

Casting structure change caused by magnetic field

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Analysis and modelling

ABSTRACT

Purpose: In this work problems of crystallization process for pure metal and alloy castings solidifying under forced convection resulting from use of rotational or rotational reversing magnetic field are presented.

Design/methodology/approach: Influence of changes caused by forced convection in solidification conditions on columnar crystals zone and its limitation was studied. Obtained results show that magnetic field changes thermal and concentration conditions. Both conditions are connected with magnetic field induction B , that is with liquid metal velocity V_{cm} ahead of crystallization front. Examples of magnetic field application for casting structure change are shown.

Findings: Model of columnar to equiaxed structure transition was based on modified concentration stability criterion of crystallization front, in which measurements of alloy addition concentration along ingot radius were incorporated. Gradient-kinetic conditions were evaluated with use of computer simulation of solidification process. Crystallization conditions at the interface enabled tracking of solidification process for actual casting from its surface to its axis. It was then possible to analyze relation between thermal and concentration conditions in time of solidification and to determine position of crystallization front stability loss, which after some simplifications can be considered as the columnar crystals zone width.

Research limitations/implications: Experimental results confirmed justness of introduced model. In analysis also simulation results were used describing liquid metal flow ahead of crystallization front for different types of the interface showing qualitative relations between crystallization front geometry and structure changes.

Practical implications: Relations are proposed, which can be used for columnar crystals zone width taking into account nominal concentration of alloy addition C_0 , forced by magnetic field liquid metal velocity V_{cm} and thermal conditions represented by pouring temperature T_{zal} , thermal gradient at the crystallization front at the moment of forced convection termination GT or difference in temperature on casting cross section δT .

Originality/value: This paper is a result of several studies conducted in Foundry Department since many years and connected of physical factors (ultrasonic vibrations, electromagnetic field) influence on crystallization process of static and continuous castings [1-7].

Keywords: Forced convection; Magnetic field; Simulation; Copper concentration; Structure transformation

1. Introduction

Crystallization of the casting inside the mould is connected with variation of all thermo-physical parameters of casting and mould material. During crystallization the shape of casting changes due to

shrinkage phenomena and casting – mould interaction. All these processes coincide with temperature and other thermal factors changes, such as: thermal gradient, temperature difference on casting cross-section, heat flux, crystallization rate. Specified changes are also present during crystallization with forced convection of liquid metal. The forced convection of liquid metal,

for example by rotational electromagnetic field is another factor that changes the casting crystallization conditions.

Use of forced convection during the casting crystallization, that is pouring in electromagnetic field have its aim mainly in structure improvement by decreasing or removing the columnar crystals zone (Fig. 1), segregation of alloy additions, and axis and interdendritic porosity [1-9].

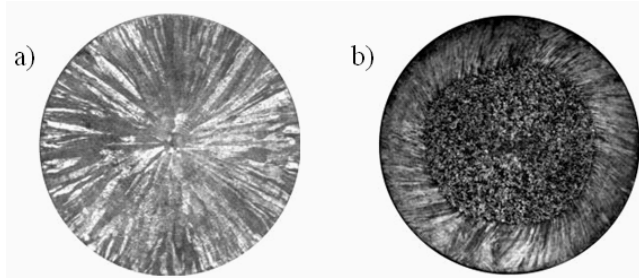


Fig. 1. Macrostructure of Al99,7 castings by traditional method (a) and under rotational magnetic field RMF (b)

For many years in Foundry Department of Silesian University of Technology studies on different types of magnetic field influence on crystallization and structure are conducted. Magnetic field was also used for solid particles embedding in castings, fabrication of wear-resistant layers on cast iron and steel castings as well as for improvement of pure metal inoculation [10,12]. During research and application studies on magnetic field influence on casting structure a stand shown in Fig. 2 was used. The stand was designed in Foundry Department.

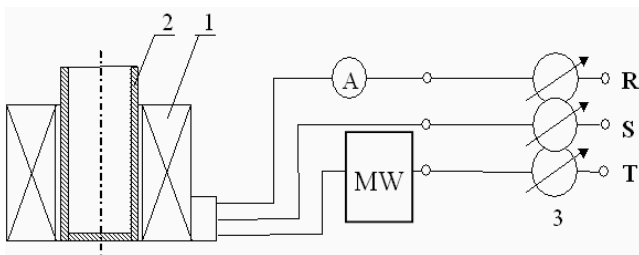


Fig. 2. Test stand scheme: 1 - magnetic field coil, 2 - mould, 3 - three-phase transformer, A- ammeter, MW – multivibrator

The stand consists of asynchronous motor stator (1), which acts as an inductor and the rotor is replaced with liquid metal placed inside the stator in a mould (2) Multi-phase winding distributed on a magnetic core cause rotational magnetic field occurrence, inducing eddy currents in liquid metal. Interaction of these currents with electromagnetic field cause formation of magnetohydrodynamic forces (MHD) which cause liquid metal movement compatible with magnetic field rotation. Rotation velocity depends on occurring forces referred to elementary volume of liquid metal and is equal to vector product of magnetic induction and current density flowing through that elementary volume:

$$d\vec{F} = \vec{J} \times \vec{B} dv \quad (1)$$

Magnetic induction B (flux density) is equal to flux Φ to area S ratio:

$$B = \frac{\Phi}{S} \quad (2)$$

Value of magnetic flux Φ generated in stator winding is directly proportional to magnetomotive force E_m also called the flow:

$$\Phi = \frac{E_m}{R_m} \quad (3)$$

It can be seen, that by changing the current, magnetic induction can be controlled which enables possibility of rotational velocity of liquid metal regulation.

