ARCHIVES
of
FOUNDRY ENGINEERING

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (1897-3310)
Volume 10
Issue Special1/2010
41-46

7/1

Structure fields in the solidifying cast iron roll

W.S. Wołczyński [a,*], E. Guzik [b], B. Kania [c], W. Wajda [a]
[a] Instytut Metalurgii i Inżynierii Materiałowej, PAN, ul. Reymonta 25, 30-059 Kraków, Polska
[b] Wydział Odlewnictwa, AGH, ul. Reymonta 23, 30-059 Kraków, Polska
[c] Wydział Fizyki, AGH, ul. Reymonta 19, 30-059 Kraków, Polska
*e-mail: nmwolczy@imim-pan.krakow.pl

Received: 26.02.2010; accepted in revised form: 30.03.2010

Abstract

Some properties of the rolls depend on the ratio of columnar structure area to equiaxed structure area created during roll solidification. The $C \rightarrow E$ transition is fundamental phenomenon that can be apply to characterize massive cast iron rolls produced by the casting house. As the first step of simulation, a temperature field for solidifying cast iron roll was created. The convection in the liquid is not comprised since in the first approximation, the convection does not influence the studied occurrence of the $C \rightarrow E$ (columnar to equiaxed grains) transition in the roll. The obtained temperature field allows to study the dynamics of its behavior observed in the middle of the mould thickness. This midpoint of the mould thickness was treated as an operating point for the $C \rightarrow E$ transition. A full accumulation of the heat in the mould was postulated for the $C \rightarrow E$ transition. Thus, a plateau at the $T(t)$ curve was observed at the midpoint. The range of the plateau existence $t_C \leftrightarrow t_E$ corresponded to the incubation period $t_C^R \leftrightarrow t_E^R$, that appeared before fully equiaxed grains formation. At the second step of simulation, behavior of the thermal gradients field was studied. Three ranges within the filed were visible:

a/ for the formation of columnar structure (the C – zone): ($\dot{T} >> 0$ and $G|_{t < t_C^R} - G|_{t = t_C^R} >> 0$),

b/ for the $C \rightarrow E$ transition (columnar to fully equiaxed structure): ($\dot{T} = 0$ and $G|_{t = t_C^R} - G|_{t = t_E^R} \approx 0$),

c/ for the formation of fully equiaxed structure (the E – zone): ($\dot{T} < 0$ and $G|_{t = t_E^R} - G|_{t > t_E^R} > 0$).

The columnar structure formation was significantly slowed down during incubation period. It resulted from a competition between columnar growth and equiaxed growth expected at that period of time. The $G|_{t = t_C^R} - G|_{t = t_E^R} \approx 0$ relationship was postulated to correspond well with the critical thermal gradient, $G_{crit.}$ known in the Hunt's theory. A simulation was performed for the cast iron rolls solidifying as if in industrial condition. Since the incubation divides the roll into two zones: C and E; (the first with columnar structure and the second with fully equiaxed structure) some experiments dealing with solidification were made on semi-industrial scale.

Keywords: Fundamentals of the foundry processes; Solidifying rolls; Structure types; $C \rightarrow E$ transition; Temperature gradients field

1. Introduction

Rolls made of steel, cast steel and cast iron are expensive tools which have to meet very high requirements. The rolls should be resistant to abrasive wear, to mechanical and thermal fatigues and to crack propagation. Thus, the chemical composition of rolls are imposed by the mandatory standards. However, some companies offer rolls with various combinations of the elements, such as: C, Si, Cr, Ni, Mo.

The $C \to E$ transition in solidifying rolls was already discussed to a large degree [1]. The solid / liquid interface undercooling for both structures formation was the subject of this description. The estimated values of temperature gradient were based on this undercooling [1]. By the use of the mentioned theory [1] it was possible to localize the $C \to E$ transition through analysis of the difference between *liquidus* isotherm and *solidus* isotherm velocities.

The size of columnar and equiaxed grains was compared in order to verify theoretical predictions [2]. As far as undercooling calculations are concerned, they are to some extent uncertain. They concern the solid / liquid interface and are not associated with the solidification taken as a whole.

The $C \to E$ transition was simulated numerically by means of the SOLID Software [3], The simulation requires some data from the experiment, which are difficult to obtain, particularly in the industrial conditions.

