Aspects Regarding the Solidification Kinetics of a Cast Iron Centrifugal Casting

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Abstract
There are showing the results of a study on cooling and solidification kinetic of a tubular cylindrical part of eutectic cast iron. The study was conducted by computer simulation. Six variants were compared three by centrifugal casting and three variants of gravity casting. There were analyzed: the average speed of the cooling in liquid state (in the range To - Ts), momentary cooling rate at the beginning of solidification (at Ts = solidus temperature) and the thickness of the white iron at the interface casting - mold. Comments are made on the whitening trend of parts cast by centrifugal castings compared to gravity casting. It is analyzed the influence of the external sand cores and outer coating of metal forms in centrifugal casting on the tendency whitening the structure.

Keywords
solidification, casting, centrifugal casting, solidification simulation, cast iron

1. Introduction

Cooling and solidification of centrifugal castings is different compared to conventional gravity casting. Peculiarities of heat transmission on spin casting of tubular parts are [2, 3, 4, 11]:

- The inner surface of the liquid alloy cast in the mold acts as a black body;
- Transmission of heat to the air in the central area of the casting is almost zero;
- Mold and liquid alloy rotation enhances heat transmission in the liquid alloy and at the contact surface liquid - solid;
- Mold rotation enhances convective heat transmission between mold and environment on the outer surface.

2. Paper Aim

In the case of cast iron parts, the cooling rate inside the solidification range and especially the cooling rate to achieve the eutectic temperature, considerably influence the structure and properties of cast parts. This influence is explained by the formation of white iron structure, above a certain critical cooling rate [4, 6, 7]. In the case of centrifugal casting, cooling rate is different in relation to the gravity casting, due to the special cooling conditions. Therefore, thermal field and cooling dynamics must be carefully analyzed in the case of centrifugal casting of cast iron parts. In a previous paper were presented some results on the cooling and solidification of a cast iron parts in different variants of centrifugal casting compared with gravity casting [12]. It was analyzed the hot spot position, solidification times in various points of the part, the temperature in the part wall at the end of solidification, temperature variation on the outer and inner surface of the casting.

This work is a continuation of the previous study on the solidification of centrifugal castings. There are analyzed in detail the kinetics of cooling and solidification of a cast iron part, cast centrifugally and gravitationally. It is analyzed the cooling speed in the casting wall for centrifugal casting against gravity castings. Finally it is analyzed the effect of centrifugation on the tendency of obtaining a layer of white iron at the outer surface of casting, in contact with the mold.

3. Working Mode

Study was done by computer solidification simulation. It was used software for solidification simulation of centrifugal castings of eutectic alloys [5,8]. The software is based on a mathematical model in cylindrical coordinates. It was simulated the solidification of a tubular part of cast iron with eutectic composition. The dimensions of the casting are shown in Figure 1. There were studied three types of centrifugal casting and gravity casting three variants:

- Case 1. Centrifugal casting in metallic mold;
- Case 2. Centrifugal casting in metallic mold, with outer sand core;
- Case 3. Centrifugal casting in metallic mold, painted;
- Case 4. Gravitational casting in sand mold with inner sand core;
- Case 5. Gravitational casting in metallic mold with inner sand core;
- Case 6. Gravitational casting in metallic mold with inner metallic core.

