A. V. YURCHENKO, Z. D. ZHOLDUBAYEVA, D. K. ISSIN, A. D. MEKHTIYEV, A. D. ALKINA, V. I. SYRYAMKIN

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REDUCTION OF THE CONTENT OF HARMFUL IMPURITIES DURING TECHNICAL SILICON MELTING USING THE FILTERING METHOD

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The article discusses the filtration method of cleaning silicon, the possibility of mechanical separation of inclusions, the effect of capillary phenomena, the wettability of the filter material on the efficiency of cleaning silicon from impurities. There are also considered the advantages of bulk granular filters which consist of the lumpy or granulated elements. There are described the methods of obtaining filtering elements, the functions executed by the filters depending on their type. There are presented the analysis results obtained in filter refinement of silicon which show the impact of different filters materials on the content of impurities.

Key words: silicon, refining, filter, wettability, filter elements.

INTRODUCTION

According to UNESCO [1], 75 % of the population living in developing countries accounts for only 25 % of world energy consumption. Over two billion people in these countries live without electricity [2].

At the same time, the solar flux falling on the Earth is an almost inexhaustible source of heat and light. The amount of solar energy supplied to the Earth is 3*1 024 J/kg, which significantly exceeds the amount of all world reserves of oil, gas, coal, uranium, and other energy resources (4,3*1022 J) [3]. Therefore, the problem of converting solar energy is becoming topical. Using even a small fraction of solar energy allows solving the energy problems on the Earth. This way of solving the energy problem is very attractive because it is ecologically safe and does not require long heating cycles and rotating mechanisms such as high-pressure turbines and generators.

Among the wide class of semiconductor materials used in solar energy, the leading position belongs to crystalline silicon films [4]; moreover, it will keep this leading position in the near future [5]. Currently, other types of solar cells account for less than 10 % of manufactured products [6]. The continuous increase in the production of photovoltaic modules has led to a shortage of silicon as the main material for their production. Today, silicon from three sources is used for the production of solar cells. The first source is off-grade semiconductor silicon (scrap), a traditional raw material for solar energy. The amount of scrap in the market is limited and makes up about 3,000 tons. The second source is mono- and multi-silicon obtained from polysilicon for the semiconductor industry. Because of the lack of scrap in the market, silicon obtained from polysilicon for use in the semiconductor industry is also used in the production of solar cells. However, unlike the semiconductor industry, where the price of silicon has little effect on the final cost of products, the cost of material in the production of photovoltaic modules makes up nearly 60 % [7]. Therefore, the use of semiconductor silicon significantly increases the cost of the modules. The third source of (SG-Si) is polysilicon obtained using the simplified Siemens technology [8]. To reduce the cost, the simplified cycle of production and purification of polysilicon is used; however, the use of the chlorination cycle and subsequent recovery does not allow for a radical reduction in the cost of silicon.

Thus, the limited amount of “solar type” silicon and its high price are constraining intensive growth in the production of solar modules [9].

Growth in the production of solar energy systems requires a radical reduction in the cost of silicon for solar cells and a significant increase in silicon supply to the market. In 2013, Kazatomprom, JSC (Astana, Republic of Kazakhstan) launched AstanaSolar, LLC, which is a subsidiary enterprise for assembling photovoltaic modules. It operates under the French technologies and has a full production cycle including raw material extraction, silicon smelting, and photovoltaic plate production; coefficient of efficiency of plates makes up 16,5 %. The designed capacity of the enterprise is about 60 MW with a future expansion up to 100 MW. Astana Solar produces two main types of photovoltaic modules

A. V. Yurchenko (nipp@inbox.ru), V. I. Syryamkin National Research Tomsk State University, Tomsk, Russian
Zh. D. Zholdubayeva, D. K Issin, A. D. Mekhtiyev, A. D. Alkina, Karaganda State Technical University, Karaganda, Kazakhstan

KZPV 230 M60 (215-245 W) and KZPV 270 M72 (250-300 W). In case of the state support of domestic producers and subsidies, the factory cost of solar cells ranges from 140 to 190 US dollars depending on the power. Currently, there is a huge need in the production of high-quality silicon at a lower cost, which may have favorable impact on development of Kazakhstan production of solar modules and their import to foreign countries.

