The Influence of Wall Thickness of Hollow Parts on the Thickness of White Cast Iron Layers in Centrifugally Cast Parts

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Abstract
In the case of cast iron parts centrifugally cast in metallic moulds, the thermal field in the casting is different than in the case of gravity casting because it is affected by the rotational speed. In the case of the centrifugal casting of cast iron bushings for engines or for the oil industry, a grey cast iron structure is sought. This is for a good machinability of the castings. It is important to know the effect of various technological and geometric parameters on the solidification of these castings. One of the influencing parameters is the thickness of the casting wall. This paper presents the results of a study on the effect of the thickness of the wall of centrifugally cast parts on the solidification of hollow cylindrical castings, cast centrifugally and made of grey cast iron (in the case of gravity cast in sand moulds, grey cast iron sand solidifies with a pearlitic grey cast iron structure). The paper analyses centrifugal casting in metallic moulds coated with a 1 mm thick graphite coating. The effect of this parameter on the whitening tendency of the cast iron structure at the casting-mould interface is also analysed. The study is performed by computer simulation of the cooling and solidification of centrifugally cast parts.

Keywords
casting, centrifugal casting, gravitational casting, gray cast iron

1. Introduction

Centrifugal casting is of interest to the industry [1, 2, 3, 7, 9, 10, 11, 13, 14, 15, 16]. Centrifugally cast parts have higher mechanical properties than those gravity cast. Furthermore, centrifugal casting enables the obtaining of castings with gradient of structure and properties [3, 9].

The transmission of heat to the casting-mould-environment system in centrifugal casting presents two specificities:

- the heat is basically transmitted unidirectionally and in one way;
- the transmission of heat inside the liquid alloy is higher in relation to gravity casting; this is due to the forced convection as a result of the rotation and the mould vibrations caused by the rotation.

The experimental measurement of temperature in the casting - mould system is very difficult. This is due to the very high rotation speed. An accessible method for conducting studies on the thermal field during centrifugal casting is computer simulation [6, 12, 14, 16]. A software was developed at the Transilvania University of Brasov for simulating the solidification of centrifugally cast hollow cylindrical parts [4, 5, 7, 8]. The software uses cylindrical coordinates. In this case, cylindrical coordinates have two advantages:

- they faithfully reproduce the transmission of heat through divergent - convergent flows;
- mathematical models and 2D software can be used to simulate solidification in volume (this provides much shorter simulation times).

The software considers the effect of rotation on the heat transfer in the cast alloy - mould system due to the value of the equivalent thermal conductivity coefficient of the liquid alloy.

2. Purpose

Previous simulation studies have shown that the solidification time increases in centrifugal casting even when compared to gravity casting. This is due to the unidirectional and one-way heat transmission.

As a result of centrifugal casting of cast iron parts in metallic moulds, the whitening tendency at the casting-mould interface is less compared to gravity casting in metallic moulds. [4, 5]. The cooling rate in the walls of castings and, thus, the whitening tendency at the casting-mould interface is affected by the thickness of the casting wall.

In order to design centrifugal casting technologies, this effect on centrifugal casting needs to be known as well. The purpose of this paper is to conduct a study on this effect on the solidification of hollow cylindrical parts made of cast iron and cast centrifugally. There is analysed the effect of the wall thickness of the castings on the parameters of the thermal field in the casting and on the thickness of the white cast iron layer in the case of a hollow part cast centrifugally, made of grey pearlitc cast iron with eutectic composition.

3. Work Method

The study was conducted by computer simulation of cooling and solidification. This is due to the fact that the experimental measurement of the temperature during centrifugal casting is difficult as a result of the very high speed of rotation. There was simulated the solidification of the hollow casting in Figures 1 and 2.

