Innovative processes of production functional gradient layered compositions with enhanced tribological properties

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Abstract. Arc surfacing processes are proposed as innovative methods for the synthesis of functionally gradient layered compositions. Existing composite filler materials based on aluminum and tin have been investigated. The schemes and technological parameters of arc welding allowing to produce the coatings having a composite structure with a given reinforcement ratio, satisfactory reinforcements distribution, and enhanced tribotechnical properties have been shown.

1. Introduction
The friction units used in machines and mechanisms have a wide range of constructions and represent both mono- and bimetallic structures: for example, bushings or blocks of sliding bearings. Moreover, surface layers mainly work in the friction units and their damage due to wear leads to emergency situations [1-3]. Therefore, an extremely important and promising scientific direction meeting modern requirements is the creation of functionally gradient layered compositions with enhanced tribotechnical properties based on steels or alloys with surface layers consisting of particle-reinforced composite materials (CM) based on non-ferrous alloys. The variety of CM forms allows adjusting the basic tribotechnical properties by the composition selection, changes in the ratio of components and the formation processes choice [4-9]. This will significantly reduce manufacturing costs, as well as provide the opportunity to carry out repairs during the operation of products made from similar materials [8-10]. However, the experience of obtaining and using such functionally gradient layered compositions in friction units is rather limited.

2. The choice of processes for creating functionally gradient layered compositions
Existing processes for the formation of CM coatings on the basis of steels or alloys can be divided into three groups [8]:
- processes occurring in the solid phase (for example, rolling packages of matrix material and CM, explosion welding, thermomechanical processing of the CM surface layer);
- processes occurring in the liquid phase (for example, centrifugal casting, arc, laser, plasma surfaced, modifying treatment);
- coating processes from the gas phase.

Among them the methods of creating functionally gradient layered compositions by arc welding processes are the most economical and promising according to the criteria: productivity, universality, implementation level and accessibility in industry [8-11]. The use of such processes will allow the formation of the necessary structure and the specified properties of CM coatings due to layer-by-layer
synthesis. An additional feature of these methods is the possibility to provide the necessary level of wetting and to limit the chemical interaction between the filler, matrix, and substrate material due to the correct choice of temperature-time characteristics (heating temperature, time at a given temperature), the introduction of alloying elements, or the use of intermediate transition layers [5, 8]. All these will allow to solve the important problem of thermodynamic and kinetic compatibility of CM components.

3. Composite filler material development

According to modern concepts, the CM working capacity is an integral characteristic that depends on the physical and chemical properties of the phases that make up the materials and their ratio. Therefore, the lack of appropriate filler materials until recently limited the widespread use of arc processes for composite coatings deposition in the manufacture of functionally gradient layered compositions. To date, there is positive experience in the manufacture and testing of CM based on aluminum or tin, which satisfy the basic requirements for filler materials, including:

- high-quality formation of a deposited coatings with saving and uniform distribution of reinforcing particles;
- lack of reinforcement degradation during the deposition of composite coatings;
- absence of defects in the deposited coatings.

Such CMs are characterized not only by a high level of tribotechnical properties, but also by sufficient manufacturability [8, 10, 12]. This makes it possible to obtain from them filler materials in the form of rods meeting the requirements of GOST 21449 for the arc welding processes in automatic or manual mode with using standard welding equipment, which is especially valuable when carrying out repair operations (Fig. 1).

The use of foundry technology for the manufacture of aluminum-based CM filler materials ensures uniform distribution of reinforcing particles, the absence of intense interfacial interaction and contamination at the particle-matrix interface (Fig. 1, b, c). To achieve the required quality of the composite coatings formation, such materials should contain no more than 10 wt.% reinforcement particles (SiC) of the minimum size (14 microns) and (11-13) wt.% silicon. Therefore, widely used in industry casting alloys Al-12Si and Al-12Si-2Cu-1Mg-1Ni + 10SiC\(_{14}\) are recommended as a matrix for producing composite filler rods [8].

The technology of B83-based CM filler materials production has been first developed and tested to introduce and ensure uniform distribution in the tin matrix of poorly wettable reinforcements and modifying additives of various types and fraction size. The technology consists of stages: mechanical alloying and cold pressing of the powder composite mixture; compact sintering and hot extrusion [11]. Produced according the technology filler rods from CM based on B83 alloy with a reinforcement mass fraction not more than 5% are characterized by the absence of defects (Fig. 1, d).
4. Deposition of composite coatings

The application of the produced new filler CMs required to solve a number of primary problems. The main of them are related to the choice of schemes and determination of technological parameters of the deposition processes, allowing to form high-quality coatings and ensure uniform reinforcement distribution and the absence of its degradation. In addition, the development of technologies for the formation of such coatings on low-carbon steel substrates is of particular importance. The technology will make it possible to obtain bimetallic compositions widely used in friction units, the main requirement of which is to provide standard values of adhesive strength and high level of tribotechnical properties.

