treated melt of a FeSiMg alloy (46.21 % Si, 6.47 % Mg, 0.98 % Ca, 0.67 % Al and 0.97 % RE).

To obtain different cooling rates, castings with different thermal moduli and several geometries were poured. The studied thermal moduli range was between 0.4 cm and 1.5 cm. The samples produced included plates (100 x 60 mm^2 and from 10 to 80 mm in thickness, varying each 10 mm), cylinders with the height equal to the diameter (24, 38, 48, 60, 72 and 90 mm), and keel blocks Y2 (as per the standard EN 1563). Examples of plate and cylinder distribution in the mold are shown on Fig. 1. The molds were made in all cases of chemically bonded sand.

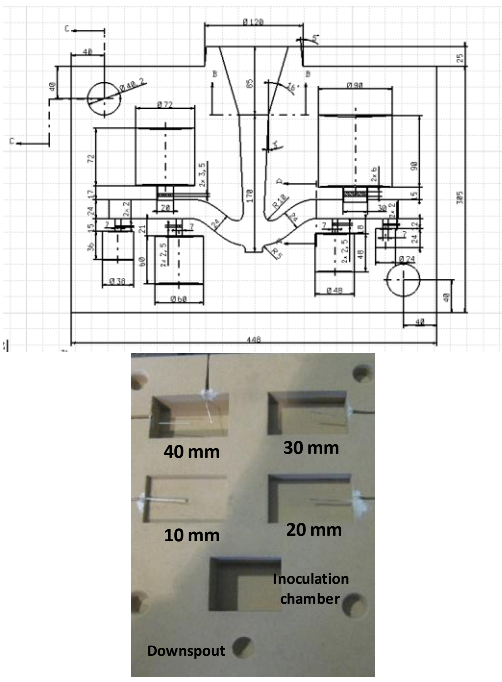


Fig. 1. Examples of some molds used to obtain samples with different cooling rates.

The inoculation was carried out in-mold using 0.2 % of a Germalloy ingot (71.7 % Si, 3.93 % Al, 0.99 % Ca) or Amerinoc (69.9 % Si, 0.49 % Bi, 0.93 % Al, 1.38 % Ca, 0.24 % Ce, 0.13 % La, 0.19 % Zr; grain size of 0.2-0.5 mm).

The range of chemical compositions in % of the cast parts was: 3.58-3.75 % C, 2.00-2.15 % Si, 0.18-0.25 % Mn, 0.007-0.010 % P, 0.006-0.009 % S, 0.038-0.049 % Mg. The alloying elements used to develop the CCT diagrams were Ni, Cu and Mo and they were on the following ranges: 2.86-5.05 % Ni, 0.01-0.22 % Mo, 0.09-0.96 % Cu.

At first, to develop the CCT diagrams, an early shakeout was applied to all the samples followed by air cooling. The cooling curve of each casting was recorded by means of a thermocouple (type K) inserted in the thermal center. With this information, the cooling rate for the different thermal moduli was experimentally calculated for the temperature range of the eutectoid transformation. Then, the specimens were cut and prepared for visual inspection by means of an optical microscope. To reveal the microstructure the metallographic samples were etched with Nital 5 %. The goal of the metallographic analysis was to find pearlite occurrence. Thus, the pearlitic nose and the minimum cooling rate needed to avoid the formation of pearlite as a function of the alloy composition were defined.

The second step was to define the processing temperatures to obtain as-cast ausferritic microstructures and relate them to the different thermal moduli of the castings. For this purpose, the alloy that presented a pearlitic nose at longer times on the CCT diagrams was considered. It's chemical composition was: 3.63-3.75 % C, 2.04-2.15 % Si, 0.19-0.24 % Mn, 0.007-0.010 % P, 0.006-0.009 % S, 0.042-0.049 % Mg, 2.86-3.01 % Ni, 0.17-0.22 % Mo, 0.09-0.19 % Cu.