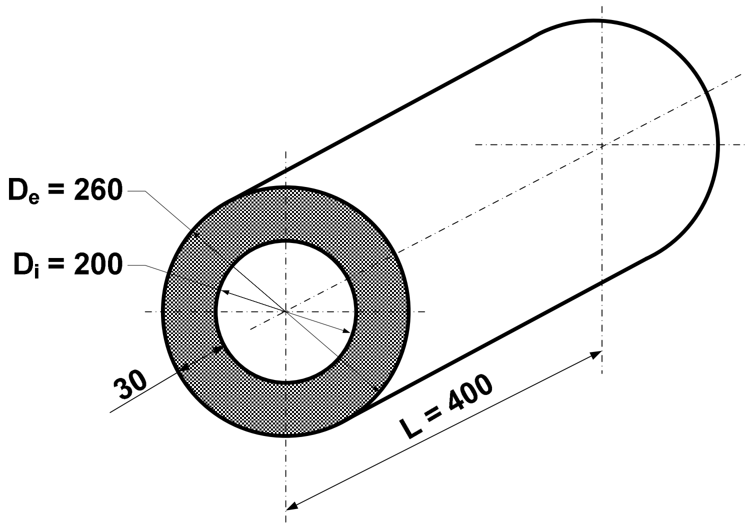


Fig. 1. Casting

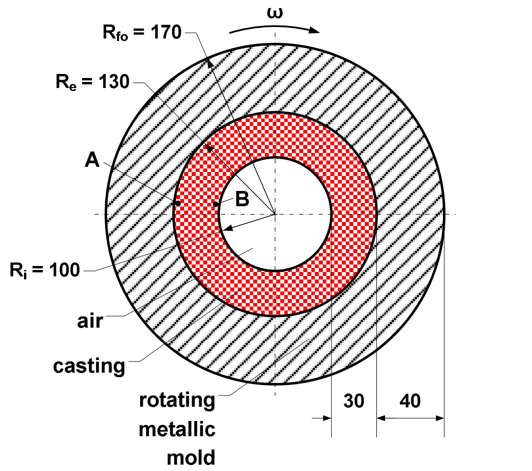
The construction and dimensions of the molds used in the six cases are shown in Figure 2 [2, 6, 7, 10]. It was analyzed the case when metal molds and cores are made of cast steel. In the case 2 the part was cast centrifugally with outer core sand (SiO_2). The core is designed to reduce the cooling rate in order to obtain gray cast iron structure. In the case 3 a coating paint of 1 mm thickness, based on graphite was applied at the surface of the metallic mold. This variant of centrifugal casting is often applied in practice. The protective layer (based on graphite) facilitates the extraction of casting from mold. Cases 4-6 correspond gravitational casting using mold and central core of sand (SiO_2) or metal (cast steel). To obtain more precise information on the cooling conditions in different points of castings, in simulation it was used a network division step of $\Delta = 1$ mm. The time step was $\tau = 0.015$ s.

The initial temperatures of the molten alloy and of the mold components taken into account for the simulation are given in Table 1 [2, 3, 10, 11].

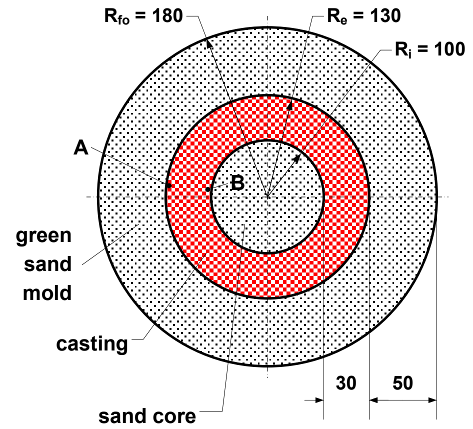
For the liquid cast iron, in centrifugal casting, an equivalent coefficient of thermal conductivity was considered. This considers the forced convection caused by the rotational movement and the centrifugal forces.

For the heat exchange coefficient with the environment there were used the following values:

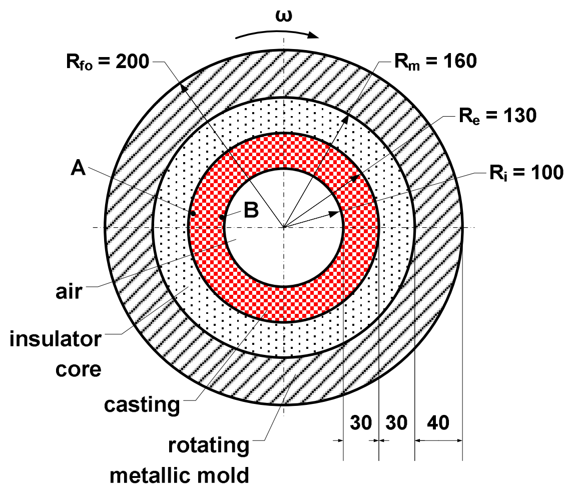
- At the outer surface sand mold - environment, at gravity casting $\alpha\_ex = 10$ W/m^{2}K;
- At the outer surface metallic mold - environment, at gravity casting $\alpha\_ex = 20$ W/m^{2}K;
- At the outer surface metallic mold - environment, at centrifugal casting $\alpha\_ex = 50$ W/m^{2}K;
- At the inner surface liquid metal - air, at centrifugal casting $\alpha\_in = 2$ W/m^{2}K.



