The Solidification of Gray Iron Parts Centrifugal Cast with External Sand Core

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Abstract
In the case of centrifugally cast iron castings, the outer sand cores are used in order to obtain a gray cast iron structure that ensures good machinability. This is the case for the cylinder bushings for the drive engines or the bushings used in oil installations. It is important to know the influence of the thickness of the outer sand cores on the solidification of these castings. A study is conducted on the influence of the thickness of the outer cores on the solidification conditions of tubular hollow cylindrical parts. The solidification time, the temperature distribution in the wall of the part, the cooling rate at the start of the solidification were analyzed. The study is performed by simulating cooling and solidification on the computer.

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

1. Introduction

Centrifugal casting is of interest to industry due to its advantages in terms of the structure and properties of moulded parts [1, 2, 3, 7, 9, 10, 11, 13 ... 16]. The centrifugal castings are more compact, have a finer structure and superior mechanical properties than those gravitationally cast. Also the centrifugal cast offers possibilities to obtain parts with structure and properties gradient [3, 9].

The transmission of heat inside the system casting-mould-environment in the case of centrifugal casting has two peculiarities;

- the heat is transmitted in just one direction and in a unique way (radial from inside to the outside of casting);
- the intensity of heat transfer inside the liquid alloy is much higher in relation to gravity casting; the cause is forced convection and mass transport, caused by centrifugal force and vibrations produced by the rotation movement.

Experimental measurement of the thermal field (or temperature) parameters in the casting - mould system is difficult (virtually impossible) due to the very high rotation speed. A more accessible method for conducting such a study is computer simulation of heat transmission and solidification of centrifugally cast parts [6, 12, 14, 16]. At Transylvania University of Brasov, a software was developed to simulate the solidification of centrifugally cast tubular cylindrical parts [4, 5, 7, 8]. Taking into account the geometrical characteristics of tubular cylindrical parts (i.e., the rotational symmetry), the software uses cylindrical coordinates. The use of cylindrical coordinates has two advantages:

- faithfully reproduces the transmission of heat through divergent or convergent fluxes;
- 2D mathematical models and 2D software can be used to simulate the solidification in volume, which provides much less simulation time.

The software takes into account the effect of rotation on the heat transfer in the system cast alloy - mould by the value of the equivalent coefficient of thermal conductivity of the liquid alloy.

2. Paper Aim

Using a software developed at Transilvania University, a comparative study on the thermal field and the solidification of a cylindrical cast iron part, cast in several centrifugal casting and gravitational casting variants, was carried out [4, 5]. This study has shown that the use of an external core at the centrifugal casting considerably changes the cooling parameters and solidification conditions of the castings. The heat transfer strength from the part to the mould and the cooling and solidification rate is considerably reduced. The solidification time increases even as compared to gravity casting in sand moulds due to unidirectional heat transmission. As a result in the case of iron parts cast in moulds with outer sand core, the castings have a completely gray cast iron structure. In the case of cylindrical tubular parts cast centrifugally in metallic moulds at the interface part-mould, a layer of white cast iron is obtained. The white cast iron layer is obtained even when the metallic moulds are coated with paint [4, 5].

In the case of centrifugally cast iron castings, the outer sand cores are used in order to obtain a gray cast iron structure that ensures good machinability. This is the case bushings for internal combustion engine or bushings used in oil installations. To design the centrifugal casting technologies it is important to know the influence of the outer sand cores thickness on the solidification of these parts. The purpose of this paper was to conduct a study on the influence of the thickness of the outer cores on the solidification of the tubular cylindrical parts of cast iron. The influence of the outer sand cores thickness on the parameters of the thermal field in the casting was analysed (solidification time, temperature distribution in the wall of the part, cooling rate at the beginning of solidification, etc.).

3. Procedure

The study was performed by simulating the cooling and solidification on the computer. This is because the experimental measurement of the thermal parameters of cooling and solidification (temperature measurement) in centrifugal casting is difficult due to the very high rotation speed.

The solidification of the tubular piece of Figure 1 has been simulated in the case of using of sand cores with different thicknesses. The part is cast from gray cast iron with eutectic composition, which under gravity casting conditions in sand moulds solidifies as gray cast iron (gray pearlite cast iron). Figure 2 shows the assembly casting - core - mould support used in simulation. The core is made of sand (SiO_2) and the mould support of steel. The core thickness "b" changed between b = 5 ÷30 mm, in six steps from 5 to 5 mm. The results are analysed compared with centrifugal casting in metallic mould, with no sand core (when the outer core thickness b = 0 mm).