The pouring temperature of the test castings was between 1390 and 1410ºC (2534 and 2570F). Once poured and solidified, the castings followed a controlled cooling process. At the beginning, all samples were shaken out at the same time and then air cooled in the temperature range of ausferrite formation. At this time, the samples were introduced into an insulating medium with a thermal conductivity lower than 0.006 W/mK. The insulating material used for these trials was expanded pearlite with a mesh size less than 5 mm and a density between 40-120 kg/m^3. The aim of this step is to maintain a constant temperature to enable the ausferritic reaction to occur. The isothermal transformation time was defined as 90 minutes for all the samples. This time was fixed in order to avoid the influence of this parameter on the ausferrite formation and to assure a complete reaction. Finally, after the isothermal holding, the samples were air cooled to room temperature. Some cooling curves for different thermal moduli are shown as an example in Fig. 2.

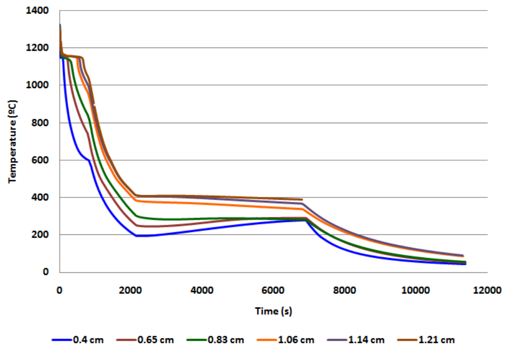


Figure 2. Example of cooling curves for different thermal moduli.

These experimental data were used to obtain the relation between the shakeout temperature and the thermal modulus.

Then, the isothermal transformation temperature as a function of the thermal modulus was calculated. This was done taking into account air cooling after the shakeout process.

Finally, the mechanical properties of the samples were studied. Tensile (10 mm diameter) and hardness specimens were machined from the samples. The ultimate tensile strength (U.T.S.), the yield strength (Y.S.) and the elongation (El.) were measured as per the standard EN 1563:2011. In addition, Brinell hardness (HB) measurements were carried out using a 10 mm diameter sphere and a load of 3000 kg as per the standard ISO 6506-1:2005.

RESULTS AND DISCUSSION

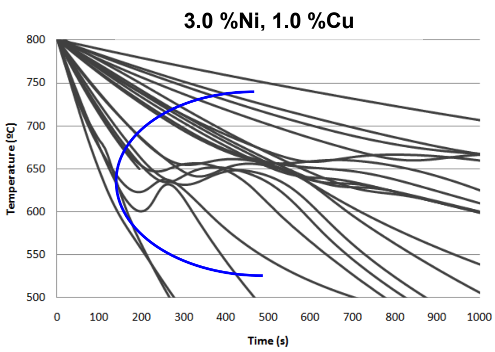
The chemical compositions of the three alloys for which the CCT diagrams were developed are shown on Table 1.

Table 1. Chemical Composition of the Alloys for Which the CCT Diagrams Were Developed (wt. %).

Alloy	C	Si	Mn	Mg	Ni	Mo	Cu
3.0 %Ni, 1.0 %Cu	3.60-3.73	2.00-2.12	0.18-0.22	0.038-0.045	2.90-3.05	<0.02	0.94-1.01
5.0 %Ni, 1.0 %Cu	3.58-3.69	2.03-2.14	0.20-0.25	0.040-0.049	4.95-5.05	<0.02	0.97-1.04
3.0 %Ni, 0.2 %Mo	3.63-3.75	2.04-2.15	0.19-0.24	0.042-0.049	2.86-3.01	0.17-0.22	0.09-0.19

To establish the experimental CCT diagrams, each alloy was cooled with rates from 0.2 ºC/s to 1.3 ºC/s in the temperature range between 800 and 500C (1472 and 932F). The results are shown on Fig. 3.

The experimental minimum cooling rates for each alloy to avoid the formation of pearlite are shown in Table 2. The minimum cooling rate values were considered for the temperature range 600-700C (1112-1292F), because the lowest registered cooling rate before the eutectoid transformation occurs on this range. This minimum cooling rate must be maintained until the eutectoid transformation temperature is reached. In order to simplify the mathematical concepts, the cooling curves in this temperature interval were considered as straight lines, which is in good agreement with the experimental results.



