Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 43
ISSUE 1
November
2010

Exogeneous inoculation of pure Al with use of electromagnetic field

J. Szajnar, T. Wróbel*
Foundry Department, Silesian University of Technology,
ul. Towarowa 7, 44-100 Gliwice, Poland
* Corresponding author: E-mail address: tomasz.wrobel@polsl.pl

Received 22.09.2010; published in revised form 01.11.2010

Manufacturing and processing

ABSTRACT

Purpose: In paper is presented problem concerning inoculation of pure aluminium primary structure, which is realized mainly by intensification of liquid metal movement in mould by use of electromagnetic field.

Design/methodology/approach: In aim of realization of forced movement during the crystallization of liquid metal was used rotate electromagnetic field, which is generated by induction coil fed with frequency of supply current from 25 to 100Hz. Effect of structure refinement obtained by influence of electromagnetic field was compared with refinement obtained by use of traditional inoculation, which consists in introducing of additions in form of titanium and boron to metal bath.

Findings: The results of investigations and their analysis show possibility of effective refinement of pure aluminium primary structure, only with use of electromagnetic field.

Research limitations/implications: I further research, authors of this paper are going to application of introduced method of Al casting with use of electromagnetic field in continuous casting stand.

Practical implications: The work presents refinement of structure method which are particularly important in continuous and semi – continuous casting where products are used for plastic forming.

Originality/value: The value of this paper resides in new effective method of inoculation of pure Al, which was realized only by use of electromagnetic field.

Keywords: Casting; Aluminium; Electromagnetic field; Frequency

Reference to this paper should be given in the following way:
J. Szajnar, T. Wróbel, Exogeneous inoculation of pure Al with use of electromagnetic field, Journal of Achievements in Materials and Manufacturing Engineering 43/1 (2010) 448-454.

1. Introduction

Columnar crystals which are parallel to heat flow, creates primary structure of pure metals independently from type of crystal lattice. This unfavourable structure for plastic forming of ingots can be eliminated by controlling of heat abstraction velocity from cast, change in chemical constitution and intensification liquid metal convection [1-3].

Effective method of columnar crystals zone elimination is inoculation, which consists in introducing into metal bath of specified substances, called inoculants. Inoculants increase grains density as result of creation of new particles in consequence of braking of grains growth velocity, decrease of surface tension on phase boundary of liquid - nucleus, decrease of angle of contact between nucleus and base and increase of density of bases to heterogeneous nucleation. This leads to increase of equiaxed crystals zone, which guarantees of mechanical properties improvement, decrease of constituents segregation and limitation of hot cracks. Active bases to heterogeneous nucleation for aluminium are particles which have high melting point i.e. TiC, TiN, TiB, TiB_2, AlB_2 and Al_3Ti (tab.1) [1,3-8].

In case of aluminium casting inoculants are introduced in form of initial alloy AlTi5B1. This inoculant has ratio of Ti:B equals 5:1. For this ratio of titanium and boron are created bases of type TiB_2 and Al_3Ti [3,9]. Type and amount of bases to heterogeneous nucleation of aluminium depend on ratio of Ti:B. For example in paper [9] is presented possibility of application of initial alloy AlTi1.7B1.4, which has ratio of Ti:B equals 1.2:1. This ration of Ti:B allows to increase in amount of fine phases TiB_2 and AlB_2 at the cost of phase Al_3Ti.

However, this method of inoculation of primary structure of ingot is limited for pure metals, because inoculants decrease the degree of purity specified in standards [10], and Ti with B introduced as modifying addition are then classify as impurities. Moreover, inoculants (mainly Ti, which segregates on grain boundary of Al) influence negatively on physical properties i.e. electrical conductivity of pure aluminium [3].

