About the Solidification of a Castings with a Small Cylindrical Core

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Abstract
At the solidification of rotationally symmetrical parts, which require small casting cores (diameter of core comparable with the part wall thickness) the hot spots are positioned at the interface casting - core. Due to casting geometry, most often, they do not use lateral feeder. Using direct feeders create problems caused by the cores fixture in the mold and the appearance of micro shrinkage areas into part, under the feeder. A study on the possibility of shrinkage elimination in such parts is presented. The study is conducted by computer solidification simulation. Seven versions of casting were studied. There were examined the possibility to direct the solidification of the alloy inside the part - feeder system by thermal insulated core, by coolers or by technological additions. There are analyzed the shrinkage position, the amount of liquid alloy in feeder, available to feed the casting during solidification, and the yield of liquid alloy used at casting.

Keywords
Alloy solidification, solidification simulation, casting, shrinkage, feeder

1. Introduction

Previous studies on the solidification of the tubular castings that require small cores (comparable in diameter to casting wall thickness or smaller) have shown that in these parts, the solidification is slower (compared to the solidification of plates of the same thickness). The cause is the core heating. Figure 1 shows the ratio tsol/to (where tsol is the time solidification of the part, and to - the solidification time of the plate with the same thickness) depending on the ratio inner radius / casting wall thickness ri/B (ri - inner radius piece, B - wall thickness).

All cylindrical castings (with small diameter cores) the shrinkage is positioned at the interface casting - core as shown in Figure 1 [4, 5, 9]. Such parts are often used in the industrial practice. This is the case of parts of the type shown in Figure 3 (hub, wheel, roller, drum, cover, etc.). At these parts, the shrinkage removing put some technological problems. Most times it can not be used lateral feeder, because they cannot feed shrinkage in the central area of the parts (the hub) due to the configuration of parts (the distance between the feeder and the hub or the presence of flanges or ribs with small thickness that cool faster than the hot spot). It is necessary to use direct feeders, placed in the central area. But direct feeders presents the risk of porosity in the casting area placed under the feeder (due to small temperature gradient in the vertical direction in the area of the junction the feeder - part) [1, 6, 7]. The causes are:

- direct feeder sizes are limited by the presence of the core;
- centering and fixing the core to the upper side is difficult;
- gases released from the core can penetrate in the shrinkage and prevent the shrinkage filling with liquid metal.

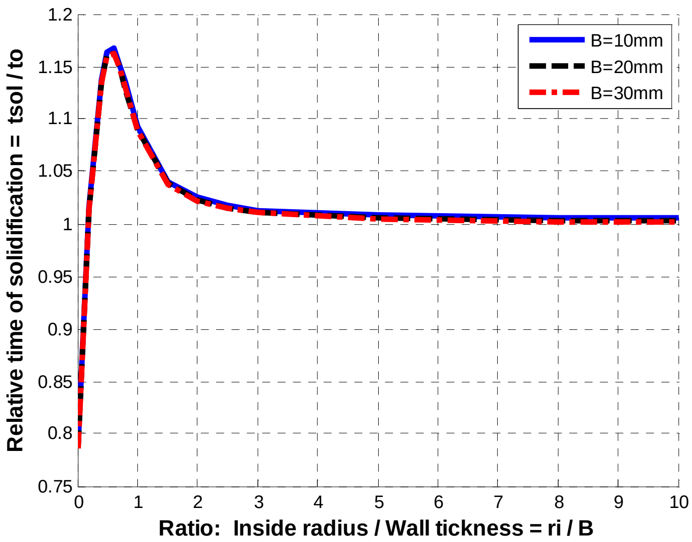

Fig. 1. Relative time of solidification (tsol/to) depending on the ratio inner radius /casting wall thickness (ri/B) for castings with wall thickness B = 10, 20, 30 mm

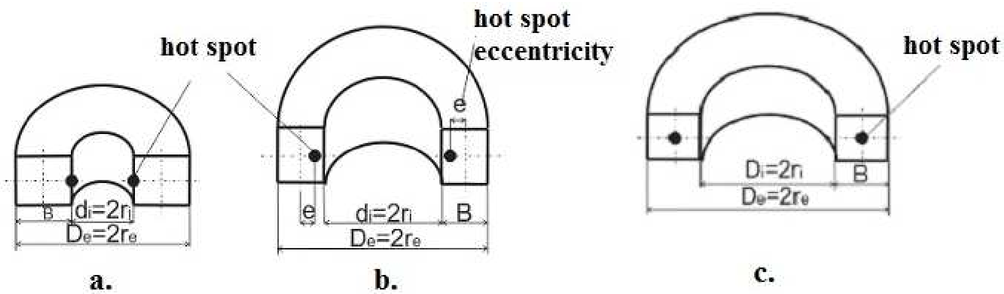

Fig. 2. Hot spot position inside the wall of cylindrical tubular casting, relative to ri / B ratio.
a) maximum eccentricity of hot spot e = B/2; b) intermediary eccentricity 0 <e < B/2;
c) minimum eccentricity e = 0

