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Structure of Pure Aluminum After Endogenous and Exogenous Inoculation

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1. Introduction

The phenomenon of crystallization following after pouring molten metal into the mould, determines the shape of the primary casting (ingot) structure, which significantly affects on its usable properties.

The crystallization of metal in the mould may result in three major structural zones (Fig.1) (Barrett, 1952; Chalmers, 1963; Fraś, 2003; Ohno, 1976):

- zone of chilled crystals (grains) formed by equiaxed grains with random crystallographic orientation, which are in the contact area between the metal and the mould,
- zone of columnar crystals (grains) formed by elongated crystals, which are parallel to heat flow and are a result of directional solidification, which proceeds when thermal gradient on solidification front has a positive value,
- zone of equiaxed crystals (grains) formed by equiaxed grains with random crystallographic orientation in the central part of the casting. The equiaxed crystals have larger size than chilled crystals and are result of volumetric solidification, which proceeds when thermal gradient has a negative value in liquid phase.

Depending on the chemical composition, the intensity of convection of solidifying metal, the cooling rate i.e. geometry of casting, mould material and pouring temperature (Fig.2), in the casting may be three, two or only one structural zone.

Due to the small width of chilled crystals zone, the usable properties of casting depend mainly on the width and length of the columnar crystals, the size of equiaxed crystals and content of theirs zone on section of ingot, as well as on interdendritic or interphase distance in grains such as eutectic or monotectic. For example, you can refer here to a well-known the Hall-Peth law describing the influence of grain size on yield strength (Fig.3) (Adamczyk, 2004):

$$\sigma_y = \sigma_0 + k \bullet d^{-1/2} \tag{1}$$

where:
σ_y – yield strength, MPa,

σ_o – approximate yield strength of monocrystal, for Al amount to 11,1 MPa,
k – material constant characterizing the resistance of grain boundaries for the movement of dislocations in the initial stage of plastic deformation (strength of grain boundaries), for Al amount to 0,05 $MN \cdot m^{-3/2}$,
d – grain size, mm.

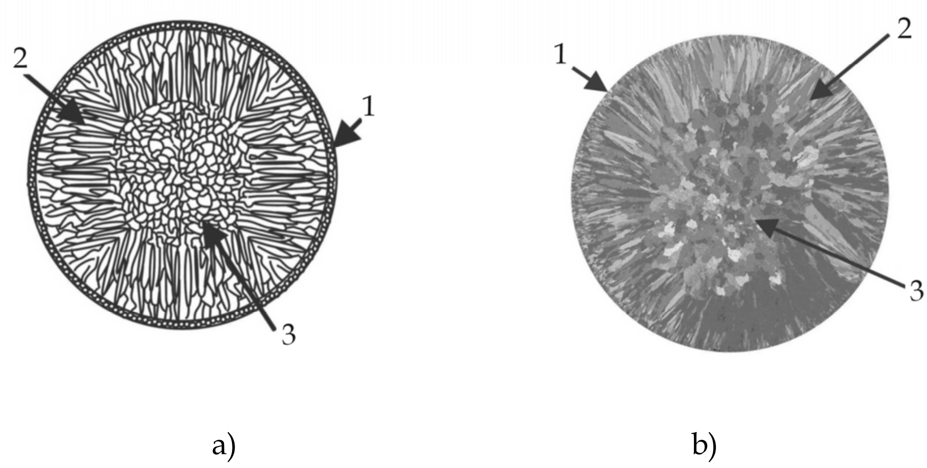


Fig. 1. The primary structure of ingot: a – scheme, b – real macrostructure;
1 – chilled crystals zone, 2 – columnar crystals zone, 3 – equiaxed crystals zone

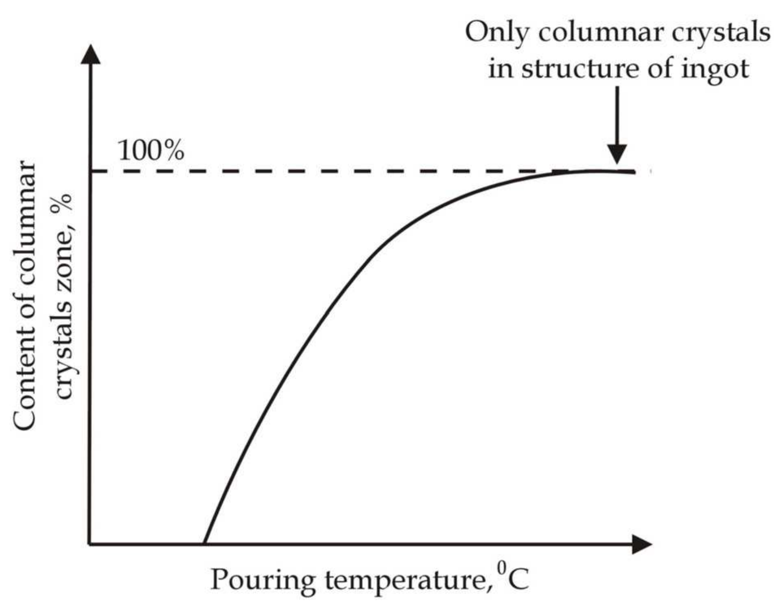


Fig. 2. The influence of pouring temperature on primary structure of ingot (Fraś, 2003)

Because the Hall-Peth law concerns only metals and alloys with the structure of solid solutions, therefore the solidification of alloys with eutectic transformation for example from Al-Si group in describing the influence of refinement of structure on the value of yield strength should take into account the value of interphase distance in eutectic (Paul et al., 1982; Tensi & Hörgerl, 1994; Treitler, 2005):

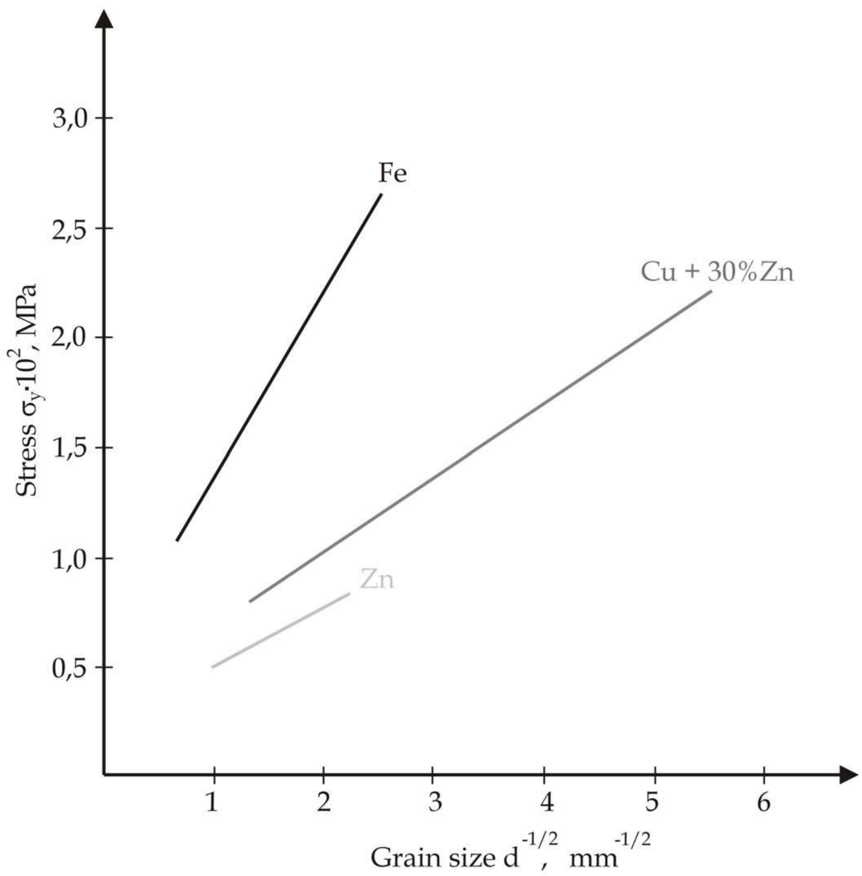


Fig. 3. The influence of grain size on yield strength of Fe, Zn and α brass (Adamczyk, 2004)

$$\sigma_y = \sigma_0 + k_1 \bullet d^{-1/2} + k_2 \bullet \lambda^{-1/2} \tag{2}$$

where:
σ_y – yield strength, MPa,
σ_o – approximately yield strength of monocrystal, MPa
k_1 and k_2 – material constants, $MN \cdot m^{-3/2}$,
d – grain size, mm,
λ – interphase distance in eutectic, mm.

The primary structure of pure metals independently from the crystal lattice type creates practically only columnar crystals (Fig.4) (Fraś, 2003). According to presented data, this type of structure gives low mechanical properties of castings and mainly is unfavourable for the plastic forming of continuous and semi-continuous ingots, because causing forces extrusion rate reduction and during the ingot rolling delamination of external layers can occur (Szajnar & Wróbel, 2008a, 2008b).

