Specifics of highly concentrated heat source influence on stone casting of technogenic and mineral raw materials

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Abstract. Extension of mineral and technogenic raw materials scope, in particular gabbroid and basaltoid groups of Ural region is an important issue since Perm region and nearby regions contain large reserves of both natural and technogenic (waste and screening from mining complexes) raw materials. One of possible ways to get new types of products from mineral raw materials is plasma arc treatment that is a highly concentrated heat source. Using plasma arc for the synthesis of stone casting silicate-oxide components from natural and technogenic raw materials makes producing new elements of various functional purpose possible. Varying technological parameters of the synthesis enables to produce materials of different shapes - granules, powder, fiber, and cast material.

1. Introduction
It is known that production process of a homogeneous oxide-silicate melt under low-temperature plasma conditions has two stages, namely, simultaneous melting of all components at 1800 - 2000 °C temperature and their homogenization that happens with temperature above 2000 °C. At the same time melt production process at technical heating rates is also known and it consists of four stages: eutectic melt formation, dissolution of refractory components in this eutectic melt, production of heterogeneous melt and its homogenization [1, 2]. Using direct action plasma arc technology differs from the known technologies in the stage of melt homogenization that is not fully achieved because of high speed of reactions, dynamic effect of plasma gas (air) and as a result of high cooling rate as well as refractory components contained in the initial mixture.

2. Selection of raw materials and technical parameters of products
The silicate charge under consideration contains oxides SiO₂, TiO₂, Al₂O₃, FeO + Fe₂O₃, MnO, MgO, CaO, K₂O + Na₂O, Cr₂O₃, has more refractory components (table 1).

Table 1. Composition of furnace burden based on technogenic raw materials

| Type of stone casting silicate melt | SiO₂ | Al₂O₃ | FeO | Fe₂O₃ | MgO | CaO | Na₂O | K₂O | TiO₂ | CaF₂ | Cr₂O₃ |
|-----------------------------------|------|-------|-----|-------|-----|-----|------|-----|------|------|-------|
| Oxide content, wt. %              |      |       |     |       |     |     |      |     |      |      |       |
Silicate-chromite type (hornblendite, Kachkanar mining and processing plant, Sverdlovskaya region)  43-45  15-16  3-5  5-8  8-9  9-17  2.5-4  1-1.5  1.5-2  2-2.5

Refractory chromium oxide interacts with carbon and forms a small amount of free chromium and carbon dioxide; as chromium interacts with oxygen almost immediately (there are quite a lot of free oxygen ions, since they are released during dissociation of silicon dioxide and plasma-forming gas - air) or immediately reacts with carbon to form chromium carbide.

Chromium carbide reacts with oxygen to form chromium oxide again (also secondary) and carbon oxide and then secondary chromium oxide interacts with iron oxide (that presents in the melt as a decomposition product of magnetite), resulting in a mineral-like compound - chromite (1). Presence of such reaction is possible under conditions of high temperatures and a sufficient concentration of carbon dioxide, for example, when a conductive graphite substrate is used. Any electrically conductive material with a high melting point (copper, tungsten, graphite) can be used as a conductive substrate necessary for formation and stable combustion of a direct-action plasma arc.

In the greater mass of resulting melt there is a high concentration of oxygen ions, it is significantly higher than carbon dioxide concentration when using a graphite substrate. Calcium oxide is also present in the melt and therefore there is a reaction where chromatite is formed (2):

\[
\begin{align*}
\text{Cr}_2\text{O}_3(\text{solid}) + \text{FeO}(\text{liq.}) & \rightarrow \text{FeCr}_2\text{O}_4(\text{solid}) \quad (1) \\
2 \cdot \text{Cr}_2\text{O}_3(\text{solid})+ 4 \cdot \text{CaO}(\text{liq.}) + 3 \cdot \text{O}_2 & \rightarrow 4 \cdot \text{CaCr}_2\text{O}_4 \quad (2) \\
\text{CaO}(\text{liq.}) + \text{SiO}_2(\text{liq.}) & \rightarrow \text{CaSiO}_3(\text{solid}) \quad (3)
\end{align*}
\]

Viscosity of the rock melt is one of the important factors of production under plasma arc influence on purpose to produce granules or fibers. According to the results of calculations (figure 1, a), graphical dependences were obtained describing viscosity values of gabbro-diabase melts of Ural region (figure1, b) [3].

**Figure 1.** Viscosity - temperature value dependency of Ural region gabbroid group raw materials: a – viscosity logarithm, $\lg \eta$; b – viscosity value, Pa $\cdot$ s
Refractory components such as MgFeCr$_2$O$_4$ that harden at 1650-1800 °C as well as complex oxide compounds based on Cr$_2$O$_3$, CaO and SiO$_2$ (3), do not have time to melt under short plasma arc influence but reach the necessary viscosity state for plasma jet blowing forming fibers.

According to findings, viscosity of the resulting melt from mineral raw materials is 130–250 Pa ∙ s at 1400 °C, that goes in accordance with requirements of petrurgical raw materials for mineral fiber production. However, taking into account dynamic effect of plasma arc as well as effect of plasma gas (air) that are conducive to formation of fibers, the range of the required viscosity can be wider.

3. Description of the experiments

Such products as mineral wool used in producing of basalt fibers, is widely known as raw material with high availability, relatively low cost, average chemical composition, favorable melting and toughness for producing this class of products [4]. In this work, rocks of gabbroid group are used for mineral fibers production [5], that are less common due to their high melting temperatures, lower melt ability and melt viscosity. However, there is a large number of screenings of these rocks available on Ural region territory and besides under high-temperature dynamic effects of plasma arc, these disadvantages can be eliminated.