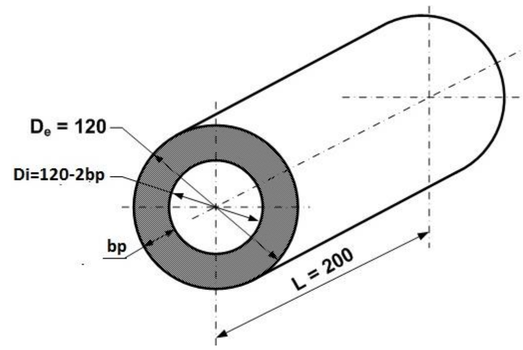

Fig. 1. Casting (wall thickness b_p = 5 – 30 mm)

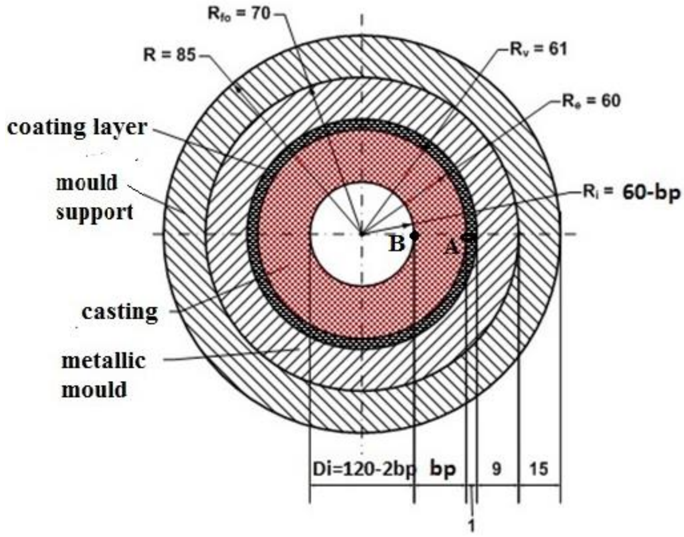

Fig. 2. Casting - mould assembly studied by simulation for castings with variable wall thickness [7]

The casting is cast in a metallic mould coated with a 1 mm thick layer of graphite-based paint. The mould and the mould support are made of steel. The part is made of grey cast iron with eutectic composition, which solidifies with pearlitic grey cast iron structure when gravity cast in sand moulds. The wall thickness of the casting (b) varied between 5 and 30 mm, every 5 mm. The values in Tables 1 and 2 were used for the initial temperature of the components in the system and for the thermophysical properties of the materials. A division grid with Δ = 1 mm pitch and τ = 0.01 s time-difference interval was used.

Table 1. Initial temperature of the casting - mould system components considered for simulation [7]

Item no.	Physical quantity	Symbol	Measure unit	Centrifugal in coated metallic mould
1	Initial temperature of cast alloy	T0_me	°C	1320
2	Initial temperature of mould	T0_fo	°C	300
3	Initial temperature of mould support	T0_po	°C	200
4	Outside ambient (air) temperature	T_ex	°C	20
5	Inside air temperature	T_in	°C	200
6	Initial temperature of paint coating	T0_vo	°C	300
7	Solidus temperature of the cast iron	TS_me	°C	1150

Table 2. Thermophysical properties used in simulations [7]

No.	Physical quantity	Symbol	Measure unit	Centrifugal in coated metallic mould
1	Specific heat of liquid cast iron	C_l_me	J/KgK	850
2	Specific heat of solid cast iron	C_s_me	J/KgK	750
3	Specific heat of mould and mould support	C_s_fo	J/KgK	750
4	Specific heat of paint coating	C_vo	J/KgK	1000
5	Cast iron latent solidification heat	L_me	J/Kg	220000
6	Thermal conductivity of the liquid cast iron	λ_l_me	W/mK	120
7	Thermal conductivity of the solid cast iron	λ_s_me	W/mK	40
8	Thermal conductivity of the mould	λ_fo	W/mK	30
9	Paint coating thermal conductivity	λ_vo	W/mK	20
10	Liquid cast iron density	ρ_me	Kg/m^3	7000
11	Mould density	ρ_fo	Kg/m^3	7600
12	Mould support density	ρ_po	Kg/m^3	7600
13	Paint coating density	ρ_izρ_vo	Kg/m^3	1800
14	Coefficient of heat exchange with ambient air	α _ex	W/m^2K	50
15	Coefficient of heat exchange between metal and air inside	α_in	W/m^2K	2
16	Mould support thermal conductivity	λ_fo	W/mK	30

4. Results

There was monitored the effect of the casting wall thickness on the thermal field and on the whitening tendency at the contact surface between the casting and the mould. In what regards the thermal field, the following parameters were analysed:

- the position of the hot spot in the casting;
- the solidification time of the casting (tsol_p);
- the solidification time of the layer (1 mm thick) on the outer surface of the casting (tsol_pex);
- the average cooling rate of the outer layer (v_ex_med) in liquid state in the initial temperature - eutectic temperature range (T0me - Ts);
- the instantaneous cooling rate of the outer layer (v_ex_Ts) at solidus temperature (eutectic temperature -Ts);
- the solidification time of the layer (1 mm thick) on the inner surface of the casting (tsol_p_in);
- the average cooling rate of the inner layer (v_ex_med) in liquid state in the initial temperature - eutectic temperature range (Tome - Ts);
- the instantaneous cooling rate of the inner layer (v_in_Ts) at solidus temperature (eutectic temperature -Ts);
- the temperature in the wall of the casting at the end of solidification;
- the solidification time in the wall of the casting;
- the evolution of temperature according to time in the hot spot, on the outer and inner surface of the casting.

In what concerns the whitening tendency, there was analysed
- the cooling kinetics on the outer surface of the casting;
- the thickness of the white cast iron layer at the casting-mould interface.

Table 3 shows the position of the hot spot in the wall of the casting, the alloy solidification time, the outer and inner layer solidification time (1 mm thick) according to the wall thickness of the casting. It is noted that the hot spot is located on the inner surface of the casting in all cases.

Table 3. Solidification time and hot spot position results [7]

No.	Casting wall thickness	Casting solidification time	Solidification time of the outer layer	Solidification time of the inner layer	Casting hot spot radius	Hot spot - inner casting surface distance nod
Symbol	bp	tsol_p	tsol_pex	tsol_pin	Rnod	Δr_nod = Rnod-Ri
u.m	mm	s	s	s	mm	mm
1	5	3.60	0.5	3.6	55	0
2	10	13.08	0.53	13.08	50	0
3	15	28.06	0.53	28.06	45	0
4	20	48.84	0.53	48.84	40	0
5	25	76.75	0.53	76.75	35	0
6	30	114.57	0.53	114.57	30	0

Tables 4 and 5 present values on the kinetics of solidification of the 1 mm thick layer on the outside and inside of the casting. It is noted that the thickness of the casting wall virtually has no effect on the kinetics of the solidification on the outer surface of the casting, and the kinetics of the solidification on the inner surface is affected to a small extent.

Table 4. Cooling kinetics and casting outer surface solidification results (point A, Figure 2) [7]

No.	Casting wall thickness	Outer surface cooling time in To-Ts interval	Mean cooling rate of the outer surface, To-Ts interval	Outer surface instantaneous cooling rate to Ts	Solidification end time of casting	Factual time interval of casting outer surface solidification	
symbol	bp	t in_sol_ex	v med raclichid	v_rac_Ts	tsol_ex	tsol_ex - tinc_sol_ex	
u.m	mm	s	°C/s	°C/s	s	s	
1	5	0.10	1700	402.354	0.5	0.4	
2	10	0.11	1545.45	402.340	0.53	0.42	
3	15	0.11	1545.45	402.343	0.53	0.42	
4	20	0.11	1545.45	402.346	0.53	0.42	
5	25	0.11	1545.45	402.351	0.53	0.42	
6	30	0.11	1545.45	402.357	0.53	0.42	

Figure 3 shows as histogram the effect of the casting wall thickness on the total solidification time of the casting. The casting solidification time increases virtually parabolically with the thickness of the casting. Figure 4 shows the distribution of the solidification time in the wall of the casting for various wall thicknesses. The curves in this figure virtually show the displacement of the solidification front in the casting wall, from the outer surface to the inner surface. The curves in this figure are close. This reveals a reduced effect of the wall thickness on the manner the solidification front moves from the outer surface to the inner surface of the casting.

Figure 5 shows the temperature distribution in the casting wall at the end of the alloy solidification. It is noted, as expected, that in all cases the wall temperature decreases continuously, almost linearly, from the inner to the outer surface. This is consistent with the displacement of the solidification front shown in Figure 5.

