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MODIFICATION OF PURE Al AND AlSi2 ALLOY PRIMARY STRUCTURE WITH USE OF ELECTROMAGNETIC STIRRING METHOD

MODYFIKACJA STRUKTURY PIERWOTNEJ CZYSTEGO Al I STOPU AlSi2 METODĄ MIESZANIA ELEKTROMAGNETYCZNEGO

The paper presents modification of primary structure of Al 99,5% and 99,8% purity and AlSi2 alloy by electromagnetic stirring of liquid metal within foundry mould. The movement of solidifying liquid metal within the mould was forced by horizontal electromagnetic field produced by the induction coil (stirrer), supplied by current of elevated frequency. The structure refinement obtained by electromagnetic stirring was compared with refinement obtained by traditional modification, i.e. by introducing Ti, B, C and Sr modifying additives into melt. The results of studies show possibility of effective primary structure refinement of pure Al and selected Al-Si alloy by using only horizontal electromagnetic field, without necessity of Ti, B and C additives application.

Keywords: casting, aluminium, primary structure, modification, electromagnetic stirring

W pracy przedstawiono problematykę modyfikacji struktury Al o czystości 99,5% i 99,8% oraz stopu AlSi2, realizowanej głównie poprzez intensyfikację ruchu ciekłego metalu w formie. W celu realizacji wymuszonego ruchu krzepnącego metalu zastosowano pole elektromagnetyczne wytwarzane przez cewkę (mieszadło) zasilane prądem o podwyższonej częstotliwości. Efekt rozdrobnienia struktury uzyskany w wyniku użycia mieszania elektromagnetycznego był porównywany z możliwym do otrzymania przy użyciu tradycyjnej modyfikacji, która polega na wprowadzeniu do ciekłego metalu dodatków tytanu, boru, węgla i strontu. Wyniki badań oraz ich analiza pokazały, że istnieje możliwość skutecznego rozdrobnienia struktury pierwotnej czystego Al i wybranego stopu Al-Si tylko przy użyciu mieszania elektromagnetycznego bez konieczności stosowania dodatków modyfikujących tj. Ti, B i C.

1. Introduction

Generally the primary structure of ingot creates three major structural zones. In the direction from mould wall to the ingot core the first zone of chilled crystals is formed by equiaxed grains with random crystallographic orientation and placed in the contact area between the metal and the mould. The second zone of columnar crystals (grains) is formed by elongated crystals, which are parallel to heat flow and are a result of directional solidification, which proceeds when the thermal gradient on solidification front has a positive value. Finally, the third zone of equiaxed crystals (grains) is formed by equiaxed grains with random crystallographic orientation in the central part of the casting. The equiaxed crystals have a larger size than the chilled ones and they are result of volumetric solidification, which proceeds when thermal gradient has a negative value in liquid phase [1, 2]. Unfortunately, the primary structure of pure metals creates practically only columnar crystals, independently of the crystal lattice type, and in case of non-modified alloys it creates a coarse equiaxed crystals [2÷5]. According to presented data in [2, 4, 5], this type of primary structure leads to low mechanical properties of castings and is unfavourable mainly for the plastic forming of continuous and semi-continuous ingots, because of causing reduction of forces extrusion rate. Furthermore, delamination of external layers can occur during the ingot rolling. The factors which help to eliminate this unfavourable primary structure of ingot through its refinement are [2, 4÷11]:

– traditional modification which consists in the introduction of additives to liquid metal,
– control of heat removal rate from the ingot by regulation of technological parameters of cast process such as pouring temperature or thermal conductivity of mould material,
– influence of physical factors such as infra- and ultrasonic vibrations or electromagnetic field on solidifying metal.

In the case of traditional modification the refinement of primary structure is a result of creation of phases which are substrates of heterogeneous nucleation of modified metal. Therefore active centres of aluminium heterogeneous nucleation are particles which have high melting point and close crystallographic match with Al, e.g. TiC, TiN, TiB, TiB_2, AlB_2, Al_3Ti and Zn_3Ti[2, 6, 9, 12-14].