This structure can be eliminated by controlling the heat removal rate from the casting, realizing inoculation, which consists in the introduction of additives to liquid metal and/or influence of external factors for example infra- and ultrasonic vibrations or electromagnetic field.

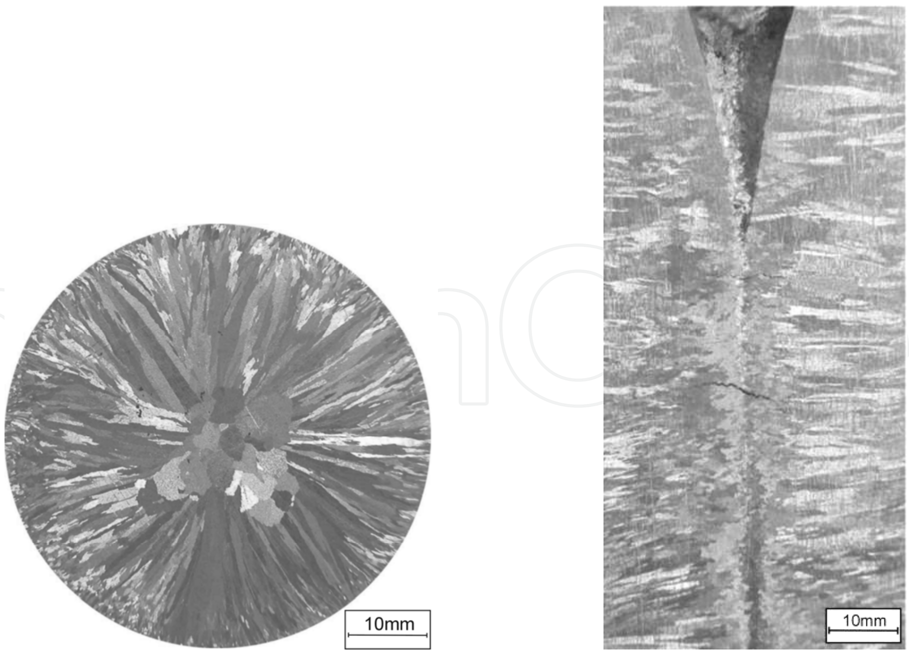


Fig. 4. Macrostructure of ingot of Al with a purity of 99,7%: a – transverse section, b – longitudinal section

2. Endogenous inoculation of pure aluminum structure

In aim to obtain an equiaxed and fine-grained structure, which gives high mechanical properties of castings, can use inoculation, which occurs in introducing into metal bath of specified substances, called inoculants (Fraś, 2003). Inoculants increase grains density as result of creation of new particles in consequence of braking of grains growth velocity, decrease of surface tension on interphase boundary of liquid – nucleus, decrease of angle of contact between the nucleus and the base and increase of density of bases to heterogeneous nucleation (Fraś, 2003; Jura, 1968). The effectiveness of this type of inoculation depends significantly on crystallographic match between the base and the nucleus of inoculated metal. This crystallographic match is described by type of crystal lattice or additionally by index (Fraś, 2003):

$$\xi = \left((1 - \frac{x_b - x_n}{x_n}) \right) \bullet 100\% \tag{3}$$

where:

ξ - match index,
x_b, x_n – parameter of crystal lattice in specified direction, suitable for base and nucleus.

When the value of index (ξ) is closer to 100%, it the more effective is the base to heterogeneous nucleation of inoculated metal.

Therefore active bases to heterogeneous nucleation for aluminum are particles which have high melting point i.e. TiC, TiN, TiB, TiB_2, AlB_2 i Al_3Ti (Tab.1) (Easton & StJohn, 1999a, 1999b; Fjellstedt et al., 2001; Fraś, 2003; Guzowski et al., 1987; Hu & H. Li, 1998; Jura, 1968; Kashyap & Chandrashekar, 2001; H. Li et al., 1997; P. Li et al., 2005; McCartney, 1988; Murty et al., 2002; Naglič et al., 2008; Pietrowski, 2001; Sritharan & H. Li, 1996; Szajnar & Wróbel, 2008a, 2008b; Whitehead, 2000; Wróbel, 2010; Zamkotowicz et al., 2003).

Phase	Melting point (circa) [°C]	Type of crystal lattice	Parameters of crystal lattice [nm]
Al	660	Cubical A1	a = 0,404
TiC	3200	Cubical B1	a = 0,431
TiN	3255	Cubical B1	a = 0,424
TiB	3000	Cubical B1	a = 0,421
TiB_2	2900	Hexagonal C32	a = 0,302 c = 0,321
AlB_2	2700	Hexagonal C32	a = 0,300 c = 0,325
Al_3Ti	1400	Tetragonal $D0_{22}$	a = 0,383 c =0,857

Table 1. Characteristic of bases to heterogeneous nucleation of aluminum (Donnay & Ondik, 1973)

Moreover the effectiveness of inoculants influence can be assessed on the basis of the hypothesis presented in the paper (Jura, 1968). This hypothesis was developed at the assumption that the fundamental physical factors affecting on the crystallization process are the amount of give up heat in the crystallization process on the interphase boundary of liquid - solid and the rate of give up heat of crystallization. After analyzing the results of own researches, the author proposed to determine the index (α), which characterizes the type of inoculant.

$$\alpha = \frac{\left(\Delta E_k/\nu\right)_s}{\left(\Delta E_k/\nu\right)_p} \bullet W \tag{4}$$

where:

ΔE_k – heat of crystallization of 1 mol of inoculant or inoculated metal, J/mol,
ν – characteristic frequency of atomic vibration calculated by the Lindemman formula, 1/s,
s – symbol of inoculant, p – symbol of inoculated metal.
W – parameter dependent on the atomic mass of inoculant and inoculated metal.
On the basis of equation (4) additives can be divided into three groups:
At $\alpha > 1$ – additives which inhibit crystals growth by the deformation of the crystallization front, thus are effective inoculants.
At $\alpha = 1$ – additives do not affect on structure refinement.
At $\alpha < 1$ – additives which accelerate crystals growth, favoring consolidation of the primary structure of the metal, thus are deinoculants.

In case of inoculation of Al the index α = 2.35 for inoculant in form of Ti and 1.76 for inoculant in form of B.

In case of aluminum casting inoculants are introduced in form of master alloy AlTi5B1. This inoculant has Ti:B ratio equals 5:1. This Ti:B atomic ratio, which corresponds to the mass content of about 0.125% Ti to about 0.005% B, assures the greatest degree of structure refinement (Fig.5). For this titanium and boron ratio bases of type TiB_2 and Al_3Ti are created (Fig.6) (Easton & StJohn, 1999a, 1999b; Fjellstedt et al., 2001; Guzowski et al., 1987; Hu & H. Li, 1998; Kashyap & Chandrashekar, 2001; H. Li et al., 1997; P. Li et al., 2005; Murty et al., 2002; Naglič et al., 2008; Pietrowski, 2001; Sritharan & H. Li, 1996; Szajnar & Wróbel, 2008a, 2008b; Whitehead, 2000; Wróbel, 2010). Type and amount of bases to heterogeneous nucleation of aluminum depend on Ti:B ratio. For example given in paper (Zamkotowicz et al., 2003) the possibility of application of master alloy AlTi1.7B1.4, which has Ti:B ratio equals 1.2:1 is presented. This ratio allows to increase in amount of fine phases TiB_2 and AlB_2 along with the Al_3Ti phase decrease.

Moreover minimum quantities of carbon and nitrogen, which come from metallurgical process of aluminum, create with inoculant the bases in form of titanium carbide TiC and titanium nitride TiN (Fig.7) (Pietrowski, 2001; Szajnar & Wróbel, 2008a, 2008b).

Additionally, because there is a possibility of creation the bases to heterogeneous nucleation of aluminum in form of TiC phase without presence of bases in form of borides, in the practice of casting the inoculation with master alloy AlTi3C0.15 is used (Naglič et al., 2008; Whitehead, 2000). However, on the basis of results of own researches was affirmed that assuming of introducing to Al with a purity of 99,5% the same quantity of Ti i.e. 25ppm, the result of structure refinement caused by master alloy AlTi3C0.15 is weaker than caused by master alloy AlTi5B1 (Fig.8).