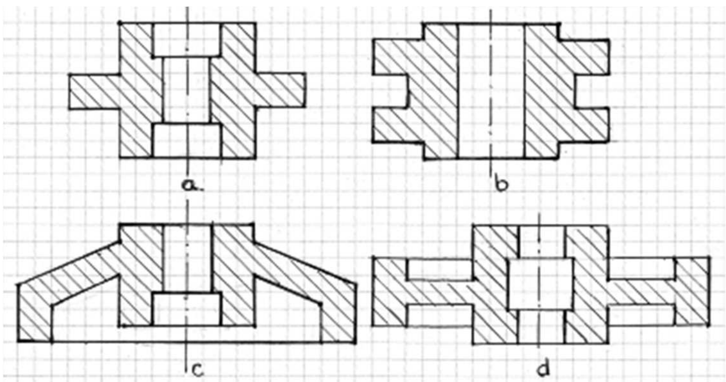

Fig. 3. Rotational parts that require small diameter cylindrical cores
a) flange; b) roller; c) cover; d) wheel

2. The Purpose of the Research

A study was conducted on the elimination of shrinkage from rotationally symmetric castings with thin cores. The purpose of the study was to analyze the effect of different methods of directing the casting solidification in the system casting - feeder, possibly to be used in practice to get sound castings. The study was conducted by computer solidification simulation. It was used a software based on a mathematical model developed in cylindrical coordinates at Transilvania University of Brasov [2, 3, 7, 8, 9]. The results are useful to establish more effective casting solution in such situations.

3. Working Mode

The solidification of casting shown in Figure 4 was studied. The part is cast in nodular graphite iron with eutectic composition. The mold is made of sand with bentonite binder. The first step was the solidification simulation of casting without feeder. This is to determine the position of the hot spot and shrinkage in the casting. The assembly casting - mold subjected of simulation in this case is shown in Figure 5. The results of solidification simulation of casting without feeder, are shown in Figures 6 and 7.Figure 6 shows the movement of the solidification front in the casting and Figure 5 shows map of isotherms throughout the assembly casting - mold at the end of the alloy solidification. Both figures show that in the casting without feeder the hot spot is positioned at the interface casting - core. Generally the shrinkage removal from castings requires that feeders to be placed in close vicinity of the hot spots. For this part, this is not possible due to the casting geometry (great distance between lateral feeders and hot spot). You can only use direct feeder. Direct feeders at their turn have the disadvantage that presents underneath (at the junction feeder - part) micro shrinkage area can occur in the casting. These are caused by small temperature gradient in the vertical direction, under the feeder.

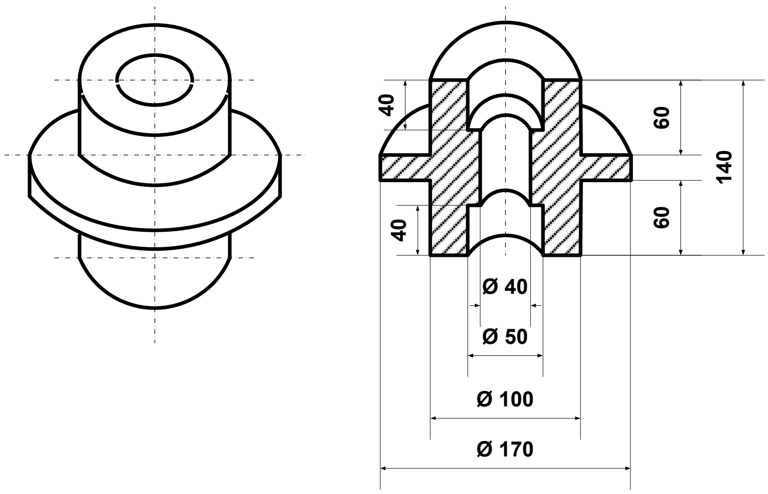

Fig. 4. The casting studied by solidification simulation

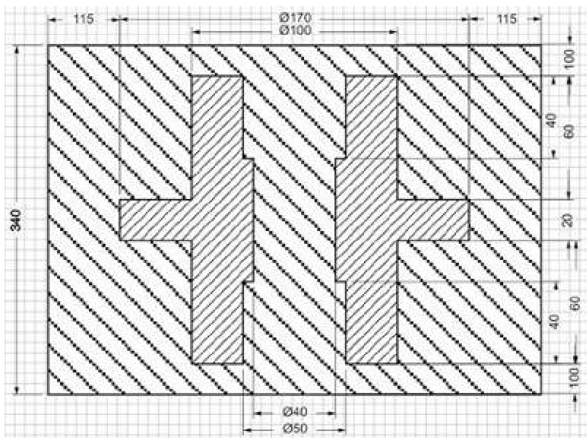

Fig. 5. Casting - mold assembly studied by simulation (case 1)

There were studied seven versions feeders. The values of thermophysical parameters used in simulation are given in Table 1. The assembly casting - feeder- mold was divided into annular square elements with section of side Δ = 5 mm. The time step was 0.5 s. Casting variants studied are shown in Figures 6 ÷ 12. We used several types and sizes of direct feeders (bulk feeder, annular feeders, frustoconical and trapezoidal). Directing solidification towards feeder was accelerated by the use of insulated cores, by external coolers or by increasing the wall thickness of the casting. In Table 2 are shown the feeders dimensions used and the way to direct the solidification to feeders.

