

(19)



(11)

EP 3 026 128 A1

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:

01.06.2016 Bulletin 2016/22

(51) Int Cl.:

C21D 5/00 (2006.01)

C21D 1/20 (2006.01)

C21D 1/68 (2006.01)

C21D 1/70 (2006.01)

C22C 37/04 (2006.01)

(21) Application number: **14382479.5**

(22) Date of filing: **27.11.2014**

(84) Designated Contracting States:

**AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO
PL PT RO RS SE SI SK SM TR**

Designated Extension States:

BA ME

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(54) **A method to control ausferritic as-cast microstructure in ductile iron parts**

(57) 1. A method to control the ausferritic as-cast microstructure in iron parts with sections of different thicknesses, which comprises:

- Calculate the cooling rate for the maximum and minimum thermal moduli considering an air cooling.
- Calculate the minimum cooling rate needed to avoid the pearlitic nose, as a function of different contents of Ni, Cu and Mo (CR_{min}).
- Select one of the compositions with a minimum cooling rate (CR_{min}) lower than the cooling rate for the maximum

thermal modulus.

d) Calculate the eutectoid temperature ($T_{eutectoid}$) as a function of the thermal modulus for the composition selected, for all the different thermal moduli of the part.

e) Calculate the shake-out temperature ($T_{shakeout}$) for all the different thermal moduli of the part.

f) Identify if $T_{shakeout}$ for the minimum thermal modulus is over the eutectoid temperature ($T_{eutectoid}$) calculated in d) and if $T_{shakeout}$ for the maximum thermal modulus is below the solidus temperature ($T_{solidus}$).

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Description**TECHNICAL FIELD**

5 **[0001]** The present invention relates to the techniques used to obtain ausferritic ductile iron parts, and more particularly to techniques to obtain ausferritic as-cast microstructures without an austempering heat treatment.

STATE OF THE ART

10 **[0002]** The possibility to replace some steel applications led to develop a new process to produce a ductile iron with an ausferritic matrix. Its excellent strength/toughness ratio allows eventually replacing casted or forged steel and even aluminum castings by this material, offering to the market components with a higher strength-to-weight ratio and lower price.

15 **[0003]** For the manufacturing of ausferritic ductile iron with high quality the most common and easiest to reproduce method consists in an austempering process. The ausferritic ductile iron obtained accordingly is usually referred to as austempered ductile iron (ADI). The austempering process is a three step heat treatment which comprises the austenitization of the casting at a temperature higher than 850°C until the matrix structure attains a reasonably uniform carbon content; quenching to an intermediate temperature range of 260 to 400°C and tempering, which consists in the transformation to austenitic-ferritic structure at the isothermal temperature. This process increases the final cost of the casting and also the lead time.

20 **[0004]** Nevertheless, a new process based in the engineered cooling was proposed in EP 2 749 658 A1. The process comprises the following steps:

- 25 (i) Casting a melt of a ductile iron alloy in a mould.
- (ii) Solidification of the casting in the mould and subsequent cooling until the casting temperature is between 800°C and 950°C.
- 30 (iii) Shaking out the casting at said temperature between 800°C and 950°C.
- (iv) Cooling the casting until the temperature of the casting reaches a value between 275°C to 450°C with a high enough cooling rate in order to avoid the pearlitic nose.
- 35 (v) Introducing the casting in an insulating material and leaving the casting inside for a period of time until a completely ausferritic microstructure is obtained.

[0005] By this method ausferritic castings can be produced in as-cast conditions. This engineered cooling reduces the energy required to produce a component (avoiding the austempering heat treatment) and improves the added value of the parts, as well as reducing the lead time. In addition, the entire life-cycle-energy is reduced.

40 **[0006]** Nevertheless, this process was used for a single alloy and for a specific casting (i.e 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.

45 **[0007]** Similar processes are described in JANOWAK J F et al: "Approaching austempered ductile iron properties by controlled cooling in the foundry", Int. Conf. on Austempered Ductile Iron, 2 April 1984, p.63/9 and in U. de la Torre et al: "As-Cast Ausferritic Ductile Iron", Proceedings of the Keith Millis Symposium on Ductile Cast Iron 2013, October 15-17, Nashville, Tennessee.

[0008] In sum, a process is needed, which enables to solve in an efficient way, the above mentioned problems of conventional processes for obtaining parts with ausferritic microstructures.

DESCRIPTION OF THE INVENTION

50 **[0009]** It is an object of the present invention to provide a method to control the ausferritic as-cast microstructure in iron parts with sections of different thicknesses, which comprises:

- 55 a) Calculate the maximum thermal modulus (the thermal modulus of the section of the part with the greatest thickness) and the minimum thermal modulus (the thermal modulus of the section of the part with the lowest thickness) of the part (in centimeters).

- b) Calculate the cooling rate for the maximum and minimum thermal moduli considering an air cooling ($^{\circ}\text{C/s}$).
 c) Calculate the minimum cooling rate ($\text{CR}_{\min}$) needed to avoid the pearlitic nose, as a function of different contents of Ni, Cu and Mo (wt.%).
 d) Select one of the compositions with a minimum cooling rate ($\text{CR}_{\min}$) lower than the cooling rate for the maximum thermal modulus.
 e) Calculate the eutectoid temperature ($T_{\text{eutectoid}}$, $^{\circ}\text{C}$) as a function of the thermal modulus for the composition selected, for all the different thermal moduli of the part.
 f) Calculate the shakeout temperature (T_{shakeout} , $^{\circ}\text{C}$) for all the different thermal moduli of the part.
 g) Identify if T_{shakeout} for the minimum thermal modulus is over the eutectoid temperature ($T_{\text{eutectoid}}$) calculated in e) and if T_{shakeout} for the maximum thermal modulus is below the solidus temperature (T_{solidus}).