Induction changes were realized by means of voltage regulation with autotransformer 3. Induction values was determined inside the mould (near the wall) before metal was filled with use of teslometer.

Metal rotation velocity V_{cm} depends also inversely proportional on liquid metal density ρ . Thus it can be written:

$$V_{cm} \approx \frac{F}{\rho} \text{ or } V_{cm} \approx \frac{B}{\rho} \quad (4)$$

With known casting conditions, such as constant mould dimensions $\phi 45 \times 180$ mm and metal, for example Al99,99, liquid metal velocity is a function of magnetic field induction B , which is a function of current I operation the inductor, so it can be written as $V_{cm}=f(B)=f(I)$.

Metal velocity inside the mould is difficult to measure, mainly because of high temperature and changing in time thermo physical parameters.

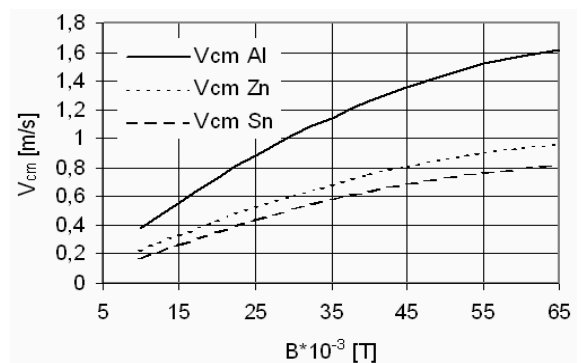


Fig. 3. Dependence of maximum circumferential velocity V_{cm} of liquid metal inside the 45 mm cylindrical mould from magnetic induction B

Rotational velocity was determined by different techniques; for example with use of stroboscopic equipment, laser scanners, with use of model liquids. Finally two methods were selected:

measurement of meniscus depth for rotating liquid (isobaric surface) [13] and theoretically according to work [14] and data presented in [15-17]. The results were then compared. Fig 3 shows obtained results.

Important feature of liquid metal movement forced by magnetic field is that rotational velocity V_{cm} decreases in solidification time. This is caused by magnetic field screening by solidified metal inside the mould, which decreases value of magnetic induction on crystallization front. This disadvantage of magnetic field forced movement must be taken into account during studies on liquid phase velocity ahead of crystallization front. Measurements have shown that by solidified layer of 12 mm the magnetic induction value drops about 50%.

One of the casting methods in magnetic field is proposed by author modification which uses rotational reversing magnetic field [1-4]. This method is protected by patent and consists in use of rotational – reversing movement (with specific frequency of direction changes) of liquid metal instead of only rotational [18]. Using such technique many experimental castings were poured from pure metals and different ferrous and non-ferrous alloys. In Fig. 4-9 effectiveness of this technique is documented with some examples. Many studies have shown that casting in rotational-reversing magnetic field is an effective way of castings structure and properties poured in continues or discontinues conditions.

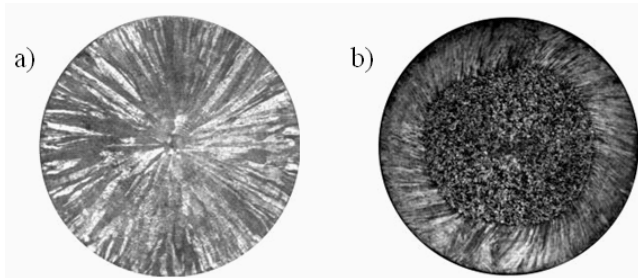


Fig. 4. Macrostructure of SnSb1 alloy ingots poured without use of magnetic field (a) and with magnetic field with induction 0,035 T (b)

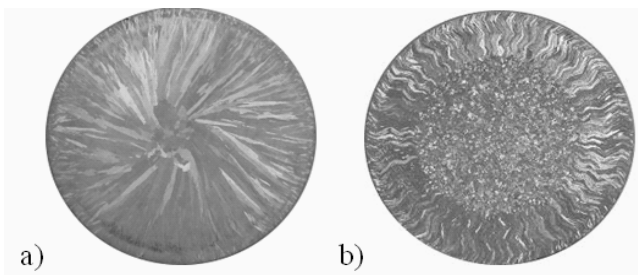


Fig. 5. Macrostructure of Al99,7 ingots poured without use of magnetic field (a) and with rotational reversing magnetic field with induction 0,035 T (b). In Fig. 5b change in columnar crystals shape can be seen which is caused by changes in magnetic field rotating direction

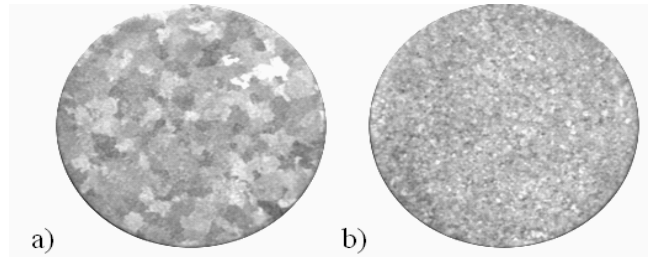


Fig. 6. Macrostructure of CuZn39Pb2 castings by traditional method (a) and under rotating reversing magnetic field with induction $B=0,055T$ (b)