Table 1. Physical characteristics used for simulation

No.	Characteristic	Symbol	Measure unit	Value
1	Environment temperature	Tex	°C	20
2	Coefficient of thermal exchange mould - environment	αex	$W/m^2/K$	20
3	Solidus temperature of cast alloy	Tsme	°C	1150
4	Coefficient of thermal conductivity of the mould	λsfo	W/m/K	0.8
5	Coefficient of thermal conductivity of the solidified alloy	λsme	W/m/K	40
6	Coefficient of thermal conductivity of the liquid alloy	λlme	W/m/K	30
7	Specific heat of the mould	Csfo	J/kg/K	1170
8	Specific heat of the liquid alloy	Clme	J/kg/K	850
9	Specific heat of the solidified alloy	Csme	J/kg/K	750
10	Mould density	ρfo	kg/m^3	1550
11	Density of the liquid alloy	ρme	kg/m^3	7000
12	Solidification latent heat of the cast alloy	Lme	J/kg	220000
13	Initial temperature of the mould	T0fo	^0C	20
14	Initial temperature of the liquid alloy	T0me	^0C	1320

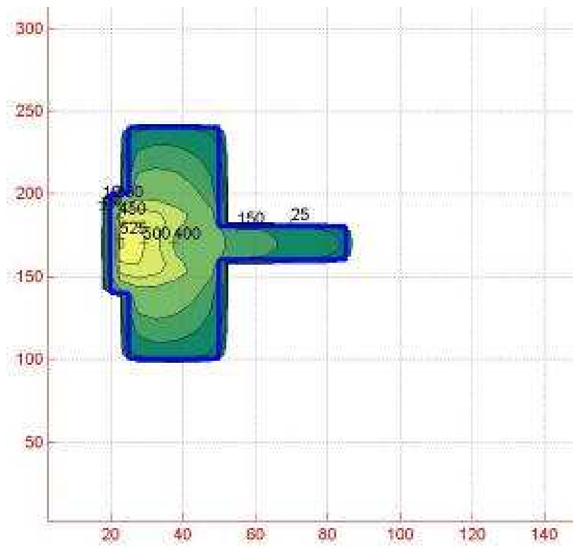

Fig. 6. Map of the solidification front movement inside casting (case 1 - casting out of feder)

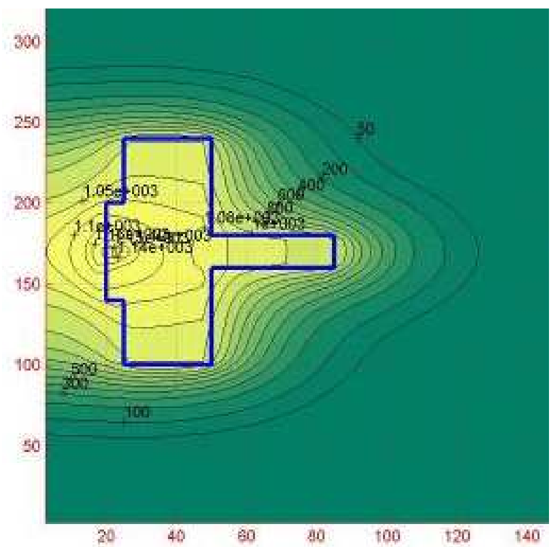

Fig. 7. Isothermal map at end time of casting solidification (case 1 - casting out of feder)

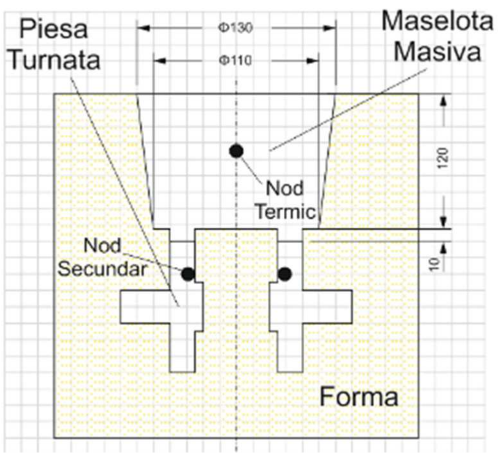

Fig. 8. Variant of casting with uninsulated bulk feeder (case 2)

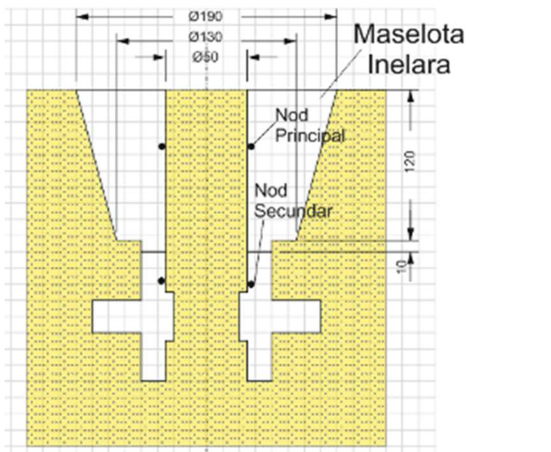

Fig. 9. Variant of casting with annular feeder free of thermal insulated coating (case 3)