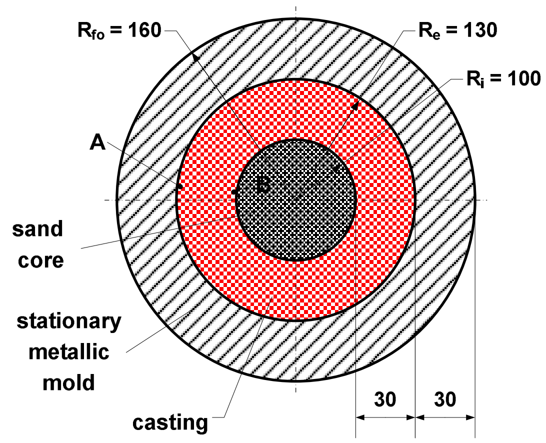
a.) Case 1 - Centrifugal casting in metallic mold



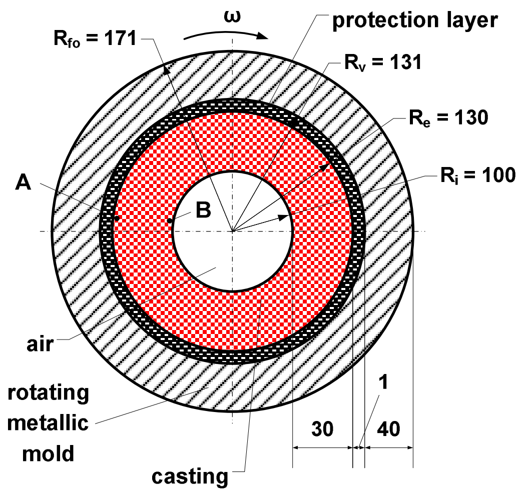
d.) Case 4 - Gravitational casting in sand mold with inner sand core



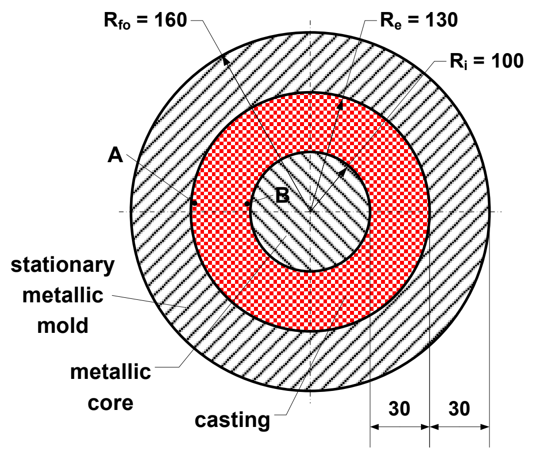
b.) Case 2 - Centrifugal casting in metallic mold, with outer sand core



e.) Case 5 - Gravitational casting in metallic mold with inner sand core



c.) Case 3 - Centrifugal casting in metallic mold, painted



f.) Case 6 - Gravitational casting in metallic mold with inner metallic core

Fig. 2. Design and dimensions of the casting molds

Table 1. The initial temperatures of the casting - mould system used for simulation

No.	Name	Symbol	Unit	Value
1	Initial cast alloy temperature (eutectic cast iron)	To_me	°C	1320
2	Initial temperature of sand mold or sand core for centrifugal or gravitational casting	To_fo	°C	20
3	Initial temperature of metallic mold for centrifugal or gravitational casting	To_fo	°C	200
4	Initial temperature of metallic core for gravitational casting	To_mi	°C	200
5	Initial temperature of the coating layer for metallic mold at centrifugal casting	T0_vo	°C	200
6	Exterior environment temperature at the outer surface of the mold for centrifugal or gravitational casting	To_ex	°C	20
7	Air temperature at the interior of the mold at centrifugal casting with sand core	To_in	°C	50
8	Air temperature at the interior of the mold at centrifugal casting in metallic mold	To_in	°C	100

Table 2. Thermo-physical characteristics of the materials used in simulation [4, 5, 6, 7]

No.	Name	Density	Specific heat	Thermal conductivity	Latent heat
Symbol		ρ	c	λ	L
Unit		Kg/m³	J/kg·K	W/mK	J/Kg
1	Liquid cast iron at gravitational casting	7000	850	30	220000
2	Liquid cast iron at centrifugal casting	7000	850	150	220000
3	Solid cast iron	7200	750	40	220000
4	Sand mold or sand core	1550	1170	0.8	-
5	Metallic mold or core	7600	750	30	-
6	Protection layer (graphite)	1800	1000	32	-

4. Results

The following parameters characterizing the casting solidification were analyzed for the six cases:
- time of the solidification beginning (time for cooling the molten alloy between initial temperature and solidus temperature To - Ts) depending on the distance from the interface metal - mold (t_in_sol);
- the average cooling rate of the liquid alloy (vr_med) in the range To - Ts (initial temperature - solidus temperature) in the casting wall, depending on the distance from the interface casting - mold;
- the momentary cooling rate of the liquid alloy (vr_Ts) at the solidus temperature (Ts) that is at the beginning of solidification of the alloy, depending on the distance from the interface casting - mold;
- the thickness of the white cast iron layer, at the interface casting - mold.