Table 1.
Characteristic of bases to heterogeneous nucleation formation of aluminium [10]

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	Regularna 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

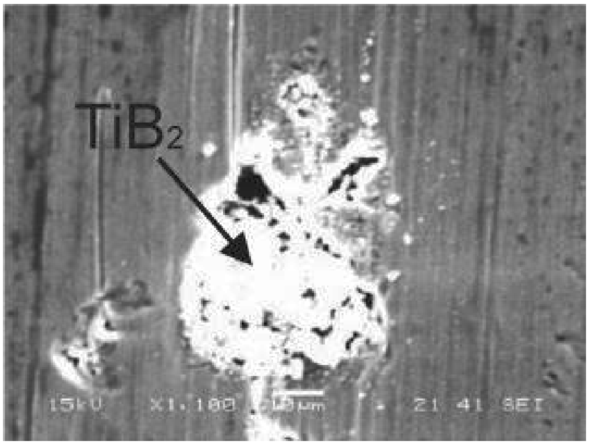
Moreover present in structure of aluminium bases to heterogeneous nucleation in form of hard deformable phases for example titanium borides, generate possibility of point cracks formation (Fig. 1) and in result of this delamination of sheet (foil) during rolling [12].

Then important is other method of inoculation, which consists in influence of electromagnetic field on liquid metal in time of its solidification in mould [3,13-15].

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 and by [3,13-15]:

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

a)



b)

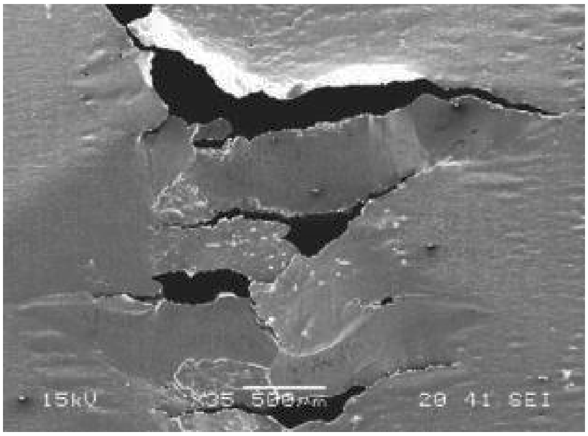


Fig. 1. Phase TiB_2 in structure of pure Al (a) and produced in result from its present crack in sheet (foil) during rolling [12]

However in papers [3,14 and 15] show that influence of forced by use of electromagnetic field liquid metal movement on changes in structure of pure metals, which solidify with flat crystallization front is insufficient. Effective influence of this forced convection calls for suitable, minimal concentration of admixture i.e. alloy addition or impurities in casting. In result of this influence of electromagnetic field can only strengthen refinement of pure metals structure, which is mainly created by introduction of small amount of inoculants to liquid metal.

2. Range of studies

The aim of studies was to develop a method of pure aluminium cast in electromagnetic field, which guarantees refinement of structure without necessity of introduction of inoculants sort Ti and B to liquid metal.

Aluminium sort EN AW-Al99.5 was melted in inductive furnace and temperature was measured with use of NiCr-NiAl thermocouple (pouring temperature was set to 740°C). Metal was poured into the graphite mould with wall thickness 10mm. Test castings as ingots with dimensions of 25mm diameter and 220mm length were cast on stand, which is presented on Figure 2.

By application of inverter was realized changes of frequency of supply current, which at constant value of current intensity (magnetic induction) makes possible regulation of inductor power and force, which generating the movement of liquid metal (Fig. 3) and in result of this the velocity of liquid metal movement in mould.

In aim of realization of refinement measurements in aluminium structure were made macroscopic metallographic studies on cross-section of ingots, which were cut at 100mm from the bottom. Analized surface was etched with use of solution of: 50g Cu, 400ml HCl, 300ml HNO_3 and 300 ml H_2O.