The transition from constrained to unconstrained growth was also studied, but during directional solidification only [4]. The model was based on the phenomenon of destabilization in order to confront the results of theoretical simulation with experimental observations.

The mentioned calculations [4], did not include the field of the thermal gradients. The thermal gradients, both in the liquid at the dendrite / cell tips and in the mushy zone, were determined in a different way.

The current work makes an attempt to find a correlation between thermal gradients field and a $C \to E$ transition in the roll to optimize the roll structure and its properties in the future.

Thus, the current work presents a new mode of description of the $C \to E$ transition by calculating the gradients field for the real temperature and by treating the incubation period as the most significant phenomenon that appears during the massive roll solidification (particularly for the $C \to E$ transition).

2. Assumptions and the analysis method

The calculations were performed on the computer located at the Academic Computer Centre CYFRONET – AGH Kraków, (computer named “BARIBAL”, financed by the research project MNiSW / SGI3700 / PAN / 021 / 2009). The details of the calculation method are described in the manual [5].

A simulation of the temperature field was made for the imposed geometry of the roll but with no regard to convection in the liquid. It was assumed that convection did not have a huge effect on a temperature value estimated for the midpoint located between two walls of the mould and at its given height.

Commercial Finite Element Software ABAQUS was used for simulation of a temperature field behavior in function of time. The temperature field resulted from the considered *Green-Naghdi* basic energy balance and the heat flux followed the *Fourier* law. The boundary conditions assumed for one from the performed simulations are shown in Fig. 1.

3. Temperature fields calculation

It was postulated that the midpoint in the ceramic mould (middle of the ceramic mould thickness), set at the middle of the roll length, is the representative place for temperature field observation. Especially, it is important for the $C \to E$ transition, Fig. 2.

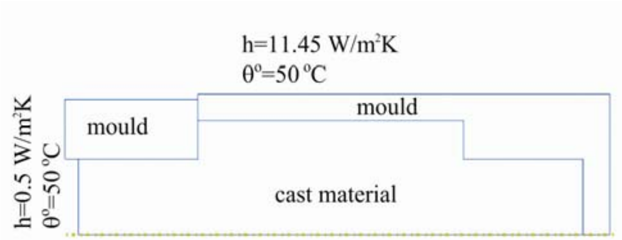

Fig. 1. Geometry of the system subjected to calculations of the temperature field within a roll and applied boundary conditions.

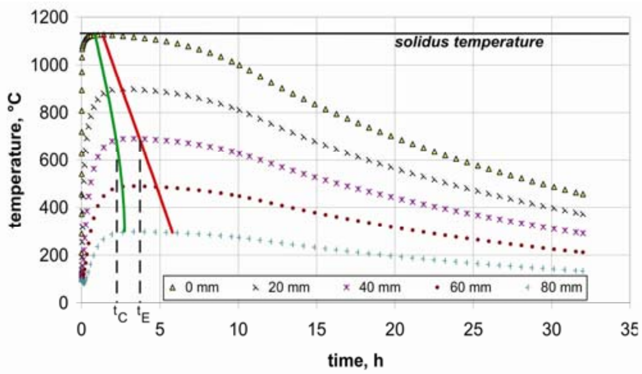

Fig. 2. Changes of temperature in function of time at different points situated in the mould as calculated for a given cast iron roll.

This place was named the operating point of the temperature field for the solidifying roll. In fact, changes of temperature versus time at the operating point forms a plateau, Fig. 2. The plateau is situated between $t_C \leftrightarrow t_E$ for the applied ceramic mould. The estimated values of both parameters are as follows: $t_C \approx 2.6$ h and $t_E \approx 3.8$ h.

Intersection of vertical curves with temperature profile printed for the midpoint of the mould (denoted: x 40 mm) defines the period of time denoted $t_C \leftrightarrow t_E$, Fig. 5. The behavior of the temperature field created at the operating point situated at the half the thickness of the mould (operating point defined in Fig. 2) is shown schematically, (Fig. 3). The studied plateau appeared significantly smaller in the case of the cast iron roll solidification, Fig. 2, when compared with the plateau delimited for the cast steel roll [6].