Table 5. Cooling kinetics and casting inner surface solidification results (point B, Figure 2) [7]

No.	Casting wall thickness	Inner surface cooling time to Tsol	Mean cooling rate of the inner surface, in To-Tsol interval	Instantaneous cooling rate to inner surface solidification at Ts	Casting inner surface solidification end time	Factual time interval of casting inner surface solidification
Symbol	bp	τ in_sol_in	v_medraclichid	v rac_Ts	τ_sol_in	t in_sol_in - t_sol_in
u.m	mm	s	°C/s	°⁰C/s	s	s
1	5	1.98	85.859	0.456	3.6	1.62
2	10	6.92	24.566	0.200	13.08	6.16
3	15	14.49	11.341	0.131	28.06	13.57
4	20	24.57	6.919	0.095	48.84	24.24
5	25	37.08	4.585	0.097	76.75	39.67
6	30	52.07	3.265	0.058	114.57	62.50

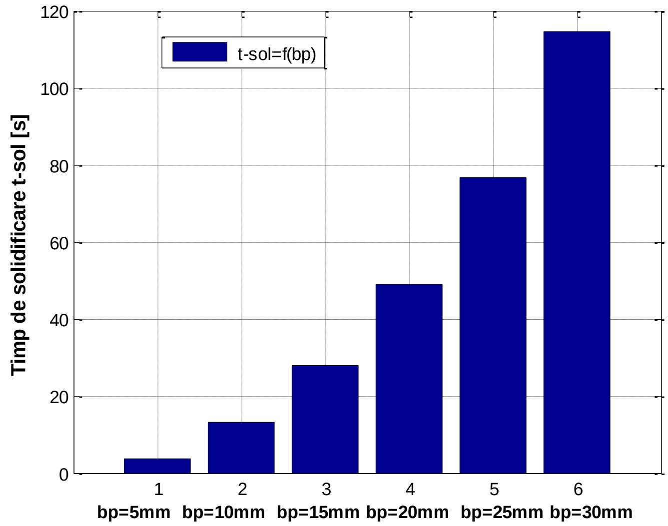

Fig. 3. Casting solidification time (in the hot spot) according to the wall thickness [7]
Vertical axis = solidification time of casting t-sol [s]; horizontal axis = casting wall thickness [mm]

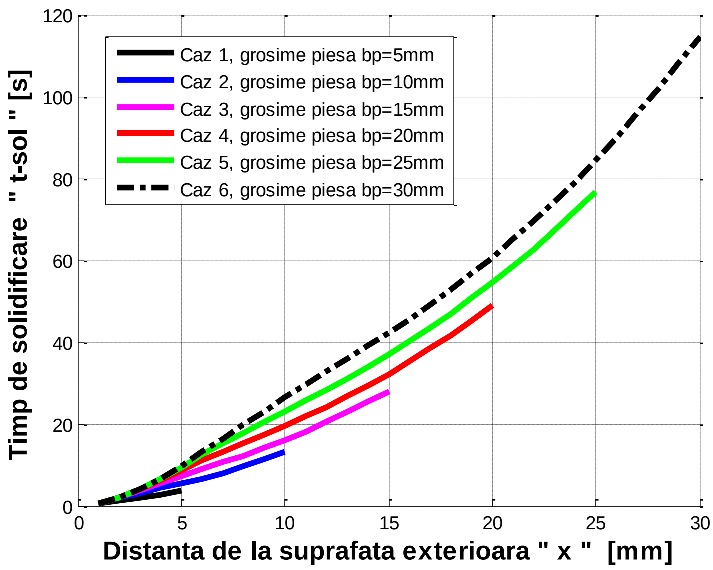

Fig. 4. Solidification time inside the casting wall for various wall thicknesses [7]
Vertical axis = solidification time of casting t-sol [s]; horizontal axis = distance from the casting outward side "x" [mm]