Table 3 shows the values of time of beginning solidification depending on the radius and the distance from the outer surface of the casting. In the tables 4 and 5 are given the values of average cooling speed of the liquid alloy in the range of To - Ts, and the momentary cooling speed values at the temperature Ts (cooling rate at the time of start of solidification) as a function of the distance from the interface casting - mold.

In Figures 3 and 4 it was plotted the average cooling rate in the range To - Ts, in the casting wall for the case of centrifugal casting and gravitational casting. Similarly, in Figures 5 and 6 it was plotted the momentary cooling speed at Ts (at the time of solidification starting). From the point of view nucleation and structure formation to analyze the tendency of a white iron structure formation it is important the local cooling rate when start the eutectic transformation (at Ts). The critical cooling rate for the transition gray - white highly dependent on the chemical composition of pig iron (content elements affecting graphitization). Generally for regular irons (unalloyed) this speed has values around 30 - 40 °C/s.

Table 3. Cooling time (τr_Ts) in the temperature range To = 1320 °C – Ts = 1150 °C (initial temperature - solidus temperature), inside casting wall (thickness layers 1 mm)

No.	Mean radius of the layer	Mean distance from outer surface of casting	Case 1 Centrifugal casting in metallic mold	Case 2 Centrifugal casting with external sand core	Case 3 Centrifugal casting in coated metallic mold	Case 4 Gravity casting in sand mold and sand core	Case 5 Gravity casting in metallic mold with sand core	Case 6 Gravity casting in metallic mold and core
	R med	x med	τr_Ts	τr_Ts	τr_Ts	τr_Ts	τr_Ts	τr_Ts
	mm	mm	s	s	s	s	s	s
1	100.5	29.5	43.514	375.315	44.122	86.250	33.088	0.038
2	101.5	28.5	86.536	1077.75	87.784	120.700	49.298	0.304
3	102.5	27.5	81.734	1777.92	82.950	148.350	65.978	0.886
4	103.5	26.5	77.086	1824.33	78.274	177.850	62.506	1.820
5	104.5	25.5	72.596	1759.62	74.336	210.400	58.864	3.126
6	105.5	24.5	68.262	1695.36	69.952	246.300	55.344	4.818
7	106.5	23.5	64.082	1631.55	65.724	285.750	51.946	6.864
8	107.5	22.5	53.874	1568.20	61.650	328.900	48.672	9.124
9	108.5	21.5	53.872	1505.31	57.212	375.950	45.526	11.416
10	109.5	20.5	52.470	1442.88	53.464	427.050	42.508	13.644
11	110.5	19.5	48.910	1380.93	49.870	482.450	39.610	15.798
12	111.5	18.5	45.510	1319.47	46.436	542.350	36.802	17.944
13	112.5	17.5	42.272	1258.51	43.166	606.950	34.030	20.192
14	113.5	16.5	39.172	1198.08	40.034	587.850	31.244	22.644
15	114.5	15.5	36.190	1138.18	37.022	547.300	28.452	23.878
16	115.5	14.5	33.308	1078.87	34.112	507.850	25.668	21.642
17	116.5	13.5	30.498	1020.16	31.276	469.450	22.908	19.552
18	117.5	12.5	27.736	962.115	28.492	432.200	20.192	17.592
19	118.5	11.5	24.992	904.770	25.730	396.200	17.536	15.694
20	119.5	10.5	22.242	848.220	22.966	361.350	14.960	13.790
21	120.5	9.5	19.458	792.540	20.170	327.850	12.484	11.844
22	121.5	8.5	16.614	737.850	17.318	295.650	10.136	9.854
23	122.5	7.5	13.690	684.255	14.388	264.850	7.952	7.866
24	123.5	6.5	10.698	631.905	11.384	235.450	5.984	5.968
25	124.5	5.5	7.734	580.96	8.380	207.550	4.268	4.268
26	125.5	4.5	5.036	531.585	5.586	181.150	2.832	2.832
27	126.5	3.5	2.868	483.945	3.282	132.650	1.688	1.688
28	127.5	2.5	1.316	438.210	1.592	132.650	0.840	0.840
29	128.5	1.5	0.382	394.455	0.518	109.150	0.296	0.296
30	129.5	0.5	0.028	343.770	0.030	76.350	0.038	0.038

In the study conducted in this paper it was analyzed the case of a cast iron which has the critical gray – white speed v_crit = 40 °C/s.