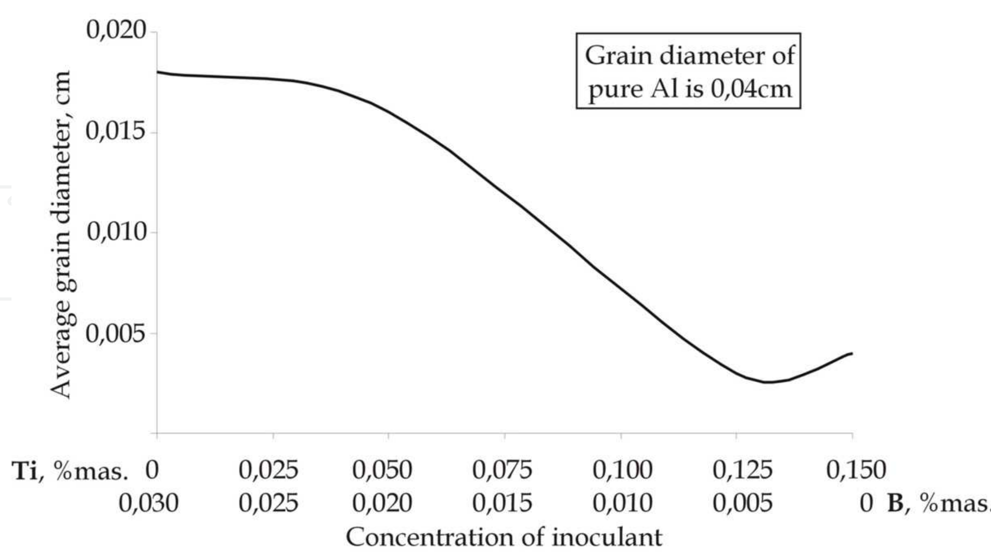


Fig. 5. Influence of Ti and B contents on the average size of Al ingots (H. Li et al., 1997)

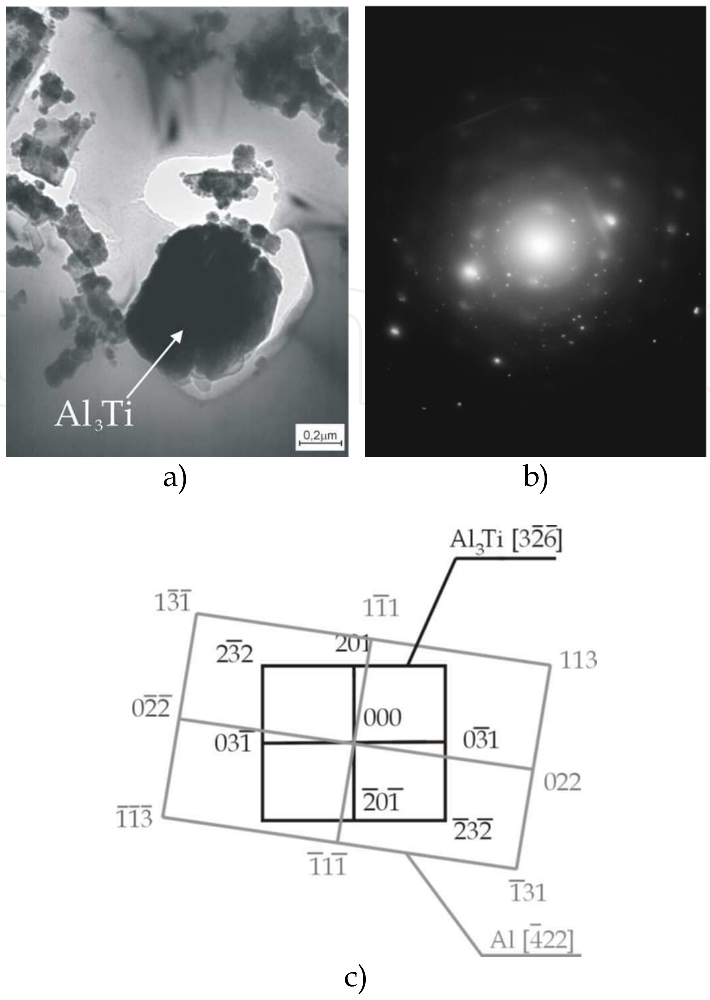


Fig. 6. Structure of thin foil from pure Al after inoculation with (Ti+B), a) TEM bright field mag. 30000x , b) diffraction pattern from the area as in Fig. a, c) analysis of the diffraction pattern from Fig. b

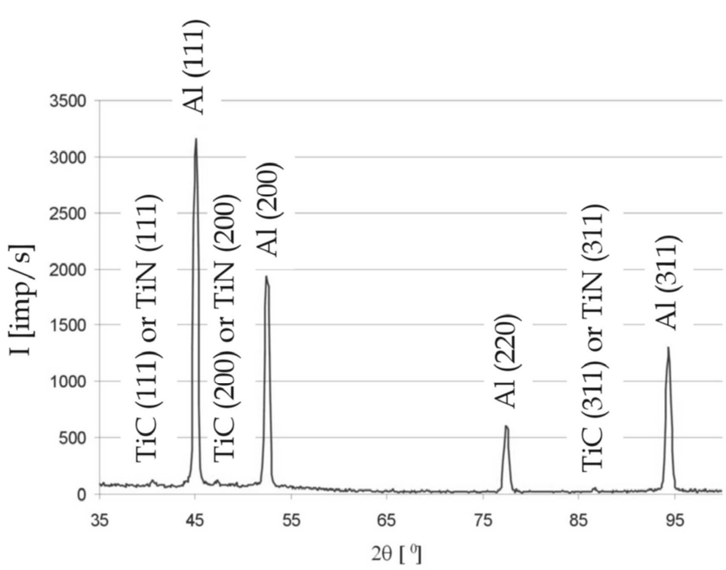
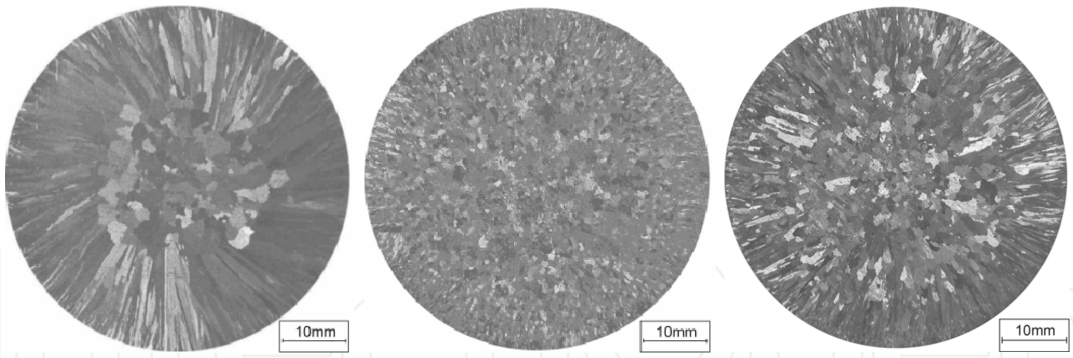


Fig. 7. Result of X-ray diffraction of Al with a purity of 99,5% after inoculation with Ti



a) b) c)

Fig. 8. Macrostructure of ingot of Al with a purity of 99,5%: a – in as-cast condition, b – after inoculation with (Ti+B), c – after inoculation with (Ti+C)

However, this undoubtedly effective method of inoculation of primary structure of ingot is limited for pure metals, because inoculants decrease the degree of purity specified in European Standards, and Ti with B introduced as modifying additives are then classify as impurities. Moreover, inoculants, mainly Ti which segregates on grain boundary of Al (Fig.9) influence negatively on physical properties i.e. electrical conductivity of pure aluminum (Fig.10) (Wróbel, 2010).