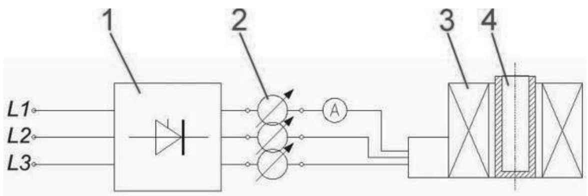


Fig. 2. Scheme of test stand: 1 - inverter, 2 - autotransformer, 3 - induction coil, 4 - mould containing liquid metal, A - ammeter

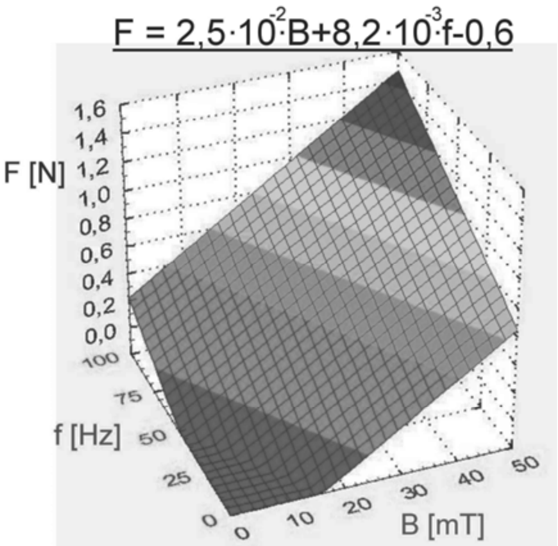


Fig. 3. Influence of frequency of supply current (f) and magnetic induction (B) on value of force (F), which generating the movement of liquid metal in mould with diameter 25mm

On the basis of the analysis of ingots macrostructure, which was made with use of computer program MultiScanBase v. 13.01 were calculated parameters of refinement:

- SKR - equiaxed crystals zone content on cross-section of ingot, %,
- PKR - average area of equiaxed crystal, mm^2,
- PKK - average area of columnar crystal, mm^2,
- L_{SKK} - width of columnar crystals zone, mm.

Moreover in aim of simultaneous regard of average area of equiaxed crystal (PKR), average area of columnar crystal (PKK) and width of columnar crystals zone (L_{SKK}) as parameters, which represent indirectly degree of primary structure refinement, was introduced factor (R) developed in paper [14].

The factor (R) is defined as field of varilateral triangle, which was created in cartesian co-ordinate system by connection of three characteristic points for each ingot i.e. PKR, PKK and L_{SKK} (Fig. 4). On the basis of assumed criterion the value of factor (R) aiming to minimum equal increase in degree of ingot structure refinement.

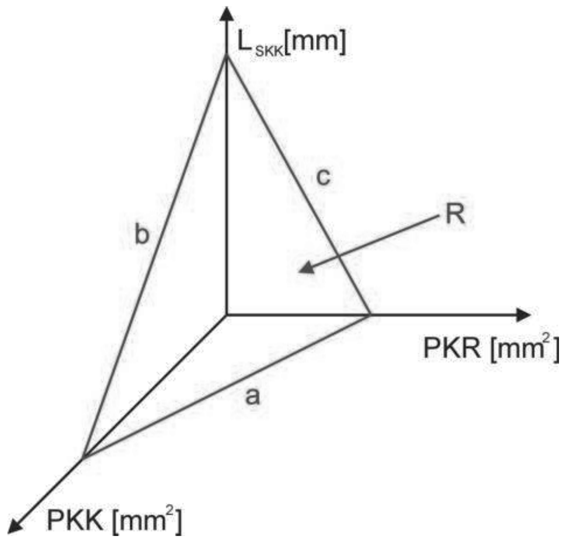


Fig.4. Graphic interpretation of refinement factor (R) [14]

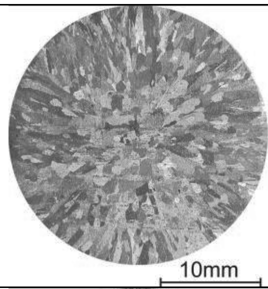
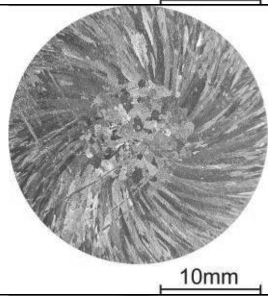
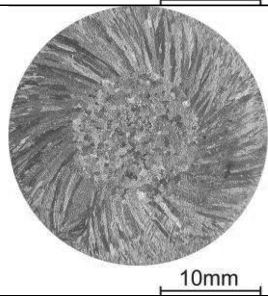
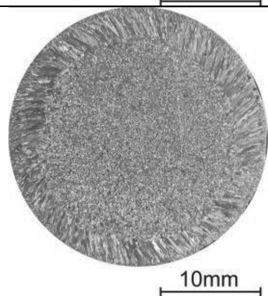
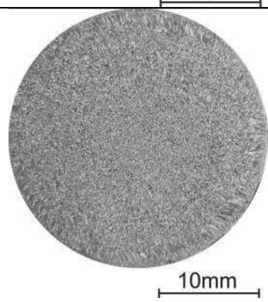
3. Results of studies