Analyzing the results of Table 5 shows that the momentary cooling rate at the temperature Ts has values in a very large range (between 0.0001 °C/s and 3500 °C/s).

In Table 5 the values of speed vr_Ts higher than the critical speed (v_crt = 40 °C/s) are written in red.

The structure of the white iron appears in the layer in which this speed is higher than the critical speed.

In Table 6 is given the thickness of the layers from the surfaces of the casting in which white iron is formed, for the six cases studied.

Table 4. Mean cooling rate (vr_med) of the alloy in the temperature range To-Ts(initial temperature - solidus temperature), inside casting wall (thickness layers 1 mm)

No.	Mean radius of the layer	Mean distance from outer surface of casting	Case 1 Centrifugal casting in metallic mold	Case 2 Centrifugal casting with external sand core	Case 3 Centrifugal casting in coated metallic mold	Case 4 Gravity casting in sand mold and sand core	Case 5 Gravity casting in metallic mold with sand core	Case 6 Gravity casting in metallic mold and core
	R med	x med	vr_med	vr_mrd	vr_med	vr_med	vr_med	vr_med
	mm	mm	$^0C/s$	$^0C/s$	$^0C/s$	$^0C/s$	$^0C/s$	$^0C/s$
1	100.5	29.5	3.907	0.453	3.853	1.971	5.138	4473.68
2	101.5	28.5	1.964	0.158	1.936	1.408	3.448	559.210
3	102.5	27.5	2.080	0.095	2.049	1.146	2.576	191.873
4	103.5	26.5	2.205	0.093	2.172	0.9556	2.719	93.406
5	104.5	25.5	2.342	0.097	2.287	0.808	2.888	54.382
6	105.5	24.5	2.490	0.100	2.430	0.690	3.072	35.284
7	106.5	23.5	2.653	0.104	2.586	0.595	3.272	24.767
8	107.5	22.5	3.155	0.108	2.757	0.517	3.492	18.632
9	108.5	21.5	3.156	0.113	2.971	0.452	3.734	14.891
10	109.5	20.5	3.240	0.118	3.180	0.397	3.999	12.459
11	110.5	19.5	3.476	0.123	3.409	0.352	4.292	10.761
12	111.5	18.5	3.735	0.129	3.661	0.313	4.643	9.474
13	112.5	17.5	4.021	0.135	3.938	0.280	4.995	8.419
14	113.5	16.5	4.340	0.142	4.246	0.289	5.441	7.507
15	114.5	15.5	4.697	0.149	4.592	0.311	5.975	7.119
16	115.5	14.5	5.104	0.157	4.983	0.335	6.623	7.855
17	116.5	13.5	5.574	0.167	5.435	0.362	7.421	8.694
18	117.5	12.5	6.129	0.177	5.966	0.393	8.419	9.663
19	118.5	11.5	6.802	0.188	6.607	0.429	9.694	10.832
20	119.5	10.5	7.643	0.200	7.402	0.470	11.363	12.327
21	120.5	9.5	8.737	0.214	8.428	0.518	13.617	14.353
22	121.5	8.5	10.232	0.230	9.816	0.575	16.772	17.252
23	122.5	7.5	12.418	0.248	11.815	0.642	21.378	21.612
24	123.5	6.5	15.891	0.269	14.933	0.722	28.841	28.485
25	124.5	5.5	21.981	0.292	20.286	0.819	39.831	39.831
26	125.5	4.5	33.757	0.320	30.433	0.938	60.028	60.028
27	126.5	3.5	59.274	0.351	51.797	1.088	100.651	100.711
28	127.5	2.5	129.179	0.388	106.783	1.281	202.381	202.381
29	128.5	1.5	445.026	0.431	328.185	1.557	574.324	574.324
30	129/5	0.5	6071.43	0.494	5666.67	2.226	4473.684	4473.68

6. Conclusions

The results in Table 6 lead to the following observations:

- In the case of centrifugal casting the tendency to whitening of the structure is smaller compared with gravity casting;
- The thickness of the white cast iron at the outer surface of the centrifugally cast parts in contact with the metal mold is much lower (by more than 50% less) relative to the gravity casting;
- In the case of centrifugal casting, in all the studied variants, on the inner surface of the casting it was obtained grey cast iron. (This is explained by the very low rate of cooling at inner surface);
- At centrifugal casting, when it used outer sand core, the cooling rate is low too and gray iron is obtained;