One way to improve the quality of silicon is filter refining. The high refining effect achieved in this case is explained by the fact that the entire volume of the melt is filtered sequentially, and the process itself can be carried out directly when casting metal from furnace into the ladle or when pouring metal into the mold, crystallizer, or mould. This reduces the amount of both primary and secondary non-metallic inclusions formed by the time of filtration, decreases oxygen activity, and the subsequent contamination of the melt is eliminated partially or completely [10].

THEORETICAL ASPECTS OF THE FILTERING MECHANISM

There are different types of filters. *Volumetric* filters, which include ceramic foam filters (CFF) and granular filters, are considered the most efficient ones and are used worldwide [11–12].

Today, it is generally accepted that filtering primarily allows the elimination of non-metallic inclusions (NMI) from metals and alloys. The filtering effect is mainly due to removing non-metallic impurities suspended in a metal melt.

A distinctive feature of granular filters is their large contacting surface with the metal during the filtering process and the presence of long thin intergranular channels of variable cross section, which enable more effective removing of both large- and fine-dispersed inclusions from the melt.

A lump filter is produced by crushing a refractory material with its further sifting in order to obtain pieces of a certain size. Filtering elements in the form of granules are obtained either by pressing or by the corresponding powder rolling. The first method allows obtaining high-quality filtering elements but is time consuming and inefficient, and the resulting elements are characterized by low porosity.

Depending on their type, the filters can perform the following functions: 1) mechanical sieve and 2) adsorbing medium (Figure 1).

In the first case, large inclusions are removed, the size of which is larger than the size of the filter pore channels (Figure 1, a). Because this sorting of particles occurs on the input side of the filter (along the melt flow), this mechanism is called surface or grid (sieve). Such refining is common to two-dimensional filters (plate, grid, and funnel-shaped). A variation of the grid mechanism is the grid and cake method for removing

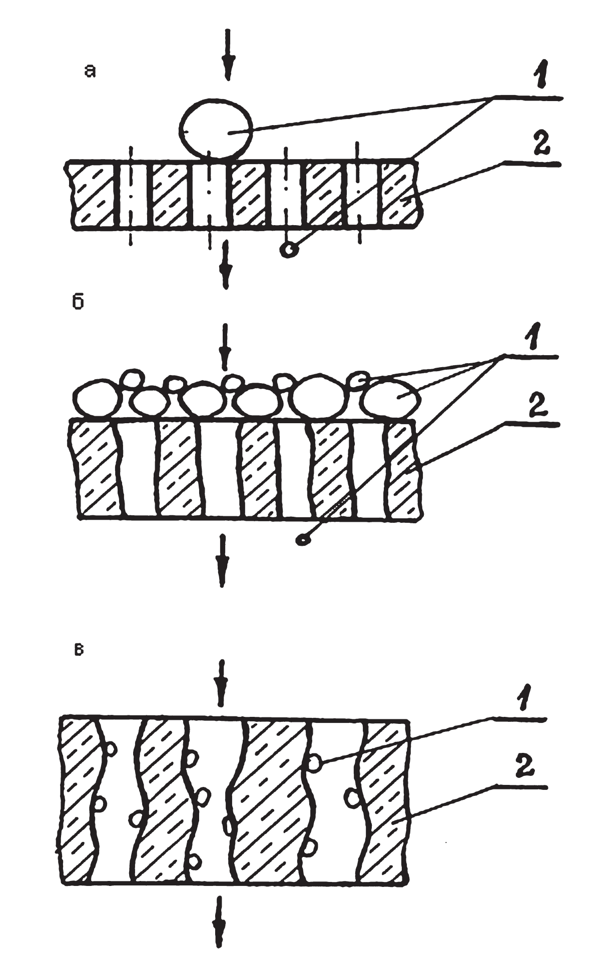

Figure 1 The mechanism of filter refining of liquid metals from suspended non-metallic inclusions [3]: 1 – non-metallic inclusion, 2 – filter; a) grid; b) grid and cake; c) – adhesive

non-metallic inclusions; according to this method, as inclusions deposit in the upper layer of the filter, the size of intergranular channels decreases and, therefore, smaller inclusions can be separated (Figure 1, b).