[0010] The method preferably comprises the following steps:

- b1) Obtain continuous cooling transformation (CCT) diagrams for several alloys with different contents of Ni, Cu and Mo.
 b2) Consider the cooling curves obtained in step b1) straight lines and represent the slope of the lines in a cooling rate/thermal modulus diagram.
 b3) Obtain a regression line for the slopes of step b2).

[0011] In the step b3) the regression line is preferably represented by the exponential function $y = 1.4763 e^{-0.811x}$

[0012] In the step c) the minimum cooling rate is preferably calculated using the following formula:

$$\text{CR}_{\min} (^{\circ}\text{C/s}) = 2.35 - 0.33 * \text{Ni} (\text{wt}\%) - 0.1 * \text{Cu} (\text{wt}\%) - 4.0 * \text{Mo} (\text{wt}\%)$$

[0013] In the step e) the eutectoid temperature ($T_{\text{eutectoid}}$) as a function of the thermal modulus is preferably calculated using the formula:

$$T_{\text{eutectoid}_M} (^{\circ}\text{C}) = -41.93 * M^2 (\text{cm}^2) + 115.03 * M (\text{cm}) + 593.24$$

[0014] In the step f) the shakeout temperature (T_{shakeout}) for the different thermal moduli is preferably calculated using the formula:

$$T_{\text{shakeout}_M} (^{\circ}\text{C}) = 568.40 * M (\text{cm}) - 341.04 + T_{\text{shakeout}_{0.6\text{cm}}} (^{\circ}\text{C})$$

[0015] The step g) preferably comprises identifying if T_{shakeout} for the minimum thermal modulus is over the eutectoid temperature + 50 $^{\circ}\text{C}$ and if T_{shakeout} for the maximum thermal modulus is below the solidus temperature - 50 $^{\circ}\text{C}$ (1050 $^{\circ}\text{C}$).

[0016] A further object of the invention is a method which comprises the step of:

- h) Identifying if the isothermal transformation temperature $T_{\text{isothermal}}$ transformation for the minimum and maximum thermal moduli are between 450 $^{\circ}\text{C}$ and 170 $^{\circ}\text{C}$.

[0017] The isothermal transformation temperature for a given modulus is preferably calculated using the formula:

$$T_{\text{isothermal transformation}_M} (^{\circ}\text{C}) = 293.39 * M (\text{cm}) + T_{\text{isothermal transformation}_{0.6\text{cm}}} (^{\circ}\text{C}) - 180$$

[0018] A further object of the invention comprises the steps of:

- i) Calculate the ultimate tensile strength (UTS) of a given thermal modulus using the following formula:

$$UTS \text{ (MPa)} = -1.2231 * T_{\text{isothermal transformation}_M} (^{\circ}\text{C}) + 1308.2$$

and/or

j) Calculate the theoretical hardness (HB) of the parts using the following formula:

$$HB = -0.483 * T_{\text{isothermal transformation}_M} (^{\circ}\text{C}) + 466.34$$

[0019] A further object of the invention comprises the steps of:

ii) Calculate the optimum isothermal transformation temperature using the following formula:

$$T_{\text{isothermal transformation}_M} (^{\circ}\text{C}) = 1069.58 - 0.82 * UTS \text{ (MPa)}$$

and/or

jj) Calculate the optimum isothermal transformation temperature using the following formula:

$$T_{\text{isothermal transformation}_M} (^{\circ}\text{C}) = 965.50 - 2.070 * HB$$

[0020] The method of the invention applies preferably for parts with a minimum thermal modulus greater than 0.4 and a maximum thermal module lower than 1.5.

[0021] The method of the invention preferably applies to the following composition of the alloys:

Ni: 3.0 - 5.0 % in wt.

Mo: 0.0 - 0.2 % in wt.

Cu: 0.0 - 1.0% in wt.

[0022] Additional advantages and features of the invention will become apparent from the detail description that follows and will be particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] To complete the description and in order to provide for a better understanding of the invention, a set of drawings is provided. Said drawings form an integral part of the description and illustrate an embodiment of the invention, which should not be interpreted as restricting the scope of the invention, but just as an example of how the invention can be carried out. The drawings comprise the following figures:

Figure 1 shows the cooling curves as a function of the thermal modulus.

Figure 2 shows CCT diagrams for three different alloys.

Figure 3 shows the influence of the alloy content and the thermal modulus on the eutectoid transformation temperature.

Figure 4 shows a graphical description of the calculus of the optimum shakeout temperature.

Figure 5 shows microstructures for different thermal moduli.

Figure 6 shows the evolution of the mechanical properties as a function of the isothermal transformation temperature.

DESCRIPTION OF A WAY OF CARRYING OUT THE INVENTION

[0024] In this text, the term "comprises" and its derivations (such as "comprising", etc.) should not be understood in an excluding sense, that is, these terms should not be interpreted as excluding the possibility that what is described and

defined may include further elements, steps, etc.