The $C \to E$ transition for the solidification of the cast iron roll manifests itself in the ceramic mould at the period of time defined as follows $t_C \approx 2.6\,h$; $t_E \approx 3.8\,h$, Fig. 2. The temperature fields considered before and just after that time are shown in Figs 4-6. The results of simulation shown in Figs 4 - 6 allows to develop the graph that presents the movement of the *liquidus* isotherm, that is velocity of the *liquidus* isotherm in function of time for the whole solidification process under investigation, Fig. 7. It is evident that the movement of the *liquidus* isotherm is inseparably connected to the solid phase formation.

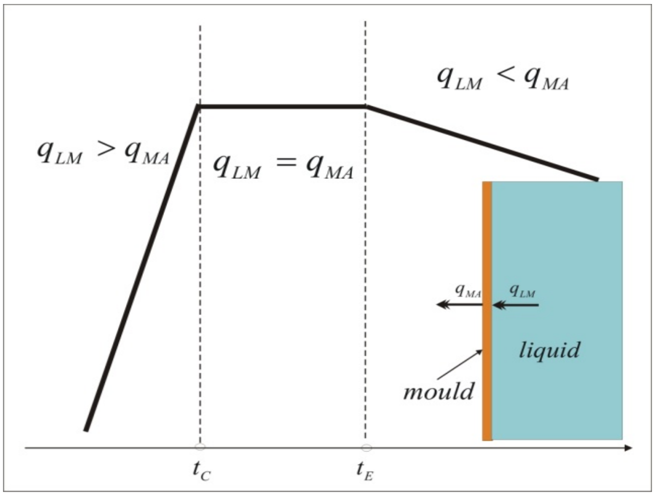

Fig. 3. Changes of temperature in function of time at the operating point situated in the ceramic mould; a/ $\dot{T} >> 0$, for $t < t_C$, b/ $\dot{T} = 0$, for $t_C < t < t_E$, c/ $\dot{T} < 0$, for $t > t_E$; q_{LM} - heat flux from the liquid into the mould; q_{MA} - heat flux from the mould into the air.

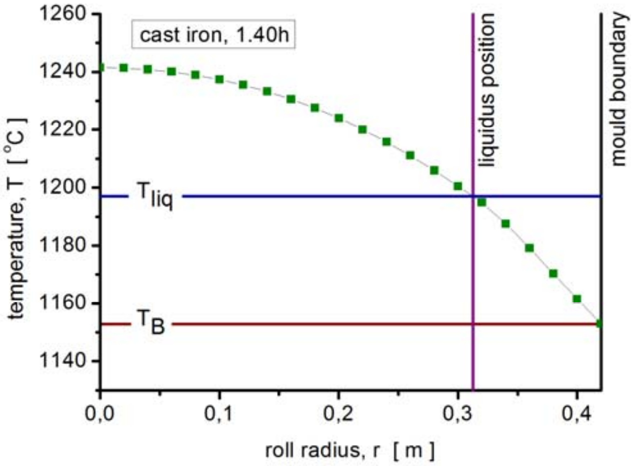

Fig. 4. Temperature field calculated for the time equal to 1.4 [h] within the cast iron roll of the 950 [mm] in diameter.

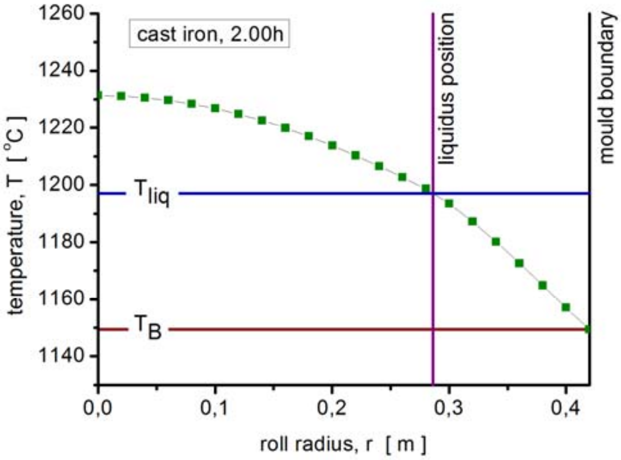

Fig. 5. Temperature field calculated for the time equal to 2.0 [h] within the cast iron roll of the 950 [mm] in diameter.

