Application of the friction surfacing process for the production of functional gradient layered composition

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Abstract. The possibility of applying the friction surfacing process for the production of functional gradient layered compositions for tribotechnical purposes has been considered. The influence of technological parameters of the friction surfacing process: the rod rotation frequency, the longitudinal linear speed of the rod movement and the method of the substrate surface preparation on the deposited layer formation has been shown.

1. Introduction
The need for new materials for machines and mechanisms with a high level of functional characteristics attracts more and more attention to the development of particle reinforced composite materials based on aluminum and its alloys (CM) [1-3]. At the same time, in order to ensure operability in extreme operating conditions, characterized by the influence of different physical and chemical nature factors, in many cases it becomes necessary to create functional-gradient layered compositions (FGLC) for tribotechnical purposes based on structural steels with working CM layers [4-7].

Technological processes for the FGLC formation include solid-phase (for example, rolling of packages of matrix material and CM, explosion welding, diffusion welding, thermomechanical processing of the surface CM layer) and liquid-phase methods (for example, infiltration of specially assembled powder frames of variable composition, centrifugal casting, arc surfacing, modifying treatment), as well as methods of applying coatings from the gas phase [6]. However, most of them are relatively expensive and time consuming. One of the most preferable approaches for solving this problem is the use of a simple and economical technology of friction surfacing [8-11]. This technology is comparable to the friction stir welding process, in which a rotating rod made of CM is a consumable material that provides the formation of a working layer on the steel substrate surface. Heating of the weld zone occurs due to the work against the friction forces arising on the surfaces to be welded during the physical contact of the rotating rod with the substrate, pressed against each other by normal force. It is important to note that the maximum heating temperature of the weld zone achieved in the friction surfacing process does not exceed the melting temperature of the aluminum matrix alloy of the CM rod [12]. Thus, a viscoplastic boundary layer is formed at the end face of the rod part in contact with the substrate. This layer forms a weld coating during translational movement of the rod and the substrate relative to each other. Due to the relatively low heating temperatures, the friction surfacing process, in comparison with other methods of manufacturing FGLC, is characterized by a narrow heat-affected zone and limited diffusion interaction at the substrate-coating interface. The latter is especially valuable when coating steel substrates from aluminum-matrix CMs, since it prevents the intensive growth of brittle intermetallic compounds with different stoichiometric compositions of the Fe-Al system at the interface, which reduces the level of adhesion strength of FGLC. Therefore, the present work is devoted to the study of the possibility of using the friction surfacing process to obtain FGLC for tribotechnical purposes based on structural steels with working layers of aluminum matrix CM.
2. Materials and methods

The plates with a size of 100x200x3 mm made of high-quality low-carbon steel 20 (0.17-0.24 wt.% C; 0.17-0.37 wt.% Si; 0.35-0.65 wt% Mn; ≤0.25 wt% Cr; Fe - the rest according to GOST 1050) were used as a substrate for coating. The presence or absence of high-modulus, refractory reinforcing particles does not affect the mechanisms of formation and growth of the intermetallic phase at the steel-aluminum interface. Therefore, aluminum grade A5 (0.2-0.35 wt.% Fe; 0.1-0.25 wt.% Si, ≤0.015 wt.% Cu; Al - the rest according to GOST 7871) was used as the deposited material in the form of rod with a diameter of 18 mm. An additional criterion determining the choice of pure aluminum as a coating material was the elimination of the influence of alloying elements on the formation mechanism and characteristics of the diffusion zone of the substrate-coating interface.

An experimental equipment made on the basis of a vertical milling machine was used to carry out the friction surfacing process. The main technological parameters of the friction surfacing process are: pressure (P); rod rotation frequency (n); as well as longitudinal (V₁) and transverse (V₂) linear speeds of the rod movement (Fig. 1). Among them, the greatest influence on the quality of the deposited layer formation is exerted by the rotation frequency and longitudinal linear speed of the rod movement [9]. Therefore, the friction surfacing process was carried out in a wide range of values of the above parameters, selected according to literary data [8-10, 13, 14]:

1) rod rotation frequency (n) — from 1400 to 2160 rpm;
2) longitudinal linear speeds of the rod movement (V₁) — from 82 to 104 mm/min.

The pressure in the weld zone was 10 MPa and remained constant in all experiments. The coatings were deposited by frictional surfacing process in one or several runs. The coefficient of overlap of adjacent welds was 0.5 of the weld width when forming coatings by several runs.

Additionally, the influence of the substrate surface preparation method on the possibility of obtaining and the features of the deposited layer formation was studied. For this, the steel substrate surface was prepared by different ways, presented in table 1.