[0025] In the context of the present invention, the term "approximately" and terms of its family (such as "approximate", etc.) should be understood as indicating values very near to those which accompany the aforementioned term. That is to say, a deviation within reasonable limits from an exact value should be accepted, because a skilled person in the art will understand that such a deviation from the values indicated is inevitable due to measurement inaccuracies, etc. The same applies to the terms "about" and "around" and "substantially".

[0026] The following description is not to be taken in a limiting sense but is given solely for the purpose of describing the broad principles of the invention. Next embodiments of the invention will be described by way of example, with reference to the above-mentioned drawings showing apparatuses and results according to the invention.

[0027] The melts were prepared in a 100 kg medium frequency induction furnace (250 Hz, 100 kW). 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.), in addition to 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 adding the needed above mentioned materials according to the required carbon, silicon, nickel, copper and molybdenum contents.

[0028] The tapping process from the furnace to the ladle was carried out at a temperature range between 1510 and 1530 °C. The spheroidization treatment was performed following the sandwich methodology, adding 1.2 % (by weight considering the total weight of the treated melt) of a FeSiMg alloy (46.21 % Si, 6.47 % Mg, 0.98 % Ca, 0.67 % Al and 0.97 % RE).

[0029] To obtain variable cooling rates, castings presenting different thermal moduli with several geometries were poured. The studied thermal moduli range was between 0.4 cm and 1.5 cm. The produced samples varied from plates (100 x 60 mm²) of different thicknesses to cylinders with different diameters (diameter=height) and keel blocks Y2. The molds were made in all cases of chemically bonded sand.

[0030] The inoculation was carried out in mold using 0.2 % (by weight with respect to the total weight of the casting plus feeding and feeling systems) of a Germalloy ingot (71.7 % Si, 3.93 % Al, 0.99 % Ca, Traces % Mg, Traces % RE) 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).

[0031] The range of chemical compositions in wt% of the cast parts was as follows: 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 changed 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, 0.09-0.90 % Cu.

[0032] On the first part of the experiments, in order to develop the CCT diagrams, an early shakeout was applied to all the samples followed by an air cooling. The cooling curve of each casting was recorded by means of a thermocouple (type K) inserted in their thermal centre. With this information, the cooling rate for the different thermal moduli was experimentally calculated on the temperature ranges where the eutectoid transformation takes place. Afterwards, the samples were metallographically analyzed to define if pearlite appeared. This way were defined the pearlitic nose and the minimum cooling rate needed to avoid the formation of this phase as a function of the alloy content. For the metallographic analysis, the specimens were cut and prepared for a visual inspection by means of an optical microscope. The used etchant to reveal the microstructure was Nital 5 %.

[0033] The second step of the trials was to define the processing temperatures to obtain an ausferritic microstructure as-cast and relate them to the different thermal moduli of the castings. For that purpose, the alloy that presented a pearlitic nose on more prolonged times was considered, that is (in weight %): 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.

[0034] The pouring temperature was between 1390 and 1410 °C. Once poured and solidified, the castings followed a controlled cooling process. At the beginning, all the samples were shaken out at the same instant and air cooled till they reached the temperature range where the ausferrite formation can occur. At this moment, the samples were introduced into an insulating medium presenting a thermal conductivity lower than 0.006 W/mK. The insulating material used for these trials was expanded perlite with a mesh size less than 5 mm and a density between 40-120 kg/m³. 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. Finally, after the isothermal process, the samples were air cooled to room temperature. On Figure 1 an example of some cooling curves as a function of the thermal modulus is shown.

[0035] With the experimental data, the relation between the shakeout temperature and the thermal modulus was obtained.

[0036] Afterwards, taking into account an air cooling after the shakeout process, the isothermal transformation temperature as a function of the thermal modulus was calculated.

[0037] 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. In addition, Brinell hardness (HB) measurements were carried out using a 10 mm diameter sphere and a load of 3000 kg.

[0038] Regarding the CCT diagrams, the three alloys mentioned on the former sections were considered. The chemical compositions 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 0.0 % Mo	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 0.0 %Mo	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 0.0 %Cu 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

[0039] On the temperature range between 800 and 500 °C, cooling rates from 0.2 °C/s up to 1.3 °C/s were considered for each alloy. The results are shown on Figure 2.

[0040] On the Table 2 the experimental minimum cooling rates for each alloy to avoid the formation of pearlite are shown. In order to simplify the mathematical concepts, the cooling curves on the temperature range between 700 °C and 600 °C were considered as straight lines, which is in good accordance with the experimental results. The selected temperature range, takes into account the steps before and during the eutectoid transformation for these alloys.

Table 2. Minimum cooling rates to avoid the pearlite formation.

Alloy	Minimum cooling rate (°C/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

[0041] Considering the studied chemical compositions, 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 (Equation 1) was developed.

$$CR_{min} (°C/s) = 2.35 - 0.33 * Ni (wt\%) - 0.1 * Cu (wt\%) - 4.0 * Mo (wt\%) \quad \text{Eqn 1}$$

[0042] This equation was validated on the studied composition ranges (3.0-5.0 % Ni; 0.1-1.0 % Cu and 0.0-0.2 % Mo).