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Moreover, the changes of ingot primary structure can result from influence of electromagnetic field and they can be achieved by forced movement of liquid metal during its solidification in mould. In this case the refinement results mainly from mechanism connected with thermal and mechanical erosion of crystallization front [4, 5, 10, 11]. However, according to the data presented in [4, 5] refinement of primary structure caused by electromagnetic stirring is much smaller than the one achieved by traditional modification with use of additives introduced to liquid metal.

Therefore the aim of this paper is to describe a new effective method of modifying pure Al and AlSi2 alloy primary structure. The method is based only on electromagnetic stirring without necessity of application of modifying additives. In assumption this method of primary structure refinement can be applied in continuous casting technology of Al and Al-Si alloys ingots.

2. The range of studies

During these examinations the effectiveness of primary structure refinement of pure Al and AlSi2 alloy, obtained in traditional refinement of α(Al) by introducing master alloys AlTi5, AlB3, AlTi5B1, AlTi5B3 and AlTi3C0.15, was compared with the effectiveness of melt electromagnetic stirring.

In the first stage aimed at evaluating efficiency of different master alloys, cylindrical ingots of Al of purity of 99,5% were cast to graphite mould (pouring temperature 740°C). In this case small amounts of the modifying additives, i.e. Ti, B and C, were introduced into metal bath, not exceeding the values specified in the obligatory European Standards. In these studies the authors assumed that amount of all the introduced additives $M \leqslant 30$ ppm. In the second stage of studies, aimed at optimizing parameters of electromagnetic stirring, cylindrical ingots of Al of purity 99,5% were cast into graphite moulds (pouring temperature T_p 740°C) with use of stand consisting of source of electric energy, inverter, autotransformer, ammeter and induction coil (stirrer). In the second stage studies a three-phase electromagnetic stirrer with a maximum power 3kW at rated current of 8A was used (Fig. 1). The efficiency of influence of horizontal electromagnetic field on intensity

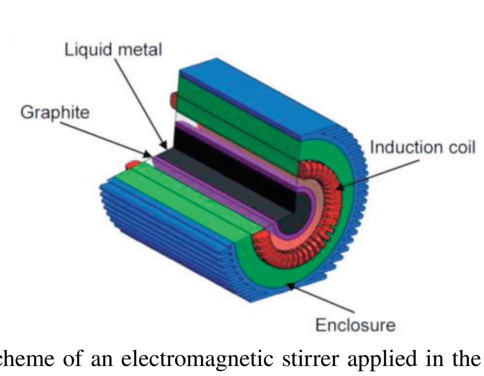

Fig. 1. Scheme of an electromagnetic stirrer applied in the studies

of liquid metal stirring depends mainly on value of magnetic induction inside the induction coil. However, authors of this paper showed that there is possibility of increasing the force which creates movement of liquid metal (and as result of this the velocity of its rotation in mould) also by increasing the frequency (f) of the current supplied to the electromagnetic stirrer (Fig. 2).

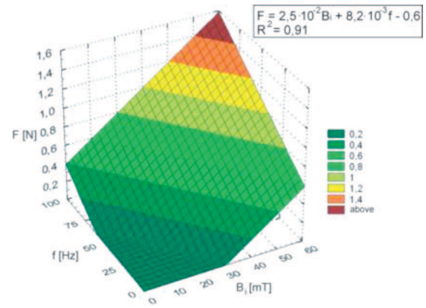

Fig. 2. The common influence of magnetic induction (B_i) and frequency (f) of the current supplied to the electromagnetic stirrer, creating force of value (F), which creates movement of liquid metal

