Special features of fused welding flux granular forming in carbon steel surfacing during plasma granulation

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Abstract. This paper proposes a qualitatively new approach for production fused welding fluxes in carbon steel surfacing based on direct-action plasma arc influence on a metal substrate and charge materials made from the Ural region raw minerals. During plasma granulation there is an intense burnout of alkali metal oxides that is compensated by the use of liquid potassium and/or sodium glass as a binder of charge materials before granulation. Forming a slag crust on granules surface resulted in iron content exceeding more than 90 wt. % in the granule center. Otherwise without the formation of a slag on granules surface the iron was oxidized and its content reached 38.42 wt. % Studies have shown that the volume of granules that are completely coated and protected by slag crust on an oxide-silicate basis, reaches up to 95%. Such welding flux granules with a high content of metal components provide high performance (deposition rate) during repair works and surfacing of products using submerged arc welding.

1. Introduction

Welding materials are an essential part of modern welding production. Mineral-based welding materials are particularly in demand, namely, coated electrodes, flux-cored wires, welding fluxes of different purpose. Using high-quality welding materials with high welding and technological properties is required during welding and repairing (surfacing) of critical structures and general-purpose building structures. To this end, chemical composition of welding materials should be conducive to the stability of the arc and favorable process of physical and chemical reactions in welding (surfacing). Manufacture methods of welding materials are also being improved to reduce energy and material costs and increase welding properties on the whole [1-3].

Currently, plasma technologies for processing materials are increasingly used in various industries, primarily due to a highly concentrated source of heat, equipment simplicity and easy readjustment for various tasks and cost-effectiveness of the process while receiving final high-quality products [4].

Plasma technologies of processing and production of powders of various dispersity from rutile, iron oxide, clay and other mineral raw materials are proved to be quite well-known [5–9]. Studies of technological features of these processes revealed one of the most promising ways of processing charge materials using a highly concentrated heat source (plasma arc) that makes it possible to produce welding materials for arc welding and submerged arc welding. The essence of this technology lies in the influence of a direct-action plasma arc on a charge of mineral raw materials in order to produce fused welding flux granules.
Therefore, the aim of this work is to identify characteristics of welding flux granules formation in carbon steel surfacing when exposed to direct action plasma arc on the charge of mineral raw materials from the Ural region.

2. Selection of raw materials and technical parameters of products
Rocks with oxide-silicate base from the Ural region gabbroid group were chosen as mineral raw material for observation. These raw materials contain all the necessary components for fused flux slag base and low content of harmful impurities. Hornblendite and other rocks of the Ural region gabbroid group have good fusibility, required melting point, homogeneity in chemical and phase composition and a number of other geological advantages [10, 11].

Possible production volume is a technical parameter that determines the quantitative characteristics of fluxes produced by electric arc method and it depends on equipment transmission capacity. Technical parameters that determine quality characteristics of the equipment and surfacing fluxes being developed are the following: structural elements and complexity of the equipment design, chemical composition of developed fluxes, structure and size of granules and bulk density. These parameters affect the quality of welded joints of critical structures produced by welding under a layer of developed flux.

3. Description of the experiments
Welding materials with a high deposition rate are mainly used for surfacing. That is achieved by adding metal powder to the electrode coating mixture during production of coated electrodes or to the charge during production of ceramic flux [12, 13]. Figure 1 shows granules produced by granulating of metal plate with a raw mineral substrate using a highly concentrated heat source (plasma arc).

![Figure 1. Formation of welding flux granules, different in morphology and chemical composition, x100: a – granule on metal base, coated partly by slag; b – granule coated with slag; c – porous granules on slag base; d – oxidized metal granule.](image)
Under plasma arc influence ignited on metal plate made of Steel 20 (similar to S235) with a thickness of not more than 1 mm combined with a substrate 10-15 mm thick from finely dispersed mineral raw materials mixed on liquid sodium glass, there is a spraying of metal layer and subsequent melting of substrate that forms granules coated with an oxide-silicate base (figure 1, a, b). Scanning electron microscopy (electron microscope Carl Zeiss EVO50) was used to study the morphology and chemical composition of granules and the results of studies determining chemical composition of granules are presented in table 1.