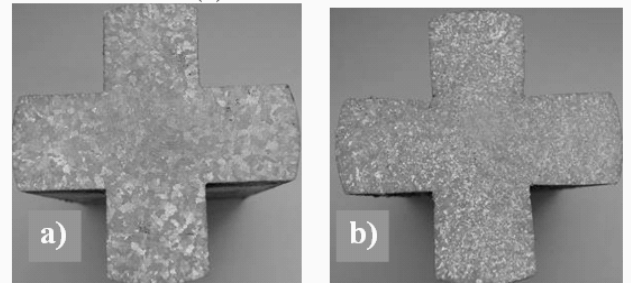


Fig. 7. Macrostructure of Al99,7 cross ingots poured without use of magnetic field (a) and with rotating reversing magnetic field with induction 0,04 T (b)

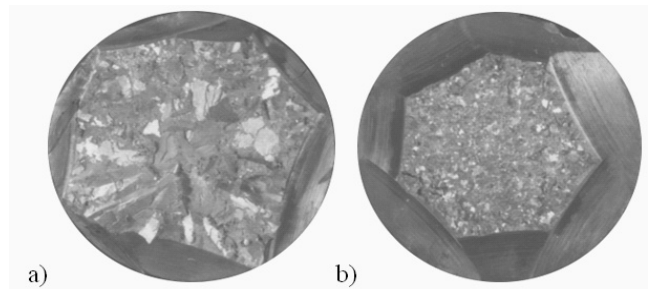


Fig. 8. Macrostructure of EN-GJN-XCr28 100 mm grinding ball poured without use of magnetic field (a) and with rotating reversing magnetic field with induction 0,05 T (b)

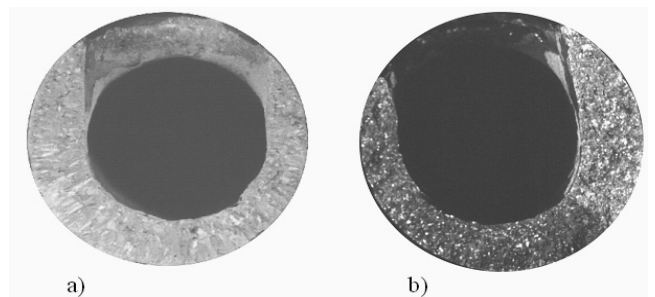


Fig. 9. Macrostructure of nozzle for pneumatic transport poured without use of magnetic field (a) and with rotating reversing magnetic field with induction 0,05 T (b); EN-GJN-XCr28

2. Casting crystallization in magnetic field

Two factors have main influence on casting structure; these are: thermal conditions of solidification and addition concentration.

Change in heat release conditions is one of the basic methods for casting structure control. Such changes are mainly caused by mould material selection. In many cases because of technological problems these changes cannot be made or have restricted application.

Increase of thermal conductivity of the mould can cause changes in casting structure. Important role has here also the casting alloy. Both features of casting process (metal and mould) are connected in so called laminar crystallization criterion $\delta T \gg \Delta T_{kr}$ or volumetric crystallization criterion $\delta T \ll \Delta T_{kr}$, where: δT – temperature difference on casting cross-section, ΔT_{kr} – solidification range. These simple relations show, whether there will be wide zone of columnar crystals ($\delta T \gg \Delta T_{kr}$) or only equiaxed crystals zone ($\delta T \ll \Delta T_{kr}$). When there is no possibility of alloy composition changes, the only parameter to control is the thermal factor δT . These changes can be made by use of different mould materials or use of physical factors during solidification (mechanical vibration, magnetic field etc.) [2,19-21].

As a result of magnetic field forced convection and depending on type of casting crystallization there can be two types of alloy addition distribution. First is the chemical composition homogeneity occurring by volumetric crystallization (Fig. 6 and 8). Second is the differentiation of alloy addition distribution on casting intersection by directional crystallization of columnar crystals (Fig. 1,4,5). Obtaining this kind of changes requires completion of two basic factors [1-5]:

- alloy addition concentration have to exceed a certain minimal value (Fig. 10),
- liquid metal flux speed ahead of crystallization front have to exceed so called minimal value.

Changes in heat release of casting caused by forced convection as well as changes in alloy additions distribution are the reason for structure transition of casting solidifying in magnetic field.

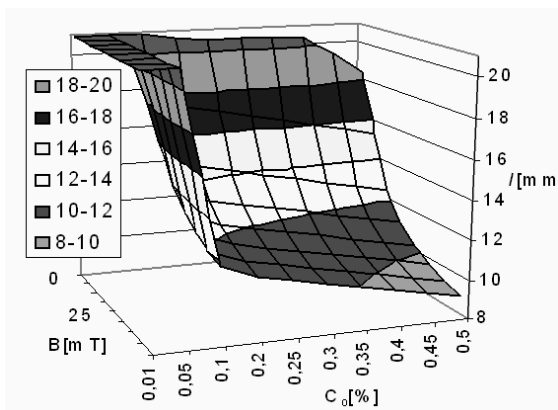


Fig. 10. Change of columnar crystal zone width l in a function of copper concentration V_{cm} and magnetic field induction B

Studies conducted by the author [1-9] enable selection of casting factors for pouring in magnetic field and describing three basic conditions which define the casting structure:

1. kinetic factor – concerns the liquid metal velocity V_{cm} ahead of crystallization front. This value is the main variable factor and is dependent of electromagnetic field induction B . Liquid metal flux ahead of crystallization front changes the alloy additions concentration – thus the second factor,
2. the concentration factor describes the nominal concentration C_o of alloy addition or impurity, but above all changes in concentration distribution in casting caused by forced liquid metal movement, the thermal factor concerns rate of heat release and connected with it thermal gradient G_T on crystallization front. Its influence is hard to describe because of different theories in this matter [22-26]. Nevertheless, this factor should decrease during solidification reaching its minimum as soon as possible, as it takes place during solidification of castings without forced convection [27-29]. On the other hand with assumption that liquid metal flux has a nucleating action, for example by erosion of crystallization front and crystals dispersion [2,30,31], then the changes in heat release may have other course and influence structure in other way.