5.0 %Ni, 1.0 %Cu

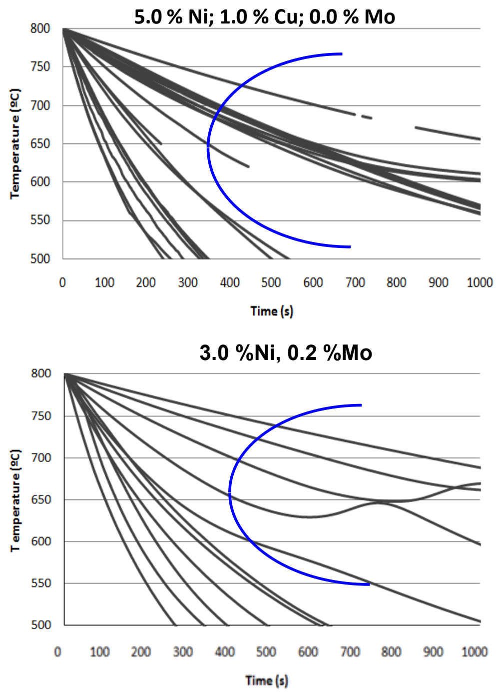


Fig. 3. CCT diagrams for three different alloys (in blue, experimental pearlitic nose).

Table 2. Minimum Cooling Rates to Avoid the Pearlite Formation.

Alloy	Minimum cooling rate (ºC/s)
3.0 % Ni; 1.0 % Cu	1.25
5.0 % Ni; 1.0 % Cu	0.60
3.0 % Ni; 0.2 % Mo	0.53

As a first step of the experimental model an equation to calculate the minimum cooling rate (CR_{min}) to avoid the pearlitic nose as a function of the nickel, copper and molybdenum contents was developed for the studied chemical compositions:

$$CR_{min} = 2.35 - 0.33 \cdot \%Ni - 0.10 \cdot \%Cu - 4.0 \cdot \%Mo \quad \textbf{Eqn 1}$$

This equation was experimentally validated for the studied composition ranges.

The second step of the experimental model deals with the definition of the thickness window in which this methodology is valid. The need to establish a thickness window is because a casting has different sections and also different thermal moduli. The higher the thermal modulus the longer the solidification process and the lower the cooling rate.

The shakeout process cannot be carried out at any temperature. The upper limit (1050C [1922F]) was defined around 50C (122F) below the solidus temperature. This is due to the fact that shaking out a casting which is not completely solid can lead to casting defects such as microporosity or high thermal stress. The lower limit was defined as 50C above the eutectoid temperature. This temperature is a function of the thermal modulus and the alloy content. Figure 4 shows the influence of the thermal modulus and the content of alloying elements on the eutectoid transformation temperature.

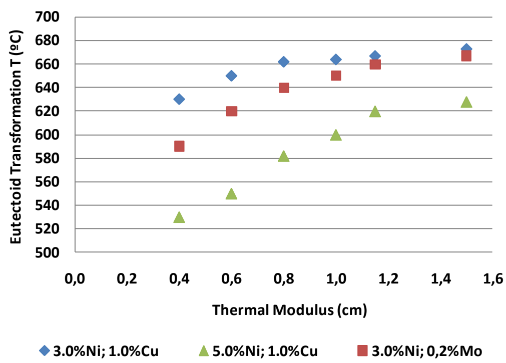


***Fig. 4. Influence of the content of alloying elements and of the thermal modulus on the eutectoid transformation temperature*.**

To define the lower limit of the shakeout temperature, the most restrictive of the curves, which corresponds to the 3.0 % Ni, 1.0 % Cu alloy, was considered. The following expression that fits the experimental results allows calculating the eutectoid transformation temperature (T_{etd} in ºC) as a function of the thermal modulus (M):

$$T_{etd} = -41.93 \cdot M^2 + 115.03 \cdot M + 593.24 \quad \textbf{Eqn. 2}$$

Taking into account the experimental castings with different thermal moduli, the solidification time and the subsequent cooling in the mold till shakeout, the shakeout temperature was calculated as a function of the thermal modulus. Thermal moduli in the range between 0.4 and 1.5 cm were studied and it was seen that a straight line relates the shakeout temperature to the thermal modulus, as follows.

$$T_{shkout\_M} = 568.40 \cdot M - 341.04 + T_{shkout\_0.6cm} \quad \textbf{Eqn. 3}$$

The value of the shakeout temperature for an M = 0.6 cm is a constant determined by an iterative calculus method. It is considered as a reference value for all alloys. This reference value is needed to change the time of the shakeout, which enables to fit, for the different sections, the shakeout temperature into the range defined by the upper and lower limit.

