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Influence of electromagnetic field on pure metals and alloys structure

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ABSTRACT

Purpose: The first aim of investigations was the reduction of grain size and unification of structure for pure Al casting by introduction of small amount of inoculant (less than obligatory standard PN-EN 573-3, which concerning about aluminium purity) and with electromagnetic field. The second aim was to determination of electromagnetic field influence on morphology of graphite in cast iron ingots, which were poured with variable founding parameters.
Design/methodology/approach: To investigations of pure Al and grey cast iron were used two types of rotate electromagnetic field i.e. without reversion (WPM) and with reversion and with a pause between following changes of electromagnetic field direction (IRPM).
Findings: The results of investigations and their analysis show possibility of effective inoculation of pure aluminium structure by use of influencing of stirring electromagnetic field into metal during solidification and inoculation by introducing AlTi5B1 inoculant into liquid aluminium. Moreover results of studies show advantageous influence of electromagnetic field on graphite morphology.
Research limitations/implications: In further researches, authors of this paper are going to apply his method of inoculation in industrial tests.
Practical implications: The work presents a method of structure refinement which is particularly important in continuous and semi – continuous casting. In pure metals large columnar crystals zone result in forces extrusion rate reduction and during the ingot rolling delamination of external layers can occur. Thus, in some cases ingot skinning is needed, which rises the production costs. Whereas morphology of graphite in cast iron ingots for automobile industry is very important in viewpoint of wear resistance.
Originality/value: Contributes to research on size reduction in pure metals structure and forming of graphite in cast iron.
Keywords: Casting; Aluminium; Cast iron; Electromagnetic field

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1. Introduction

First research works on the application of stirring of liquid metal at the time of its solidification in order to improve the castings quality were carried out by Russ Electroofen in 1939 and concerned the casting of non-ferrous metals and their alloys. In order to obtain the movement of the liquid metal in the crystallizer in the researches carried out at this period of time and also in the future, a physical factor in the form of a electromagnetic field defined as a system of two fields i.e. an electric and magnetic field was introduced [1]. The mutual relationship between these fields describes the Maxwell equation [1, 2].

Generated by the inductor powered by electric current intensity (I_0) electromagnetic field affecting the solidifying metal (Figure 1) induces a local electromotive force (E_m), whose size depends on the value of the local speed of the liquid metal (V) and magnetic induction (B) [2,3].

$$E_m = \overline{V} \times \overline{B} \tag{1}$$

This is a consequence of the intersection of the magnetic field lines with the current guide in form of liquid metal. It also leads to inducing a eddy current of intensity I in liquid metal [2, 3]:

$$\bar{I} = \sigma(\overline{V} \times \overline{B}) \tag{2}$$

where:
σ - electrical conductivity proper to the liquid metal.

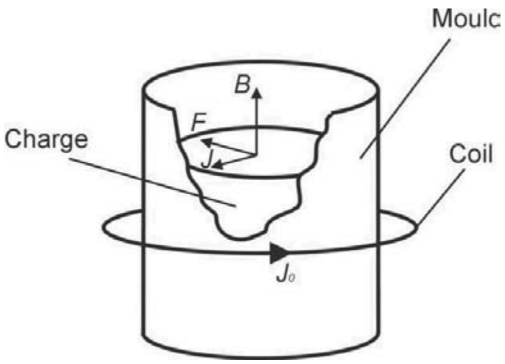

Fig. 1. Diagram of electromagnetic field influence on the liquid metal [3]

The impact of the induced current on the magnetic field results in establishing of the Lorenz (magnetohydrodynamic) force (F) [2, 3]:

$$\overline{F} = \bar{I} \times \overline{B} \tag{3}$$

that puts liquid metal in motion e.g. rotary motion in the direction consistent with the direction of rotation of the magnetic field. Strength (F) has a maximum value when the vector (V) and (B) are perpendicular. The relationship between the induced current intensity and the speed of the liquid metal is described by the Ohm's law [2, 3]:

$$\bar{I} = \sigma\left[\overline{E} + \left(\overline{V} \times \overline{B}\right)\right] \tag{4}$$