The last factor is directly connected with the analysis of crystallization rate V influence on structure changes caused by forced convection, because this value is thermal gradient dependent. Forced movement of liquid metal will affect G_T , and this will next affect the crystallization rate. The crystallization rate is a value, which cannot be controlled after the metal is poured into the mould and which results from heat release conditions – mainly G_T . The crystallization rate should be calculated, mainly for continues casting process where crystallization rate is a technological parameter and it can be controlled.

Complex analysis of crystallization process shown in this work, incorporates three described conditions: thermal, concentration and kinetic connected with forced movement of liquid phase. Very important is the relation between two basic conditions in solidification process – thermal and concentration conditions. It is also very important – and is the main aim of this work – what kind of influence causes the forced convection on these two conditions, that is the kinetic factor incorporating forced movement of liquid metal.

All described conditions are incorporated, directly or indirectly, in concentration criterion of crystallization front stability. Analysis of this criterion will enable determination of region where columnar crystals zone decay and thus determination of columnar crystals zone width.

In following part of this studies analysis of thermal and concentration conditions was shown and its correlation with loss of stability region (US) for crystallization front in castings solidifying under forced convection. For determination of this region modified concentration criterion of stability was used [7]. Realizing the aim of the studies, assumption has been made that US region would determine columnar crystals zone width, thus showing the region of columnar to equiaxed transition zone.

2.1. Changes in thermal conditions of casting solidification under influence of rotational magnetic field

Change in casting structure is also connected with crystallization front stability. Stable front, in case of directional (laminar) solidification, is connected with wide zone of columnar crystals.

The basic criterion, which can be used for columnar crystals zone analysis, is concentration criterion of stability. This model can be simplified by use of some assumptions [32-35]:

$$G_T/V \geq -mC_0(1-k_0)/(Dk_0) \quad (7)$$

where:

G_T – thermal gradient on crystallization front,
 V – crystallization rate,
 m – inclination of liquidus line coefficient,
 C_0 – nominal concentration of alloying addition,
 k_0 – equilibrium coefficient of separation,
 D – diffusion coefficient.

The left side of the relation incorporates parameters resulting from thermal conditions (so called gradient-kinetic parameters). Their change caused by different mould material and also by forced convection will affect the casting structure.

Restriction in application of concentration criterion of stability for columnar crystals zone analysis in traditional castings was mainly connected with changes in time and place of thermal gradient as well as the crystallization rate. These changes, very often hard to identify with use of registered cooling curves, are possible to determine during computer simulation and advanced software.

In literature one can find statements that forced convections increases stability of crystallization front, what is utilized in some equipment for directional crystallization [36, 37]. It is interpreted as a decrease in diffusion layer and change (decrease) of the right side of the concentration criterion of stability with no change on the left side of the relation (7). In traditional casting the left side of the relation changes, which affects also the material parameter. Forced by rotational magnetic field convection causes changes left and right side of the relation (7), which results in change of stability conditions for crystallization front. Thermal conditions represented mainly by thermal gradient are incorporated also in other crystallization front stability criteria, that is: in dynamic criterion of stability and in margin criterion of stability [36-39].

Thermal gradients and crystallization rate was calculated with use of computer simulation software SIMTEC [4,40,41] assuming time step of 0,15 s and mesh as in Fig. 11. Analysis was also based on registered cooling curves.

The experimental consisted of carrying out AlCu0,2 $\varnothing 45 \times 185$ mm ingots cast under rotational magnetic field for three values of magnetic induction (0,015 T; 0,025 T; 0,035 T) which correspond to three liquid metal velocities: 0,55 m/s; 0,89 m/s; 1,15 m/s respectively.

Ingots were cast into graphite permanent mould, 7 mm thick. Pouring temperatures were 973 K and 1023 K. Magnetic field operation time was 20 s.

The main aim of this analysis was to determine differences in heat realize during casting solidification under rotational magnetic field and comparison of obtained results with traditional casting solidification. Furthermore, changes in solidification conditions with different velocity of liquid metal were identified.

As a result from computer simulation a temperature field was obtained, which was then used for thermal gradients G_T determination on crystallization front (equation 8, Fig. 12 and 13) and crystallization rate V (Fig. 14 and 15).

$$G_T(x_i) = \frac{T(x_{i-1}) - T_s(x_i)}{x_i - x_{i-1}} \quad (8)$$

where:

$T_s(x_i)$ – solidus temperature in point x_i ,
 $T(x_{i-1})$ – liquid metal temperature ahead of crystallization front in point x_{i-1} 2 mm away,
 x_i – crystallization front position in casting in points 1 to 11 as in Fig. 11.

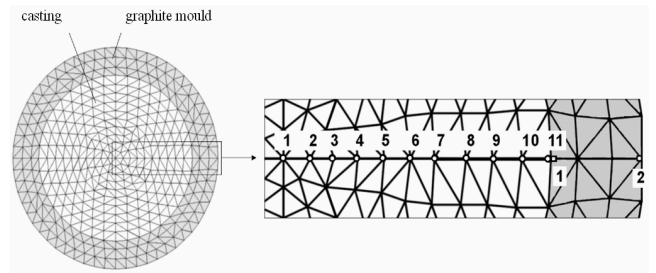


Fig. 11. Grid of casting division with marked nodes

In casting solidification process analysis it is very important to set the thermal conditions after the magnetic field is disabled. basing on this state the changes resulting from forced convection was determined as well as the forecast of columnar crystals zone width.