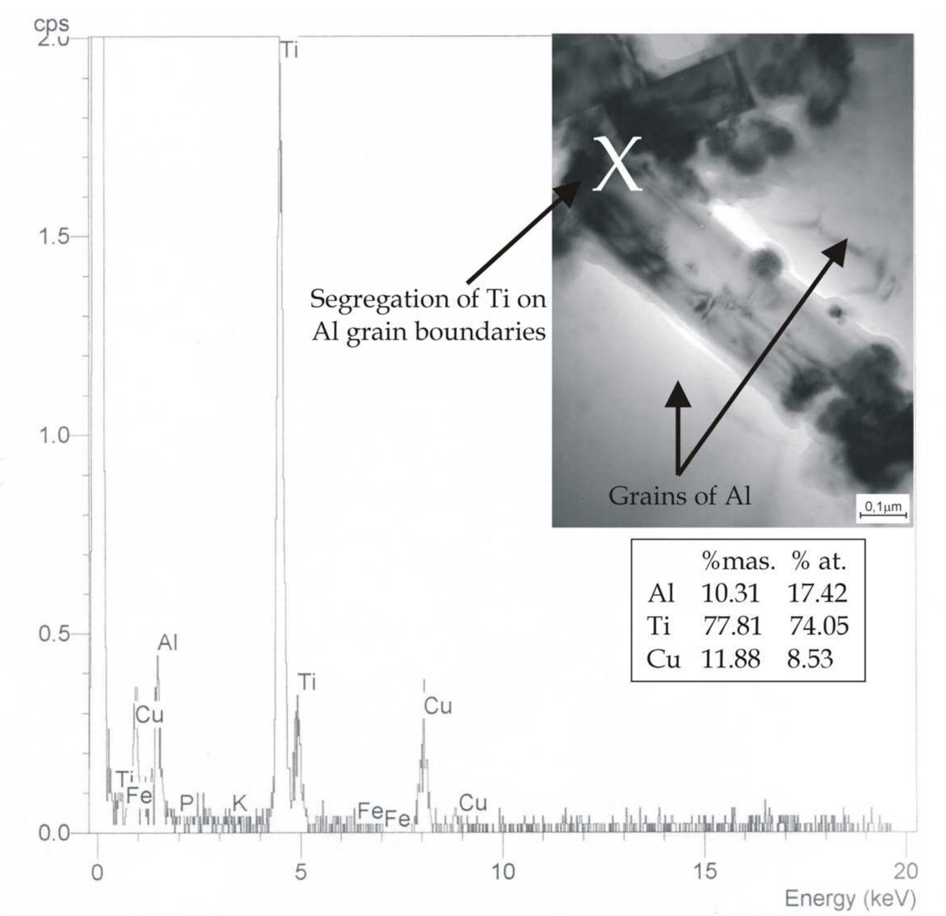


Fig. 9. Segregation of Ti on grain boundaries of Al

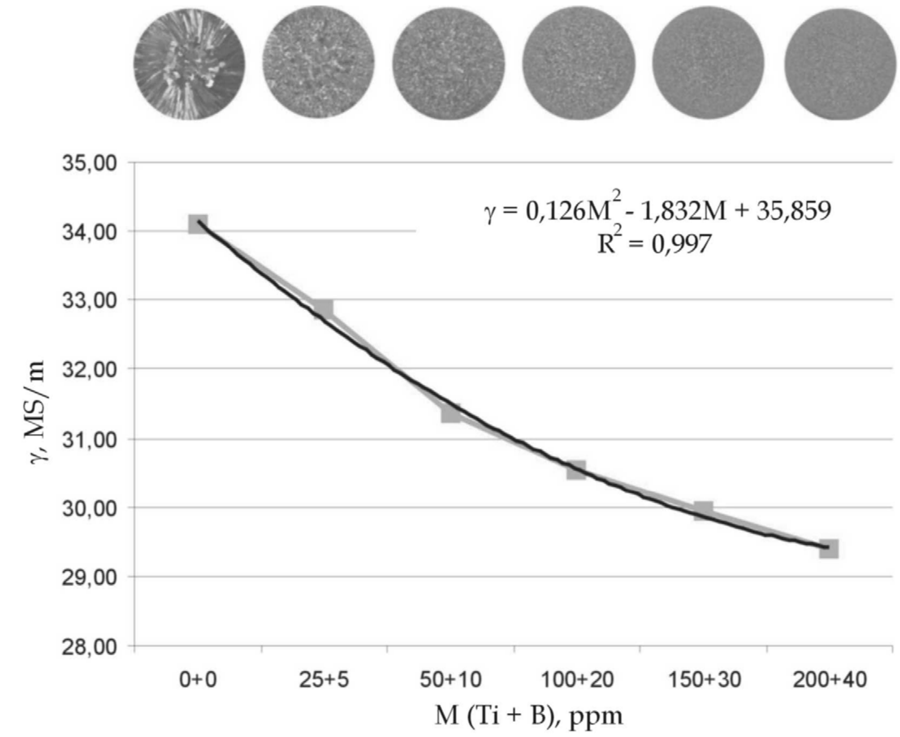


Fig. 10. The influence of quantity of inoculants in form of Ti and B on electrical conductivity γ of Al with a purity of 99,5%

Moreover the presence of the bases to heterogeneous nucleation in form of hard deformable phases for example titanium borides in structure in aluminum, generate possibility of point cracks formation (Fig. 11) and in result of this delamination of sheet (foil) during rolling (Keles & Dundar, 2007).

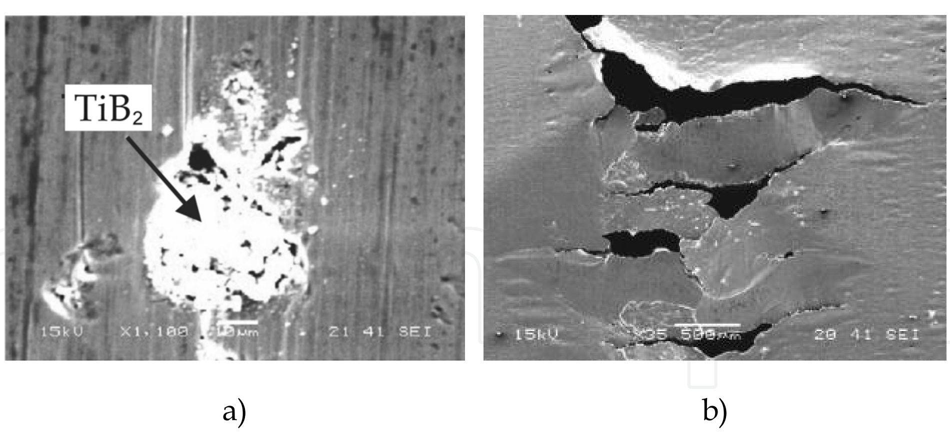


Fig. 11. Phase TiB_2 in structure of pure Al (Fig. a) and produced in result from its present crack in sheet (foil) during rolling (Fig. b) (Keles & Dundar, 2007)

Therefore important is the other method of inoculation, which consists of influence of electromagnetic field (Asai, 2000; Campanella et al., 2004; Doherty et al., 1984; Gillon, 2000; Griffiths & McCartney, 1997; Harada, 1998; Szajnar, 2004, 2009; Szajnar & Wróbel, 2008a, 2008b, 2009; Vives & Ricou, 1985; Wróbel, 2010) or mechanical vibrations (Abu-Dheir et al., 2005; Szajnar, 2009) on liquid metal in time of its solidification in mould.

3. Exogenous inoculation of pure aluminum structure

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 (Wróbel, 2010). 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. The mutual relationship between these fields are described by the Maxwell equations (Sikora, 1998).

Generated by the induction coil powered by electric current intensity (I_0) electromagnetic field affects the solidifying metal induces a local electromotive force (E_m), whose value depends on the local velocity of the liquid metal (V) and magnetic induction (B) (Gillon, 2000).:

$$E_m = \overline{V} \times \overline{B} \tag{5}$$

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 an eddy current of intensity (I) in liquid metal (Gillon, 2000; Vives & Ricou, 1985):

$$\overline{I} = \sigma\left(\overline{V} \times \overline{B}\right) \tag{6}$$

where:

σ - electrical conductivity proper to the liquid metal.

The influence of the induced current on the magnetic field results in establishing of the Lorenz (magnetohydrodynamic) force (F) (Gillon, 2000; Vives & Ricou, 1985):

$$\overline{F} = \overline{I} \times \overline{B} \tag{7}$$

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 (Fig.12).

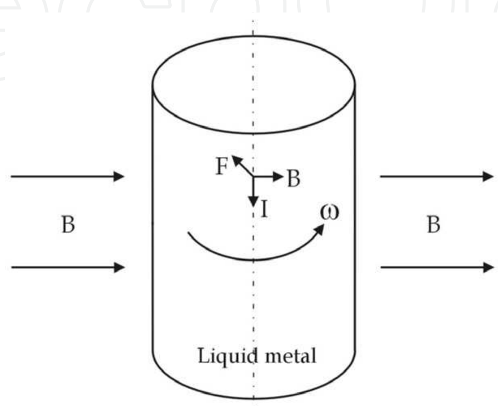


Fig. 12. Scheme of electromagnetic field influence on the liquid metal

In addition, as presented in the paper (Szajnar, 2009) the rotating velocity of the liquid metal (V) is inversely proportional to the density of the metal (ρ), because with some approximation we can say that (Fig.13):

$$\overline{V} \approx \frac{\overline{F}}{\rho} or \frac{\overline{B}}{\rho} \tag{8}$$