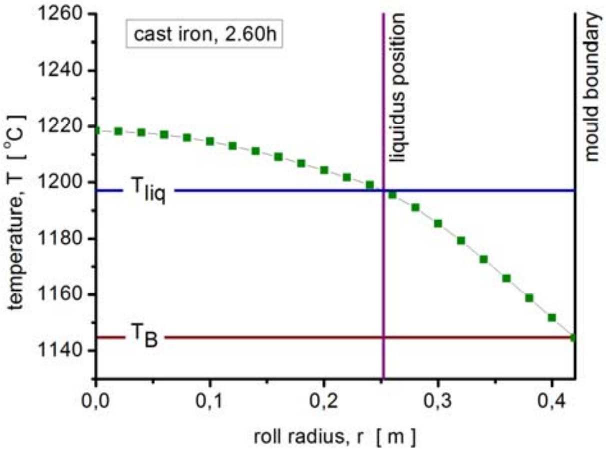

Fig. 6. Temperature field calculated for the time equal to 2.6 [h] within the cast iron roll of the 950 [mm] in diameter.

Additionally, the rate of temperature changes observed at the inner surface of the mould are also taken into account, to compare it with the rate of the *liquidus* isotherm movement, Fig. 7. Both curves were expected to be similar. A distinct similarity is visible. Yet, a certain delay between the curves also occurred.

The $t_C^R \leftrightarrow t_E^R$ period of time was marked on the basis of the *liquidus* isotherm movement analysis presented in Fig. 7. According to the analysis, it should be emphasized that *liquidus* isotherm velocity decreases within period of time $t < t_C^R$, when columnar structure growth is expected. It means that columnar growth slows down and the *liquidus* isotherm velocity manifests its minimum.

The competition between columnar and equiaxed structure formation starts before the minimum when the *liquidus* isotherm accelerates. It is assumed that the *liquidus* isotherm tears away from the columnar dendrite / cell tips at time $t = t_C^R$. Therefore, the t_C^R - time is situated at the first flexibility point of the v - curve and at the minimum of the $\dot{T}_B$ - curve, simultaneously. Columnar structure is still formed within the period of time $t_C^R \leftrightarrow t_E^R$, but its growth vanishes due to the lost competition, and at the time $t = t_E^R$ equiaxed structure growth dominates, exclusively. The t_E^R - time is located at the second flexibility point of the v - curve.

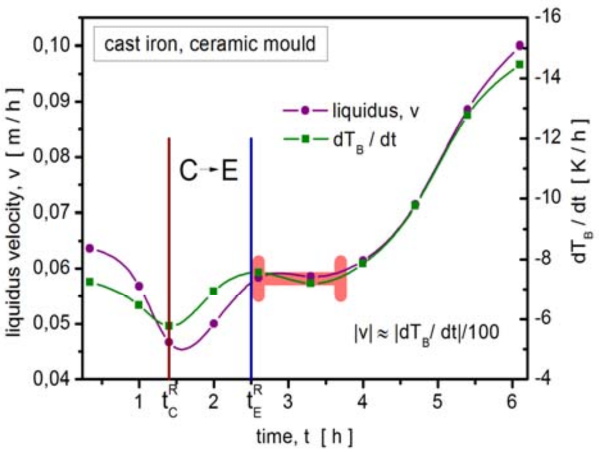

Fig. 7. Velocity of the *liquidus* isotherm movement in function of time; additionally dT_B / dt, as observed at the roll / mould border is shown; the $t_C^R \leftrightarrow t_E^R$ period of time is distinguished.

The delay in time, between minima of the both curves, Fig. 7, is justified, because a sequence of the envisaged phenomena occurs in the air / mould / ingot system. First, the q_{MA} - heat flux appears as a result of the q_{LM} - heat flux existence, and next a movement of the *liquidus* isotherm is expected in the sequence.

Not only the analysis of temperature field but also an analysis of the thermal gradients field is possible. The thermal gradients behavior observed at the columnar dendrite / cell tips allowed to differentiate the zone of the columnar structure formation from the zone of the fully equiaxed structure formation [1].