In addition, as reported in the work [4] the speed of the rotating liquid metal (V) is inversely proportional to the density of the metal (ρ), because with some approximation we could say that:

$$\overline{V} \approx \frac{\overline{F}}{\rho} \text{ or } \overline{V} \approx \frac{\overline{B}}{\rho} \tag{5}$$

Forced liquid metal movement influences in diversified way on changes in structure of casting i.e. by changes of thermal and concentration conditions on crystallization front, which decrease or completely stops the velocity of columnar crystals growth [4-7] and by [4-8]:

- tear off of crystals from mould wall, which are transferred into metal bath, where they can convert in equiaxed crystals,
- parting of dendrite by coagulation and melting as result of influences of temperature fluctuation and breaking as result of energy of liquid metal movement,
- crystals transport from free surface to inside the liquid metal,
- crystals from over-cooled outside layer of bath are transported into liquid metal.

However, in the work [4] it is shown that the effect of electromagnetic fields forced movement of liquid metal to changes in the structure of pure metals, which solidify with flat front crystallization is negligible. The effective impact of so-induced forced convection requires a minimum concentration of impurities such as alloy additive or contaminants in the casting. The corresponding increase in the concentration of impurities, to the specific conditions of thermal coagulation, results in the change of crystallization front morphology by the schema shown in Figure 2. This means that increasing the amount of impurities by changing the geometry of crystallization front intensifies the impact of the stream of liquid metal on the surface of phase separation and consequently on the changes in the process of creating a structure of casting [4].

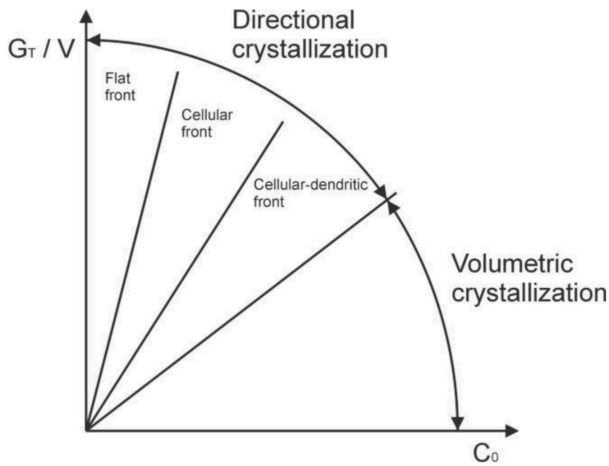

Fig. 2. Diagram of the relationship between thermal and concentration conditions and the type of crystallization; C_0 - the concentration of impurities, the G_T - the temperature gradient at the crystallization front, V - crystallization speed [4, 8]

The impact of electromagnetic fields on the liquid metal in order to reduce the structure size, eliminate the porosity and axial segregation zone and to achieve greater uniformity of structure, has found its use principally in the technology of continuous [1-14] and the semi-continuous casting [15].

Table 1.
Chemical composition of aluminium EN AW-Al99,5

Mass contents in %									
Fe	Si	Cu	Mg	Mn	Zn	Ti	Ni	Pb	Al
0.300	0.110	0.020	0.010	0.003	0.020	0.003	0.004	0.002	rest

Table 2.
Chemical composition of grey cast iron EN GJL-300

Mass contents in %											
C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	Ti	Fe
3.890	1.920	0.350	0.372	0.054	0.433	0.020	0.074	0.057	0.101	0.017	91.700

2. Range of studies

The aim of studies was to determine a influence of stirring of liquid metal in cylindrical mould with use of rotate electromagnetic field on single-phase structure of pure metal i.e. aluminium EN AW-Al99.5 (Table 1) and on multiphase structure of alloy i.e. grey cast iron EN-GJL-300 (Table 2).

Test stand to cast in electromagnetic field is shown in Fig. 3. It is composed of inductor coil - which generates electromagnetic field, autotransformer - which regulates three–phase voltage feeding the inductor coil, multivibrator - which changes the direction of electromagnetic field. By change of current intensity value was regulated value of magnetic induction inside of inductor coil (Fig.4).