From Fig 16 and 17 it can be seen, that in time of 20 s forced movement of liquid metal for castings poured at 1023 K caused smaller differences in casting structure than for castings poured at 973 K. The smallest differences were registered for casting poured under rotational magnetic field with induction $B=0,015$ T ($V_{cm}=0,055$ m/s) and $T_{zal}=1023$ K.

In literature thermal gradient is not directly included in relations for columnar crystals zone determination. Thermal gradient is considered in models describing dendrite growth and crystallization front stability criteria. In most of the cases its influence on columnar crystals growth is visible only at low crystallization rates (10^{-5} m/s) [23-29, 36, 39]. From conducted studies it can be seen, that columnar crystals zone appears in shorter time than magnetic field action (Fig. 18). Thus, forced by magnetic field liquid metal movement changes thermal conditions for crystallization of entire columnar crystals zone.

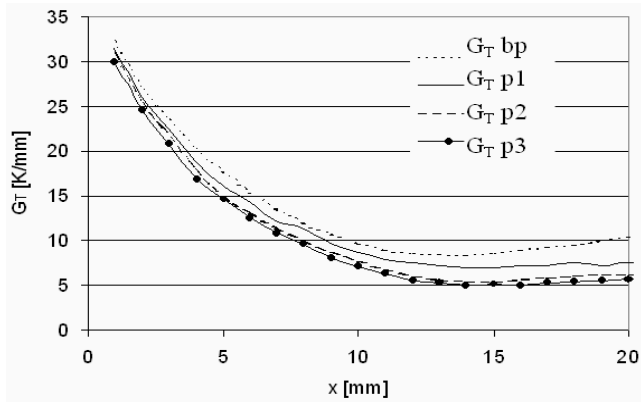


Fig. 12. Thermal gradient on crystallization front in traditional castings (G_T bp) and under rotational magnetic field at $V_{cm}=0,55$ m/s (G_T p1), $V_{cm}=0,89$ m/s (G_T p2) and $V_{cm}=1,15$ m/s (G_T p3); pouring temperature $T_{zal}=973$ K

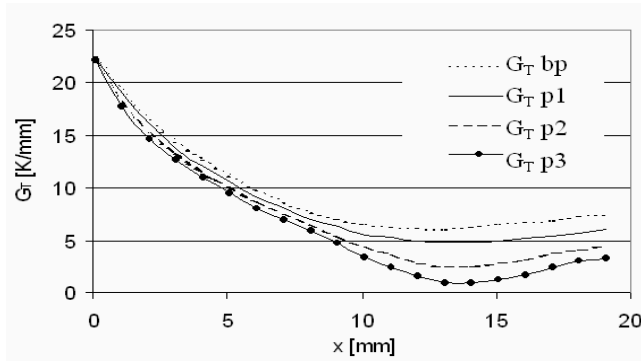


Fig. 13. Thermal gradient on crystallization front in traditional castings (G_T bp) and under rotational magnetic field at $V_{cm}=0,55$ m/s (G_T p1), $V_{cm}=0,89$ m/s (G_T p2) and $V_{cm}=1,15$ m/s (G_T p3); pouring temperature $T_{zal}=1023$ K

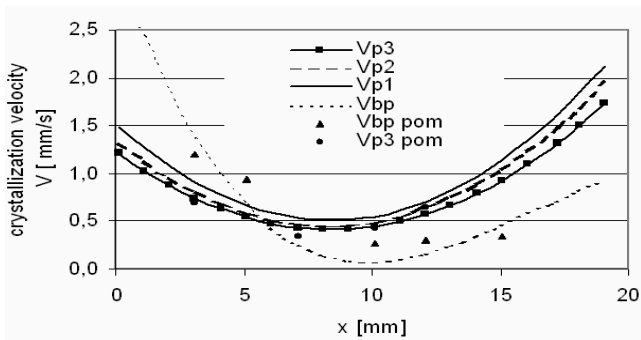


Fig. 14. Crystallization rate of castings made at pouring temp. $T_{zal}=973$ K: traditionally (broken line) and at liquid metal forced movement at $V_{cm}=0,55$ m/s (V_p 1 line), at $V_{cm}=0,89$ m/s (V_p 2 line) and $V_{cm}=1,15$ m/s (V_p 3 line): points (\bullet , \blacktriangle) indicate velocity calculated on the basis of crystallization front position measurements

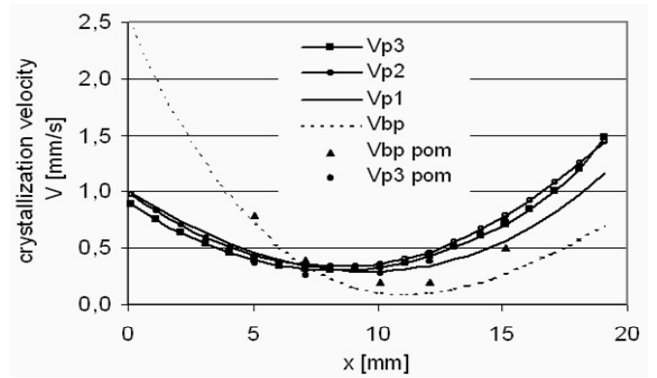


Fig. 15. Crystallization rate of castings made at pouring temp. $T_{zal}=1023$ K: traditionally (broken line) and at liquid metal forced movement at $V_{cm}=0,55$ m/s (V_p 1 line), at $V_{cm}=0,89$ m/s (V_p 2 line) and $V_{cm}=1,15$ m/s (V_p 3 line): points (\bullet , \blacktriangle) indicate velocity calculated on the basis of crystallization front position measurements