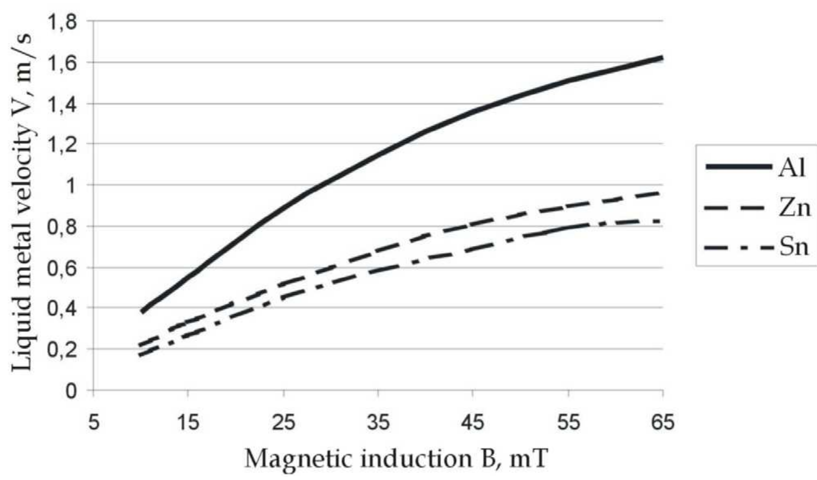


Fig. 13. Dependence of peripheral velocity of liquid metal (V) in a cylindrical mould of inside diameter 45mm on magnetic induction (B) for example metals (Szajnar, 2009)

Forced liquid metal movement influences by 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 (Szajnar, 2004, 2009) and by (Campanella et al., 2004; Doherty et al., 1984; Fraś, 2003; Ohno, 1976; Szajnar, 2004, 2009; Szajnar & Wróbel, 2008a, 2008b, 2009; Wróbel, 2010):

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

One of the hypotheses regarding the mechanism of dendrites fragmentation caused by the energy of the movement of liquid metal is presented in work (Doherty et al., 1984). It is based on the assumption of high plasticity of growing dendrites in the liquid metal, which in an initial state are a single crystal with specified crystallographic orientation (Fig.14a). The result of liquid metal movement is deformation (bending) of plastic dendrite (Fig.14b), which caused creation of crystallographic misorientation angle Θ (Fig.14c). Created high-angle grain boundary ($\Theta > 20°$) has the energy γ_{GZ} much greater than double interfacial energy of solid phase - liquid phase γ_{S-L}. In result of unbalancing and satisfying the dependence $\gamma_{GZ} > 2\,\gamma_{S-L}$ the grain boundary is replaced by a thin layer of liquid metal. This leads to dendrite shear by liquid metal along the former grain boundary (Fig.14d). Dendrite fragments of suitable size after moving into the metal bath can transform into equiaxed crystals.

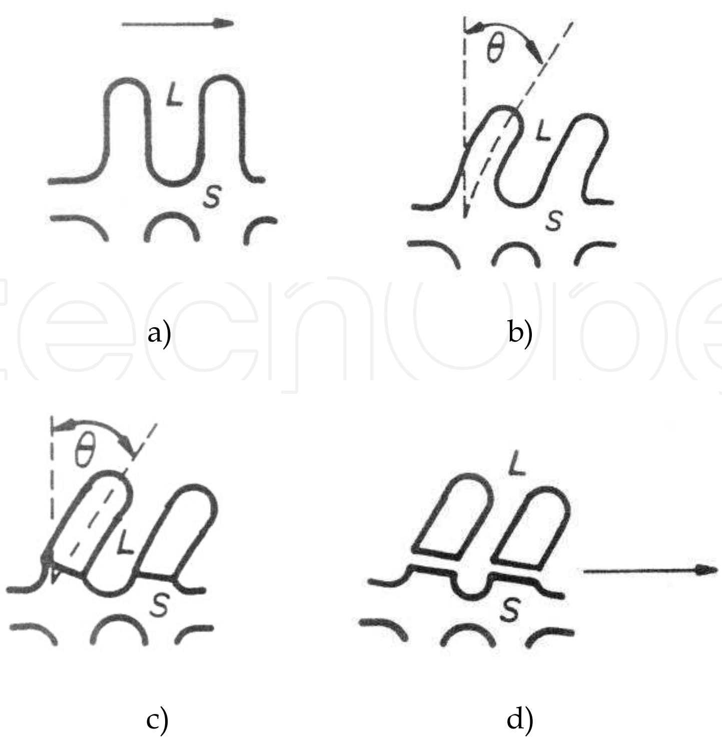


Fig. 14. Schematic model of the grain boundary fragmentation mechanism: a – an undeformed dendrite, b – after bending, c – the reorganization of the lattice bending to give grain boundaries, d – for $\gamma_{GZ} > 2\ \gamma_{S\text{-}L}$ the grain boundaries have been "wetted" by the liquid phase (Doherty et al., 1984).

The influence of electromagnetic field on liquid metal in aim of structure refinement (Fig.15), axial and zonal porosity elimination and obtaining larger homogeneity of structure, was applied in permanent mould casting (Griffiths & McCartney, 1997; Szajnar & Wróbel, 2008a, 2008b, 2009; Wróbel, 2010) and mainly in technologies of continuous (Adamczyk, 2004; Gillon, 2000; Harada, 1998; Miyazawa, 2001; Szajnar et al., 2010; Vives & Ricou, 1985) and semi-continuous casting (Guo et al., 2005).

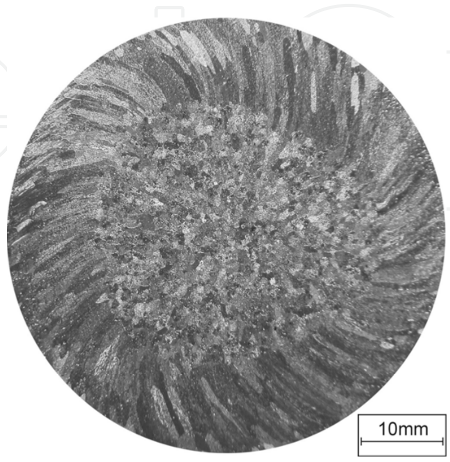
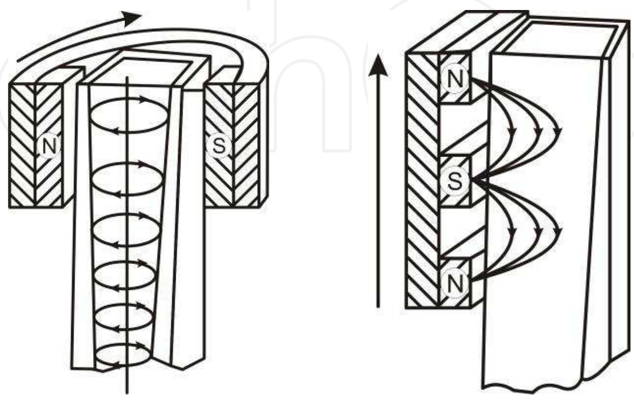


Fig. 15. Macrostructure of ingot of Al with a purity of 99,5% after cast with influence of rotating electromagnetic field

In case of continuous ingots of square and circular transverse section, rotating electromagnetic field induction coils are used. Rotating electromagnetic field forces rotational movement of liquid metal in perpendicular planes to ingot axis (Fig.16a). Whereas, mainly for flat ingots, longitudinal electromagnetic field induction coils are used, which forced oscillatory movement of liquid metal in parallel planes to ingot axis (Fig.16b) (Adamczyk, 2004; Miyazawa, 2001).



a) b)

Fig. 16. Scheme of an electromagnetic stirrer (induction coil) forced rotational (a) and oscillatory movement of liquid metal (Adamczyk, 2004)

Whereas the authors of paper (Szajnar & Wróbel, 2008a, 2008b) suggests the use of reversion in the direction of electromagnetic field rotation during permanent mould casting. The advantage of casting in rotating electromagnetic field with reversion compared to casting in rotating field, mainly based on the fact that the liquid metal located in the permanent mould and put in rotary-reversible motion practically does not create a concave meniscus, and thus is not poured out off the mould under the influence of centrifugal forces. Moreover, the influence of this type of field combines impact of high amplitude and low frequency vibration with action of rotating electromagnetic field. Also important is double-sided bending of growing crystals, causing the creation in the columnar crystals zone of ingot characteristic crystals so-called corrugated (Fig.17).

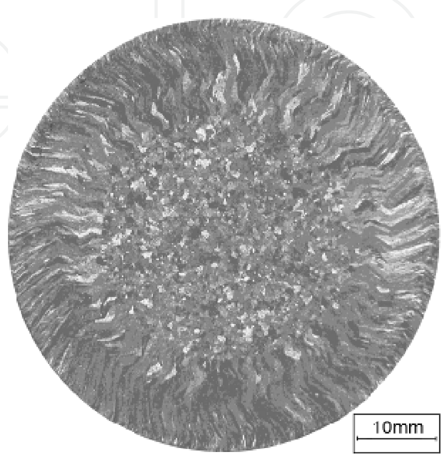


Fig. 17. Macrostructure of ingot of Al with a purity of 99,5% after cast with influence of rotating electromagnetic field with reversion

However in papers (Szajnar, 2004, 2009; Szajnar & Wróbel, 2008a, 2008b, 2009) was shown that influence of forced movement of liquid metal by use of electromagnetic field to changes in structure of pure metals, which solidify with flat crystallization front is insufficient. The effective influence of this forced convection requires a suitable, minimal concentration of additives i.e. alloy additions, inoculants or impurities in casting. Suitable increase of additives concentration causes at specified thermal conditions of solidification, occurs in change of morphology of crystallization front according to the scheme shown in Figure 18.