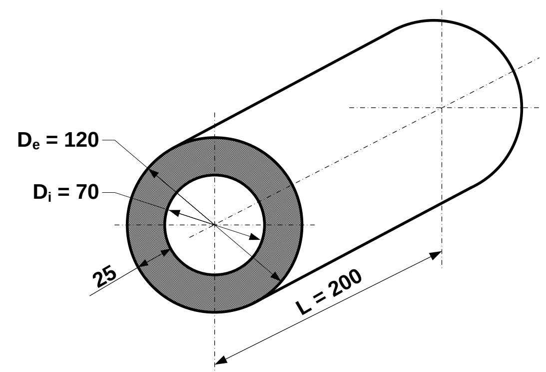

Fig. 1. Centrifugal casting [7]

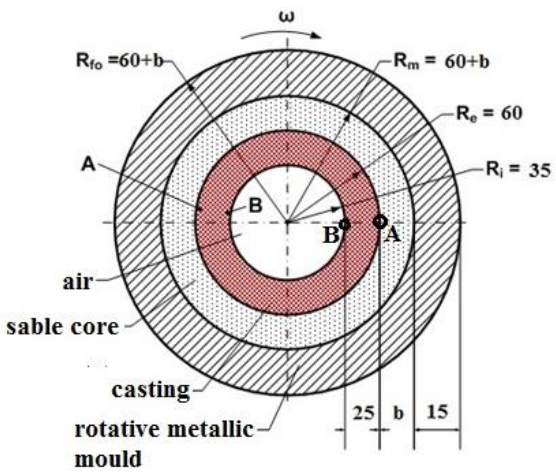

Fig. 2. The studied assembly casting - sand outer core - mould support (core thickness b = 5 ÷ 30 mm) [7]

Simulation software was used to simulate the solidification of cylindrical tubular parts centrifugally cast. The software uses a 2D mathematical model in cylindrical coordinates [7, 8, 12]. A mash with step Δ = 1 mm and time step τ = 0.01 s was used. Initial temperatures and thermo physical characteristics used in in simulation are given in Tables 1 and 2.

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

No.	Parameter	Symbol	Measure unit	Value
1	Initial temperature of cast alloy	T0_me	°C	1320
2	Initial temperature of the sand core	T0_mi	°C	30
3	Initial temperature of the mould support	T0_po	°C	200
4	Environment temperature (on the external side)	T_ex	°C	20
5	Environment temperature on the inner side	T_in	°C	150
6	Solidus temperature of the cast iron	TS_me	°C	1150

Table 2. Thermophysical characteristics used for simulation [7]

No	Parameter	Symbol	Measure unit	Value
1	Specific heat of the liquid cast iron	C_l_me	J/KgK	850
2	Specific heat of the solid cast iron	C_s_me	J/KgK	750
3	Specific heat of the support mould	C_s_fo	J/KgK	750
4	Specific heat of the external sand core	C_iz	J/KgK	1170
5	Solidification latent heat of the cast iron	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 support mould	λ_fo	W/mK	30
9	Thermal conductivity of the external sand core	λ_iz	W/mK	0.8
10	Density of the liquid cast iron	ρ_me	Kg/m^3	7000
11	Density of the support mould	ρ_po	Kg/m^3	7600
12	Density of the external sand core	ρ_iz	Kg/m^3	1550
13	Heat transfer coefficient for support mould - environment	α _ex	W/m^2K	50
14	Heat transfer coefficient casting - environment at the inner side	α_in	W/m^2K	2

3. Results

The following parameters of the thermal field were analysed:

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

Table 3 gives the hot spot position and the total solidification time of the casting and also for the outer layer and the inner layer (1 mm thick).

Figure 3 shows the solidification time of the casting wall. This figure best highlights the movement of the solidification front and the hot spot position. The maximum of these curves shows the hot spot position (the layer where the casting solidification ends). It is noted that in all cases the solidification front moves from the outside towards the inner surface of the part. This is explained by the very low heat exchange melt alloy - air on the inner surface of the casting. In the case of cores with thickness b = 5÷15 mm the hot spot is placed on the inner surface of the casting. For thicker cores (20÷30 mm), solidification ends theoretically at about 1÷2 mm from the inner surface. In fact, due to the displacement of particles with different densities under the action of centrifugal force, the solid nuclei which eventually form on the inner surface of the molten alloy are displaced outwards. Thus in these cases the real hot spot is placed on the inner surface of the casting. Table 3 shows that the increase in core thickness does not have a major influence on the solidification kinetics of the casting at the interface with the mould. The solidification time and the cooling rate at this interface are in all studied cases in the range of solidification of the gray cast iron structure (under the gray-white transition critical speed). We considered the case of a cast iron with gray-to-white transition speed of 40 °C/s. Figure 3 shows that increasing the cores thickness over a certain limit is not recommended as the total solidification time of the part increases exaggerated in the detriment of productivity.