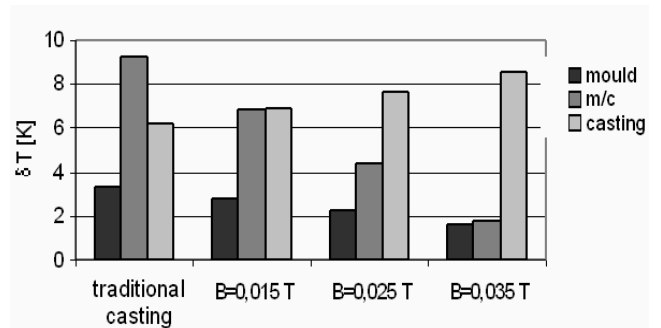


Fig. 16. Temperature difference in casting-mould system at the moment of rotating magnetic field influence end, i.e. after 20 s; $T_{zal}=973$ K

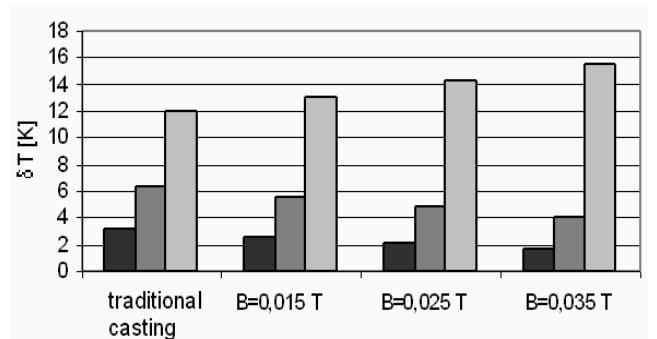


Fig. 17. Temperature difference in casting-mould system at the moment of rotating magnetic field influence end, i.e. after 20 s; $T_{zal}=1023$ K

3. Changes in alloy addition concentration caused by forced convection

Changes caused by forced convection during heat release from the casting as well as the changes in alloy addition concentration are the reasons for structure transition of casting solidifying under magnetic field.

In this part author tried to determine changes in alloy addition distribution caused by forced convection and its influence on the casting structure and columnar crystal shape.

Copper concentration was determined along the cross-section of Al-Cu ingot, especially in columnar crystals zone. A thesis has been put that region of columnar to equiaxed transition is placed with correlation to changes in copper distribution and the differences in concentration of copper in respect to columnar crystal axis is a reason for change of crystal growth direction (Fig. 5b).

The experimental consisted of carrying out AlCu0,2 Ø45 × 185 mm ingots cast under rotational magnetic field with the same parameters as in 2.1.

Probes for chemical analysis were cut 70 mm from the bottom of the ingots. Chemical analyses were carried out on roentgenographic analyzer. Alloy addition concentration was measured along radius of the ingots every 1 mm on 2 mm distance (Fig. 19a). Results are showed on Fig. 19b).

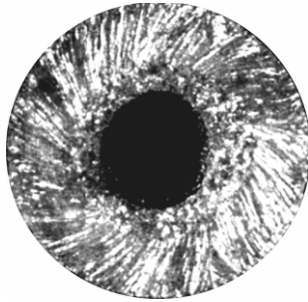


Fig. 18. Solidified layer macrostructure after 20 s in AlCu0,5 casting made under rotating magnetic field influence with induction $B=0,035$ T ($V_{cm}=1,15$ m/s)

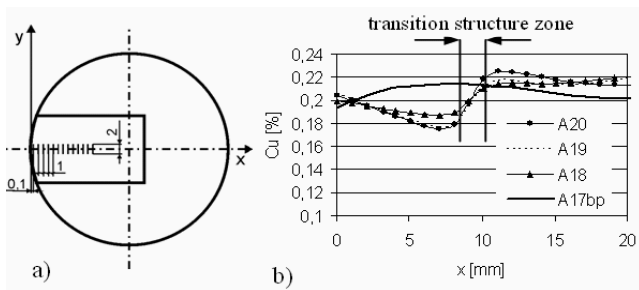


Fig. 19. Place of alloy addition concentration measurement (a), and (b) approximated distribution of copper concentration in AlCu0,2 castings. Traditional castings (17bp) and castings made under rotating magnetic field influence at various velocity of liquid metal in a mould: A18 - $V_{cm}=0,55$ m/s, A19 - $V_{cm}=0,89$ m/s, A20 - $V_{cm}=1,15$ m/s

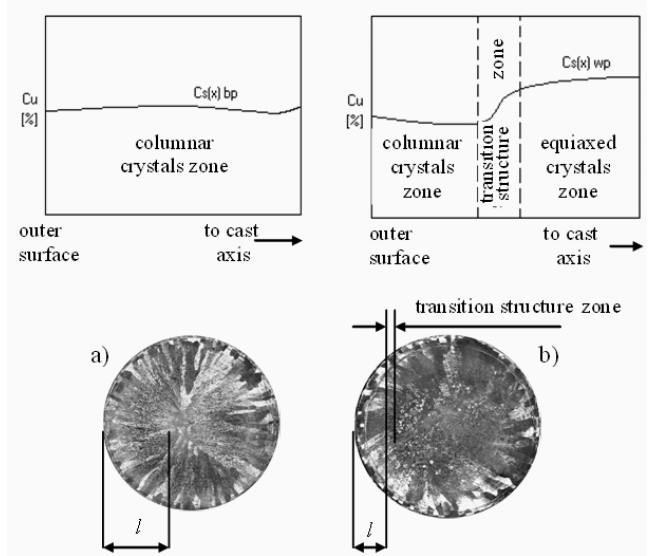


Fig. 20. Changes of copper concentration in AlCu ingots after measurement results approximation and macrostructure changes: a) traditional casting, b) casting with rotating magnetic field

The results showed, that the change in copper concentration in castings solidifying without magnetic field influence is considerably different from copper concentration in ingots cast under rotational magnetic field.