Aluminium was melted in inductive furnace and temperature was measured with use of NiCr-NiAl thermocouple (pouring temperature was set to 740 ^{o}C). Metal was poured into the graphite mould with wall thickness 7 mm. Test castings as ingots with dimensions of 45mm diameter and 180mm length were cast with exactly specified parameters: pulse frequency (f) of electromagnetic field, magnetic induction (B_i) (Table 3). On the basis of literature data [1-5] was used inoculant of type AlTi5B1. This inoculant increases size reduction, because its introduction results in formation of "active base" to heterogeneous nucleation of aluminium. Inoculants quantity was (25Ti+5B) ppm. This is less than obligatory standard PN-EN 573-3, which concerning about aluminium purity.

In aim of measurements realization of size reduction in aluminium EN AW-Al99.5 structure was made metallographic macroscopic examinations. Surfaces of samples, which were cut at 55mm from the base of ingot, were etched to macrostructure analysis with use of solution of: 50g Cu, 400ml HCl, 300ml HNO_3 and 300ml H_2O. Value of size reduction in structure was represented by equiaxed crystals zone content (SKR) on cross-section of ingot of aluminium EN AW-Al 99.5 and average area of equiaxed crystal (PKR), were calculated by computer program Multi Scan Base v. 13.01 to processing and image analysis after macroscopic metallographic research.

Whereas in range of studies of grey cast iron were cast standard ingots of 200mm length without influence of electromagnetic field and ingots with influence of rotate electromagnetic field (WPM and IRPM) during solidification process (Table 3).

In research was used different velocity of solidification, which results from application of different material of moulds (different thermal conductivity λ) i.e. graphite, shell mould, Sibral SI-R30 (Table 3).

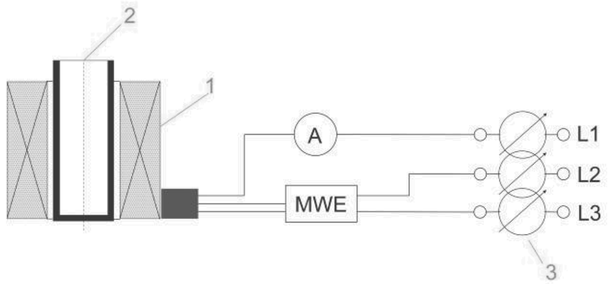

Fig. 3. Test stand scheme: 1 - inductor coil, 2 - mould, 3 - three-phase transformer, A - ammeter, MWE - multivibrator

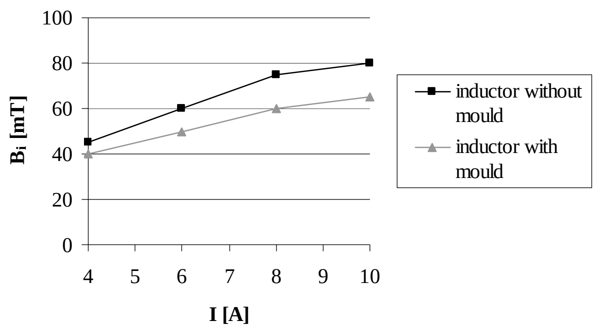

Fig. 4. Dependence between current intensity (I), which feeds inductor coil and magnetic induction (B_i) inside of inductor coil

In research was applied two type of rotate electromagnetic field i.e. without reversion (WPM) and with reversion and with a pause between following changes of electromagnetic field direction (IRPM).

In aim of consideration of different value of thermal conductivity and dimensions of mould i.e. wall thickness (g) and size of ingot (r – radius of cylindrical ingot), was introduced factor (J), which in simplification mode describes thermal condition in configuration ingot-mould [4]:

$$J = \frac{r}{g \cdot \lambda}\left[\frac{m \cdot K}{W}\right] \qquad (6)$$

Table 3.
Range of investigations

Sample number *	Material	$T_{pouring}$ [°C]	Parameters of cast							
			WPM		IRPM		Mould material			
			f [Hz]	B_i [mT]	f [Hz]	B_i [mT]	λ** [W/m·K]	g [mm]	r [mm]	J [m·K/W]
1	EN AW-Al99.5	740	-	-	-	-	90.00	7.0	22.5	0.035
1M			-	-	-	-				
2			0	40	-	-				
2M			0	40	-	-				
3			0	60	-	-				
3M			0	60	-	-				
4			-	-	0.5	40				
4M			-	-	0.5	40				
5			-	-	0.5	60				
5M			-	-	0.5	60				
6			-	-	1.0	40				
6M			-	-	1.0	40				
7			-	-	1.0	60				
7M			-	-	1.0	60				
I	EN GJL-300	1450	-	-	-	-	90.00	10.0	10.0	0.050
II			-	-	-	-	1.50	10.0	10.0	0.500
III			-	-	-	-	0.35	10.0	15.0	5.000
IV			0	60	-	-	90.00	10.0	10.0	0.050
V			0	60	-	-	1.50	10.0	10.0	0.500
VI			0	60	-	-	0.35	10.0	15.0	5.000
VII			-	-	0.5	60	90.00	10.0	10.0	0.050
VIII			-	-	0.5	60	1.50	10.0	10.0	0.500
IX			-	-	0.5	60	0.35	10.0	15.0	5.000
X			-	-	1.0	60	90.00	10.0	10.0	0.050
XI			-	-	1.0	60	1.50	10.0	10.0	0.500
XII			-	-	1.0	60	0.35	10.0	15.0	5.000

* - M – inoculation of sample with use of 25 ppm Ti + 5 ppm B,
** - Thermal conductivity of: graphite λ = 90 [W/(m·K)], shell mould λ = 1.5 [W/(m·K)], sibral λ = 0.35 [W/(m·K)];

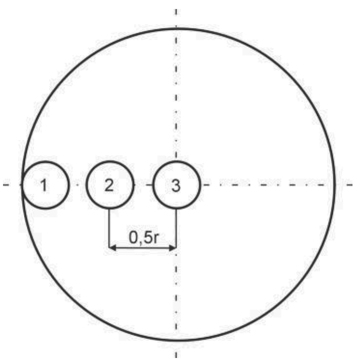

Fig. 5. Scheme of measurement fields on cross-section of test castings: 1 – periphery, 2 – half of radius, 3 - centre

On the basis of metallographic microscopic examinations was made qualitative influence of liquid metal stirring by electromagnetic field on graphite morphology (form and distribution). Metallographic examinations were made with use of light microscopy Nikon OPTIPHOT. On Figure 5 is presented scheme of measurement fields of graphite morphology on cross-section of test castings.

In research take the criterion, that suitable graphite for the sake of expected and required value of abrasive wear resistance of studied grey cast iron, has uniform distribution of type (A) and form of type (I) according to standard PN-EN ISO 945 – particularly at outside surface of ingot.

3. Results and analysis

3.1. Influence of electromagnetic field on structure of pure Al

Selected results of metallographic macroscopic research are presented on Figs. 6-10. Aluminium EN AW-Al99.5 has columnar structure in initial state (Fig. 6). After inoculation with 25 ppm Ti and 5 ppm B, increase in size reduction of primary structure is observed (Fig. 7). Increase in size reduction of aluminium structure after inoculation with Ti and B, result from "active base" of type TiC, TiN, TiB, TiB_2, AlB_2 and Al_3Ti, to heterogeneous nucleation formation. These "active base" are high-melting and have analogy in crystal lattice with Al.

Whereas, increase in size reduction in aluminium EN AW-Al99.5 structure, after casting with influence of electromagnetic field (Figs. 8 and 9) result from high velocities that are attained in liquid metal and which lead to columnar crystals tearing occurring on crystallization front and additional crystal nucleuses formation. Effect of mechanical erosion of crystallization front is strengthened by melting of dendrite as result of influences of temperature fluctuation, which result from large diversification of temperature in ingot, which was cast with influence of electromagnetic field [5-7].

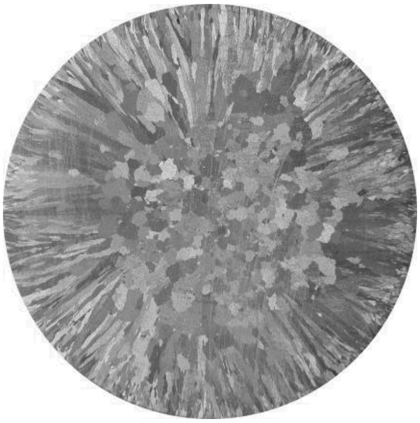

Fig. 6. Macrostructure of aluminium EN AW-Al99.5 in initial state (sample 1): SKR = 32%, PKR = 6.7mm^2