In the second case, the melt is cleared from fine-dispersed inclusions, some of which inevitably collide with the surface of channels when moving inside the filter through its branched channels; these inclusions deposit on the surface of channels and are held by adhesion forces. Therefore, such a mechanism for trapping non-metallic inclusions is called internal or adhesive (Figure 1, c).

Unlike two-dimensional filters, volume filters (ceramic foam and even more granular) perform both of these functions.

The possibilities of mechanical separation of inclusions during the melt passage through the filter are largely determined by capillary and hydrodynamic effects.

The effect of capillary phenomena on the completeness of the separation of inclusions is associated with the nature of wetting filter materials by the metal melt. If the liquid metal does not wet the filter material (wetting angle θ – 90 °), the melt is forced to flow through the pore channels of large diameter, which means that only inclusions larger than the minimum jet diameter can be removed from the melt. This means that the effectiveness of the grid effect is reduced. In the case when the metal *wets* the filter material ($\theta < 90^{o}$), the capillary pressure promotes the retraction of the melt into narrow channels, hence the minimum diameter of the channels filled with the metal decreases. Because of the grid effect, the cleaning efficiency of melts increases. The ability of alloys to fill the intergranular channels of the filters also depends on the magnitude of their surface tension; with its increase, the filling of thin channels with the melt becomes difficult because additional forces are required to overcome the tension.

METHODS AND EXPERIMENTAL WORK

Because the filtration of metal melts is usually carried out through non-wetting refractory materials, the minimum diameter of the capillaries must be not less than 1 - 2 mm; therefore, it is necessary to use filter grains of at least 4 - 6 mm.

Figure 2 shows the appearance of components of the filter section: a graphite funnel (1), two graphite grids (2) installed in the funnel (1), and filter elements (3) placed between grids.

In a granular filter, refining of the melt from nonmetallic inclusions by the hydrodynamic mechanism occurs as a result of their falling out of the flow under the action of gravity, friction against the walls of intergranular channels, changes in the flow velocity when moving from narrow to wide channels, etc. The cleaning efficiency is affected by the following parameters: inclusion and melt density difference, the ratio of the average diameter (D) of the channels (chan) to the average (av) diameter (d) of inclusions (incl) $D_{av.chan}/d_{av.incl}$, and the speed and mode of melt flow through the filter channels. Usually, metal melts are filtered under the action of a slight excessive metallostatic pressure using filter elements with a diameter of at least 4 - 5 mm.

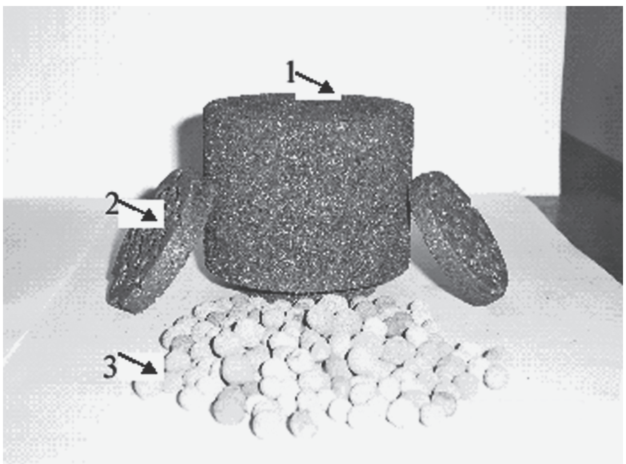

Figure 2 Appearance of composite components of the filter section

CONCLUSIONS

The results of spectral analysis show that the content of such elements as aluminum, calcium, copper, lead and sulfur decreased markedly. At the same time, we should note that the effect of silicon filter refining from impurities depends on the nature of the filter material. For example, the efficiency of cleaning silicon from calcium is 48 and 27 % when using a magnesite and corundum filter respectively, and is 60 % when filtered through a quartzite filter. Similar results are gained when cleaning silicon from copper. Corundum and quartzite filters turned out to be effective (62 %) when cleaning silicon from aluminum. In the case of silicon refining from lead, the MgO filter has no effect and the efficiency of the corundum and quartzite filters is approximately the same (70 – 60 %).

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Note: Translated from Russian into English by Tatiana B. Rumyantseva, a translator at the International Laboratory “Vision systems” of National Research Tomsk State University