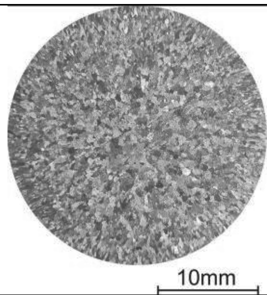
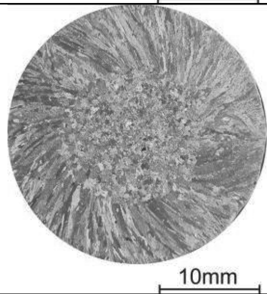
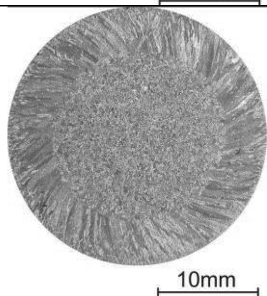
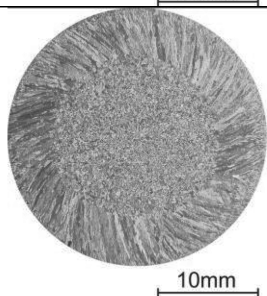
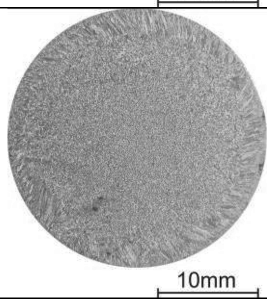
In Table 2 is presented results of macroscopic metallographic studies of pure aluminium sort EN AW -Al99.5 ingots. In initial state structure of aluminium is two-zonal, which contains mainly columnar crystals and small amount of equiaxed crystals in central area of ingot.

Increase in refinement of structure results from increase in equiaxed crystals zone content on cross-section of ingot (Fig. 5a) and decrease in average area of equiaxed crystal (Fig. 5b). This refinement was achieved by use of inoculation, which consists in introducing to metal bath of additions in form of titanium and boron in quantity suitable 25 and 5ppm.

Moreover, increase in refinement of aluminium structure results from influence of rotate electromagnetic field on liquid metal in time of its solidification in mould. However in this case effectiveness of inoculation fundamentally depends on value of frequency of supply current feeding induction coil, which generates electromagnetic field.

Table 2.
Range and results of studies

No.	Cast parameters			Refinement parameters					Macrostructure of ingot
	B [mT]	f [Hz]	(Ti+B) [ppm]	SKR [%]	PKR [mm^2]	PKK [mm^2]	L_{SKK} [mm]	R	
-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-
1	-	-		19.94	0.64	6.50	6.37	20.91	
2	60	25		15.31	0.39	7.00	7.00	24.58	
3	60	50	-	18.90	0.15	5.20	6.50	16.91	
4	60	75		54.63	0.04	2.10	3.00	3.15	
5	60	100		69.45	0.01	1.00	2.00	1.00	

-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-
6	-	-		69.83	0.42	1.05	1.90	1.10	
7	60	25		21.07	0.16	6.40	6.30	20.17	
8	60	50	25+5	30.20	0.03	4.68	5.20	12.17	
9	60	75		31.76	0.02	4.25	5.00	10.63	
10	60	100		60.28	0.01	1.10	2.60	1.43	