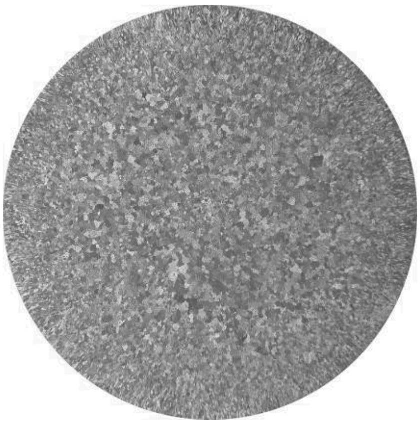

Fig. 7. Macrostructure of aluminium EN AW-Al99.5 after inoculation with 25 ppm Ti + 5 ppm B (sample 1M): SKR = 93%, PKR = 2.2 mm^2

On the basis of macrostructures analysis was affirmed, that influence on structure refinement of impulse reverse rotate electromagnetic field (IRPM) is stronger than rotate electromagnetic field without reversion (WPM). Profitable

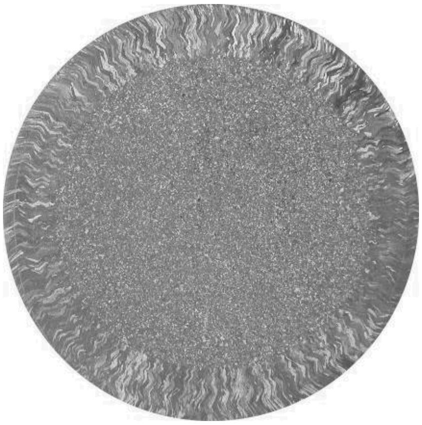

Fig. 8. Macrostructure of aluminium EN AW-Al99.5 after cast with influence of IRPM (sample 5): SKR = 60%, PKR = 0.3 mm^2

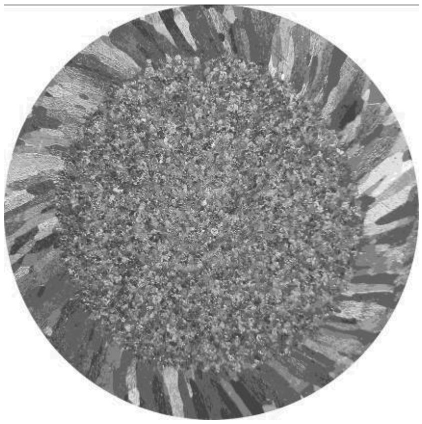

Fig. 9. Macrostructure of aluminium EN AW-Al99.5 after cast with influence of WPM (sample 3): SKR = 55%, PKR = 2.1 mm^2

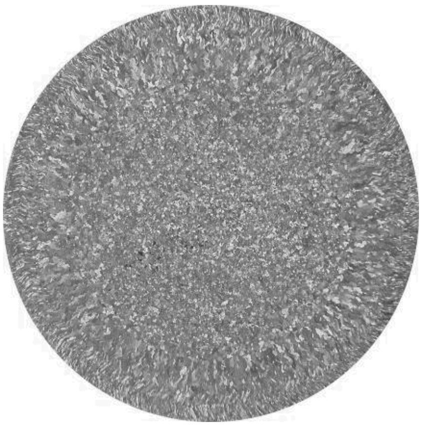

Fig. 10. Macrostructure of aluminium EN AW-Al99.5 after cast with influence of IRPM and inoculation with 25 ppm Ti + 5 ppm B (sample 5M): SKR = 85%, PKR = 0.5 mm^2

influence of applied reversion of rotation direction results from connection of vibration with large amplitude and action of rotate electromagnetic field. Important is also, double-sided bending of growing crystals, what lead to their breaking. Moreover rotating movement with reversion of liquid metal does not create concave meniscus, what lead to elimination of pour of liquid metal from mould or continuous casting mould by the action of centrifugal force. This lead also, to elimination of gassy in Al castings, which is present in ingots after cast with influence of rotate electromagnetic field (WPM).