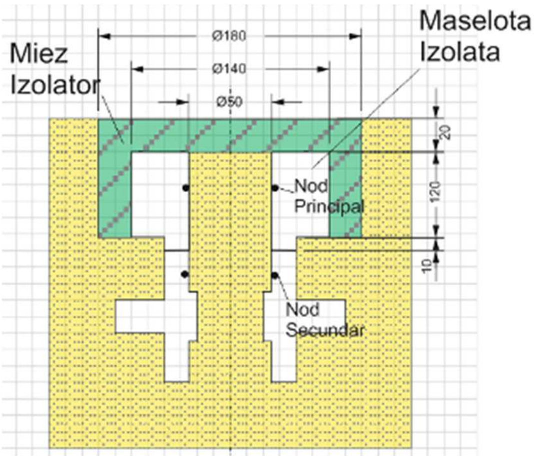

Fig. 10. Variant of casting with annular feeder with thermal insulated coating (case 4)

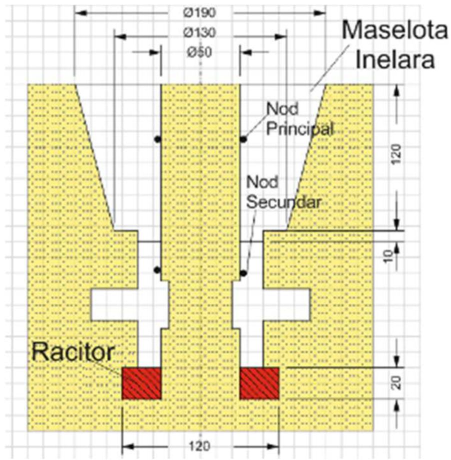

Fig. 11. Variant of casting with annular feeder free of thermal insulated coating and with cooler (case 5)

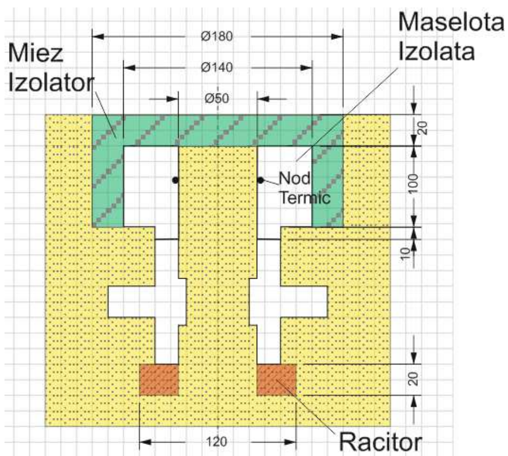

Fig. 12. Variant of casting with short annular feeder, with thermal insulated coating and cooler (case 6)

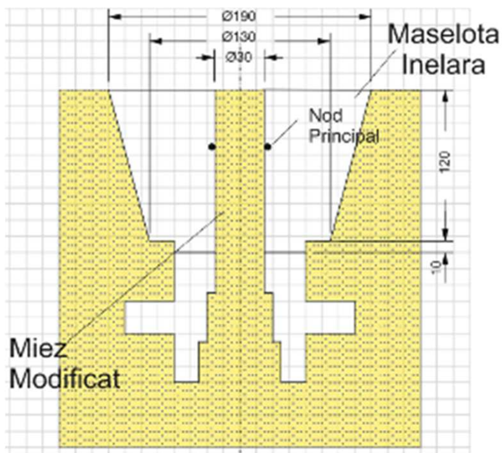

Fig. 13. Variant of casting with modified part (reduced inner diameter at the top) and with annular feeder free of thermal insulated coating (case 7)

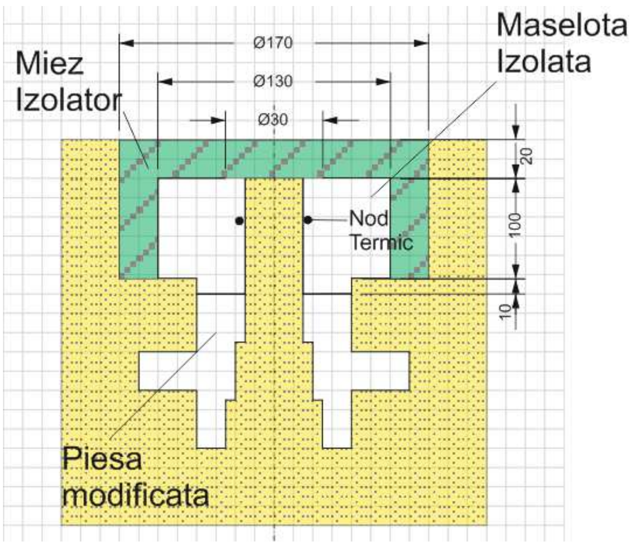

Fig. 14. Variant of casting with modified part (reduced inner diameter at the top) and with coated annular feeder (with thermal insulated core) (case 8)