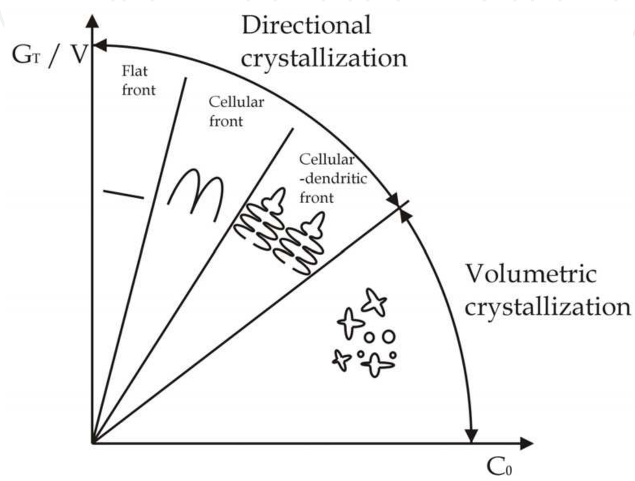


Fig. 18. Scheme of relationship between thermal and concentration conditions and type of crystallization; C_0 – concentration of additives, G_T – thermal gradient on crystallization front, V – velocity of crystallization (Fraś, 2003)

However it should be noted that, based on the latest results of author researches was affirmed that in some cases it is possible to obtain a sufficient refinement degree of pure aluminum structure in result of inoculation carried out only with the use of an electromagnetic field. Because it shows a possibility of increasing the force, which creates movement of liquid metal and in result of this the velocity of its rotation in mould, not only by increasing the value of magnetic induction according to the dependences (7) and (8), but also by increasing the frequency of the current supplied to the induction coil (Fig.19).

The effect of refinement of structure of Al with a purity of 99,5% caused by the rotating electromagnetic field produced by the induction coil supplied by current with frequency different from the network i.e. 50Hz is presented in Table 2. On the basis of macroscopic metallographic researches, which lead to the calculation of the equiaxed crystals zone content on transverse section of ingot (SKR) and average area of macro-grain in this zone (PKR) was affirmed, that application of frequency of supply current f ≤ 50Hz does not guarantee favourable transformation of pure aluminum structure (Fig.20 and 21). Whereas induction coil supplied with frequency of current larger than power network, mainly 100Hz generates rotating electromagnetic field, which guarantees favourable refinement of structure, also in comparison to obtained after inoculation with small, acceptable by European Standards amount of Ti and B i.e. 25 and 5ppm (Tab.2).

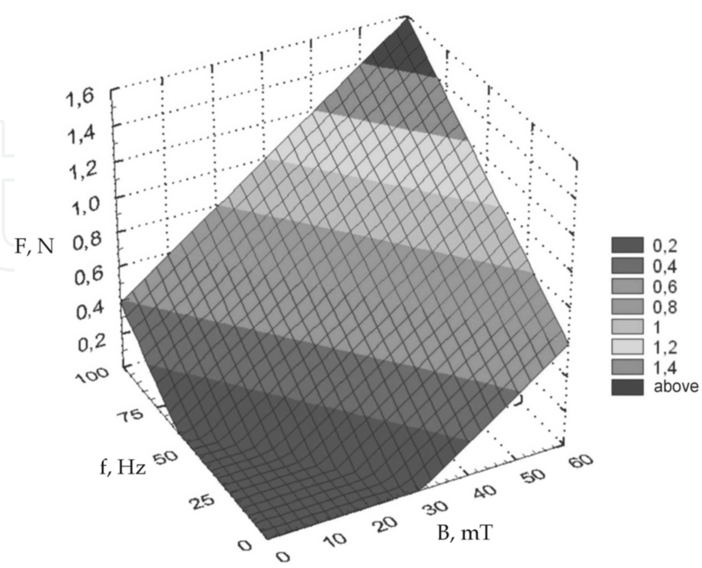


Fig. 19. The influence of magnetic induction (B) and frequency (f) of the current supplied to the induction coil on force value (F), which creates movement of liquid metal

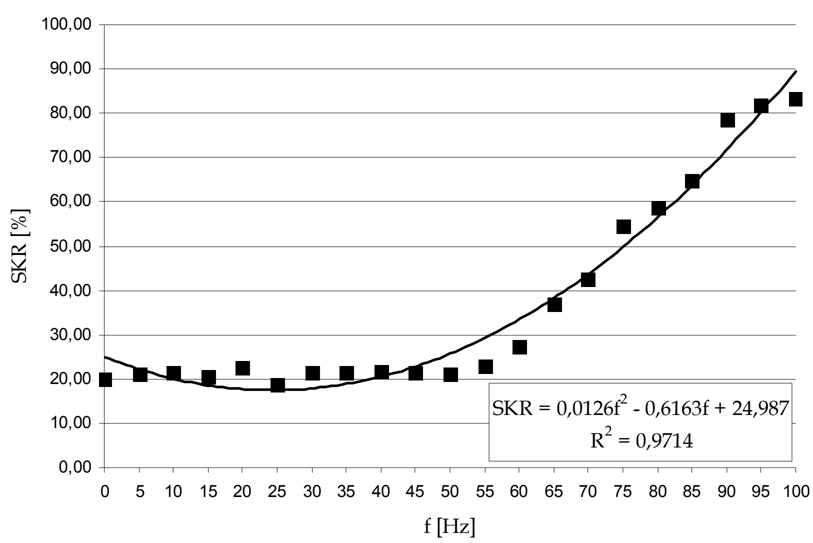


Fig. 20. The influence of current frequency (f) supplied to the induction coil on equiaxed crystals zone content (SKR) on transverse section of pure Al ingot

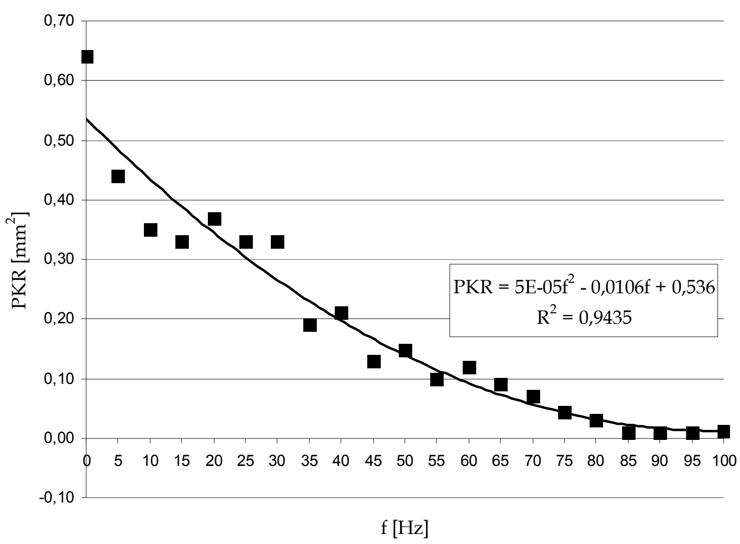
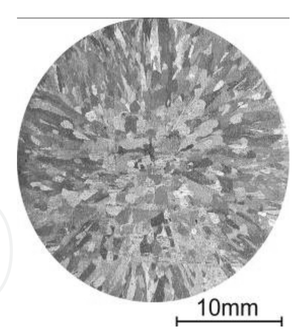
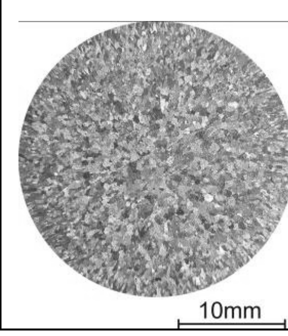
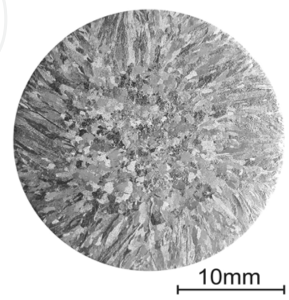
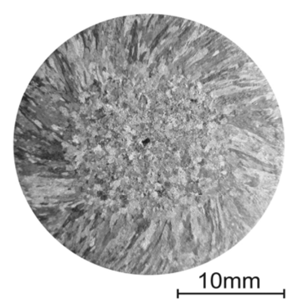
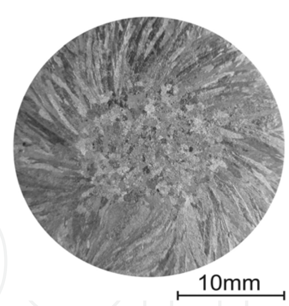
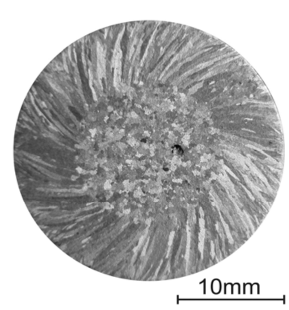
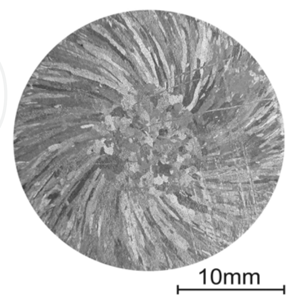
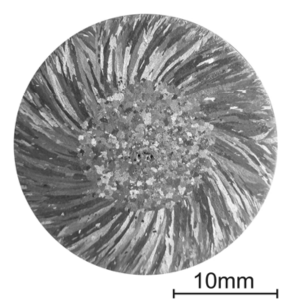
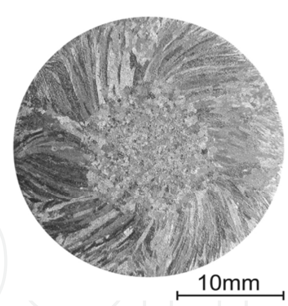
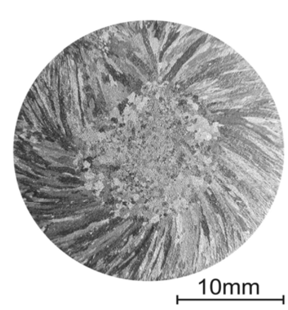