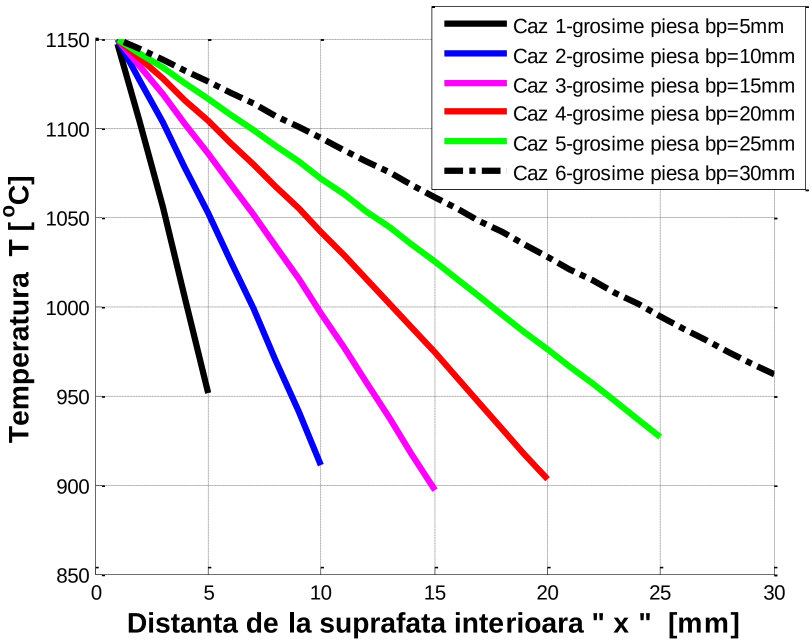

Fig. 5. Temperature inside the casting wall at alloy solidification end for various casting wall thicknesses [7]
Vertical axis = Temperature T [°C]; horizontal axis = distance from the casting outward side "x" [mm]

Figure 6 shows the evolution of the temperature according to time in the superficial layer of the casting for the wall thicknesses considered. It can be noted that with the increase in the wall thickness, the superficial layer of the casting (1 mm thick) remains at elevated temperatures after solidification and even reheats. For casting wall thicknesses bp = 25÷30 mm, the outer surface temperature is maintained at 900 °C. This confirms once again the fact that immediately after solidification the contraction in solid state is very low, and the casting-mould contact is maintained throughout the solidification of the casting.

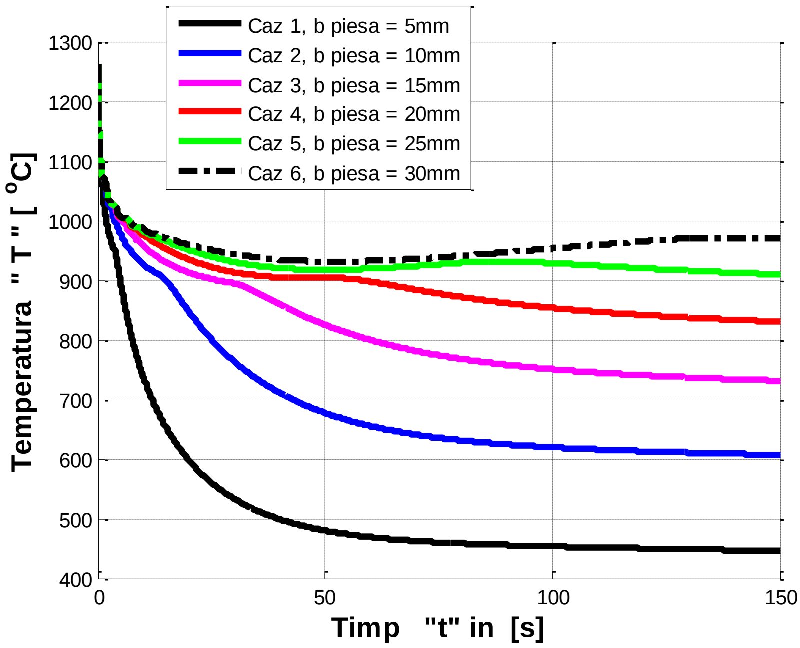

Fig. 6. Temperature evolution in the casting outer surface layer (1 mm thick) for various casting wall thicknesses [7]
Vertical axis = Temperature T [°C]; horizontal axis = time t [s]

Tables 6 and 7 show the average cooling rates of the liquid alloy in the To-Ts range and the instantaneous cooling rate values at the Ts temperature (cooling rate at solidification start) according to the distance from the casting-mould interface, for the wall thicknesses considered.