First part of distribution curve (Fig. 19b), enclosing copper concentration change in columnar crystals zone you can see decrease of copper concentration in direction from external surface to the ingot axis. Such change in alloy addition concentration is connected with liquid metal movement ahead of crystallization front forced by the magnetic field. As a result of liquid metal movement there is a convective “rejection” of alloy addition and the copper concentration in this zone is on the average lower than in the traditional solidifying ingot.

Forced movement of liquid phase cause also higher differences in copper distribution in columnar crystals zone. These differences grow with increase copper content and liquid metal velocity ahead of crystallization front (Fig. 19b). The biggest differences in concentration distribution were observed with magnetic field induction $B=0,035$ T (liquid metal velocity $V_{cm}=1,15$ m/s).

It was also observed that the lowest copper concentration is placed 8 mm from outer surface (in columnar crystals zone). From this place the addition concentration grows rapidly, because the convective “rejection” of copper from the crystallization front disappears. It is connected with substantial decrease in liquid metal velocity, caused by shielding of magnetic field by the solidified layers of casting and also by decrease of solidification velocity caused by changing thermal conditions. In addition, with decrease of temperature the viscosity increases which cause rise of diffusion zone and the condition for convective “rejection” of the alloy addition are less favorable [34,36].

That is why the concentration of addition rises directly on crystallization front and that is confirmed with calculations results [7]. Such crystallization conditions caused by rotational magnetic field are connected with rapid concentration overcooling increase ahead of crystallization front and loss of front stability and are the cause for columnar to equiaxed transition.

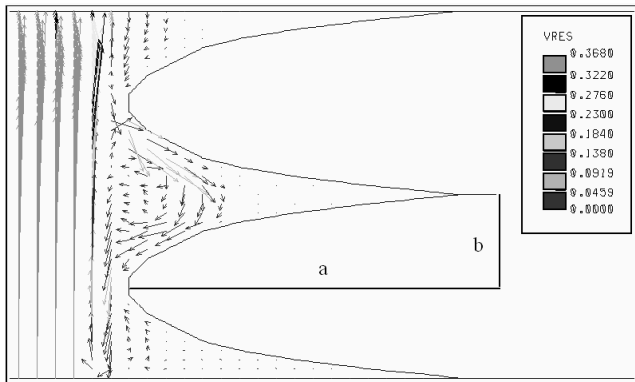


Fig. 21. Velocity vectors [m/s] near paraboloidal crystallization front at solid phase width $l_s=r_o/4$ (a); crystallization front; a:b=4:1

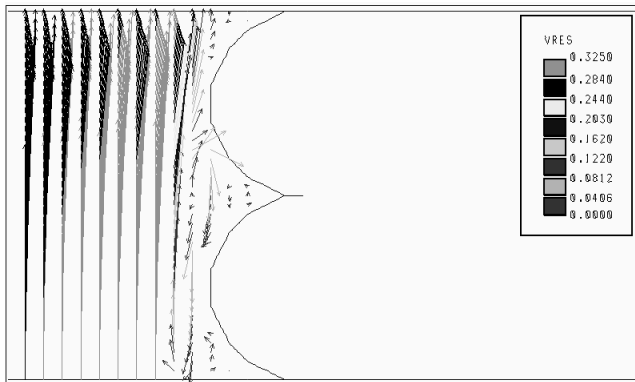


Fig. 22. Velocity vectors [m/s] near crystallization front after solidification of a layer on the distance $l_s=r_o/4$ from casting surface; Kurz-Fisher cell front

The results show that concentration increase on copper distribution curve coincides with zone of columnar to equiaxed transition zone (Fig. 19b and 20b). Ahead of this zone is equiaxed crystals zone.

Studies show, that forced convection caused by magnetic field produce differentiation of copper concentration relative to main metallographic axis of columnar crystal [9,42-44]. It happens, because the liquid metal flux differentiates width of diffusion layer round the crystals that create the interface.

It is also confirmed by computer simulation results for liquid metal flow ahead of crystallization front [6-9]. Crystallization model incorporating reciprocal influence of thermal and flow phenomena was based on thermal conductivity and Navier-Stokes equations. These equations were solved with finite elements method, assuming cellular and paraboloidal crystallization front.

As a result of simulation the liquid metal velocity vectors ahead of crystallization front were obtained (Fig. 21 and 22). More specific solution is shown in works [6-9,42-44].

In these works authors show, that considerably higher velocity of liquid metal from the liquid inflow causes decrease of diffusion layer thickness and from this front of the crystal the convective "rejection" is more intense. This causes lower content of alloy

addition on inflow front of the crystal and higher content in diffusion layer on front of the crystal. This results in lower copper content in columnar crystals on liquid phase inflow side. This asymmetry is the cause for crystal growth with tendency for heading in direction opposite to macroscopic direction of forced movement of liquid phase (Fig. 1b, 4b, 5b and 18).