For a given casting, the model can calculate several shakeout times that make the process feasible. The iterative method chooses the one that gives the lower shakeout temperature, with the aim of reducing the thermal stress due to a high temperature shakeout.

The result of this step is the shakeout temperature for the minimum and maximum thermal moduli of a casting.

The described calculation regarding the shakeout temperature is shown on Fig. 5. It also shows the possibility to change the maximum and minimum thermal modulus of the casting to be considered.

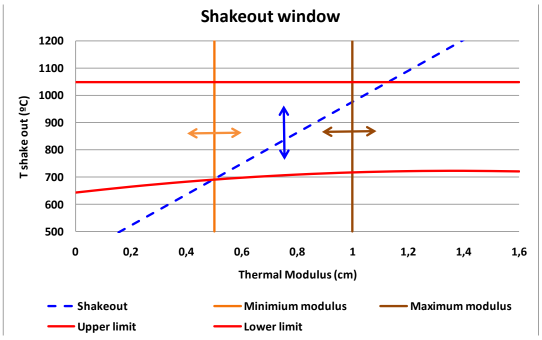


Fig. 5. Graphical description of the calculation of the optimum shakeout temperature.

The aim of the cooling process is to obtain fully ausferritic microstructures. Therefore, once the composition to avoid the pearlitic nose and the shakeout temperature as a function of the different thermal moduli of a casting are defined, the next step is to define the isothermal transformation temperature. In this work the temperature at which the different thermal moduli of a casting are to be introduced into an insulating medium was calculated based on the experimental results.

Like in the former step, the model calculates the isothermal transformation temperature as a function of the thermal modulus:

$$T_{iso\_transf\_M} = 293.39 \cdot M - 180 + T_{iso\_transf\_0.6cm} \quad \textbf{Eqn. 4}$$

Following the same methodology as for the shakeout temperature, the value of the isothermal transformation temperature for $M = 0.6$ cm is taken as a reference value. This reference value fits the isothermal transformation temperature of the different moduli into the defined range.

The isothermal transformation must take place within a temperature range to obtain the desired microstructure and thus the mechanical properties that satisfy the requirements of the ADI materials.

The upper limit was considered as 450C (842F). Above this temperature experimental evidence showed that the obtained ausferrite did not produce the desired mechanical properties, which is in good agreement with the literature [15-17].

The lower limit is defined as the martensite start formation temperature (T_{Mst}). For the alloy considered on this part of the work (3 % Ni; 0.2 % Mo), the T_{Mst} temperature was defined by means of dilatometry tests as shown in Fig. 6. For other alloys, further analysis should be carried out and relate this temperature to the content of alloying elements [18, 19].

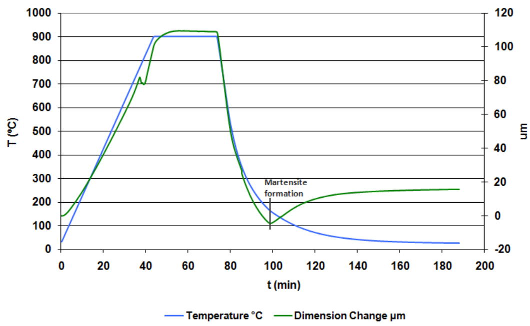


Fig. 6. Martensite start formation temperature defined by dilatometry.

Considering the Eq. 4 and the limits for the ausferritic transformation, the model establishes if a particular casting can be produced following this methodology and when feasible, the temperature at which the casting should be introduced into the insulating medium. From the different possibilities offered by the iterative calculation, the optimum solution is the one that enables to obtain the desired mechanical properties in terms of ultimate tensile strength and hardness.