Table 6. The average cooling rate (vr_med) of the alloy in the To ÷ Ts range (initial temperature - solidus temperature) in the casting cross-section (1 mm thick layers) according to the distance from the outer surface of the casting (eutectic cast iron castings) [7]

No.	Layer mean radius	Distance from the outer surface of the casting	Case 1 Casting with bp = 5 mm	Case 2 Casting with bp = 10 mm	Case 3 Casting with bp = 15 mm	Case 4 Casting with bp = 20 mm	Case 5 Casting with bp = 25 mm	Case 6 Casting with bp = 30 mm
Symbol	R med	x med	vr_med	vr_med	vr_med	vr_med	vr_med	vr_med
um	mm	mm	°C/s	°C/s	°C/s	°C/s	°C/s	°C/s
1	59	1	1545.45	1545.45	1545.45	1545.45	1545.45	1545.45
2	58	2	242.86	180.85	180.85	180.85	180.85	180.85
3	57	3	136.00	80.57	70.54	69.96	69.67	69.67
4	56	4	90.90	52.63	41.06	37.95	37.44	37.36
5	55	5	86.29	39.35	29.21	25.22	23.88	23.58
6	54	6		31.25	22.85	18.93	17.17	16.489
7	53	7		25.52	18.83	15.25	13.40	12.491
8	52	8		21.14	15.98	12.82	11.03	10.035
9	51	9		17.74	13.80	11.08	9.42	8.416
10	50	10		24.57	12.08	9.75	8.23	7.262
11	49	11			10.59	8.68	7.318	6.401
12	48	12			9.36	7.79	6.584	5.730
13	47	13			8.32	7.03	5.973	5.268
14	46	14			7.45	6.37	5.454	4.737
15	45	15			11.73	5.79	5.001	4.353
16	44	16				5.28	4.601	4.019
17	43	17				4.83	4.242	3.724
18	42	18				4.43	3.919	3.460
19	41	19				4.07	3.627	3.221
20	40	20				6.92	3.363	3.061
21	39	21					3.123	2.801
22	38	22					2.905	2.616
23	37	23					2.708	2.446
24	36	24					2.526	2.289
25	35	25					4.585	2.145
26	34	26						2.012
27	33	27						1.888
28	32	28						1.774
29	31	29						1.668
30	30	30						3.265

Table 7 shows that the instantaneous cooling rate at Ts temperature has values over a very wide range (0 ÷ 402.357 °C/s). In Table 7, the vr_Ts rates which are higher than the critical rate (v_crt = 40 °C/s) are written in red. The white cast iron structure occurs in the layer where this rate is higher than the critical rate.

In terms of cooling speed and solidification kinetics on the outer surface of the casting, it can be observed that the wall thickness has no effect. In all cases studied, the cooling rate of the outer layer prior to solidification (at the Ts temperature) is 402 °C/s (Table 4), having virtually the same value. This value is above the grey - white critical value. It follows that a layer of white cast iron is obtained in all cases at the surface of the casting.

Table 7. Instantaneous cooling rate (vr_Ts) at solidus temperature (Ts = 1150 °C) in the casting cross-section (1 mm thick layers) [7]