For selected master alloy and fixed parameters of electromagnetic stirring, i.e. magnetic induction (B_i) and frequency (f) of the current supplied to the induction coil, the ingots of Al 99,8% (T_p 740°C) and AlSi2 alloy (T_p 720°C) were cast. Additionally, a master alloy AlSr10 was used for modification of eutectic α(Al) +β(Si) of the AlSi2 alloy. In all stages of the studies the degree of primary structure refinement was represented by equiaxed crystals zone content (SKR) on transverse section of ingots and by average area of macro-grains in this zone (PKR). The examinations of structure refinement of pure Al and AlSi2 alloy were made using macroscopic metallographic studies on transverse section of ingots. The macroscopic analysis of pure Al and AlSi2 alloy was performed by chemical etching of surfaces using solution: 50g Cu, 400ml HCl, 300ml HNO_3 and 300 ml H_2O while the microscopic analysis of the AlSi2 alloy was performed using electrolytic polishing and etching by solution A2, according to [15].

3. The results and analysis of studies

In Fig. 3 there are presented results of macroscopic metallographic studies of 99,5% purity Al ingots. In initial stage the primary structure of aluminium is two-zone, which contains mainly columnar crystals and small amount of equiaxed crystals, located in central area of ingot. The increased refinement of primary structure, observed on transverse section of ingot, results from increased zone of equiaxed crystals and decrease of average area of the equiaxed crystal. This refinement was achieved by using the traditional grain-refinement, i.e. by inoculation melt through addition of titanium and/or boron and/or carbon. The best refinement was obtained after using the AlTi5B1master alloy, with respect to the values of SKR and PKR factors. It confirms that the Ti : B ratio of 5 : 1 assures the greatest degree of structure refinement in comparison with others Ti : B ratios, for example 5 : 3. Moreover, more advantageous influence of B (introduced with AlB3 master alloy) on structure refinement of pure Al was observed in comparison with the examination when only Ti addition was used. Replacement of B with C, for example in AlTi3C0.15 master alloy, weakens the effect of modification. This statement is confirmed by the refinement results obtained for ingots modified with commonly used AlTi3C0.15 and AlB3 or AlTi3C0.15 and AlTi5B1 master alloys.

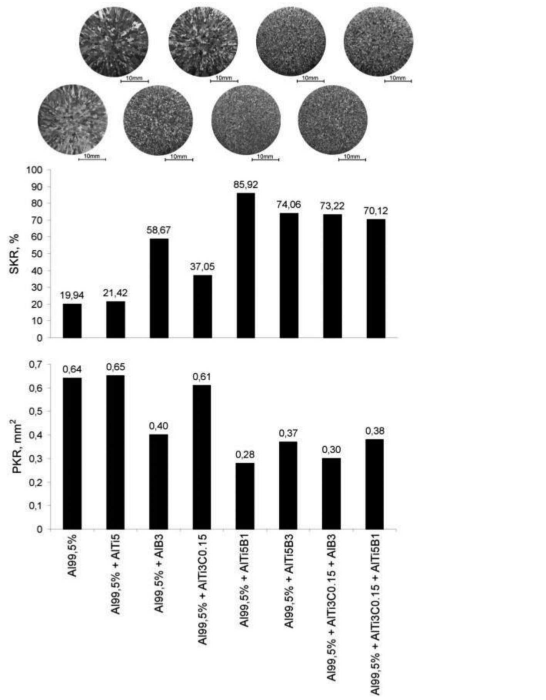

Fig. 3. The influence of master alloy type on the degree of Al (99,5% purity) primary structure refinement

However, this effective method of modification has three faults in comparison with modification basing on physical factors, for example electromagnetic stirring, i.e.:

– modifying additives decrease the purity degree of Al, specified in obligatory standards,
– modifying additives decrease the physical properties of pure Al, e.g. electrical conductivity, mainly due to Ti segregation on grain boundaries of Al, as was shown in [5],
– the hard phases – substrates of heterogeneous nucleation of α(Al), i.e. Ti borides, Ti carbides, Ti nitrides, Ti aluminides and Al borides can cause point cracks formation during rolling ingots of Al alloys, as it was shown in [16].