Table 2. Type and dimensions of the used feeders

No.	Variant of casting	Maximum outward diameter, De_max	Minimum outward diameter, De_min	Inner diameter, d	Height, Hm
1	Out of feeder	-	-	-	-
2	Uninsulated bulk feeder	130	110	0	120
3	Annular feeder free of thermal insulated coating	190	130	50	120
4	Annular feeder with thermal insulated coating	140	140	50	120
5	Annular feeder free of thermal insulated coating and with cooler	190	130	50	120
6	Short annular feeder, with thermal insulated coating and with cooler	140	140	50	100
7	Modified casting with annular feeder free of thermal insulated coating	190	130	30	120
8	Modified casting with annular feeder and thermal insulated coating	130	130	30	100

4. Results

In the Figures 15 to 21 is shown the solidification front displacement and the position of the hot spot for all seven cases of feeder studied. The numerical results on the solidification time of the alloy and the position of the hot spots are given in Table 3. Those about the volume of liquid alloy available in the feeders (to compensate the solidification contraction of the part) and the yield of liquid alloy use at casting are given in Tables 4 and 5.

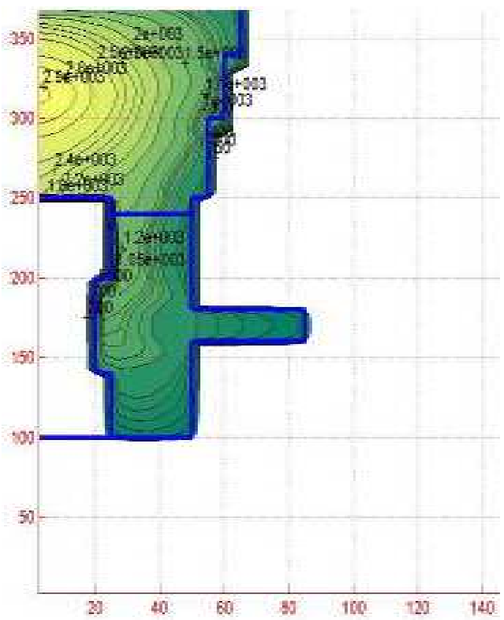

Fig. 15. Movement of solidification front and hot spot position in the case, top bulk feeder (case 2)

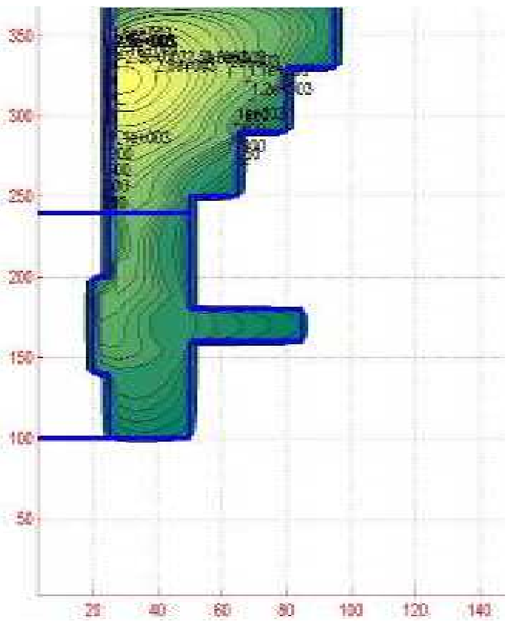

Fig. 16. Movement of solidification front and hot spot position in the case, annular feeder free of thermal insulated coating (case 3)

5. Comments

The results from these figures and tables lead to the following observations:

Variant 1. Casting without feeder (Figure 6). The hot spot is placed on the inner cylindrical surface of the casting. There is a circular shrinkage distributed on the inner surface of the casting (at the interface casting – core, with diameter Dint = 40 mm).

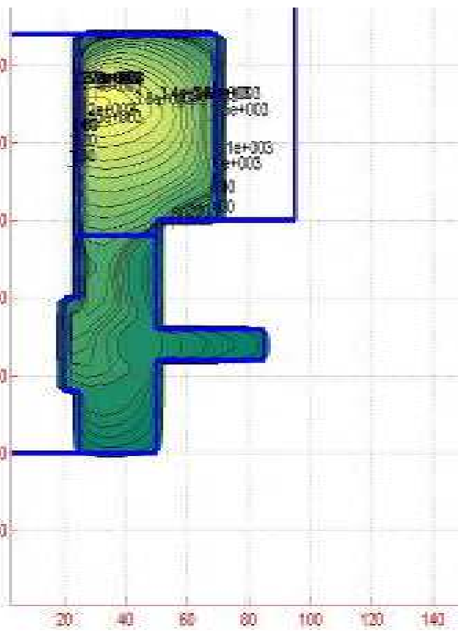

Fig. 17. Movement of solidification front and hot spot position in the case, annular feeder with thermal insulated coating (case 4)