The schemes and technological parameters of the arc welding process that differ in the temperature-time effect on the filler material were tested. It was established that the scheme with introduction of composite filler rods into the head of the weld pool (along the leading edge) was preferred (Fig. 2, a) [10]. The maximum values of the melt heating temperature and the duration of the reinforcement in it lead to an increase in fluidity, which contributes to the formation of coatings with a uniform reinforcement distribution (Fig. 2, c, d).

![Figure 2](image-url)

**Figure 2.** Scheme of the process of arc welding (a), appearance (b), microstructure in the central part (c, d) and along the fusion line (e, f) of the coating compositions, wt.%: (b, d, f) B83 + 5SiC; (c) Al-12Si + 10SiC; (e) Al-12Si-2Cu-1Mg-1Ni + 10SiC. The numbers indicate: 1 — composite filler rod; 2 - non-consumable electrode; 3 - welding torch; 4 - shielding gas; 5 - electric arc; 6 - weld pool; 7 - substrate; 8 - deposited layer.

Technological parameters of the arc welding process were selected according to minimum degree of penetration of the substrate from Al-3Mg alloy (GOST 4784), saving of the reinforcing code and high-quality formation of coatings (welding current - I = 150-160 A, arc voltage - U = 18 -20 V, welding speed - V = 7-12 m/h, shielding gas (argon) consumption - V = 12-15 l/min). The technological parameters allow receiving 2,5-3,0 mm thickness coatings in one pass, which crystallize epitaxially and, as a result, have a high level of adhesive strength (Fig. 2, e) [10]. The established scheme and regimes of the arc welding process can be used to form coatings of similar composition on the low-carbon steel bases. It will make possible to obtain bimetallic compositions widely used in friction units. However, in such cases for preventing the formation of a continuous intermetallic layer, it is necessary to limit the
thermal effect of the electric arc on the steel-aluminum interface by providing partial penetration of the intermediate aluminum layer formed by the explosion welding process [13].

Tin-based CM coatings are characterized by a smooth surface with a smooth transition to the metal of the steel substrate. The coatings have 2.0-3.0 mm thickness of each layer after the machining required to level the working surface. Preliminary tinning of the steel (St3sp in accordance with GOST 380) substrate surface provided provided fluidity increase during the formation of composite coatings due to the formation of an intermediate layer of pure tin with a thickness of not more than 0.5 mm. The technological parameters of the arc welding process are determined (welding current - I = 40-60 A, arc voltage - U = 16-18 V, welding speed - V = 7-12 m/h, shielding gas (argon) consumption - V = 12-15 l/min). The technological parameters ensure the stability of the phase composition and structure, the absence of alloying elements burnout and minimal mixing of the base and deposited metal (Fig. 2, f) [14].

5. Tribological properties of deposited coatings
To evaluate of the deposited CM coating working capacity, the results of their wear tests were compared with those for well-known and widely used in industry antifriction materials based on aluminum and tin. Tests were carried out using machines (tribometers): MTU-01 and CERT UMT Multi-Specimen Test System under dry sliding friction conditions according to scheme “bush on disk” at a sliding speed of 0.39 m/s. The formed aluminum-based CM coatings are characterized by an extended range of tribolading. The coatings have 2-3 times lower values of wear rate and wear coefficient compared to the anti-friction alloy Al-20Sn-1Cu, which goes into intensive wear at specific pressures of more than 0.46 MPa (Table 1).

| Type and composition of samples, wt% | Wear rate Iv, x10^-4 mm/m | Wear coefficient K, x10^-4, depending on specific pressure p, MPa |
|------------------------------------|--------------------------|---------------------------------------------------------------|
|                                    | 0.2                      | 0.33                                                          | 0.46 | 0.59 | 0.7 |
| Al-20Sn-1Cu                        | 10,2 / 1,69              | 15 / 1,54                                                     | 18,9 / 1,4 | intensive wear |
| Al-12Si + 5SiC<sub>40</sub>         | 4,24 / 1,41              | 6,3 / 1,35                                                    | 7,72 / 1,19 | 8,58 / 1,03 | 10,98 / 1 |
| Al-12Si-2Cu-1Mg-1Ni + 5SiC<sub>14</sub> | 4,09 / 1,95               | 6,21 / 1,9                                                   | 7,66 / 1,68 | 9,35 / 1,6 | 11,44 / 1,63 |
| Al-12Si-2Cu-1Mg-1Ni + 10SiC<sub>14</sub> | 4,28 / 2,09              | 5,95 / 1,87                                                  | 6,65 / 1,5  | 6,92 / 1,22 | 7,38 / 1,08 |
| AK12 + 10SiC<sub>40</sub>          | 4,69 / 1,7               | 5,88 / 1,37                                                  | 6,65 / 1,11 | 7,2 / 0,94 | 7,38 / 0,8 |