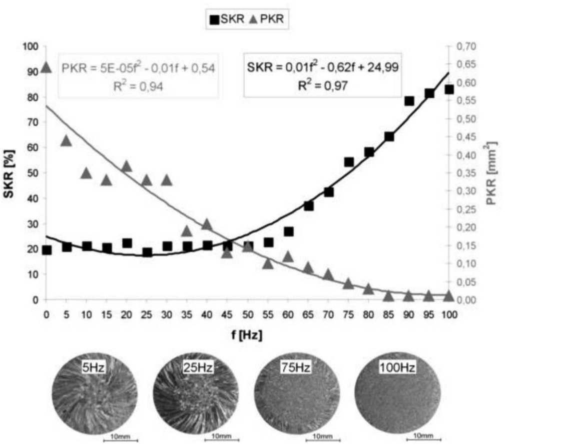

Fig. 4. The influence of current frequency (f) supplied to the stirrer on equiaxed crystals zone content (SKR) revealed on transverse section of Al ingot of purity 99,5% (a) and average area of equiaxed crystal (PKR) of the same Al ingot

Fig. 4 presents selected results of macroscopic metallographic studies of Al ingots (purity of 99,5%) cast after electromagnetic stirring. The stirring was generated by a stirrer supplied with different frequency of current of intensity I = 10A, which corresponds to magnetic induction B_i = 60mT. On the basis of the obtained results it was stated that supplied current of frequency f ⩽ 50Hz does not guarantee favourable transformation of pure aluminium primary structure. On the other hand, the electromagnetic stirrer supplied with current of frequency larger than power network, mainly 100Hz, generates horizontal electromagnetic field, which guarantees favourable refinement of primary structure, also greater in comparison with the one obtained after modification with small, acceptable by the European Standards, amounts of Ti and B, i.e. 25 and 5 ppm.

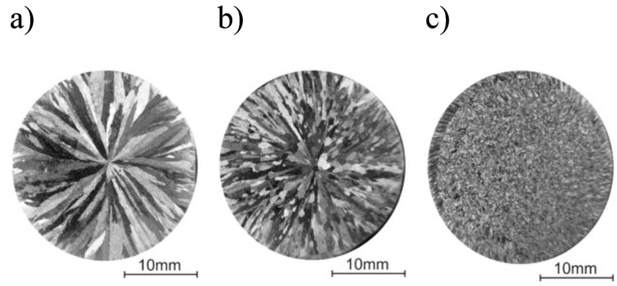

Fig. 5. Macrostructure of aluminium ingots of 99,8% purity in initial stage (a) and after modification by AlTi5B1 AlTi5B1 (25ppm Ti; 5ppm B) (b) after modification using horizontal electromagnetic field:B_i = 60mT and f = 100Hz

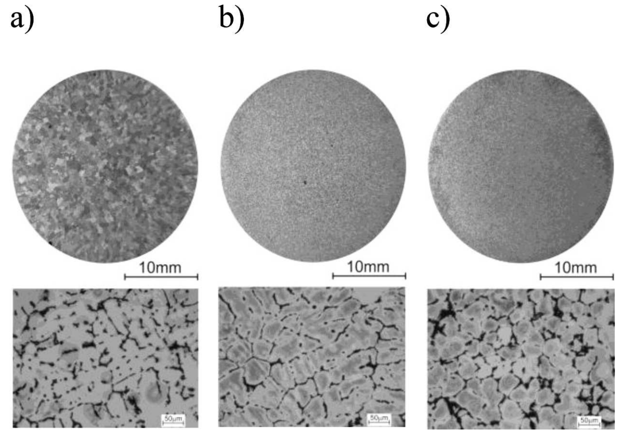

Fig. 6. Macro- and microstructure of AlSi2 ingots in initial stage (a) and after modification using AlTi5B1 and AlSr10 master alloys (Ti = 0,1%mas., B = 0,02%mas., Sr = 0,01%mas.) (b) after modification using horizontal electromagnetic field: B_i = 60mT and f = 100Hz