[0043] On a second step, the thickness window in which this methodology is feasible was defined. The higher the thermal modulus of a casting the longer the solidification process and the lower the cooling rate. The fact that a single casting has different sections and also different thermal moduli, leads to establish a thickness window in which this methodology is feasible.

[0044] On the one hand, the shakeout process cannot be carried out at any temperature. The upper limit (1050 °C) was defined around 50 °C 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 as microporosity or high thermal stress. The lower limit was defined as 50 °C over the eutectoid transformation temperature. This temperature is a function of the thermal modulus and the alloy content. The Figure 3 shows the influence of the thermal modulus and the alloy content 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; 0.2 % Cu and 0.0 % Mo alloy, was considered. The following expression was obtained as a function of the thermal modulus (M) (Equation 2). This equation fits the obtained experimental results:

$$T_{eutectoid_M} (°C) = -41.93 * M^2 (cm^2) + 115.03 * M (cm) + 593.24 \quad \text{Eqn. 2}$$

[0045] Taking into account the trials carried out using castings with different thermal moduli, the solidification time and the subsequent cooling in the mold till 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 relation could be defined in order to obtain the shakeout temperature for the different sections of a given casting. This function is shown on the equation 3.

$$T_{shakeout_M} (^{\circ}C) = 568.40 * M (cm) - 341.04 + T_{shakeout_{0.6cm}} (^{\circ}C) \quad \text{Eqn. 3}$$

[0046] The value of the shakeout temperature for a thermal modulus of 0.6 cm is a constant determined by an iterative calculus method. This reference value is needed to change the moment of the shakeout, which enables to fit, for the different sections, the shakeout temperature into the range defined by the upper and lower limit (when possible).

[0047] For a given casting, the model can calculate several shakeout moments 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.

[0048] The result is the shakeout temperature for the minimum and maximum thermal moduli of a casting.

[0049] The described calculus regarding the shakeout temperature is shown on Figure 4. It also shows the possibility to change the maximum and minimum thermal modulus of the casting to be considered.

[0050] The aim of the cooling process is to obtain fully ausferritic microstructures. Therefore, once defined the alloy to avoid the pearlitic nose and the shakeout temperature as a function of the different thermal moduli of a casting, the next step which has a decisive importance is 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. On this phase, the model calculates the isothermal transformation temperature as a function of the thermal modulus (Equation 4).

$$T_{isothermal\ transformation_M} (^{\circ}C) = 293.39 * M (cm) + T_{isothermal\ transformation_{0.6cm}} (^{\circ}C) -$$

180 **Eqn. 4**

[0051] Following the same methodology as for the shakeout temperature, the value of the isothermal transformation temperature for the modulus 0.6 cm is needed. This reference value fits (when possible) the isothermal transformation temperature of the different moduli into the defined range (explained below).

[0052] The isothermal transformation must take place into a determined temperature range to obtain the desired microstructure and thus the mechanical properties that allow meeting the requirements of the ADI materials. In this case the upper limit was considered as 450 °C, temperature above which it is not considered in the literature that the obtained ausferrite shows the desired mechanical properties. The lower limit is considered as the martensite start formation temperature (M_s). For the alloy considered on this part of the work, the M_s was defined by means of dilatometry tests in 170 °C.

[0053] Considering the equation No 4 and the limits for the ausferritic reaction, the model defines if the given 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 that offers the iterative calculus, the optimum solution is the one that enables to obtain the desired mechanical properties in terms of ultimate tensile strength and hardness.

[0054] The mechanical properties of the different samples were analyzed by means of tensile and hardness tests. The Table 3 shows the mechanical properties obtained on one of the trials as a function of the thermal moduli of the castings. All the castings were handled together (shaken out and inserted into the insulating medium at the same time).

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.

[0055] It is seen, that depending on the thermal modulus, different ADI grades were obtained. This is due to differences on the processing temperatures of the samples. On the Figure 5 are shown the microstructures obtained for the modulus 0.65 cm and 1.28 cm.

[0056] It is observed that the lower the thermal modulus, the greater the lower ausferrite appearance. This results in higher resistance for the lower thermal moduli, but lower toughness. A statistical analysis was carried out with all the data obtained on this work, to relate the process parameters to the mechanical properties. The results of this study are shown on Table 4.

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Table 4. Results of the statistical analysis.

	UTS	YS	EI	HB	Thermal Modulus	T shakeout	T Tempering	Nodule count	Pear lite	Marten site
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
EI	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
Thermal Modulus	-0.52	0.03	-0.07	-0.30	1.00	0.89	0.45	0.52	0.38	--
T shakeout	-0.33	-0.03	-0.04	-0.21	0.89	1.00	0.46	0.39	0.23	-0.42
T Tempering	-0.59	-0.57	0.60	-0.88	0.45	0.46	1.00	-0.02	0.31	-0.01
Nodule count	-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

[0057] It is seen, that the process parameter that has a greater influence on the mechanical properties is the isothermal transformation or tempering temperature (higher correlation values). For this reason, on the Figure 6, the relationship between the isothermal transformation temperature and the mechanical properties was further analyzed.