Table 3. Results regarding the solidification time and the hot spot position

No.	External sand core thickness	Solidification time of the casting	Solidification time of the outward layer	Solidification time of the inner layer	Hot spot radius	Distance hot spot - inner side of the casting
Symbol	B_miez	tsol_p	tsol_pex	tsol_pin	Rnod	Δr_nod = Rnod-Ri
u.m	mm	s	s	s	mm	mm
1	0	73.04	0.16	73.04	35	0
2	5	609.67	137.66	609.67	35	0
3	10	941.00	247.83	941.00	35	0
4	15	1181.90	289.23	1052.64	35	1
5	20	1360.38	297.63	1054.52	36	1
6	25	1489.03	293.15	1049.74	36	1
7	30	1576.86	288.66	1046.62	36	1

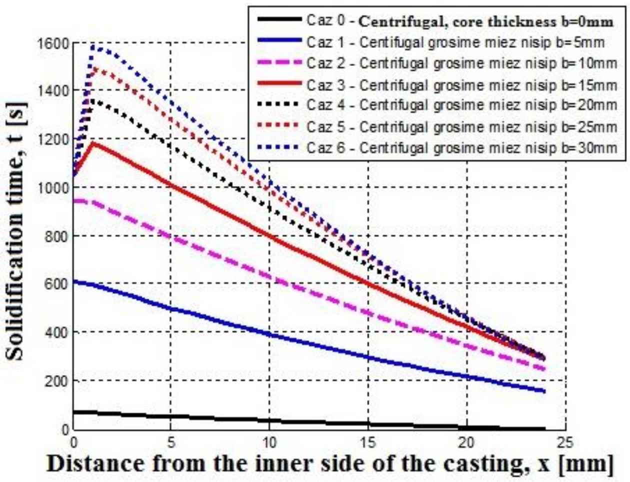

Fig. 3. Solidification time in the casting wall
(legend: caz = case; Centrifugal grosime miez nisip = Centrifugal, sable core thickness)

Figure 4 shows the temperature in the wall of the casting at the end of its solidification (at the time of the hot spot solidification). Compared to pouring in metallic mould (without the outside core) the use of sand cores has a great influence on the temperature in the casting wall. For cores with a thickness of 10÷30 mm the curves are very close (practically overlapping). This shows that the thickness of the outer cores has little influence on the temperature in the casting wall. For such casting, it results that the increase of the thickness of the outer cores over a certain limit is not necessary because it has no influence on the temperature field in the casting. The recommended thickness for the cores is 10÷20 mm and should be set according to the core manufacturing technology. Another observation relates to the fact that in the case of centrifugal casting in the sand mould (core), at the end of the solidification of the part, the alloy temperature is high. The temperature in the moulded wall is over 1100 °C, very close to the solidus temperature (across all the wall thickness). The shrinkage in solid state of the solidified layers in this temperature range is very low and the metal has high plasticity. This confirms the hypothesis of the direct contact between the casting and the mould during solidification of the casting. Thus, the assumptions that consider the existence of an air gap at the interface casting - mould in the study of the solidification of the centrifugally cast parts are invalidated.

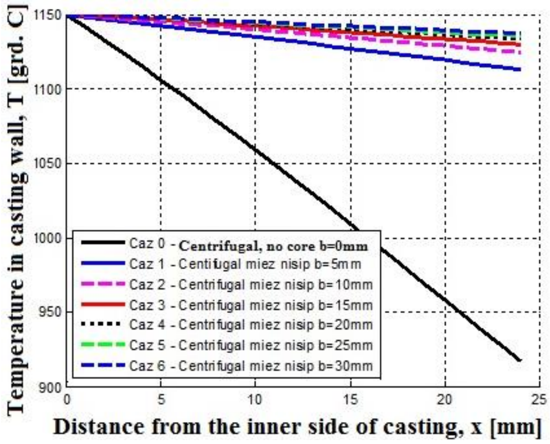

Fig. 4. Temperature in the casting wall at the end of alloy solidification
(legend: caz = case; Centrifugal grosime miez nisip = Centrifugal, sable core thickness)