The current calculation of the temperature field allows to show the thermal gradients field without taking into account the undercooling, Fig. 8. It is an advantage of the current mode of calculation. According to the current model, determination of the temperature field, rate of the liquidus isotherm movement and thermal gradients field by means of numerical treatment is sufficient to localize the $C \rightarrow E$ transition.

The $t_C^R \leftrightarrow t_E^R$ period of time representing the $C \rightarrow E$ transition is taken from Fig. 7 and juxtaposed in Fig. 8.

It can also be explained how the vanishing of columnar structure occurs in time. It is assumed that at the beginning of the columnar structure zone formation the velocity of growth is equal to the velocity of the *liquidus* isotherm movement. Starting from the t_C^R time an extrapolation of the columnar growth velocity to its zero value should be marked, Fig. 9.

The extrapolation of the columnar growth velocity to its zero value shows that columnar structure formation is no longer possible starting from time denoted t_E^R, and defined in Fig. 9. At that time, competition between columnar structure and equiaxed structure is completed and fully equiaxed structure can be formed exclusively.

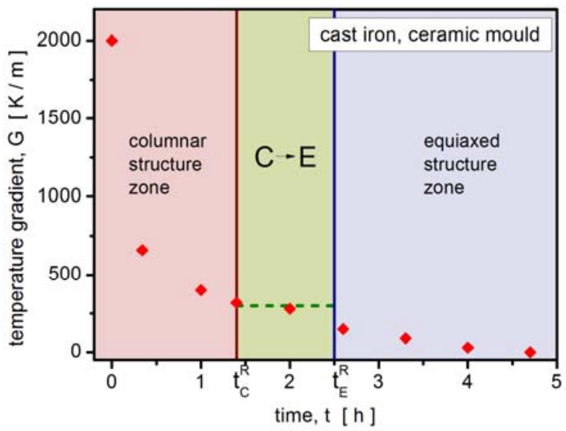

Fig. 8. Changes of the thermal gradient during solidification observed at the s/l interface: first, at the tips of columnar dendrites / cells, next at a layer of the equiaxed grains.

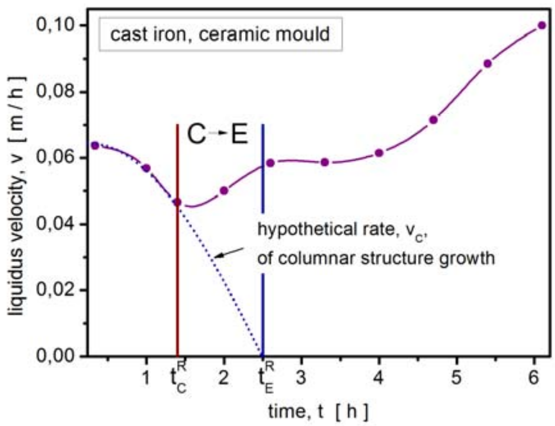

Fig. 9. Extrapolation of the columnar growth velocity to determine the time, t_E^R, that defines a full vanishing of the columnar structure.

4. Experimental observations

Experimental observations of the columnar and equiaxed structure created within the solidifying roll produced in semi-industrial conditions are shown in Figs 10-11.

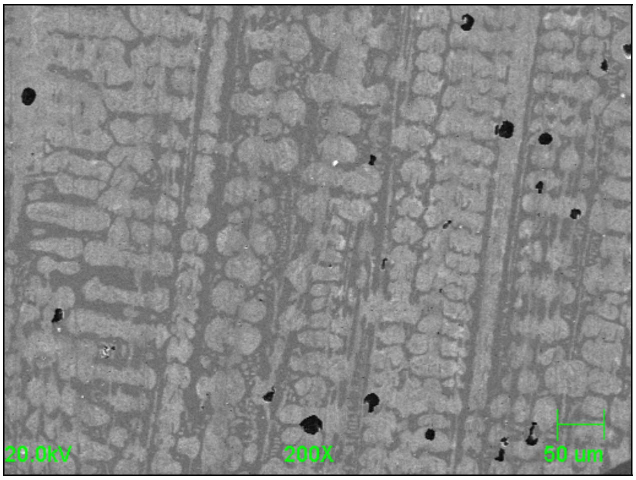

Fig. 10. Columnar structure as observed within the zone – C of the cast iron roll; nodular small particles of the graphite (black) are situated inside the austenite grains (bright).