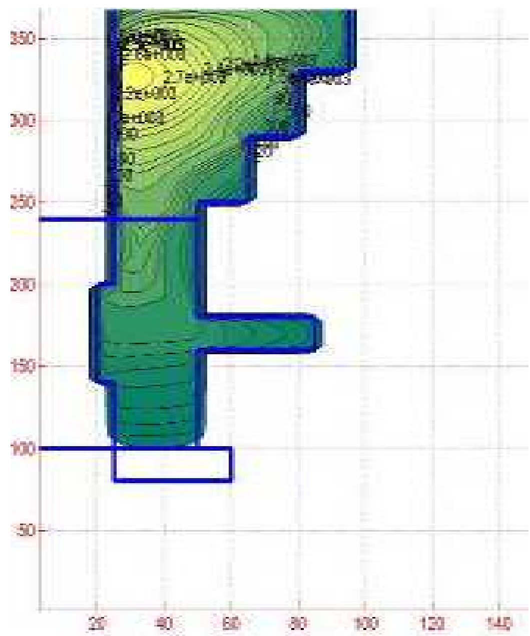

Fig. 18. Movement of solidification front and hot spot position in the case, annular feeder free of thermal insulated coating and with cooler (case 5)

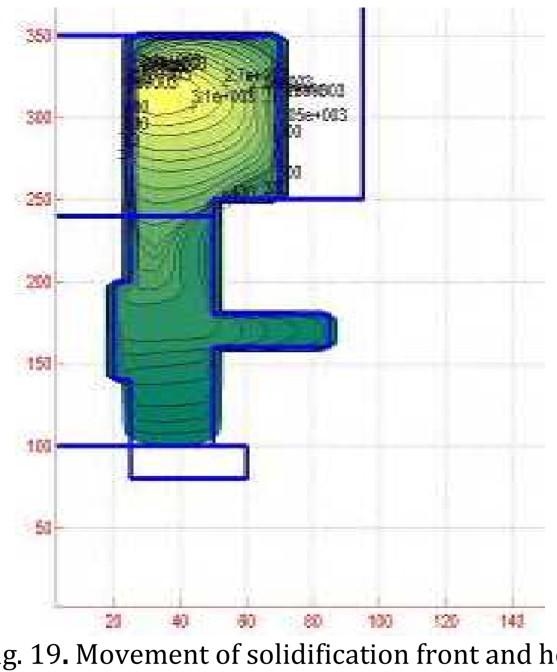

Fig. 19. Movement of solidification front and hot spot position in the case, short annular feeder with thermal insulated coating and with cooler (case 6)

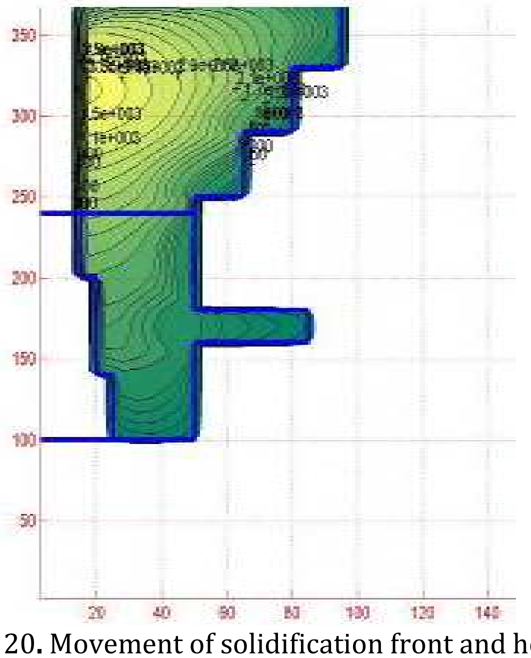

Fig. 20. Movement of solidification front and hot spot position in the case, modified casting with annular feeder free of thermal insulated coating (case 7)

Variant 2. Casting with bulk frustoconical feeder (Figure 15), placed above the core, located in the central area of the part. The hot spot is placed inside the feeder on its axis, approximately half the height of the feeder. The amount of useful liquid alloy in the feeder available to compensate the solidification shrinkage of the part is very big. This is enough to compensate the solidification shrinkage of the part. However, in casting, under the feeder, there is an area, which solidify faster than the area under it. As a result, a secondary hot spot occurs in the casting. Its feeding with liquid metal from feeder is interrupted before the complete solidification of the part. The secondary hot spot is positioned on the inner surface of the part (interface alloy - core) at a distance of about 35 mm from the upper edge of the piece. The secondary hot spot does not have large volume but can cause Shrinkage or contraction porosity in that area. Thus, although the useful liquid alloy in the feeder is enough and could compensate a large contraction of approx. 25% it cannot be obtained sound parts. Figure 15 shows that in the casting, the solidification front is practically parallel to the wall axis of the part.