Figures 5 and 6 show the evolution of the temperature and the solid fraction on the outer surface of the casting (in a 1 mm thick layer). It can be observed that the thickness of the core does not have much influence on the cooling in liquid state (in the To-Ts range) and on the kinetics of the solidification. In the case of cores with a thickness of 15÷30 mm, the curves of variation of the solid fraction overlap. Instead, the thickness of the core influences cooling after solidification. The thicker the core is, the cooling after solidification is slowed down. This may have an impact on structural changes in solid state. It can also influence the time of holding the casting in mould and its temperature when it is removed from the mould. If a low temperature is required to remove the part from the mould (to avoid deformations or structural deviations) the cores too thick can negatively affect the productivity. Therefore, choosing the thickness of the outer cores for this type of centrifugal casting is important and should be done with care.

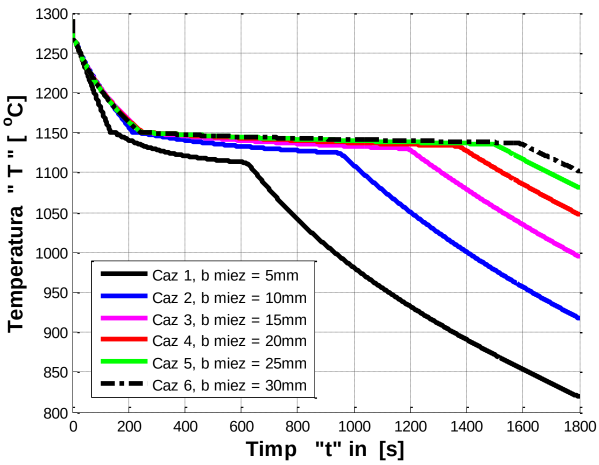

Fig. 5. The temperature evolution in the outward side layer (1 mm thickness) of casting (point A, figure 2)
(Timp = Time; Temperatura = temperature; legend: caz = case; b miez = b core thickness)

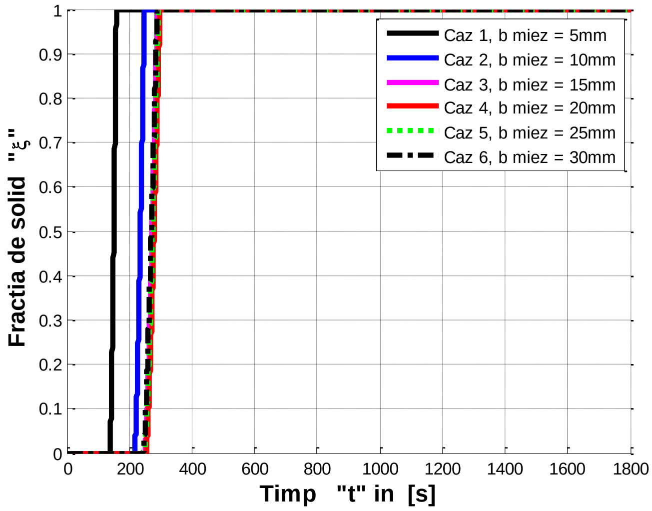

Fig. 6. The solid fraction evolution in the outward side layer (1mm thickness) of casting (point A, figure 2)
(Timp = Time; Fractia de solid = Solid fraction; legend: caz = case; b miez = b core thickness)

Tables 4 and 5 give values that characterize the kinetics of cooling and solidification in points A (on the outer surface) and B (on the inner surface). There are given the values for the solidification start time, for the effective solidification time, for the average cooling rate in liquid state (in the range To-Ts) and for the instantaneous cooling rate at the solidification temperature (at the eutectic temperature Ts).

Figure 7 graphically shows the solidification time at the important points of the casting (hot spot, interface part - outer core and part - interior air) depending on the thickness of the outer core. It can be seen that at core thicknesses over b = 15 mm, the solidification time on the casting surfaces is no longer influenced.

In terms of solidification time, cooling rate and solidification kinetics on the casting surfaces, very large differences are observed between centrifugal casting in metallic mould without core and those with sand core. It is also noted that in all cases when external cores are used, the cooling rate of the outer layer at the time prior to solidification (when reaching the temperature Ts) is very low (in the order of 0.3 - 0.8 °C/s, Table 4), below the critical gray - white value (in this case 40 °C/s). It results that the core thickness has a very low influence on the solidification conditions at the outer surface of the casting. In the case of casting with sand core, whatever is the thickness of the outer core (between 5 mm – 30 mm), gray cast iron is obtained at the outer surface of casting. In non-core centrifugal casting, this velocity is very high (about 3500 °C/s) well above the gray-white critical value.