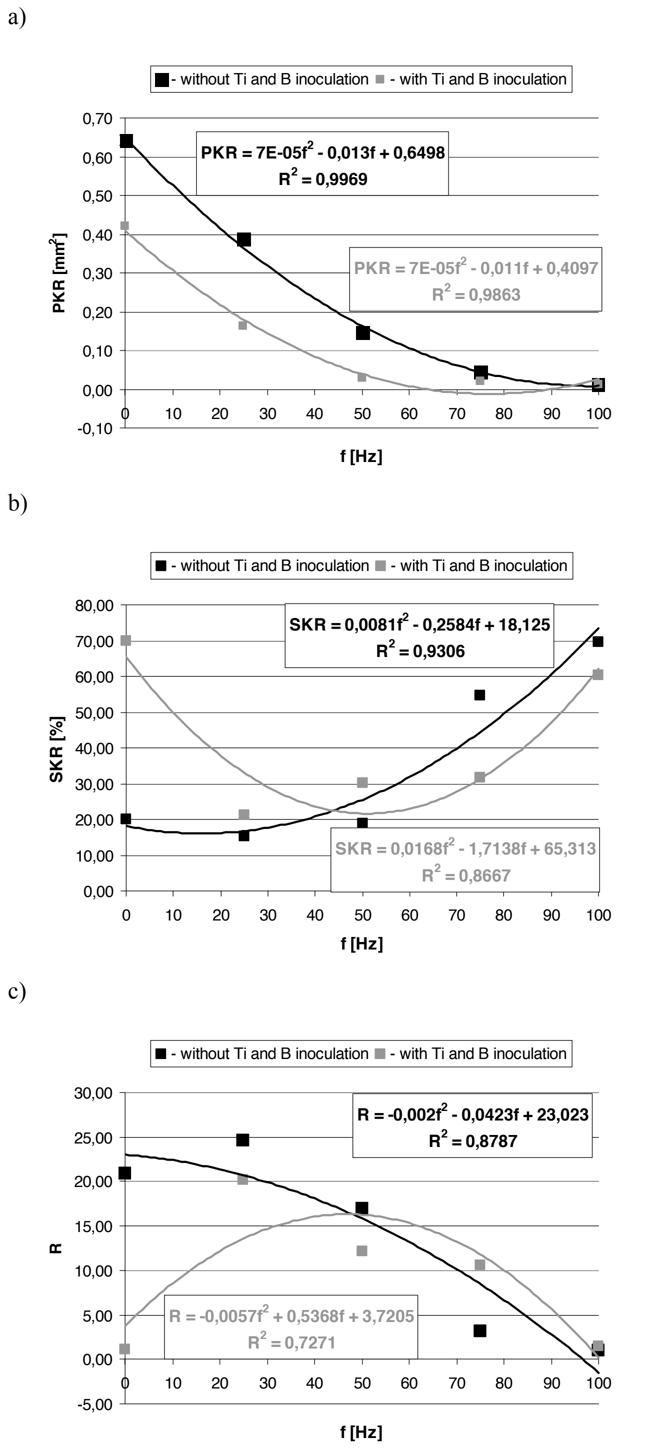


Fig. 5. Influence of frequency (f) of supply current feeding induction coil, which generates electromagnetic field on selected refinement parameters of structure of pure Al ingot

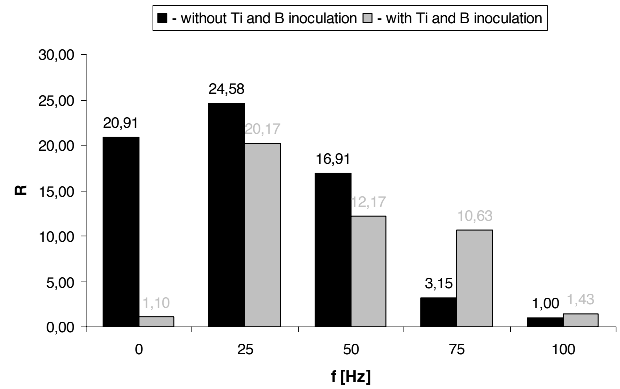


Fig.6. Value of refinement factor (R) for different versions of inoculation

Application of frequency of supply current f ≤ 50Hz does not guarantee favourable transformation of pure aluminium structure. Whereas induction coil fed with frequency of supply current larger than power network i.e. 75Hz or mainly 100Hz, generates rotate electromagnetic field, which guarantees favourable refinement of structure from point of view of assumed criterion of minimum value of factor R (Tab. 2, Fig. 5c and 6). In this case value of factor R is more favourable in comparison with value obtained for aluminium after Ti and B inoculation and after common influence of both modifying factors.