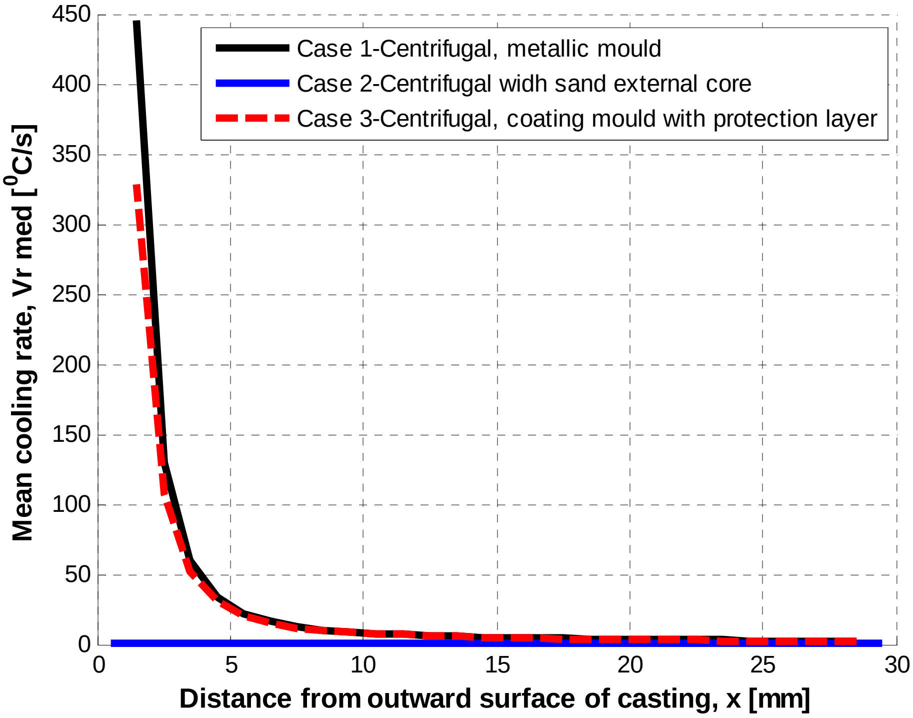


Fig. 3. Mean cooling rate in the temperature range To-Ts, inside the casting wall, centrifugal casting case

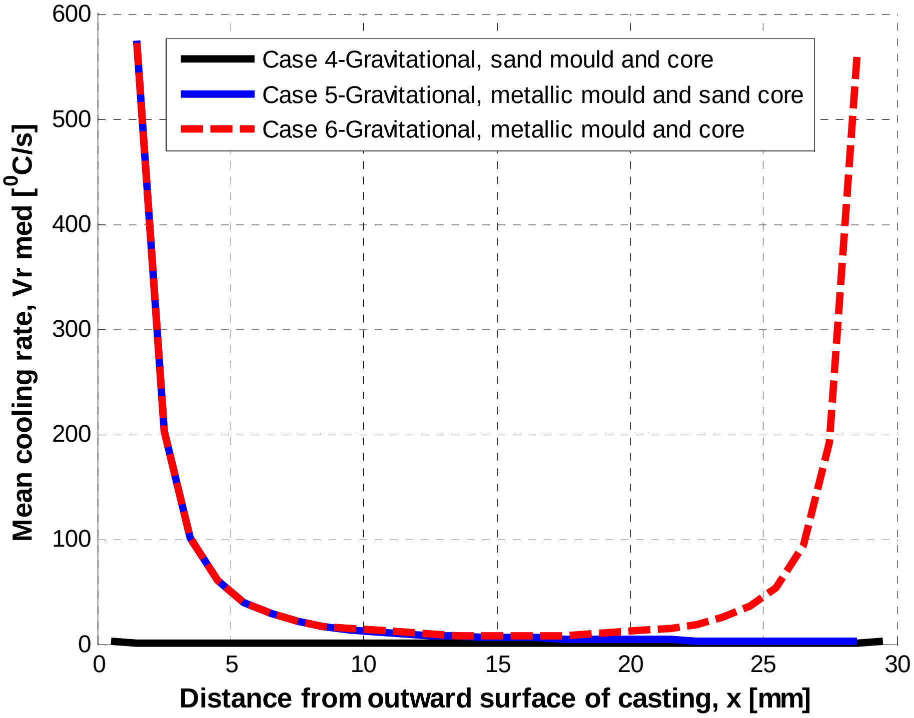


Fig. 4. Mean cooling rate in the temperature range To-Ts, inside the casting wall, gravitational casting case

- Coating the metal mold with a thin protective layer based on graphite does not lead to total elimination of the whitening trend;
- Coating the metal mold with a thin protective layer based on graphite, lead to a small reduction (by 0.8 mm) of the thickness of the white cast iron layer at the outer surface of the centrifugally cast part.