Table 4. Results regarding the cooling and solidification kinetics of the outward side of the casting (point A, Figure 2)

No.	External sand core thickness	Cooling time to Tsol of outward side	Mean cooling rate of the outward layer in To-Tsol range	Instantaneous cooling rate at Ts of the outward side	Time of the solidification end of the outward side of casting	Effective duration of solidification of the outer surface of the part
Symbol	B_miez	t in_sol_ex	v med rac lichid	v_rac_Ts	tsol_ex	tsol_ex - tinc_sol_ex
u.m	mm	s	°C/s	°C/s	s	s
1	0	0.04	4250	3533.15	0.16	0.12
2	5	137.66	1.235	0.795	158.29	20.63
3	10	216.48	0.785	0.449	247.83	31.35
4	15	249.39	0.682	0.330	289.23	39.84
5	20	252.83	0.672	0.290	297.63	44.80
6	25	247.96	0.686	0.290	293.15	45.19
7	30	244.45	0.695	0.298	288.66	44.21

Table 5. Results regarding the cooling and solidification kinetics of the inner side of the casting (point B, figure 2)

No.	External sand core thickness	Cooling time of inner side up to Tsol	Mean cooling rate of the inner side in To-Tsol range	Instantaneous cooling rate at inner side solidification at Tsol	Time of the solidification end of the casting inner side	Effective duration of solidification of the inner surface of the part
Symbol	B_miez	τ in_sol_in	v_med rac lichid	v rac_Ts	τ_sol_in	T in_sol_in - t_sol_in
u.m	mm	s	°C/s	°C/s	s	s
1	0	35.46	4.794	0.077	73.04	37.58
2	5	178.97	0.950	0.037	609.67	430.70
3	10	251.68	0.675	0.034	941.00	689.32
4	15	280.58	0.606	0.032	1052.64	772.06
5	20	282.47	0.602	0.032	1054.52	772.05
6	25	277.69	0.612	0.032	1049.74	772.05
7	30	274.58	0.619	0.032	1046.62	772.04

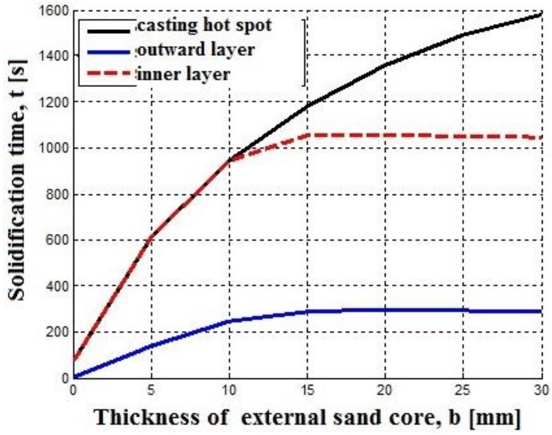

Fig. 7. Solidification time in the hot spot, in the outward layer and in the inner layer of casting relative to external sand core thickness

4. Conclusions

The main conclusions regarding the influence of the sand cores thickness on the centrifugal casting of iron parts are:

- the use of external sand cores for centrifugal casting significantly alters the cooling and solidification conditions at the external surface of castings in relation to casting without such cores [4, 5];
- the cooling rate of the outer layer of the casting at the time prior to solidification is very low between 0.3 - 0.8 °C/s (much below the critical gray - white speed);
- the cooling rate of the inner layer of the part at the time prior to solidification is also very small (between 0.03 ÷ 0.08 °C/s);
- although the cooling rate at the outer surface of the casting is very low, the solidification is directed from the outside to the inside;
- the real hot spot is placed on the inner surface of the casting;
- increasing the thickness of the cores over a certain limit has no influence on the solidification kinetics at the casting surface;
- increasing the thickness of the cores over a certain limit greatly slows the cooling of the casting in the solid state (after solidification);
- increasing the thickness of the cores over a certain limit, can affect the casting temperature when it is removed from the mould, the hot warp tendency of the part after extraction from the mould and the productivity.

The results lead to the following recommendations for industrial practice:

- core thicknesses should be as low as possible (correlated with the thickness of the casting wall and with the cores manufacturing capabilities - to ensure easy and cost-effective execution);
- cores thickness must be (0.5 ÷ 1)×bp, where bp - is the casting wall thickness.

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