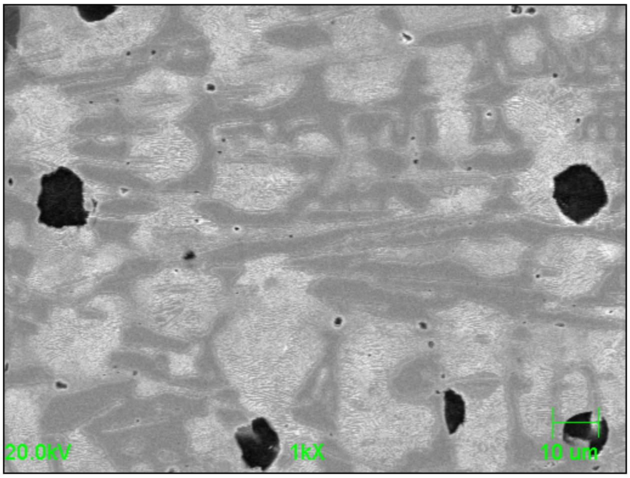

Fig. 11 Equiaxed structure (austenite and cementite) as observed within the zone – E of the cast iron roll; nodular small particles of the graphite (black) are situated inside the austenite grains (bright); nodular large particles of the graphite are also visible.

5. Concluding remarks

The proposed method of the localization of the $C \to E$ transition requires neither arduous measurement nor experiment, as it is suggested in the literature [3]. It is sufficient to know some material parameters which are easily accessible, even in the case of industrial situation.

Moreover, the theoretical predictions could be verified to some extent by the temperature measurement: a/ at the operating point, b/ at the roll / mould border (T_B - temperature).

A difference between localization in time of the $t_C \leftrightarrow t_E$ period and the $t_C^R \leftrightarrow t_E^R$ incubation period is established.

The $t_C^R - t_C$ difference equals -1.2 [h], with the $t_C \approx 2.6\, h$, Fig. 2, and with the $t_C^R \approx 1.4\, h$, Figs 7-9. The $t_E^R - t_E$ difference is equal to -1.3 [h], with the $t_E \approx 3.8\, h$, Fig. 2, and with the $t_E^R \approx 2.5\, h$, Figs 7-9.

The $t_C \leftrightarrow t_E$ period of time (plateau in Fig. 2) corresponds well with the period of time: $2.6\, h \leftrightarrow 3.7\, h$, (a bar in Fig. 7) for which the curve dT_B / dt manifests an expected flatness.

The stationary state of the heat transfer manifests itself during the $t_C \leftrightarrow t_E$ period of time, Figs 2-3. It can be justified by the identity: $q_{LM} \approx q_{MA}$, Fig. 3.

Since the abatement of the T_B - temperature, Figs 4-6, to some extent corresponds to the movement of the *liquidus* isotherm, Fig. 7, it is justified to measure some changes of the T_B - temperature during the industrial foundry processes.

A differentiation between velocity of the columnar structure tips and velocity of the *liquidus* isotherm, Fig. 9, defines the time t_C^R at which the fully equiaxed growth is observed.

An independent relationship which shows the interplay between velocity of columnar structure tips and tips radius at a given temperature gradient observed at the tip is known, [6].

This analytical relationship allows to determine the velocity of the columnar structure growth and to compare it with the one resulting from the analysis shown in Fig. 7.

It could be very useful in a more specific determination of the mentioned t_C^R - time.

It should be said that the differentiation, Fig. 7, occurs when the thickness of the solid layer is large enough to convert the activity of the solid more as an isolator than as a conductor.

The *solidus* isotherm appears when first precipitates are present between columnar dendrites /cells and the fully developed mushy zone is observed within the solidifying roll.

It is concluded that only the midpoint in the mould is neutral for heat transfer (no influence of air and no influence of the liquid cast iron).

Thus, the midpoint can be representative in determining the $t_C \leftrightarrow t_E$ period of time as it was assumed.