This shows a very low temperature gradient (negligible) in the vertical direction and a very high risk of producing an axial porosity in the vertical wall of the part. In addition, this variant of casting also presents another disadvantage. This is due to the fact that the core is covered by the liquid metal of the feeder. The feeder prevents the removal of gas that is released from the core. Thus, the gases remain in the casting as murmurs.

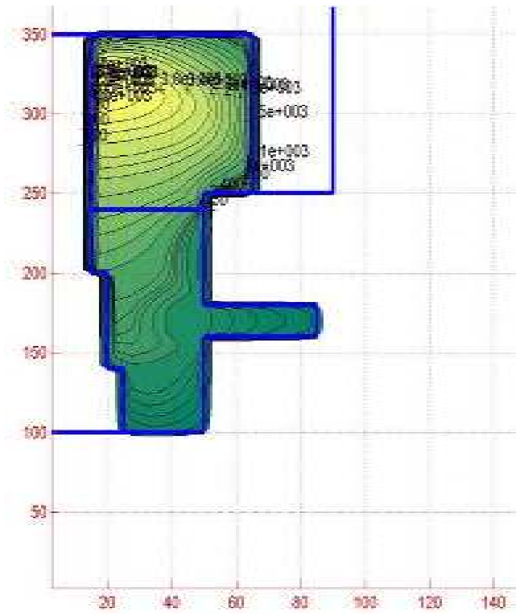

Fig. 21. Movement of solidification front and hot spot position in the case, modified casting and with thermal insulated coating annular feeder (case 8)

Variant 3. Casting with annular direct feeder, uninsulated (Figure 16). The hot spot is placed inside the feeder on its inner surface, at about half the height of the feeder. The amount of useful liquid alloy in feeder, available to compensate the solidification shrinkage is big (bigger than in the previous case). This is sufficient to compensate the solidification shrinkage of the part. However, similar to previous case, in the casting (under the feeder) there is an area which solidified faster than the part area located below.

The map of the solidification front displacement inside the casting shows that the temperature gradient in the vertical direction is very small (negligible). This increases the tendency of producing axial porous areas in the vertical wall of the part. In the casting is created in this case a secondary hot spot whose supply with liquid metal from feeder is interrupted before the complete solidification of the part. The secondary hot spot is positioned on the inner surface of the part (the interface alloy - core) at a distance of about 35 mm from the top edge of the part. As in the previous case, although the useful liquid alloy in the feeder can compensate a very high shrinkage percentage (approx. 25%), in the casting were obtained micro shrinkages.

Variant 4. Casting with annular direct feeder, and thermal insulated (Figure 17). While the feeder is insulated by a core of low thermal conductivity, the solidification dynamics is similar to the previous cases. A small secondary hot spot appears in the part, located on the inner surface at about 35mm from the upper edge of the part. The temperature gradient in vertical direction on part wall axis is very low (negligible). There are conditions to occur axial micro shrinkage in the part wall under the feeder.

Table 3. Results concerning casting solidification and hot spot position

No.	Variant of casting	Casting solidification time from casting - feeder joint, tsol_p, [s]	Time of feeder solidification, tsol_m, [s]	Solidification time of casting hot spot, [s]	Position of secondary hot spot inside casting
1	Out of feeder		-	527.5	-
2	Uninsulated bulk feeder	739.0	1459.5	644.5	On inner side of casting 35 mm under feeder (radius ri = 20 mm)
3	Annular feeder free of thermal insulated coating	725.5	1490.0	646.0	On inner side of casting, 40 mm under feeder (radius ri = 20 mm)
4	Annular feeder with thermal insulated coating	782.0	2033.0	653.0	On inner side of casting, 35 mm under feeder (radius ri = 35 mm)
5	Annular feeder free of thermal insulated coating and with cooler	618.0	1448.5	504.5	On inner side of casting, 30 mm under feeder (radius ri = 20 mm)
6	Short annular feeder, with thermal insulated coating and with cooler	648.5	1692.0	Free of secondary hot spot	-
7	Modified casting with annular feeder free of thermal insulated coating	1057.5	1802.0	Free of secondary hot spot	-
8	Modified casting with annular feeder and thermal insulated coating	1081.0	2113.5	Free of secondary hot spot	-

Table 4. Results concerning feeders' volume and yield of liquid alloy use (part volume is V_P = 1163.96 cm^3)

No.	Variant of casting	Feeder volume, V_M [cm^3]	Total volume of the cast alloy, V_{TOT} [cm^3]	Yield of liquid alloy use, I.U. [%]
1	Out of feeder	-	1163.960	
2	Uninsulated bulk feeder	1422.356	2586.316	45.00
3	Annular feeder free of thermal insulated coating	2292.577	3456.537	33.67
4	Annular feeder with thermal insulated coating	1670.541	2834.501	41.06
5	Annular feeder free of thermal insulated coating and with cooler	2292.577	3456.537	33.67
6	Short annular feeder, with thermal insulated coating and with cooler	1401.935	2565.895	45.36
7	Modified casting with annular feeder free of thermal insulated coating	2455.940	3670.165	41.63
8	Modified casting with annular feeder and thermal insulated	1328.108	2542.333	45.78