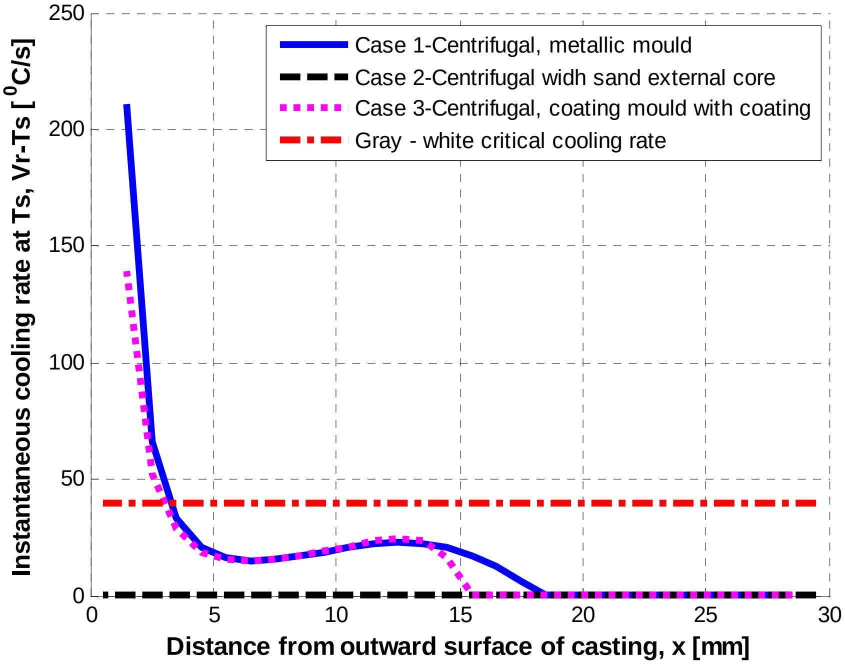


Fig. 5. The instantaneous cooling rate at the temperature Ts in the casting wall, case of centrifugal casting

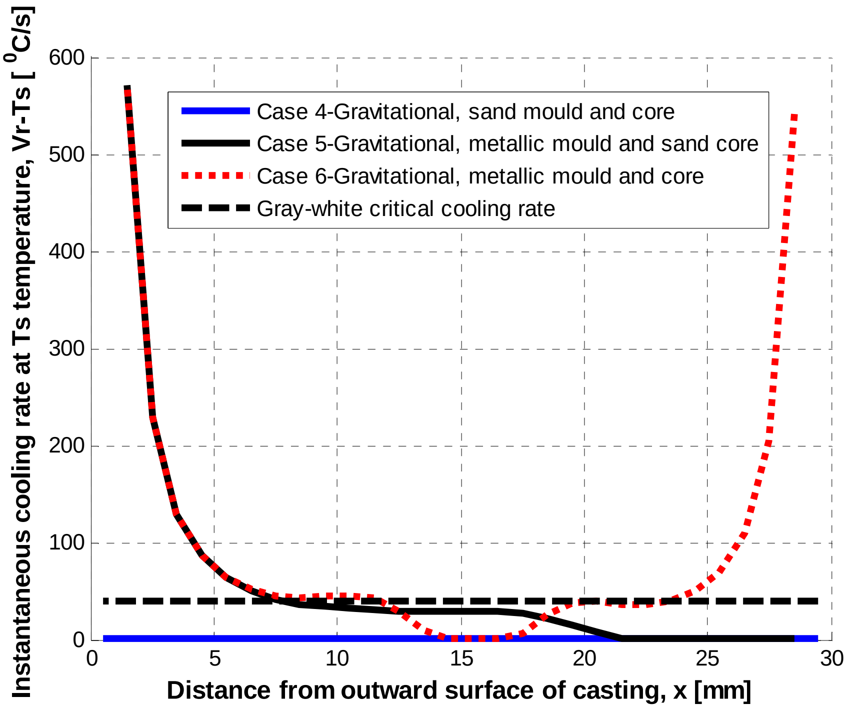


Fig. 6. The instantaneous cooling rate at the temperature Ts in the casting wall, case of gravitational casting

These results are determined by the characteristics of heat transmission in spin casting, namely:

- The heat transmission from the alloy to the external environment takes place practically in one sense;
- The solidification thickness respectively real solidification module of the casting is considerably higher (almost double) compared to similar ports cast with sand cores;
- The rate of cooling on the inner surface of the castings is very small, even smaller than in the case of castings with sand cores;

- The rate of cooling on the outer surface in the case of centrifugal castings depends much on the mold material (by the use of sand cores or by coating metal molds with protective layers).