Three ranges within the thermal gradient field determined for the solidifying roll were distinguished:

a/ for the formation of columnar structure (the C – zone):
$\dot{T} >> 0$, Fig. 2, and $G\big|t < t_C^R - G\big|t = t_C^R >> 0$, Fig. 8,

b/ for the $C \to E$ transition (from columnar to fully equiaxed structure): $\dot{T} \approx 0$, Fig. 2, and $G\big|t = t_C^R - G\big|t = t_E^R \approx 0$, Fig. 8,

c/ for the formation of fully equiaxed structure (the E – zone):
$\dot{T} < 0$, Fig. 2, and $G\big|t = t_E^R - G\big|t > t_E^R > 0$, Fig. 8

The b/ - range can be referred directly to the analysis based on the undercooling calculation that results in determination of the $G_{crit.}$ [1]. According to mentioned analysis [1], there are:

a/ high thermal gradients for the columnar structure formation; the gradients should be higher than their critical value, $G_{crit.}$, b/ low thermal gradients for the equiaxed structure formation; the gradients should be lower than above critical value, $G_{crit.}$. The current model of the behavior of thermal gradients, Fig. 8, is similar to that based on the undercooling calculation.

There are some difficulties and uncertainties how the high thermal gradients and low thermal gradients together with the critical thermal gradient could be precisely determined, [1]

The current model shows the mode of determination of the gradient – time diagram, Fig. 8, together with Fig. 7, Fig. 9, according to which an accurate value of the $t_C^R \leftrightarrow t_E^R$ period of time is the result of the numerical treatment of the heat transfer.

This type of calculation can be applied directly even in the industrial conditions.

Hypothetical time, t_E^R, of the complete vanishing of columnar structure formation, Fig. 7, was confirmed with a good agreement through the extrapolation explained in Fig. 9.

6. Symbols used in the text

G	thermal gradient, $G = \partial T / \partial r \Big\vert_{liquidus}$,
h	heat transfer coefficient, Fig. 1,
r	roll radius,
r_{liq}	*liquidus* temperature position,
t	time,
t_C	time when the operating point reveals vanishing of the columnar structure formation, Fig. 2,
t_E	time when the operating point reveals the fully equiaxed structure formation, Fig. 2,
t_C^R	time when columnar structure vanishes in the roll and competition between columnar structure and equiaxed structure formation appears, Figs 7-9,
t_E^R	time when competition between columnar and equiaxed structure growth is completed and fully equiaxed structure formation is expected, Figs 7-9,
T	temperature,
T_B	temperature at the roll / mould border, Figs 4-6,
T_{liq}	*liquidus* temperature,
v	rate of the *liquidus* isotherm movement,
v_C	rate of the columnar structure growth,
θ^0	external temperature, Fig. 1.

Acknowledgements

The financial support from the Polish Ministry of Science and Higher Education (MNiSW) under contract N R15 006 004 is gratefully acknowledged.
The assistance of the "Huta Buczek - Poland" - Rolls Foundry is also greatly appreciated.

References

[1] J.D. Hunt, *Steady State Columnar and Equiaxed Growth of Dendrites and Eutectics*, Materials Science & Engineering, vol. 65 (1984) 75-83.

[2] A. Ares, C. Schvezov, *Solidification Parameters in Columnar -to-Equiaxed Transition in Lead-Tin Alloys*, Metallurgical & Materials Transactions, vol. 31A (2000) 1611-1625.

[3] M. Hamdi, M. Bobadilla, H. Combeau, G. Lesoult, in: *Modelling of Casting, Welding and Advanced Solidification Processes VIII,* eds B.G.Thomas and Ch.Beckerman. TMS, Warrendale, PA, 1998, 375-382.

[4] Ch.A. Gandin, *From Constrained to Unconstrained Growth in Solidification,* Acta Materialia,vol. 48 (2000) 2483-2501.

[5] ABAQUS Theory Manual, Academic Computer Centre, CYFRONET – AGH University of Science and Technology.

[6] W. Wołczyński, R. Martynowski, J. Kowalski, W. Wajda, *Langer & Muller-Krumbhaar Criterion in the Description of the Liquid Concentration at a Growing Dendrite Tip,* Proceedings of the 7th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, eds J.S. Szmyd, J. Spałek, T.A. Kowalewski, Chapter: Material Processing, Kraków, 2009, 1913-1920.