Moreover, with decrease in pulse frequency of electromagnetic field and with increase in magnetic induction, increase in equiaxed crystals zone is observed. It results from high velocities that are attained in liquid metal and which lead to columnar crystals tearing occurring on crystallization front and additional crystal nucleuses formation.

Whereas, common influence of impulse reverse electromagnetic field and inoculation with (Ti+B) (Fig. 10) result in larger equiaxed crystals zone content and smaller size of macrograin than in standard sample (Fig. 6) and comparable in sample which was cast only with inoculation (Ti+B) (Fig. 7) but it has larger size of macrograin than sample which was cast with influences of electromagnetic field and inoculation.

3.2. Influence of electromagnetic field on graphite morphology in grey cast iron

On the basis of metallographic microscopic examinations of grey cast iron EN GJL-300 ingots, which were cast without influence of electromagnetic field was affirmed, that the most advantageous for the sake of form and distribution of graphite guarantees thermal condition in configuration ingot-shell mould (Figs. 11-13). Graphite morphology on the basis of standard PN-EN ISO 945 was qualified as 95%IA + 5%VA.

Application of graphite mould, which assures large cooling rate, generates hard spots in periphery zone of ingot. Whereas graphite morphology was qualified as 95%IIC + 5%IC (Fig. 14). Decrease of solidification velocity (sibral mould) results in graphite morphology of type 95%IC + 5%IVC (Fig. 15).

On Figs. 16-18 are presented microstructures in measurement fields on cross-section (Fig. 5) of grey cast iron ingot, which was cast in shell mould with influence of rotate electromagnetic field. Application of stirring of liquid cast iron in mould with use of rotate electromagnetic field, guarantees refinement and unification of flake graphite, what leads to obtainment of form and distribution of type almost 100%IA. This is progress in comparison with microstructure of grey cast iron, which was cast in shell mould without influence of electromagnetic field.

Moreover, on the basis of conducted studies was affirmed, that as distinct form cast of pure Al influence on grey cast iron structure of rotate electromagnetic field without reversion (WPM) is stronger and more advantageous than rotate electromagnetic field with reversion (IRPM).

Summarize, on present stage of studies was affirmed, that in order to obtain accepted criterion required is exactly definite solidification velocity. Use of this velocity results in such values of interfacial distances in considered irregular eutectic, to λ_m was little larger from λ (Fig. 19).

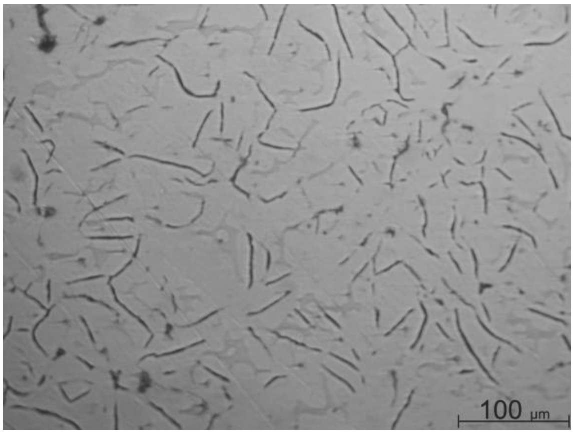

Fig. 11. Microstructure of grey cast iron EN GJL-300 after cast to shell mould (sample II): measurement field 1

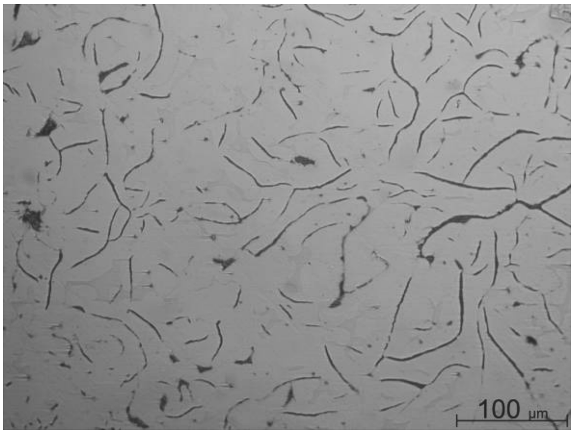

Fig. 12. Microstructure of grey cast iron EN GJL-300 after cast to shell mould (sample II): measurement field 2