A larger number of reinforcing particles in the coatings reduces the matrix fraction in the friction surface. It reduces the risk of intensive wear and helps to reduce the load on each particle individually when they play the role of supporting elements on the contact surface. This increases the wear resistance, which is especially noticeable at specific pressures of more than 0.46 MPa. Also the tribo-loading parameters range (specific pressures, sliding speeds and loading durations) is significantly expanded.

The friction process of tin-based CM coatings obtained by arc welding is characterized by high stability (stability coefficients characterizing the level of vibration and noise achieved by friction, not less than 0.8) in the entire tribo-loading range. It is associated with an increase in hardness due to dispersion of the matrix alloy structure during deposition process [15]. The presence in the composition of submicron-sized particles (e.g. boron or boron carbide) increases the wear resistance of coatings by 35% and 30% (from Im = 2,62x10^-5 g/m to Im = 1,71x10^-5 g/m and Im = 1,77x10^-5 g/m, respectively). Also it reduces the value of the friction coefficient by 40-60% compared with coatings made of antifriction alloy B83 (Fig. 3). The use of developed composite filler rods containing SiC particles provides an increase in wear resistance by 30% and a decrease in the friction coefficient by 30–40% even at the maximum specific pressure tested (0.7 MPa) [15].
Figure 3. The ratio of the friction coefficients of the deposited CM coatings with composition, wt.%:
1 – B83 + 0.25B₄C(<0.5); 2 – B83 + 0.25B₄C(<1); 3 – B83 + 5SiC₄₀; 4 - B83 + 5SiC₄₀ + 0.25B₄C(<1) and
coatings from babbit B83 depending on specific pressure.

Comprehensive studies of the relief and composition of the friction surfaces, the morphology of the
wear products made it possible to determine that the wear of the deposited composite coatings occurred
according to the abrasive and oxidative mechanisms. These mechanisms are characteristics of the initial
and steady-state stages of the friction regime. After testing at maximum specific pressures of 0.7 MPa,
plastic deformation bands and setting zones are formed on fairly smooth friction surfaces of the samples.
These zones are characterized by fragmentation and small area in comparison with samples of
antifriction alloys (Fig. 4, a, b, c). The secondary cellular structures of 5-10 μm in size are formed in the
plastic deformation bands at the stage of steady wear. The structures are contoured by ceramic particles
with an average size of 1 μm, which minimize the destruction of surface layers and screen unacceptable
setting processes. Moreover, the friction surfaces of composite coatings containing different
reinforcement particles are characterized by the minimally pronounced plastic deformation bands, as
well as the largest area occupied by the mechanical mixture from the transition layer composition formed
during the friction process. The small (up to 10 μm) particles of equiaxial shape formed as a result of
wear by the oxidation mechanism are dominated among the wear products (Fig. 4, d) [10, 15].

Figure 4. Friction surfaces (a, b, c) и wear products (d) of the coatings after testing at a specific pressure
of 0.7 MPa. The composition of the samples, wt.%: a) B83; b, d) Al-12Si-2Cu-1Mg-1Ni + 5SiC₄₀, c)
B83 + 5SiC₄₀ + 0.25B₄C₈₁.

Thus, the proposed processes make it possible to create functional gradient layered compositions
with high tribological properties in a wide range of tribo loading: specific pressure from 0.2 to 3.3 MPa,
sliding speed from 0.39 to 1.0 m/s. This allows us to recommend the developed materials for use in
friction units of machines and mechanisms with high work stresses, which include bearings and bearing
shells of steam and gas turbines, marine small and medium-sized diesels.
6. Conclusion
Arc surfacing processes are proposed as innovative methods for the synthesis of functionally gradient layered compositions. Existing composite filler materials based on aluminum and tin were investigated. The schemes and technological parameters of arc welding were shown. They allow to produce the coatings having a composite structure with a given reinforcement ratio, satisfactory reinforcements distribution, and enhanced tribotechnical properties (increased wear resistance up to 3 times, reduced friction coefficient 60% compared with traditional antifriction alloys Al-20Sn-1Cu and B83).

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