Table 5. Results concerning the useful liquid alloy in feeder available
and the appearance of shrinkage inside casting

No.	Variant of casting	Volume of useful liquid alloy in feeder, V_{LU} [cm^3]	Total volume of cast alloy, Vtot [cm^3]	Shrinkage possible to be compensated by feeder, βmax [%]	The appearance of shrinkage inside casting
1	Out of feeder	-	1163.960	-	yes
2	Uninsulated bulk feeder	646.916	2586.316	25.01	
3	Annular feeder free of thermal insulated coating	1018.568	3456.537	29.46	yes
4	Annular feeder with thermal insulated coating	1100,290	2834.501	38.81	yes
5	Annular feeder free of thermal insulated coating and with cooler	1227.509	3456.537	35.51	yes
6	Short annular feeder, with thermal insulated coating and with cooler	963.842	2565.895	37.56	no
7	Modified casting with annular feeder free of thermal insulated coating	863.509	3670.165	23.52	no
8	Modified casting with annular feeder and thermal insulated coating	755.589	2542.333	29.68	no

Variant 5. Casting with uninsulated annular feeder and cooler (Figure 18), placed at the bottom of the part hub. In this variant was used a feeder, similar to that of the variant 3. The cooler at the bottom of the part hub has the role to accelerate the cooling in that area. Alloy solidification is driven from below upwards and the temperature gradient in alloy (in the vertical direction) is emphasized. This gradient eliminates the risk of axial porosity. A careful analysis of the movement of the solidification front shows that on the inner surface of the workpiece, at a distance of about 35mm from the upper edge of it (in the area where in the variant 3 appears node secondary heat), remains a very small area (of the order 5 - 10 mm) which solidified with delay in relation to the neighboring elements. As a result in this variant too there is a risk of occurrence of contraction porosity on the inner surface of the hub.

Variant 6. Casting with thermal insulated annular feeder and cooler (Figure 19). In this case, we aimed to meet the advantages due to the insulating core located on the feeder, with those obtained by the use of a cooler. The insulated feeder is similar to the version 4, but the feeder height is reduced by 20mm. In this case the solidification is directed properly from part to the feeder. The map of movement of the solidification front show that in the system is formed a single hot spot, placed in the feeder at an upper portion thereof. The temperature gradient in the part wall in vertical direction is emphasized and favorably oriented (from bottom to top). It is a variant that ensures total elimination of shrinkage from casting, but are however drawbacks related to the use of external coolers.

It is possible that after dropping the cooler in the mold, on their surface, to form oxides or to condense moisture. On contact with the liquid alloy, they can cause defects (inclusions of gas). In addition for gray iron castings (with graphite) the use of coolers can cause local modification of the structure and properties of castings. Therefore, this variant it is not usable for cast iron components.

Variant 7. Casting with simple annular feeder and technological addition on inner diameter (Figure 20). Feeder has the same dimensions as in version 2. It was intended to direct the solidification from part to feeder by wall thickening (technological addition) under the feeder. In this way part solidification in this area is slowed. Therefore, the liquid alloy may to flow from feeder to the secondary hot spot (in the part) until the end of solidification. Following of secondary hot spot is removed from the casting. The results in Tables 3 ÷ 5 and the map the movement of the solidification front for this case (Figure 20) shows that the system forms a single hot spot. This is placed in the feeder (toward the top thereof). The route of the solidification front lines shows that the temperature gradient in the vertical direction, in the part wall is properly and the tendency to form axial micro shrinkages is eliminated. This variant ensures a sound casting. It presents the disadvantage of a low yield of liquid alloy use at casting (Table 4). In addition, the cost of further mechanical processing (for removing technological addition on the inner diameter) is greater.

Variant 8. Casting with technological addition on inner diameter and thermal insulated feeder (Figure 21). Feeder has the same dimensions as in the version 6. It aimed to direct the solidification from part towards the feeder by technological additions and also by thermal insulation of the feeder. This case benefits by the fact that feeder insulation provides the greatest amount of useful liquid alloy available in feeder to compensate part contraction at casting. The hot spot is placed in feeder node at the upper half of it. This is far more favorable variant, because it is applicable to all types of alloys (including gray cast iron, because it does not use cooler). This provides the highest yield on the use of liquid alloy in casting. It is possible that the feeder dimensions to be reduced (in order to enhance the yield of liquid alloy use in the casting). In this sense an optimization study through simulation is required.

6. General Conclusions

The main findings of this study (on the solidification of rotationally symmetric parts and thin core with diameter comparable to casting wall thickness) are:

- in the casting without feeder the shrinkage is formed on the inner surface of the part;
- in the case of casting with simple direct feeders (or even warmed) the shrinkage can not be completely removed from the casting (secondary shrinkage appears in the casting);
- The recommended casting variant that can ensure total elimination of shrinkage from the casting (which does not affect the part structure and have a high yield) consists in applying technological additions at the top of part (increasing casting thickness at the junction part - feeder) using and thermal insulated cores on feeder.

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