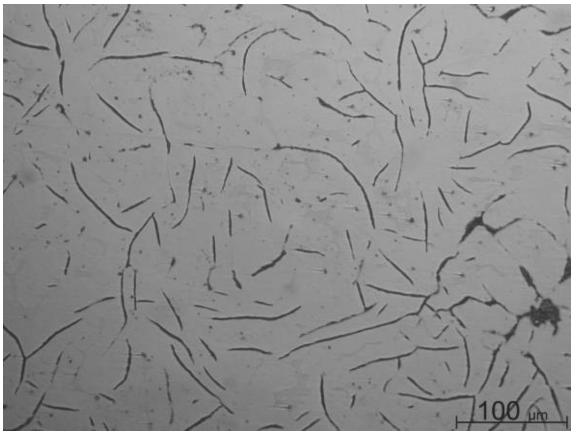

Fig. 13. Microstructure of grey cast iron EN GJL-300 after cast to shell mould (sample II): measurement field 3

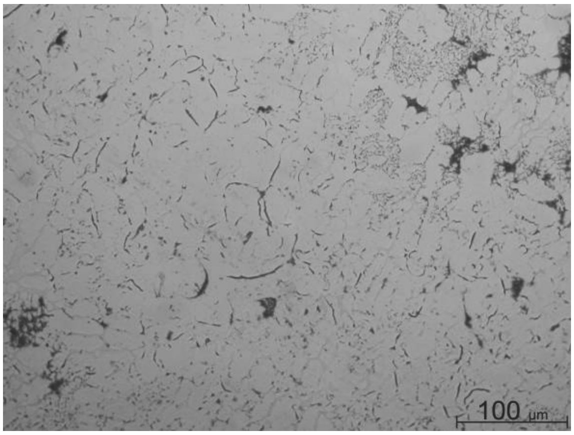

Fig. 14. Microstructure of grey cast iron EN GJL-300 after cast to graphite mould (sample I): measurement field 3

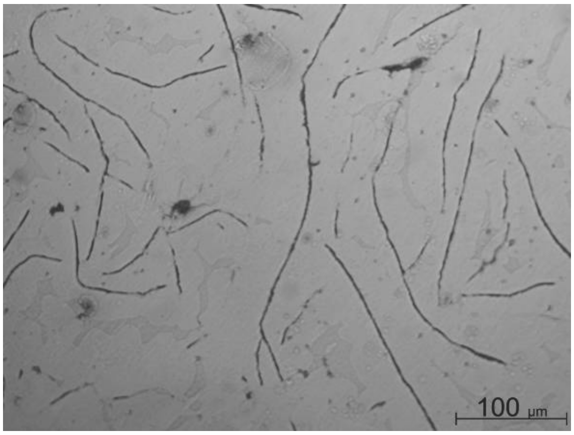

Fig. 15. Microstructure of grey cast iron EN GJL-300 after cast to sibral mould (sample III): measurement field 3

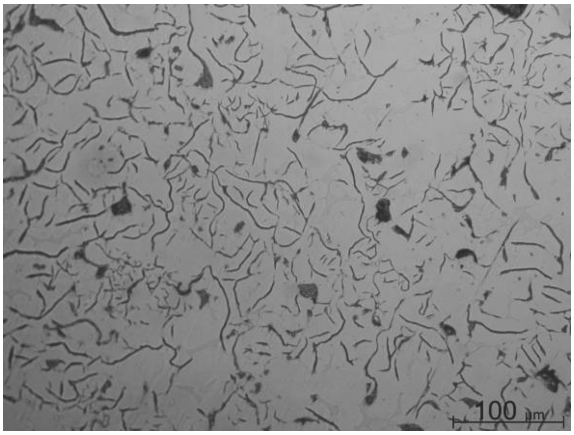

Fig. 16. Microstructure of grey cast iron EN GJL-300 after cast to shell mould with influence of WPM (sample V): measurement field 3