[0058] The evolution of the elongation is not very clear, presenting a high scattering of the results. This could be due to the high sensitiveness of this property with casting defects like for example microporosity. The yield strength neither presents a clear relationship. It seems to be more or less constant regardless of the tempering 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 both properties. This allows assuming that depending on the ADI grade that is being looked for, the optimum transformation temperature will be one or another. Based on the relationship between the isothermal transformation temperature and the thermal modulus, the model will define the optimum isothermal transformation temperature by means of the equation No 4 and the following equations No 5 and 6.

$$UTS \text{ (MPa)} = -1.2231 * M \text{ (cm)} + 1308.2 \quad \text{Eqn. 5}$$

$$HB = -0.483 * M \text{ (cm)} + 466.34 \quad \text{Eqn. 6}$$

[0059] All this steps define the different processing parameters in order to obtain fully ausferritic microstructures on all the sections of the casting.

[0060] On the other hand, the invention is obviously not limited to the specific embodiment(s) described herein, but also encompasses any variations that may be considered by any person skilled in the art (for example, as regards the choice of materials, dimensions, components, configuration, etc.), within the general scope of the invention as defined in the claims.

Claims

1. A method to control the ausferritic as-cast microstructure in iron parts with sections of different thickness, which comprises:

a) Calculate the maximum thermal modulus (the thermal modulus of the section of the part with the greatest thickness) and the minimum thermal modulus (the thermal modulus of the section of the part with the lowest thickness) of the part (in centimeters).

b) Calculate the cooling rate ($^{\circ}\text{C/s}$) for the maximum and minimum thermal moduli considering air cooling.

c) Calculate the minimum cooling rate ($\text{CR}_{\min}$) needed to avoid the pearlitic nose, as a function of different contents of Ni, Cu and Mo (wt.%).

d) Select one of the compositions with a minimum cooling rate ($\text{CR}_{\min}$) lower than the cooling rate for the maximum thermal modulus.

e) Calculate the eutectoid temperature ($T_{\text{eutectoid}}, ^{\circ}\text{C}$) as a function of the thermal modulus for the composition selected, for all the different thermal moduli of the part.

f) Calculate the shakeout temperature ($T_{\text{shakeout}}, ^{\circ}\text{C}$) for all the different thermal moduli of the part.

g) Identify if T_{shakeout} for the minimum thermal modulus is over the eutectoid temperature ($T_{\text{eutectoid}}$) calculated in e) and if T_{shakeout} for the maximum thermal modulus is below the solidus temperature ($T_{\text{solidus}}, ^{\circ}\text{C}$).

2. The method of claim 1, wherein the step b) comprises the following steps:

b1) Obtain continuous cooling transformation (CCT) diagrams for several alloys with different contents of Ni, Cu and Mo.

b2) Consider the cooling curves obtained in step b1) straight lines and represent the slope of the lines in a cooling rate/thermal modulus diagram.

b3) Obtain a regression line for the slopes of step b2).

3. The method of claim 2, wherein in step b3) the regression line is represented by the exponential function $y = 1,4763 e^{-0,811x}$.

4. The method of claim 1, wherein in the step c) the minimum cooling rate ($\text{CR}_{\min}$) is calculated using the following

formula:

$$CR_{min} (^{\circ}C/s) = 2.35 - 0.33 * Ni (wt\%) - 0.1 * Cu (wt\%) - 4.0 * Mo (wt\%)$$

- 5
5. The method of claim 1, wherein in the step e) the eutectoid temperature ($T_{eutectoid}$) as a function of the thermal modulus is calculated using the formula:

$$T_{eutectoid_M} (^{\circ}C) = -41.93 * M^2 (cm^2) + 115.03 * M (cm) + 593.24$$

- 10
6. The method of claim 1, wherein in the step f) the shakeout temperature ($T_{shakeout}$) for the different thermal moduli is calculated using the formula:

$$T_{shakeout_M} (^{\circ}C) = 568.40 * M (cm) - 341.04 + T_{shakeout_{0.6cm}} (^{\circ}C)$$

- 15
7. The method of claim 1, wherein step g) comprises identifying if $T_{shakeout}$ for the minimum thermal modulus is over the eutectoid temperature + 50 °C and if $T_{shakeout}$ for the maximum thermal modulus is below the solidus temperature - 50 °C.

- 20
8. The method of claim 1, which further comprises the step of:

25 h) Identifying if the isothermal transformation temperature $T_{isothermal}$ transformation for the minimum and maximum thermal moduli are between 450 °C and 170 °C.

9. The method of claim 8, wherein the isothermal transformation temperature is calculated using the formula:

$$\begin{aligned} T_{isothermal\ transformation_M} (^{\circ}C) \\ = 293.39 * M (cm) + T_{isothermal\ transformation_{0.6cm}} (^{\circ}C) - 180 \end{aligned}$$

- 30
10. The method of claim 1, which further comprises the step of:

i) Calculate the ultimate tensile strength (UTS) of a given thermal modulus using the following formula:

$$UTS (MPa) = -1.2231 * T_{isothermal\ transformation_M} (^{\circ}C) + 1308.2$$

- 35
11. The method of claim 1, which further comprises the step of:

40 j) Calculate the theoretical hardness (HB) of the parts using the following formula:

$$HB = -0.483 * T_{isothermal\ transformation_M} (^{\circ}C) + 466.34$$

- 45
12. The method of claim 1, which further comprises the steps of:

ii) Calculate the optimum isothermal transformation temperature using the following formula:

$$T_{isothermal\ transformation_M} (^{\circ}C) = -0.8176 * UTS (MPa) + 1069.58$$

- 50
13. The method of claim 1, which further comprises the steps of:

jj) Calculate the optimum isothermal transformation temperature using the following formula:

$$T_{\text{isothermal transformation}_M}(^{\circ}\text{C}) = 965.50 - 2.070 * HB$$