Plasma technology for mineral (ceramic) fibers production is based on using a plasmatron to get a stream of high - temperature gas (air, argon, nitrogen, etc.). Furnace burden melts in a special chamber under plasma influence, Liquid melt is blown up by the gas flow and a large amount of fine mineral fibers is formed [6-8].

There are known methods [9] for producing mineral wool using gas - flame burners, however, plasma equipment has several advantages, in particular:

1) Plasmatron gives a significantly higher temperature and provides more efficient melt blown and as a result, thinner fibers.
2) Plasmatron enables temperature adjusting of in a wide range and so it is possible to select optimal modes for producing fiber.
3) Plasma arc technology can significantly reduce energy consumption.
4) Long service life of plasmatrons before replacing the electrodes (500 to thousands of hours) with a short time to replace the electrodes that is up to 15 minutes [10].

Plasma cutting system with a direct-action plasmatron was used to get laboratory samples of mineral fibers based on gabbro - rocks from Pervouralsk deposit, the arc was ignited on tungsten substrate.

For feeding plasma jet to the zone of action gabbro-rocks were crushed to the state of a finely dispersed charge of fractional composition up to 0.1 mm and mixed with liquid sodium glass so that the charge did not scatter under plasma jet influence and also melted easier and formed fibers.

Figure 2 (a) shows how a particle is lengthened under the action of high temperatures and plasma jet dynamic effect, forming a fiber [11].
Figure 2. Gabbro-rocks mineral fiber (hornblendite): a – granule that is not lengthened and blown up to fiber under plasma jet influence, x100, b – lengthened fiber in one direction, x500, c – fiber, x3000, d – fiber with deposited oxide layer of tungsten x10000.

A distinctive feature of production of fibers is melting of charge in a direct-action plasma arc. Despite the fact that plasmatron is designed for air plasma cutting of metals, there is possible easy adjustment of equipment for mineral fiber production. The thickness of fibers is in a wide range from 500 nm to 20 μm (Figure 2 b, c). The thickness of fibers is affected by many parameters, including feeding rate of the charge on the binder, the ratio between gabbro-rocks and sodium liquid glass, fractional composition of the charge, flow rate and gas pressure, the mode of operation of the plasmatron, etc.

There is a deposited finely dispersed layer with particles less than 100 nm on the surface of the fibers. Scanning electron microscopy with microprobe analysis showed that chemical composition of the layer consists mainly of tungsten oxide (W = 70.6 wt.%). Particles found on the fiber in form of solid components of aerosols are formed as a result of a partial burning out of tungsten substrate that the arc was ignited on. Oxidation of metallic tungsten in oxygen atmosphere at temperature above 500 °C [12, 13] goes by the reaction

$$2 \cdot W + 3 \cdot O_2 \rightarrow 2 \cdot WO_3$$  \hspace{1cm} (4)

Formation of tungsten oxide on the surface of fibers is confirmed by presence of yellow pigment on fibers and it is often used for coloring glasses and ceramics that are adjacent in composition and structure of products.

Using granulation pool and adjusting thermal regime of plasma arc (power, speed and pressure of gas supply), granulated welding flux can be obtained from the natural and technogenic raw materials of gabbroid group in a wide range of fractional composition.

After plasma arc influence, produced welding flux granules are homogeneous and have a uniform favorable spherical shape with particle size from 0.2 to 3 mm that corresponds to fractional composition of welding fluxes [14].

In granulation process of mineral raw materials based on gabbroid group there is a slight change in chemical composition of granules, but the processes leading to the change are well studied and can be predicted with the further development of welding materials with a specified chemical composition.

Silicate-oxide materials are in demand in many industries, including defense industry, however, their use is limited by forming technological possibilities. Therefore, the expansion of range of technological solutions for shaping products from silicate-oxide materials is an important issue [15].

Using plasma arc to melt furnace burden of natural or technogenic raw materials can significantly speed up the melting process with less energy (on average in 2 times). Silicate-oxide melt is formed under conditions of constant influence of plasma jet to the charge in the melting pot, that can be shaped into a product by casting method.

Stone casting silicate-oxide material produced in this way has high physical and mechanical characteristics (strength, hardness, wear resistance, dissipativity) compared with ceramic materials of similar composition.
These properties are achieved by high plasma temperature influence (10,000 - 15,000 K), which increases degree of homogeneity of the melt, eliminates the formation of porosity, and contributes to favorable factors for forming a fine-grained structure.

4. Conclusion
There is a proved possibility of using plasma arc for the synthesis of stone casting silicate-oxide materials from raw materials of gabbroid rocks of Ural region, both natural (gabbro diabase) and technogenic origin (hornblendite), that enables producing new materials of various functional purpose. Despite the fact that it is difficult to get silicate-oxide melt from this raw material due to technological features, for example, presence of sodium oxide and potassium in the form of veins that impede raw material stable melting, increased melting temperature and lower viscosity in comparison with basalt, using plasma technologies in producing stone casting silicate-oxide materials from gabbro-rocks solves the problems outlined above. By varying technological parameters of the synthesis, it is possible to obtain materials of different shapes - granules, powder, fiber, and cast material. Size of produced fibers and granules depend on many factors, but the most important are physical and chemical properties of raw materials and technical characteristics of the plasmatron.

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