On the basis of this results was affirmed, that electromagnetic field influences on effect of inoculation, which consists in introducing of additions in form of titanium and boron to metal bath, because created bases to heterogeneous nucleation of aluminium are concentrated in central area of ingot in result from liquid metal movement with high velocities. In result of this phenomena is decreasing of equiaxed crystals zone content on cross-section of ingot and simultaneously decreasing of size of macrograins in this zone (Tab. 2, Fig. 5a and b).

4. Summary

On the basis of conducted analysis of studies results was affirmed, that rotate electromagnetic field generated by induction coil fed with frequency of supply current larger than power network, influences on 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 inoculation is important, because Ti and B decrease the degree of purity and electrical conductivity of pure aluminium. Moreover Ti and B are reason of point cracks formation during rolling of ingots. This exogeneous method of inoculation was been possible to apply in conditions of continuous casting because allows on producing of ingots from aluminium about purity 99.5% with structure without columnar crystals, which are unfavourable from point of view of usable properties.

References

[1] E. Fraś, Crystallization of metals. WNT, Warsaw, 2003 (in Polish).
[2] B. Chalmers, The structure of ingots, Journal of the Australian Institute of Metals 8 (1963) 255-262.
[3] T. Wróbel, Inoculation of of pure aluminium structure with use of electromagnetic field. Tendency of Optimization of Production Systems in Foundry - Monograph, Łódź, 2010, 253-262 (in Polish).
[4] S. Pietrowski, Modyfication of AK20 silumin with use of Ti, B and P admixtures, Archives of Foundry 43 (2000) 451-456 (in Polish).
[5] S. Pietrowski, Complex silumins, Journal of Achievements in Materials and Manufacturing Engineering 24/1 (2007) 101-105.
[6] M. Robert, E. Zoqui, F. Tanabe, T. Motegi, Producing thixotropic semi-solid A356 alloy: microstructure formation x forming behaviour, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 19-26.
[7] M. Kciuk, Structure, Mechanical properties and corrosion resistance of AlMg5 alloy, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 185-188.
[8] T. Sritharan, H. Li, Optimizing the composition of master alloys for grain refining aluminium, Scripta Materialia 9 (1996) 1053-1058.
[9] Z. Zamkotowicz, T. Stuczński, B. Augustyn, M. Lech-Grega, W. Wężyk, Sedimentation of intermetallic compounds in liquid aluminium alloys of type AlSiCu(Ti), Proceedings of the Scientific Conference Founding of Nonferrous Metals - Science and Technology (2003) 77-82 (in Polish).
[10] Polish Standard: PN-EN 573-3. PKN, Warsaw, 2005 (in Polish).
[11] J. Donnay, H. Ondik: Crystal date - Determinative Tables, NSRDS - JCPDS (1973).
[12] O. Keles, M. Dundar, Aluminium foil: its typical quality problems and their causes, Journal of Materials Processing Technology 186 (2007) 125-130.
[13] J. Szajnar, M. Stawarz, T. Wróbel, W. Sebzda, B. Grzesik, M. Stępień, Influence of continuous casting conditions on grey cast iron structure, Archives of Materials Science and Engineering 1 (2010) 45-52.
[14] T. Wróbel, J. Szajnar, Influence of supply voltage frequency of induction coil on inoculation efficiency of pure aluminium structure, Archives of Foundry Engineering 2 (2010) 203-208.
[15] J. Szajnar, M. Stawarz, T. Wróbel, W. Sebzda: Influence of electromagnetic field on pure metals and alloys structure**,** Journal of Achievements in Materials and Manufacturing Engineering 34/1 (2009) 95-102.