Table 5. Momentary cooling rate (vr_Ts) at the solidus temperature (Ts = 1150 °C) inside casting wall (layers thickness 1 mm)

No.	Mean radius of the layer	Mean distance From outer surface of casting	Case 1 Centrifugal casting in metallic mold	Case 2 Centrifugal casting with external sand core	Case 3 Centrifugal casting in coated metallic mold	Case 4 Gravity casting in sand mold and sand core	Case 5 Gravity casting in metallic mold with sand core	Case 6 Gravity casting in metallic mold and core
	Rmed_i	xmed_i	v_Ts	v_Ts	vTs	v rac_Ts	v rac_Ts	v rac_Ts
	mm	mm	°C/s	°C/s	°C/s	°C/s	°C/s	°C/s
1	100.5	29.5	0.06516	0.02981	0.06454	0.79143	2.93053	**3261.067**
2	101.5	28.5	<0.00001	<0.00001	<0.00001	0.84344	0.26911	**540.76075**
3	102.5	27.5	<0.00001	<0.00001	<0.00001	0.00238	<0.00001	**205.01003**
4	103.5	26.5	<0.00001	<0.00001	<0.00001	0.00025	<0.00001	**110.09865**
5	104.5	25.5	<0.00001	<0.00001	<0.00001	0.00001	<0.00001	**69.85635**
6	105.5	24.5	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	**49.16623**
7	106.5	23.5	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	38.86836
8	107.5	22.5	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	35.56961
9	108.5	21.5	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	36.60142
10	109.5	20.5	<0.00001	<0.00001	<0.00001	<0.00001	8.25697	38.89322
11	110.5	19.5	0.00083	<0.00001	0.00004	<0.00001	14.74170	37.21075
12	111.5	18.5	0.40734	<0.00001	0.00045	<0.00001	22.25077	24.76038
13	112.5	17.5	5.95957	<0.00001	0.01265	<0.00001	27.08562	5.55590
14	113.5	16.5	12.48429	<0.00001	0.01785	<0.00001	28.66278	0.00001
15	114.5	15.5	17.01854	<0.00001	0.55972	<0.00001	29.06218	<0.00001
16	115.5	14.5	20.71594	<0.00001	16.67016	<0.00001	29.12071	0.00128
17	116.5	13.5	22.58403	<0.00001	23.60143	<0.00001	29.27574	10.28546
18	117.5	12.5	22.94694	<0.00001	24.2667	<0.00001	29.64548	29.64623
19	118.5	11.5	22.16798	<0.00001	23.66032	<0.00001	30.39774	**42.13234**
20	119.5	10.5	20.57539	<0.00001	21.14250	<0.00001	31.59594	**45.38781**
21	120.5	9.5	18.68502	<0.00001	19.25399	<0.00001	33.50115	**44.45906**
22	121.5	8.5	16.89730	<0.00001	17.49919	<0.00001	36.55835	**43.45366**
23	122.5	7.5	15.54046	<0.00001	15.73736	<0.00001	**41.65383**	**45.01497**
24	123.5	6.5	14.99780	<0.00001	14.88741	<0.00001	**49.86932**	**50.98461**
25	124.5	5.5	16.19338	<0.00001	15.43933	0.00001	**63.46363**	**63.55288**
26	125.5	4.5	21.14679	<0.00001	18.98183	0.00017	**86.35019**	**86.35340**
27	126.5	3.5	33.53584	<0.00001	28.63914	0.00126	**129.17472**	**129.17472**
28	127.5	2.5	**66.34576**	<0.00001	**52.26857**	0.00603	**228.88840**	**228.88840**
29	128.5	1.5	**211.1892**	0.00003	**139.1666**	0.02302	**571.84564**	**571.8456**
30	129.5	0.5	**3454.746**	0.21699	**1217.041**	0.80429	**3296.8031**	**3296.8031**

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Table 6. The thickness of white cast iron layer at the casting surface

Case no.	Casting variant	Thickness of white cast iron layer	
		On outward surface of casting	On inward surface of casting
Unit		mm	mm
1	Centrifugal casting in metallic mold	3.8	0
2	Centrifugal casting in metallic mold, with outer sand core	0	0
3	Centrifugal casting in coating metallic mold	3.0	0
4	Gravitational casting in sand mold with inner sand core	0	0
5	Gravitational casting in metallic mold with inner sand core	7.7	0
6	Gravitational casting in metallic mold with inner metallic core	11.6	6.4

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Received in April 2016