Fig. 21. The influence of current frequency (f) supplied to the induction coil on average area of equiaxed crystal (PKR) of pure Al ingot

No.	Cast parameters			Refinement parameters		Macrostructure of ingot
	B [mT]	f [Hz]	(Ti+B) [ppm]	SKR [%]	PKR [mm²]	
-1-	-2-	-3-	-4-	-5-	-6-	-7-
1	-	-	-	19,94	0,64	
2	-	-	25+5	80,30	0,42	

No.	Cast parameters			Refinement parameters		Macrostructure of ingot
	B [mT]	f [Hz]	(Ti+B) [ppm]	SKR [%]	PKR [mm²]	
-1-	-2-	-3-	-4-	-5-	-6-	-7-
3		5		21,01	0,44	
4	60	10	-	21,36	0,35	
5		15		20,66	0,33	
6	60	20	-	22,63	0,37	

No.	Cast parameters			Refinement parameters		Macrostructure of ingot
	B [mT]	f [Hz]	(Ti+B) [ppm]	SKR [%]	PKR [mm²]	
-1-	-2-	-3-	-4-	-5-	-6-	-7-
7		25		18,90	0,33	
8		30		21,42	0,33	
9		35		21,44	0,19	
10		40		21,68	0,21	

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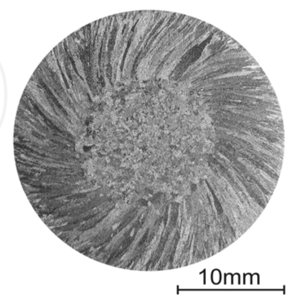
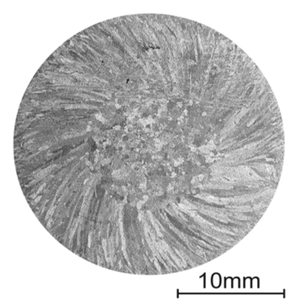
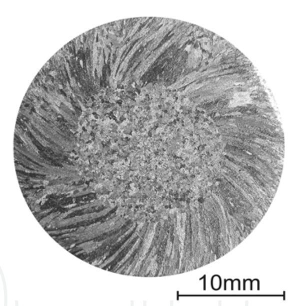
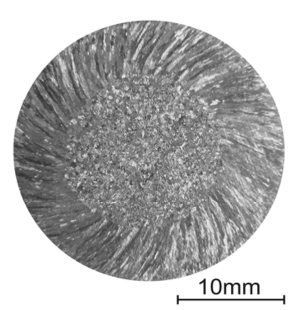
<tr><th>B
[mT]</th><th>f
[Hz]</th><th>(Ti+B)
[ppm]</th><th>SKR
[%]</th><th>PKR
[mm²]</th></tr>
<tr><td>-1-</td><td>-2-</td><td>-3-</td><td>-4-</td><td>-5-</td><td>-6-</td><td>-7-</td></tr>
<tr><td>11</td><td rowspan="4">60</td><td>45</td><td rowspan="4">-</td><td>21,46</td><td>0,13</td><td></td></tr>
<tr><td>12</td><td>50</td><td>21,21</td><td>0,15</td><td></td></tr>
<tr><td>13</td><td>55</td><td>22,87</td><td>0,10</td><td></td></tr>
<tr><td>14</td><td>60</td><td>27,22</td><td>0,12</td><td></td></tr>
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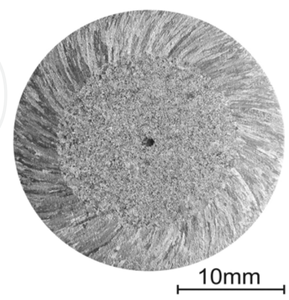
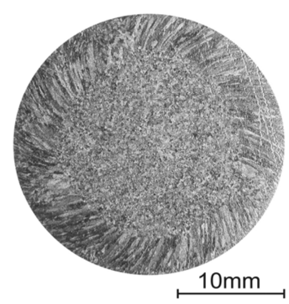
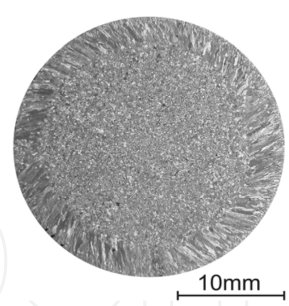
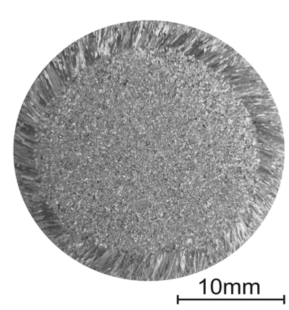
No.	Cast parameters			Refinement parameters		Macrostructure of ingot
	B [mT]	f [Hz]	(Ti+B) [ppm]	SKR [%]	PKR [mm²]	
-1-	-2-	-3-	-4-	-5-	-6-	-7-
15		65		37,05	0,09	
16		70		42,53	0,07	
17	60	75	-	54,63	0,04	
18		80		58,56	0,03	

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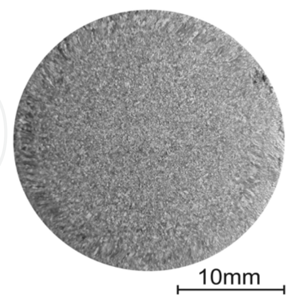
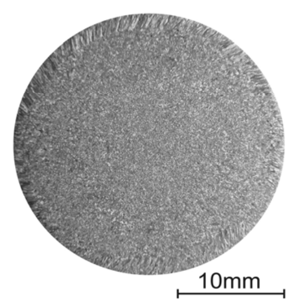
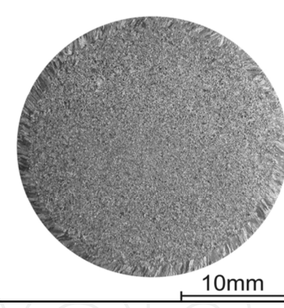
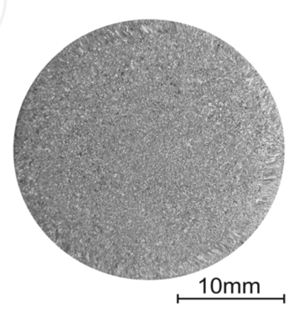
<tr><th>B
[mT]</th><th>f
[Hz]</th><th>(Ti+B)
[ppm]</th><th>SKR
[%]</th><th>PKR
[mm²]</th></tr>
<tr><td>-1-</td><td>-2-</td><td>-3-</td><td>-4-</td><td>-5-</td><td>-6-</td><td>-7-</td></tr>
<tr><td>19</td><td rowspan="4">60</td><td>85</td><td rowspan="4">-</td><td>64,70</td><td>0,01</td><td></td></tr>
<tr><td>20</td><td>90</td><td>78,67</td><td>0,01</td><td></td></tr>
<tr><td>21</td><td>95</td><td>81,78</td><td>0,01</td><td></td></tr>
<tr><td>22</td><td>100</td><td>83,36</td><td>0,01</td><td></td></tr>
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Table 2. The influence of rotating electromagnetic field on structure of Al with a purity of 99,5%