### Table 1. Results of chemical analysis of fused welding flux granules.

| Granules in Figure 1 | Chemical composition, wt. % |
|----------------------|----------------------------|
|                      | O  | Na  | Mg  | Al  | Si  | Ca  | Ti  | Cr  | Mn  | Fe  |
| a (slag)             | 35.35 | 2.14 | 3.19 | 2.76 | 12.45 | 4.53 | 0.38 | 0.58 | 0.19 | 38.42 |
| a (metal)            | 5.29   | 1.46 | 0.62 | 0.39 | 1.04  | 0.18  | -   | -   | -   | 91.02  |
| b                    | 28.92 | 0.96 | 0.96 | 0.76 | 3.79 | 1.61 | 0.08 | 0.35 | 0.30 | 62.27 |
| c                    | 22.01 | 0.56 | 0.08 | 0.11 | 0.63 | 0.72  | -   | -   | 0.16 | 75.73 |

High content of sodium oxide is a result of using a binder of liquid sodium glass for mixing the oxide-silicate base of the substrate and bonding with metal plate. Magnesium, aluminum and other metal oxides are present in a small amount, since their content in mineral raw materials substrate does not exceed 7 wt. %, as well as in the process of granulation it is partially burned out under the influence of plasma arc. If slag crust was formed on the surface of the granules, iron content exceeded more than 90 wt. % in granule center. Otherwise, without the formation of slag on the surface of the granules, the iron was oxidized and its content reached 38.42 wt. % (figure 1, a). Studies have shown that volume of granules coated with slag reaches up to 95%.

The form of welding flux granules is determined by external and surface tension forces influence. The basis of the principle of spherical shape formation of granules lies in equilibrium state. When external forces are absent or compensated, the surface of slag melt tends to form a spherical shape to have a minimum area.

Without external factors influence, there is separation of the granule from the plate when its weight becomes equal to the sum of surface tension forces. Then the granule from the melted bridge formed between the plate and a drop of slag comes off and falls freely and the remaining bridge begins to change its shape. Therefore, appearance of each large granule with a size of up to 4 mm is accompanied by formation of another small granule (figure 2, a). The volume of these granules has significantly lower values than the first granule. The above principle of granular formation is confirmed by experiment where under the influence of electric arc (diameter of electrodes is 6-18 mm) at 100-350 A current [14], there is melting of material in the form of plate and detachment of granules shown in figure 2, b. The plates used in the experiment that were subjected to melting consist of finely dispersed hornblendite powder from the Urals region, mixed in a 2:1 mass ratio with liquid glass.

In some cases, besides spherical granules, larger granules are formed due to the high viscosity of the formed slag, and also there are elongated fibers that are formed at the moment of detachment of granules from the plate when the bridge holds out to falling granule. It is possible to produce cooling on a rotating disk in order to avoid forming large granules with a fraction of more than 4 mm that are beyond the limits of regulatory documentation [15].

However, under dynamic influence of the plasma jet, process of granular formation occurs with forced detachment and acceleration of granules from the plate surface. In addition, granulation process using plasma arc instead of electric carbon one is characterized by the presence of a metal substrate that melts under plasma jet influence and gets in welding flux granules formation.
**Figure 2.** Welding flux granules, produced under electric arc influence between carbon electrodes: 
a – spherical granules, x100; b – general view of granules produced by “dry” granulation.

It has been established that granulation with influence of plasma arc, in contrast to carbon electric one, there is a decrease in volume of formed agglomerates, i.e. chains of granules that are later melted into larger particles, with that, having a complex morphology. This result is achieved due to influence of dynamic effects of a highly concentrated heat source (plasma arc) that gives a high rate of falling of the melted granules into granulation pool with water that prevents the granules from interacting with each other. The lack of porosity of the granules is achieved because of their instant cooling due to the high falling rate and immediate solidification in granulation pool with water.

Preliminary studies of welding and technological properties of welding flux granules showed high performance rates of surfacing, but an adjustment of the charge composition is required for arcing stability and surfacing as a whole.

**4. Conclusion**

Developed fused welding flux can be used in production and repair works (surfacing) of critical structures made of carbon and low-alloyed steels of several groups of technical devices provided and classified by the National Agency for Welding Control.

Thus, a method for producing welding fused flux for surfacing using a highly concentrated heat source (plasma arc) has been proposed. With produced fused flux granules that contain both slag and metal base, it is possible to vary different properties such as composition and morphology of the granules within a wide range, producing welding materials of wide application.

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