4. Description of columnar to equiaxed structure transition process

Full analysis of columnar crystals zone creation and its width requires relating all, or at least the most important parameters of crystallization process and the interface placement in the casting. Then, using stability criterion, modified for specific conditions, crystallization front stability can be evaluated:

$$G_T(x) \geq m \cdot G_C(x) \quad (9)$$

where:

$G_T(x)$, $G_C(x)$ – thermal and copper concentration gradient, respectively on crystallization front for x distance from outer surface of the casting,

m – inclination of liquidus line coefficient.

Application of the stability criterion requires other description of alloy addition distribution at crystallization front. In conducted studies the effective separation coefficient k_{ef} was used which can be calculated with iteration of eq. (10) for addition concentration in solid phase C_s [7,33,43]

$$C_s = k_o \cdot C_o \cdot (1 - g_s)^{k_o - 1} \quad (10)$$

to

$$Cu(x) = k_{ef}(x) \cdot C_o^* \cdot [1 - g_s(x)]^{k_{ef}(x) - 1} \quad (11)$$

where:

$Cu(x)$ – Cu concentration in ingot for x distance from outer surface (Fig. 19b),

$k_{ef}(x)$ – effective separation coefficient related to crystallization front position,

$g_s(x)$ – solid phase content resulting from solidified layer width,

C_o^* – sum of average copper and impurities concentration in alloy.

Separation coefficient value $k_{ef}(x)$ calculated from (11) bonds concentration criterion with crystallization front position through $Cu(x)$ value measured along ingot radius. On this basis the width of columnar crystals zone can be evaluated, with some approximation, assuming that front stability loss determines columnar to equiaxed transition, that is boundary between directional and volumetric solidification. Determination of thermal gradient $G_T(x)$ based on simulation results, the concentration gradient $G_C(x)$ from relation (12) relating it to position and crystallization conditions prevailing at the interface.

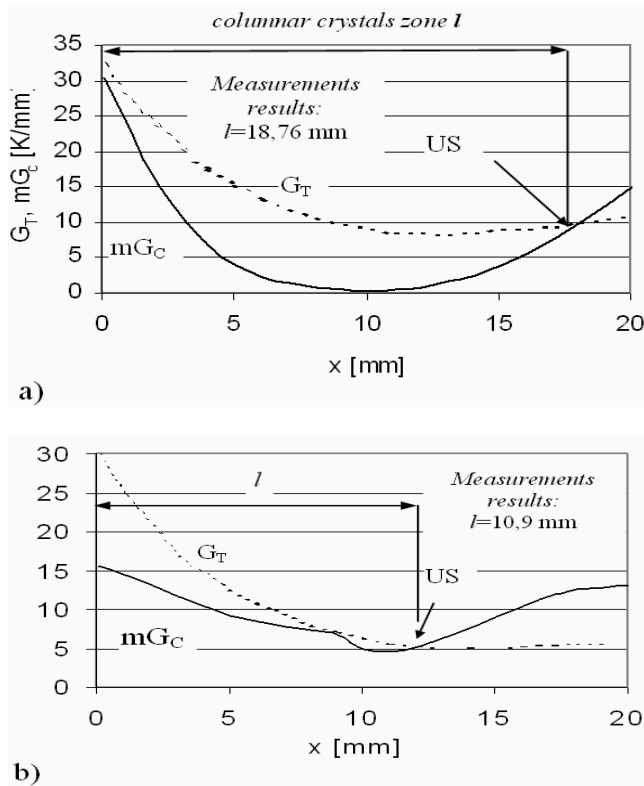


Fig. 23. Comparison of thermal (G_T) and concentration (mG_C) conditions and place of crystallization front durability end (US); a) in traditional AlCu_{0,2} casting (for A17 sample); b) in castings made under rotating magnetic field influence with induction $B=0,035$ T ($V_{cm}=1,15$ m/s) (for A20); Pouring temp. $T_{zal}=973$ K

$$G_C(x) = \frac{V(x) \cdot C^*(x)}{D_L} \cdot [1 - k_{ef}(x)] \quad (12)$$

where:

$V(x)$ – crystallization rate (calculated from simulation),
 $C^*(x)$ – alloy addition concentration at the crystallization front,
 D_L – diffusion coefficient of copper in liquid aluminum,
 $k_{ef}(x)$ – effective separation coefficient.

In relation (12) instead of concentration $C^*(x)$, for description its variability at crystallization front, the $Cu(x)$ concentration in solid phase was used. Thus, concentration at the crystallization front may be written as:

$$C^*(x) = Cu(x) / k_{ef} \quad (13)$$

Placing eq. (13) into eq. (12) and transforming eq. (9) one will receive:

$$G_T(x) \leq m \cdot \frac{V(x) \cdot Cu(x)}{D_L \cdot k_{ef}(x)} \cdot [1 - k_{ef}(x)] \quad (14)$$

concentration undercooling. In such conditions additional nuclei can occur due to erosive action of liquid phase flux on crystallization front. All these conditions tend towards directional solidification of columnar crystals retention. Proof of justness of introduced assumptions is the compatibility of crystallization front stability loss position and width of columnar crystals zone (Fig. 23).

Use of alloy addition concentration measurements $Cu(x)$ along ingot radius and gradient-kinetic conditions [$G_T(x)$, $V(x)$] at crystallization front obtained from computer simulation enables possibility of columnar crystals zone width l evaluation with modified concentration criterion of crystallization front stability.

Calculated crystallization conditions at the interface enable tracking of solidification process for actual casting from its surface to its axis. It is then possible to analyze relation between thermal and concentration conditions in time of solidification and to determine position of crystallization front stability loss, which after some simplifications can be considered as the columnar crystals zone width.

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