The mechanical properties of the different samples were analyzed by means of tensile and hardness tests. Table 3 shows the results obtained in some castings as a function of their thermal moduli.

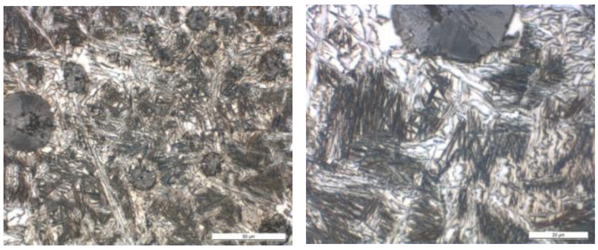
Table 3. Mechanical Properties as a Function of the Thermal Modulus.

Thermal Modulus (cm)	UTS (Mpa)	YS (Mpa)	E (%)	HB
0.65	1020	569	2.4*	356
0.83	1040	614	7.1	321
0.97	848	548	3.9*	308
1.07	846	627	7.9	288
1.15	822	552	11.3	280
1.22	760	552	7.9	263
1.28	775	573	7.0	266

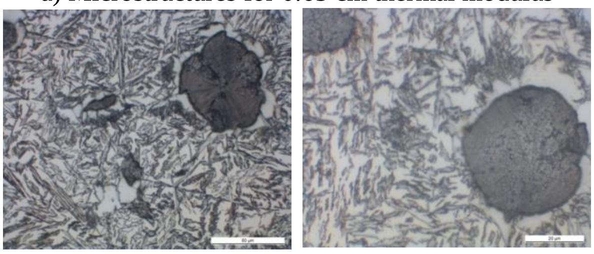
*Microshrinkage on the surface of the specimen.

Depending on the thermal modulus, and consequently on the processing temperatures of the samples, different ADI grades were obtained. As an example, on Fig. 7 are shown the microstructures obtained for the modulus 0.65 cm and 1.28 cm. It is observed that the lower thermal modulus is associated with a higher amount of lower ausferrite. This results in higher strength for the lower thermal moduli, but lower ductility.

Statistical analysis was carried out with all the experimental data in order to relate the process parameters to the mechanical properties based on the Pearson correlation. It indicates the strength of a linear relationship between two variables. These results are shown on Table 4. It is seen, that the process parameter that has a greater influence on the mechanical properties (higher correlation values) is the isothermal transformation temperature. Figure 8 shows the relationship between the isothermal transformation temperature and the mechanical properties.



a) Microstructures for 0.65 cm thermal modulus



b) Microstructures for 1.28 cm thermal modulus

Fig. 7. Microstructures for different thermal moduli.

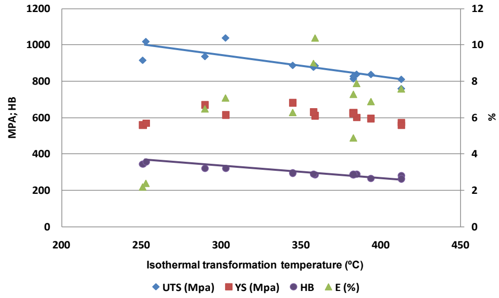


Fig. 8. Evolution of the mechanical properties as a function of the isothermal transformation temperature.

Table 4. Results of the Statistical Analysis.

	UTS	YS	El	HB	M	T_{shkout}	T_{iso_transf}	N	Pearlite	Martensite
UTS	1.00	0.11	0.01	0.67	-0.52	-0.33	**-0.59**	-0.30	-0.59	-0.22
YS	0.11	1.00	-0.36	0.42	0.02	-0.03	**-0.57**	0.05	0.11	-0.63
El	0.01	-0.36	1.00	-0.45	-0.07	-0.04	**0.60**	-0.44	-0.03	-0.29
HB	0.67	0.42	-0.45	1.00	-0.30	-0.21	**-0.88**	0.10	-0.35	-0.19
M	-0.52	0.03	-0.07	-0.30	1.00	0.89	0.45	0.52	0.38	--
T_{shkout}	-0.33	-0.03	-0.04	-0.21	0.89	1.00	0.46	0.39	0.23	-0.42
T_{iso_transf}	**-0.59**	**-0.57**	**0.60**	**-0.88**	0.45	0.46	1.00	-0.02	0.31	-0.01
N	-0.30	0.05	-0.44	0.10	0.52	0.39	-0.02	1.00	0.05	0.73
Pearlite	-0.59	0.11	-0.03	-0.35	0.38	0.23	0.31	0.05	1.00	--
Martensite	-0.22	-0.63	-0.29	-0.19	--	-0.42	-0.01	0.73	--	1.00