- 5
14. The method of claim 1, wherein the minimum thermal modulus of the part is greater than 0.4 and the maximum thermal modulus of the part is lower than 1.5.
- 10
15. The method of claim 1, wherein the chemical composition of the alloys is:
- Ni: 3.0 - 5.0 % in wt.
Mo: 0.0 - 0.2 % in wt.
Cu: 0.0 - 1.0 % in wt.
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- 50
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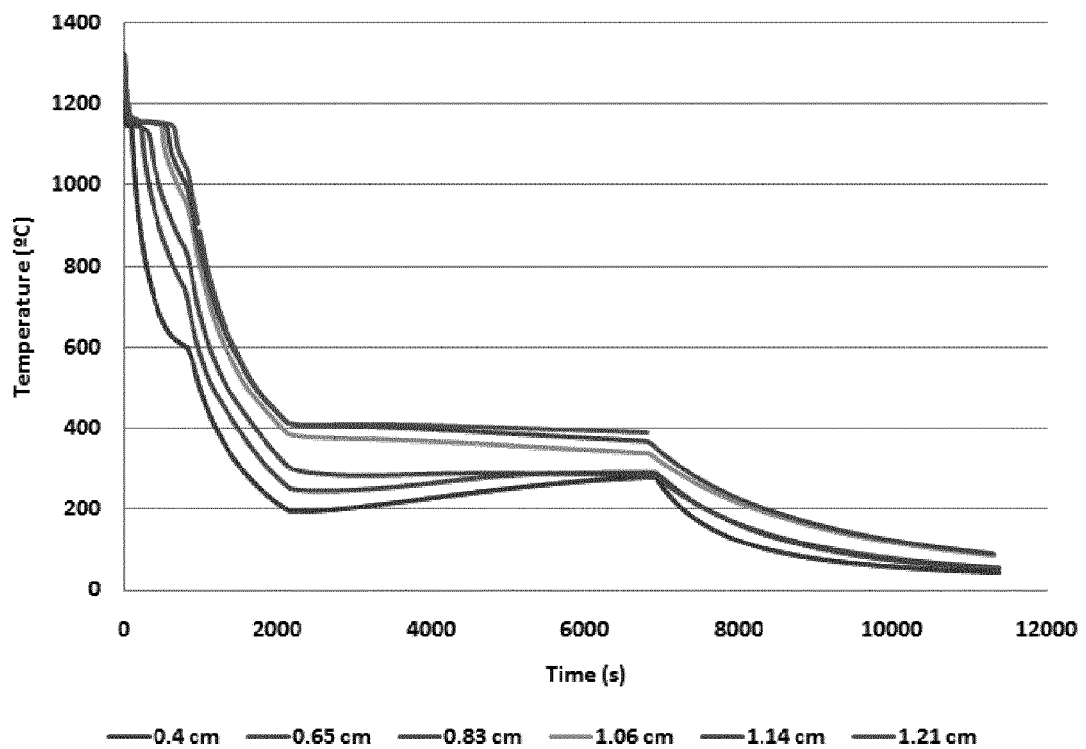