No.	Layer mean radius	Distance from the outer surface of the casting	Case 1 Casting with bp = 5 mm	Case 2 Casting with bp = 10 mm	Case 3 Casting with bp = 15 mm	Case 4 Casting with bp = 20 mm	Case 5 Casting with bp = 25 mm	Case 6 Casting with bp = 30 mm
Symbol	Rmed_i	xmed_i	v_Ts	v_Ts	vTs	v rac_Ts	v rac_Ts	v rac_Ts
um	mm	mm	^{0}C/s	^{0}C/s	^{0}C/s	^{0}C/s	^{0}C/s	^{0}C/s
1	59	1	402.354	402.340	402.343	402.347	402.351	402.357
2	58	2	193.075	87.594	84.574	84.562	84.563	84.564
3	57	3	140.495	67.336	42.425	39.308	39.199	39.195
4	56	4	10.517	71.001	36.684	26.577	24.453	24.128
5	55	5	0.456	71.032	40.198	24.494	18.951	17.443
6	54	6		46.673	45.065	26.405	18.035	14.605
7	53	7		5.140	46.497	29.358	19.035	14.061
8	52	8		$<10^{-6}$	38.764	32.278	20.863	14.62
9	51	9		$<10^{-6}$	21.330	34.103	23.377	15.858
10	50	10		0.200	3.607	31.258	25.494	17.463
11	49	11			$<10^{-6}$	23.367	26.772	18.974
12	48	12			$<10^{-6}$	13.924	26.161	20.501
13	47	13			$<10^{-6}$	2.262	23.414	21.567
14	46	14			$<10^{-6}$	0.0007	16.680	21.613
15	45	15			0.130	$<10^{-6}$	6.739	19.578
16	44	16				$<10^{-6}$	$<10^{-6}$	17.400
17	43	17				$<10^{-6}$	$<10^{-6}$	12.616
18	42	18				$<10^{-6}$	$<10^{-6}$	7.022
19	41	19				$<10^{-6}$	$<10^{-6}$	0.710
20	40	20				0.0945	$<10^{-6}$	0.002
21	39	21					$<10^{-6}$	$<10^{-6}$
22	38	22					$<10^{-6}$	$<10^{-6}$
23	37	23					$<10^{-6}$	$<10^{-6}$
24	36	24					$<10^{-6}$	$<10^{-6}$
25	35	25					0.067	$<10^{-6}$
26	34	26						$<10^{-6}$
27	33	27						$<10^{-6}$
28	32	28						$<10^{-6}$
29	31	29						$<10^{-6}$
30	30	30						0.058

Figures 7 and 8 graphically show the distribution in the casting wall of the instantaneous cooling rate to the temperature Ts (solidification start rate). In these figures, the rate is compared to the critical grey-white rate to determine the thickness of the white cast iron layer at the surface of the castings. It is considered the case of cast iron with the critical grey-white critical rate v_crit = 40 °C/s.

Table 8 shows the thickness of the white cast iron layer at the outer surface of the casting.

Figure 9 shows as a histogram the dependence between the thickness of the white cast iron layer - casting wall thickness for the casting conditions (casting diameter, graphite-coated metallic mould, thermophysical properties) in Figure 2 and Tables 1 and 2. The results show that for small casting wall thicknesses (bp < 15 mm) the thickness of the white cast iron layer at the surface of the casting increases. Above this wall thickness (for bp > 15 mm), the thickness of the white cast iron remains constant.

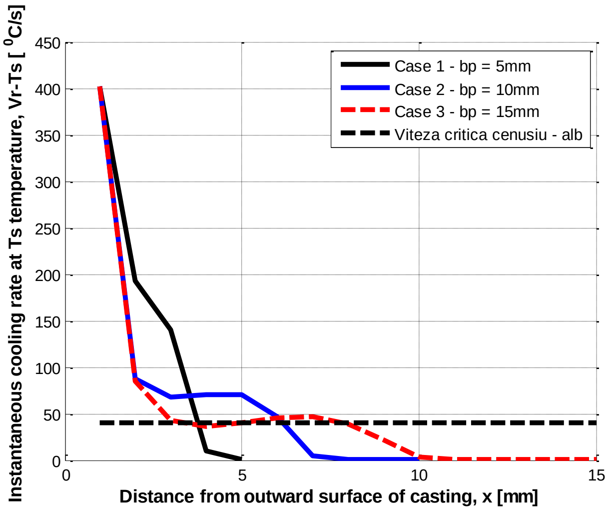

Fig. 7. Instantaneous cooling rate to temperature Ts and the grey-white critical rate in the casting wall (bp – 5 mm, 10 mm, 15 mm, casting thick castings) [7]

key: - - - critical cooling rate gray-white (40 °C/s); Horizontal axis-Distance from outward side of casting in [mm]; Vertical axis-Cooling rate at Ts, $v_{r\text{-}Ts}$ in [°C/s]