M: thermal modulus; T_{shkout}: shakeout temperature; T_{iso_transf}: isothermal transformation temperature; N: Nodule count;

The evolution of elongation is not very clear, presenting a high scattering of the results. This could be due to the high sensitivity of this property on casting defects like microporosity. The yield strength also does not present a clear relationship. It seems to be more or less constant regardless of the isothermal transformation temperature. However, the ultimate tensile strength and hardness show a clear tendency linked to the isothermal transformation temperature. The higher this temperature the lower these properties. This leads to the assumption that, depending on the ADI grade that is being targeted, the optimum transformation temperature will be higher or lower:

$$UTS = -1.2231 \cdot T_{iso\_transf} + 1308.2 \qquad \textbf{Eqn. 5}$$

$$HB = -0.483 \cdot T_{iso\_transf} + 466.34 \qquad \textbf{Eqn. 6}$$

Based on the desired mechanical properties, combining the Eqs. 4, 5 and 6, the model calculates the optimum isothermal transformation temperature for the minimum and maximum thermal moduli of the casting.

These steps define the different processing parameters needed to obtain fully ausferritic microstructures on all the sections of the casting, and mechanical properties that meet the requirements.

THE MODEL

As explained previously, the Excel spreadsheet model developed, establishes if a specific casting, with specific thickness differences, can be produced through engineered cooling and if it is possible to obtain fully ausferritic microstructures on all sections.

The inputs of the model are the minimum and maximum thermal modulus of the casting where an ausferritic microstructure must be guaranteed and the mechanical property requirements.

Taking into account these inputs, in the first step the model analyzes the required alloying elements. By means of an iterative method, the model calculates the minimum nickel, molybdenum and copper content to prevent the formation of pearlite (Eq. 1). As several alloy combinations can be considered, different criteria like economical or qualitative could be the decisive factor in selecting the proper alloy.

In the second step, the model deals with the shakeout process. Based on the relation between the shakeout temperature and the thermal modulus described by Eq. 3, the model determines if the process is feasible for the maximum and minimum thermal modulus of the component and if it is, the optimum shakeout temperature.

The third step deals with the isothermal transformation temperature window. The model structure of this step is very similar to the precedent. For the same maximum and minimum thermal modulus, the model determines if it is feasible to achieve the target microstructure and if it is, defines their optimal isothermal transformation temperatures, based on the required mechanical properties in terms of ultimate tensile strength and Brinell hardness.

CONCLUSIONS

The present work addresses the processing limits of the technology for producing as-cast ausferritic microstructures.

In previous works it was demonstrated that the methodology to obtain ausferritic microstructures by means of the engineered cooling was feasible. In this work a step forward has been taken in order to apply it to an industrial process.

An experimental/statistical model was developed to determine in a simple way the process parameters capable of producing as-cast ausferritic parts with given mechanical properties. It takes into account the different thicknesses of a specific casting and the cooling differences they present.

The model defines the optimal chemical composition and the two processing temperatures for the different sections (shakeout and isothermal transformation). These two critical temperatures have to be inside defined ranges that permit the formation of an ausferritic microstructure which meets the requirements of the ADI materials. Depending on the different thermal moduli of the casting, these temperatures will change. Based on these changes, the model calculates the thickness window in which this methodology is feasible and by extension, if a given casting could be produced with the engineered cooling process.

The experimental model has been validated with different geometries in a defined range of thermal moduli (0.4-1.5 cm) and for specific range of chemical composition (3.0-5.0 %Ni; 0.0-0.2 %Mo; 0.1-1.0 %Cu by weight).

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