Figure 1

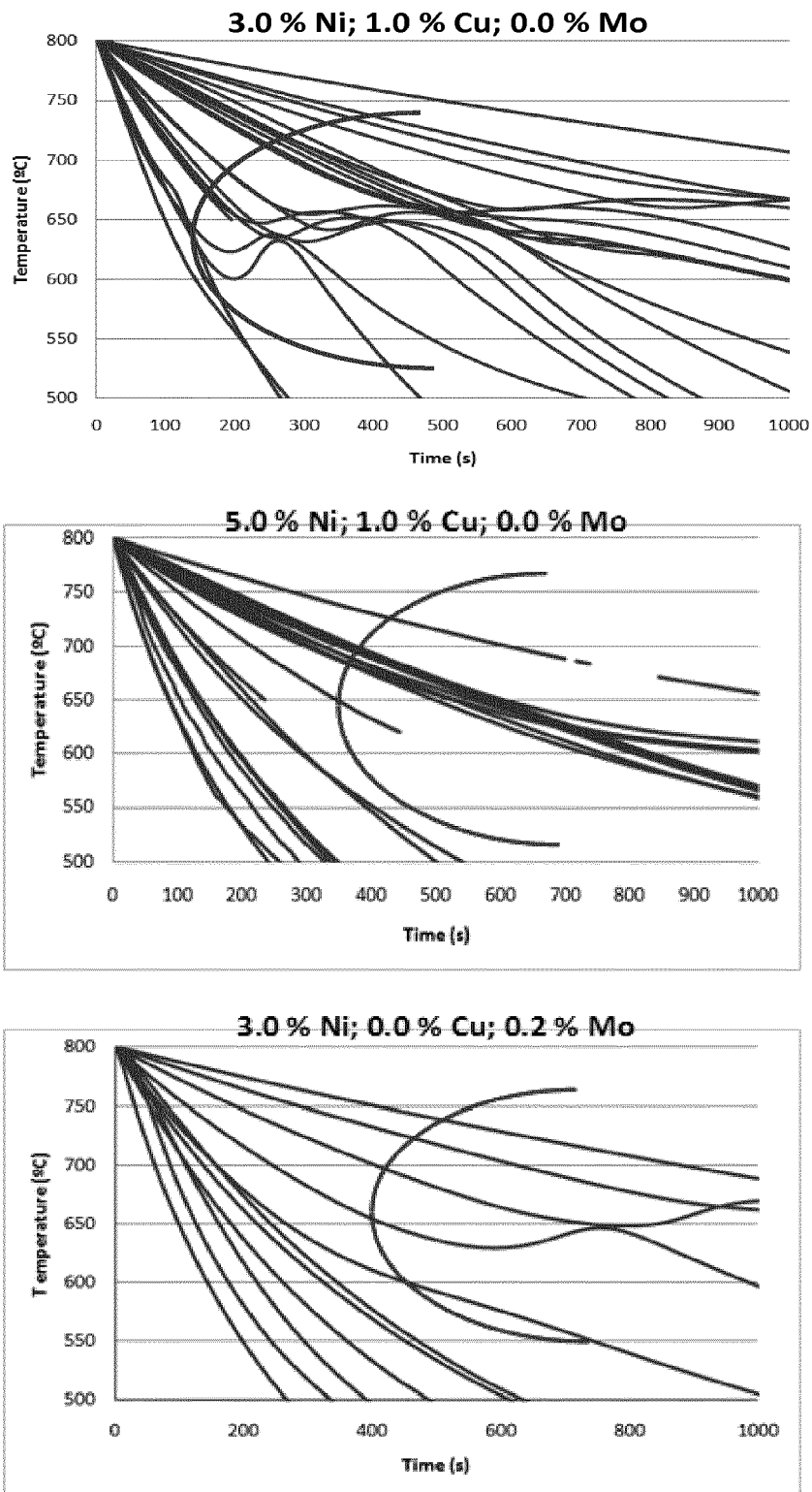


Figure 2

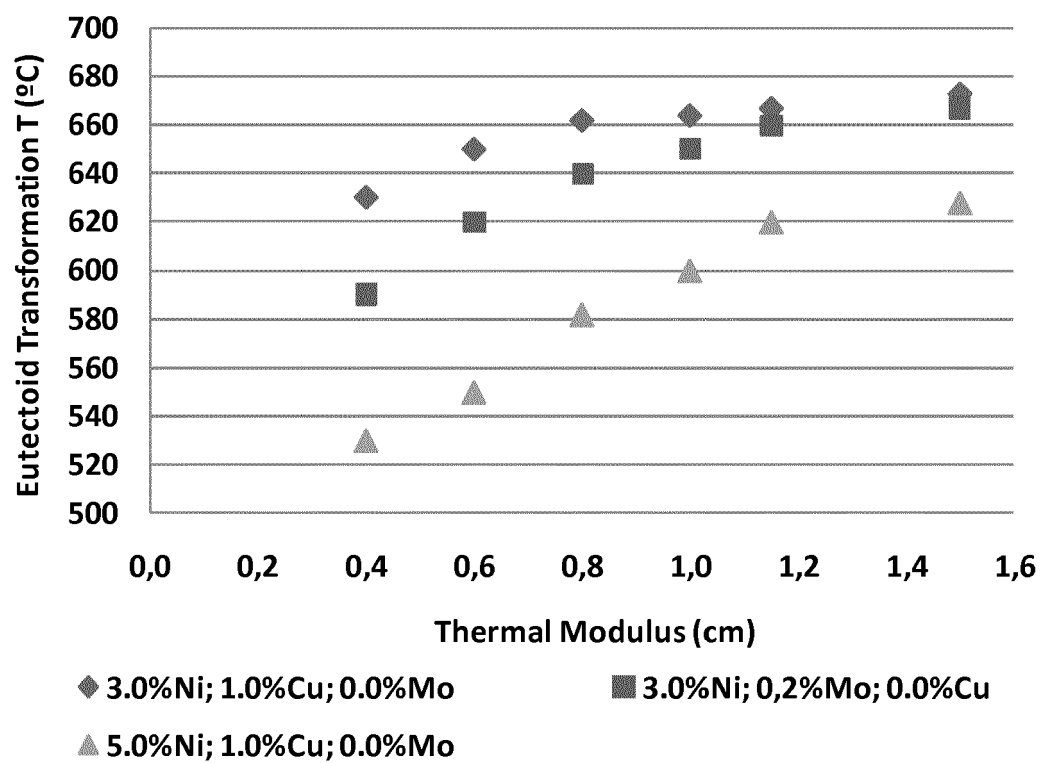


Figure 3

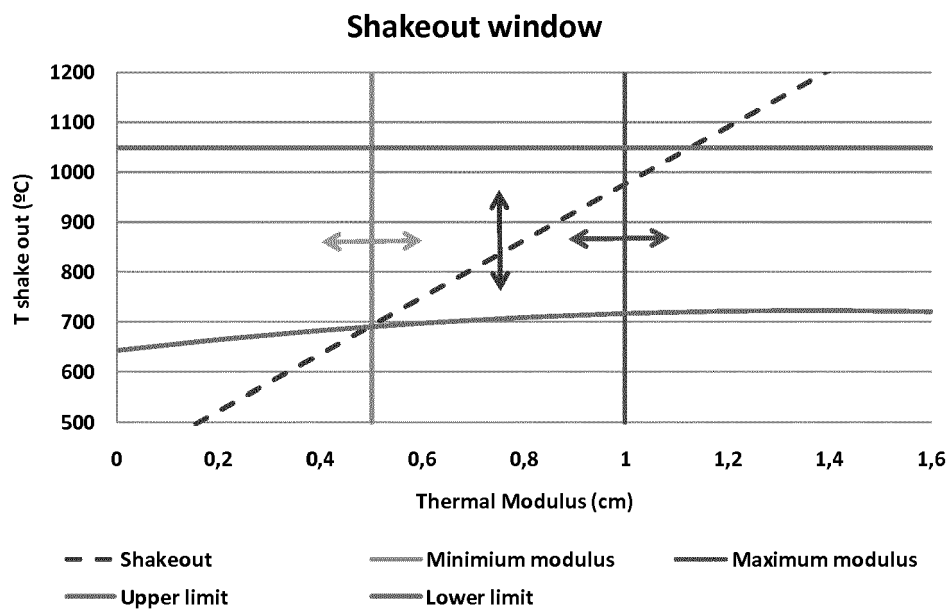


Figure 4

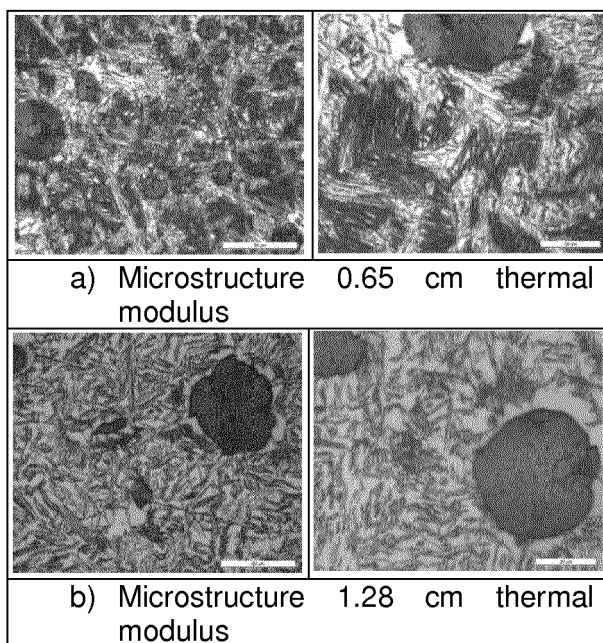


Figure 5

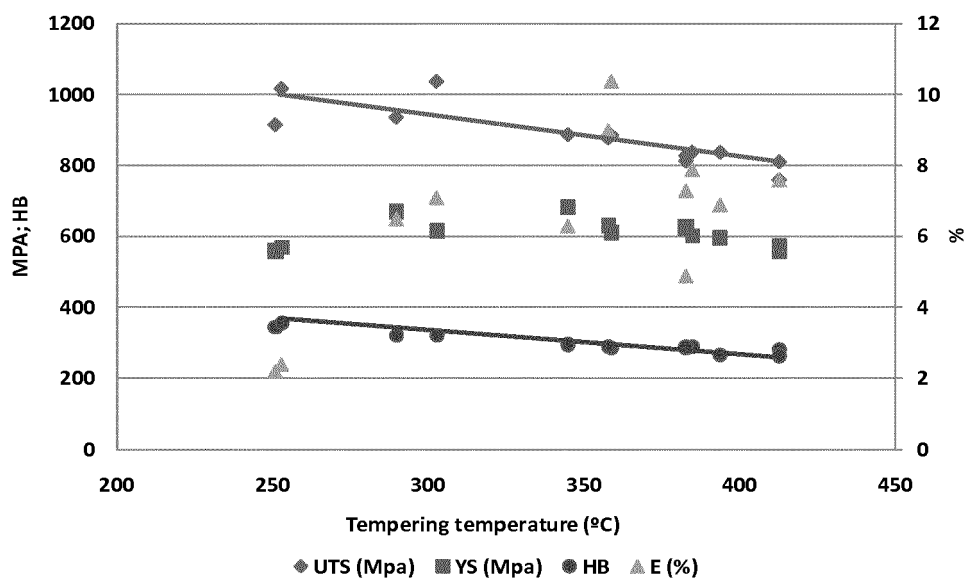


Figure 6



EUROPEAN SEARCH REPORT

Application Number
EP 14 38 2479

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DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X,D	EP 2 749 658 A1 (VEIGALAN ESTUDIO 2010 S L U [ES]; THERMAL QUALITY CONTROL TECHNOLOGIES) 2 July 2014 (2014-07-02) * the whole document *	1-15	INV. C21D5/00 C21D1/20 C21D1/68 C21D1/70 C22C37/04
A	JANOWAK J F ET AL: "APPROACHING AUSTEMPERED DUCTILE IRON PROPERTIES BY CONTROLLED COOLING IN THE FOUNDRY", INTERNATIONAL CONFERENCE ON AUSTEMPERED DUCTILE IRON, XX, XX, 2 April 1984 (1984-04-02), pages 63-69, XP001182603, * the whole document *	1-15	
			TECHNICAL FIELDS SEARCHED (IPC)
			C21D C22C
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 28 April 2015	Examiner Liu, Yonghe
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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EPO FORM 1503 03.02 (P04C01)

28-04-2015

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 2749658	A1	02-07-2014	NONE

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

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