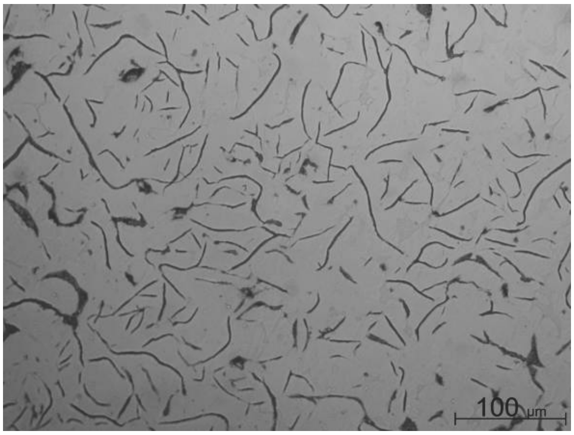

Fig. 17. Microstructure of grey cast iron EN GJL-300 after cast to shell mould with influence of WPM (sample V): measurement field 2

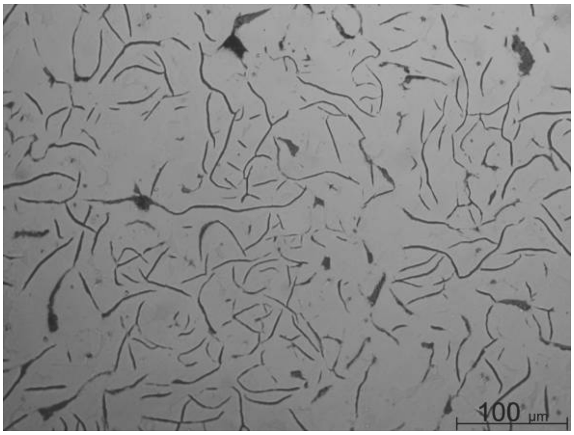

Fig. 18 Microstructure of grey cast iron EN GJL-300 after cast to shell mould with influence of WPM (sample V): measurement field 1

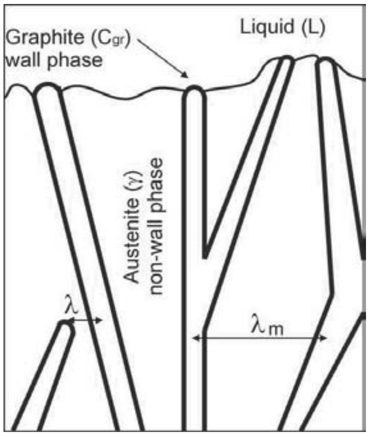

Fig. 19. Diagram of microstructure of Fe-C_{gr} irregular eutectic with characteristic distance: λ_m – distance after achievement of which begins to branch wall phase, λ – typical distance for regular eutectic after achievement of which wall phase stops to grow [8]

However increase of solidification velocity, for example by use of graphite mould results in too small difference between values of λ_m and λ. This results in short form and irregular distribution of graphite in structure of grey cast iron. Additionally appears problem of hard spots in ingots.

Whereas decrease of solidification velocity, for example by use of sibral mould results in dependence $\lambda_m >> \lambda$ and to creation of long form of flake graphite.

In relationship with this was affirmed, that proper solidification velocity guarantees shell mould for accepted dimensions of ingot.

Additionally for this solidification velocity is possibility of use of forced liquid metal movement during solidification process by influence of electromagnetic field, which increases refinement of graphite in results from thermal and mechanical erosion of crystallization front. The proof on erosion influence of forced liquid metal movement on crystallization front is increase of graphite refinement in direction from centre to periphery of ingot (Figs. 16-18), so in direction of increase of velocity and force liquid metal, which tears eutectic wall phase.

Moreover in further researches, authors of this paper are going to determine of influence of electromagnetic field on pearlite matrix by influence on graphite on which grow austenite.

4. Conclusions

Based on conducted studies following conclusions have been formulated:

1. Forced liquid metal movement during solidification process by use of electromagnetic field influences effectively on refinement and unification of complete single-phase structure of pure metal for example Al or on selected components in multiphase structure for example graphite in of grey cast iron.
2. Influence of electromagnetic field on solidification process of pure aluminium, aided size reduction, which creates mainly by introduction of small amount of inoculant sort AlTi5B1 - less than obligatory standard PN-EN 573-3 (concerning about aluminium purity).
3. Shaping of graphite in grey cast iron structure by influence of electromagnetic field is effective only for proper value of thermal condition in configuration ingot-mould.

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