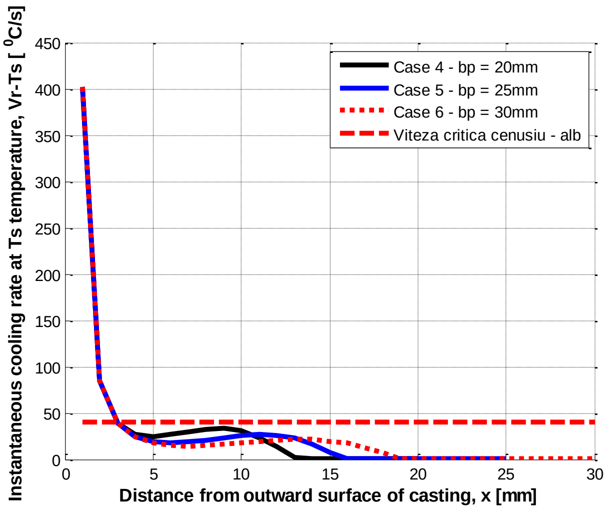

Fig. 8. Instantaneous cooling rate to temperature Ts and the grey-white critical rate in the casting wall (bp – 20 mm, 25 mm, 30 mm, casting wall thickness) [7]

key: - - - critical cooling rate gray-white (40 °C/s); Horizontal axis-Distance from outward side of casting in [mm]; Vertical axis-Cooling rate at Ts, $v_{r\text{-}Ts}$ in [°C/s]

Table 8. White cast iron thickness at the outer surface of the casting [7]

Case number	Casting wall thickness	White cast iron layer thickness
Symbol	bp [mm]	bw [mm]
1	5	3.8
2	10	6.2
3	15	8.0
4	20	3.0
5	25	3.0
6	30	3.0

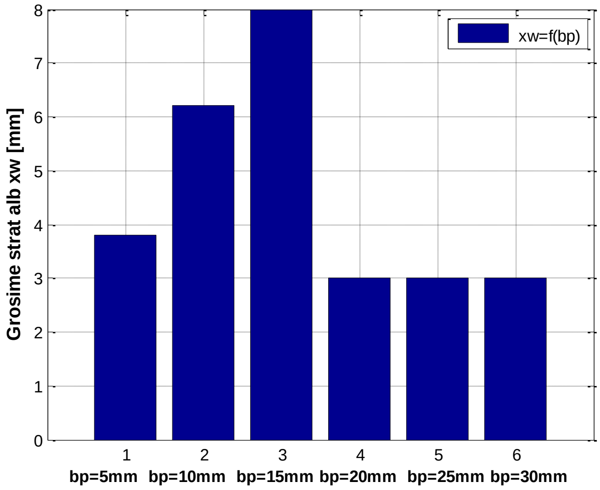

Fig. 9. White cast iron layer thickness at the centrifugally cast part surface according to the casting wall thickness [7]

Horizontal axis- casting wall thickness bp, in mm; Vertical axis - white layer thickness, xw, in mm

5. Conclusions on the Effect of the Casting Wall Thickness

The results in Tables 3 to 8 and Figures 3 to 9 lead to the following observations:

- regardless of the casting wall thickness, heat is transmitted in one direction, from inside to outside;
- in all cases, even for small wall thicknesses, the solidification ends on the inner surface of the casting;
- the solidification time increases parabolically with the casting wall thickness;
- the cooling rate on the outer surface of the casting, prior to solidification at temperature Ts is not affected by the casting wall thickness;
- in the case considered (casting in metallic mould coated with protective layer), the cooling rate at Ts is higher than the critical grey - white rate;
- in case of the analysed wall thicknesses (over 5 mm), the cooling rate at Ts on the inner surface is low, below the critical grey-white rate;
- for casting wall thicknesses ≤ 15 mm, the thickness of the white cast iron layer at the outer surface of the casting increases (in the case considered, up to 8 mm);
- for casting wall thicknesses ≥ 15 mm, the thickness of the white cast iron layer on the outside surface remains constant (in the case considered, at 3 mm);
- the coating of the metallic mould with a thin layer of graphite-based protection does not lead to the complete elimination of the whitening tendency.

These results are determined by the heat transmission specificities during centrifugal casting and by the solidification specificities of moulded cast irons.

The study can also be developed for other casting conditions, for example centrifugal casting with outer cores or with different thicknesses of the protective layer.

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