4. The influence of exogenous inoculation on the result of endogenous inoculation in pure aluminum

In the practice of casting is also a problem of connection of endogenous inoculation i.e. realized by use of additives, for example Ti and B with exogenous inoculation i.e. realized by use of electromagnetic field. However as presented in papers (Szajnar & Wróbel, 2008a, 2008b, Wróbel, 2010) occurs that the phenomenon of convection transport (rejection) of impurities for example Cu and inoculants for example Ti from crystallization front into metal bath volume in result of intensive, forced by electromagnetic field the movement of liquid metal. This leads to an increase in density of bases to heterogeneous nucleation of aluminum and in consequence to increase in density of grains in the central area of ingot. Results of determination of Cu and Ti concentration in near-surface and central areas of investigated ingots with use of emission optical spectrometry is a proof of such reasoning. On their basis was affirmed, that in ingot of Al with a purity of 99,5% which was cast under the influence of electromagnetic field and with (Ti + B) inoculation, the Cu and Ti concentration in central area increase was observed (Fig.22a). Whereas in Al, which was cast only with (Ti + B) inoculation, the Cu and Ti concentrations in the near-surface and central areas of ingot are similar (Fig.22b).

The second proof of convection transport (rejection) of Cu and Ti from crystallization front into liquid metal volume is the analysis of macrostructure of investigated ingots and counting of all macro-grains in equiaxed crystals zone. Macrostructure of ingot of Al with a purity of 99,5%, which was cast with the combined effect of the electromagnetic field and with (Ti+B) inoculation has smaller equiaxed crystals zone than the ingot which was cast only with the influence of endogenous inoculation, but the first ingot has a smaller size of macro-grain in its equiaxed crystals zone than the ingot which was cast only with (Ti+B) inoculation (Fig.23).

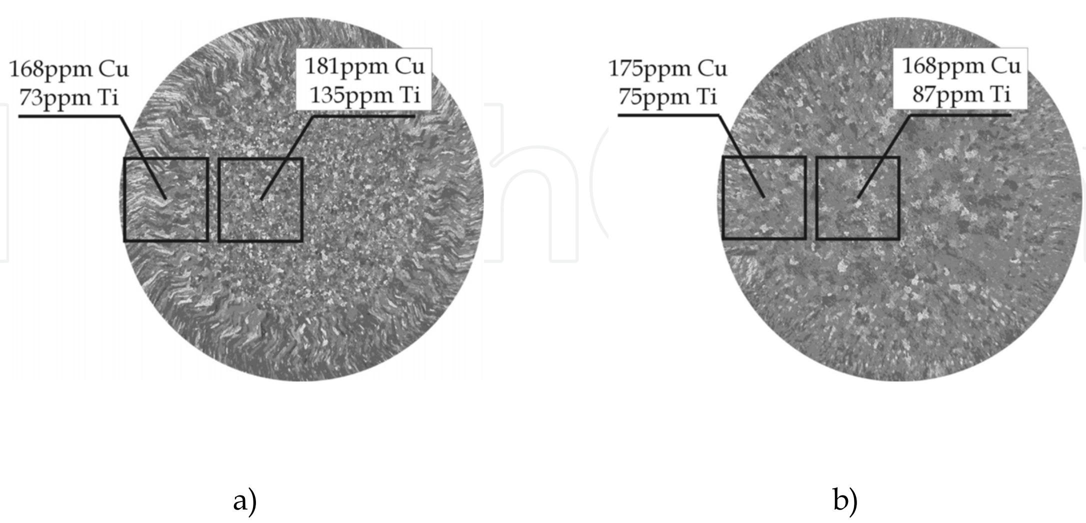
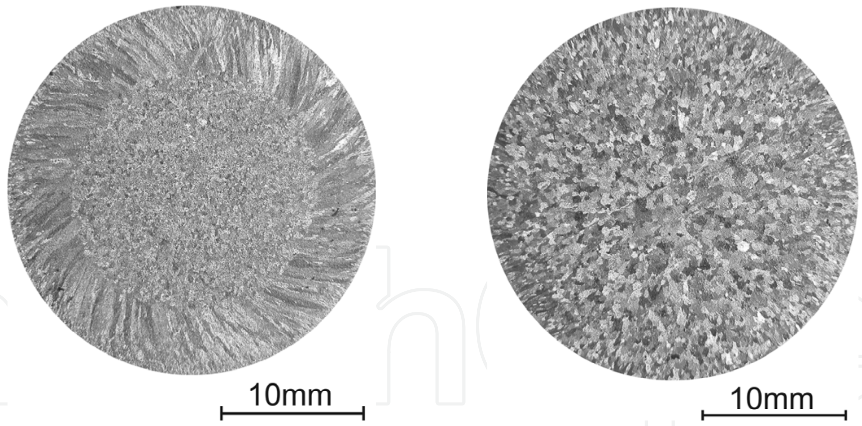


Fig. 22. Concentration of Cu and Ti in near-surface and central areas of Al with a purity of 99,5%ingots: a – after common exogenous (electromagnetic field) and endogenous (Ti + B) inoculation, b – only after endogenous (Ti + B) inoculation



a) b)

Fig. 23. Macrostructure of ingot of Al with a purity of 99,5%: a – after common exogenous (electromagnetic field) and endogenous (Ti + B) inoculation, b – only after endogenous (Ti + B) inoculation

Based on conducted calculations of number of macro-grains in equiaxed crystals zone following formula was formulated:

$$n_{ex+en} > n_{ex} + n_{en} \tag{9}$$

where:

n_{ex+en} – number of macro-grains in equiaxed crystals zone of ingot which was cast with common influence of exogenous (electromagnetic field) and endogenous (Ti + B) inoculation,

n_{ex} – number of macro-grains in equiaxed crystals zone of ingot which was cast only with influence of exogenous (electromagnetic field) inoculation,

n_{en} – number of macro-grains in equiaxed crystals zone of ingot which was cast only with influence of endogenous (Ti + B) inoculation.

Summarize, was affirmed that application of common exogenous (electromagnetic field) and endogenous (Ti + B) inoculation strengthens effect of structure refinement in comparison with application of one type of inoculation, only if is used skinning of ingot surface i.e. machining in aim of columnar crystals zone elimination.

5. Conclusions

In conclusion can say, that even endogenous inoculation with small amount of (Ti + B) strongly increase on refinement in pure aluminum structure. It results from reactions, which proceed between inoculating elements and inoculated metal or charge impurities. These reactions lead to formation of active bases to heterogeneous nucleation of aluminum as high melting small particles of type TiB, TiB_2, AlB_2, Al_3Ti and TiC or TiN, which have analogy in crystal lattice with Al.

However on the basis of conducted analysis of the literature and results of authors researches it was affirmed, that the rotating electromagnetic field generated by induction coil supplied by current with frequency larger than power network, influences liquid metal in time of its solidification in mould, guarantees refinement of structure of pure Al without necessity of application of inoculants sort Ti and B.

This method of exogenous inoculation is important, because Ti and B decrease the degree of purity and electrical conductivity of pure aluminum. Moreover Ti and B are reason of point cracks formation during rolling of ingots.

Presented method of inoculation by use of electromagnetic field is possible to apply in conditions of continuous casting because it allows producing of ingots from aluminum of approx. 99,5% purity with structure without columnar crystals, which are unfavourable from point of view of usable properties.

6. Acknowledgment

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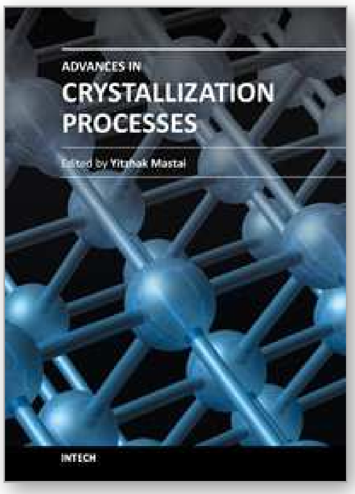

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Crystallization is used at some stage in nearly all process industries as a method of production, purification or recovery of solid materials. In recent years, a number of new applications have also come to rely on crystallization processes such as the crystallization of nano and amorphous materials. The articles for this book have been contributed by the most respected researchers in this area and cover the frontier areas of research and developments in crystallization processes. Divided into five parts this book provides the latest research developments in many aspects of crystallization including: chiral crystallization, crystallization of nanomaterials and the crystallization of amorphous and glassy materials. This book is of interest to both fundamental research and also to practicing scientists and will prove invaluable to all chemical engineers and industrial chemists in the process industries as well as crystallization workers and students in industry and academia.