Analogous results were obtained in case of Al 99,8% purity, which in initial, non-modified stage has primary structure containing only columnar crystals (Fig. 5). As in the previous case, larger degree of refinement of Al 99,8% primary structure was obtained after using horizontal electromagnetic field, generated by the stirrer supplied by current with elevated frequency of 100Hz, but in smaller degree than after using traditional inoculation with AlTi5B1 master alloy, by adding 25ppm Ti and 5ppm B. Of course, according to the higher purity of Al 99,8%, the primary structure refinement using the same method is smaller than for lower purity Al99,5%. In case of AlSi2 alloy, both modification methods, i.e. Ti and B additives or horizontal electromagnetic field assure total refinement of primary structure of ingots (Fig. 6). However, modification of eutectic (α(Al) +β(Si)) with Sr addition is more effective than the influence of the electromagnetic stirring.

4. Conclusions

Basing on the conducted examinations the following conclusions have been formulated:

1. Even a very small amount of modifying additives introduced to metal bath in the form of Ti, B and C or Ti, B and Sr guarantees a significant increase of primary structure refinement of pure Al and AlSi2 ingots.
2. The master alloys containing Ti and C have worse effect on refinement of pure Al primary structure than the master alloys containing Ti and B.
3. The horizontal electromagnetic field generated by stirrer supplied by current with elevated frequency of 100Hz, influencing liquid metal during its solidification in mould, guarantees effective refinement of primary structure of pure Al and AlSi2 alloy without necessity of application of modifying additives, such as Ti and B (Fig. 7). This method of modification is important, because modifying additives decrease the degree of purity and electrical conductivity of Al. Moreover, these modifying additives are the reason of point cracks formation during rolling of ingots.

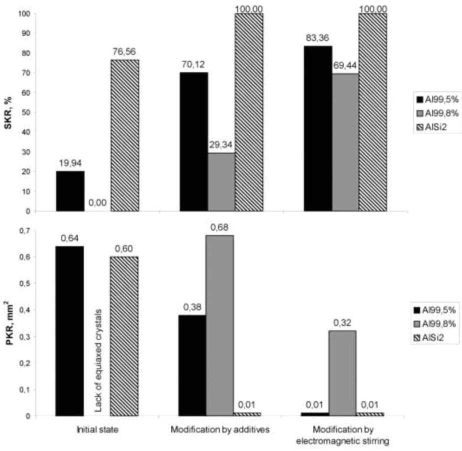

Fig. 7. Characteristics of primary structure of pure Al and AlSi alloy in initial stage, after modification by Ti, B and/or Sr additives and after modification by use of electromagnetic stirring

a) b)

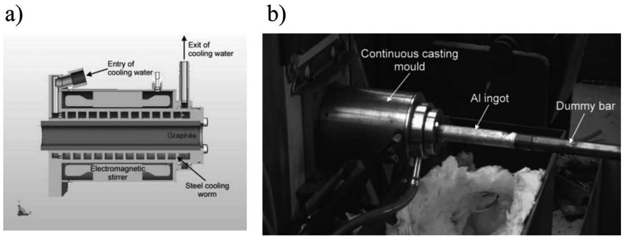

Fig. 8. Scheme (a) and view (b) of continuous casting mould containing electromagnetic stirrer, which is a part of stand of continuous casting of Al and its alloys, developed and manufactured at Foundry Department of Silesian University of Technology in Gliwice, Poland

4. Modification of eutectic (α(Al) +β(Si)) with Sr is more effective than modification by electromagnetic stirring, which effectively reduces only α(Al) size.
5. The results of the conducted studies can be useful in development and manufacturing of a stand of continuous casting of Al and its alloys with electromagnetic stirrer (Fig. 8), which make it possible to obtain primary structure refinement without using modifying additives.

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