Measurements of the geometrical dimensions of the deposited coatings were carried out. Samples were mechanically cut from the prepared blanks across the direction of the surfacing for metallographic studies. The study of the diffusion zone structure between the substrate and the deposited coatings was carried out by means of optical and electron microscopy using a BIOMED light microscope, equipped with a digital camera, and a Tescan VEGA II LMU scanning electron microscope equipped with an attachment for X-ray spectral microanalysis.
Table 1. Steel substrate surface preparation methods

| Preparation method | Features of preparation                                      |
|--------------------|-------------------------------------------------------------|
| Without preparation | -                                                           |
| Mechanical         | Surface treatment of a steel plate with an angle grinder to give it a metallic sheen. |
| Chemical           | Surface treatment of steel substrates with aqueous KOH solution to remove organic contaminants. |
| Tinning            | Application of a pure tin layer with a thickness of no more than 0.5 mm to the surface of a steel substrate using an electric soldering iron. |

3. Results and discussion

The manufactured FGLC samples are characterized by a continuous deposited layer of A5 aluminum, the thickness of which does not exceed 2 mm (Fig. 2). However, not all of the tested friction surfacing process technological parameters allow obtaining a deposited layer (Table 2). In particular, the deposited layer was not formed at a rod rotation frequency of 1400 rpm and in the absence of preparation of the steel substrate surface (sample № 1, Table 2). The reason for this may be not only the unsatisfactory quality of the substrate surface preparation, but also the heating temperature of the weld zone that is insufficient for the formation of a viscoplastic boundary layer. An increase in the value of the rotation frequency of the rod to 2160 rpm while maintaining the rest of the technological parameters of the friction surfacing process without changing, makes it possible to slightly increase the heating temperature of the joint zone. However, this is insufficient for the formation of a welded joint (sample № 4, Table 2). It is probably that excessive contamination on the steel plate surface prevents physical contact between the rotating rod and the substrate during frictional surfacing, thereby limiting the possibility of obtaining a welded joint.

![Figure 2. Typical samples of FGLC fabricated by the friction surfacing process.](image_url)

The tinning operation, which consists in applying a thin (no more than 0.5 mm thick) layer of tin on the steel substrate surface, does not allow obtaining a deposited coating on the surface of the steel substrate even at the maximum of the tested rod rotation frequency (sample № 3, Table 2). It is likely that the contact area between the aluminum rod and the tin surface layer is characterized by low values of the friction coefficient. As a result, the heat release in the weld zone is insufficient for the formation of a viscoplastic boundary layer, which prevents the formation of a welded joint during the friction surfacing process.
Comprehensive preparation of the substrate surface, including mechanical and chemical treatment, results in obtaining of welded joint between the steel substrate and the aluminum surface coating even at the minimum of the tested values of the longitudinal linear velocity of the rod (sample № 2, Table 2). An increase in the linear velocity of the rod movement from 82 to 104 mm/min, while maintaining the rest of the technological parameters of the friction surfacing process without changing, probably leads to a certain decrease in the heating temperature of the joint zone (sample № 5, Table 2). A consequence of changing the conditions for the formation of a viscoplastic boundary layer is a decrease from 26 to 22 mm in the width of the deposited layer formed in one run (Fig. 3).

![Figure 3. Deposited coatings of samples № 2 (a) and № 5 (b). Designation of samples according to Table 2.](image)

It is important to note that the friction surfacing process makes it possible to apply not only single weld, but also coatings consisting of two or more welds. In particular, at the values of the rotation frequency and the longitudinal linear speed of the rod movement of 2160 rpm and 82 mm/min, respectively, coatings of two welds were obtained, characterized by the value of the overlap coefficient of adjacent welds 0.5 of the weld width (sample № 6, Table 2).

| Sample | Surface preparation method | Number of runs | Longitudinal linear speed of the rod movement mm/min | Rod rotation frequency rpm | Result |
|--------|----------------------------|----------------|----------------------------------------------------|---------------------------|--------|
| 1      | Without preparation        | 1              | 82                                                 | 1400                      | Welded joint not formed |
| 2      | Mechanical and chemical    | 1              | 82                                                 | 2160                      | Welded joint formed     |
| 3      | Tinning                   | 1              | 82                                                 | 2160                      | Welded joint not formed |
| 4      | Without preparation        | 1              | 82                                                 | 2160                      | Welded joint not formed |
| 5      | Mechanical and chemical    | 1              | 104                                                | 2160                      | Welded joint formed     |
| 6      | Mechanical and chemical    | 2              | 82                                                 | 2160                      | Welded joint formed     |

*6) friction surfacing process with the overlap coefficient of adjacent welds 0.5 of the weld width.

Studies of the structure of the manufactured FGLC samples, performed by means of electron microscopy and X-ray spectral microanalysis, made it possible to establish that a continuous
intermetallic layer is formed at the interface between the steel substrate and the aluminum coating in the entire range of tested parameters of the friction surfacing process (Fig. 4). In terms of its chemical composition, it is a compound of the Fe-Al system of different stoichiometry. On the side of the aluminum layer, intermetallic compounds based on aluminum FeAl₃ and Fe₂Al₅ are predominantly formed, which have the highest hardness values among intermetallic compounds of the Fe-Al binary system. Iron-based intermetallic compounds Fe₂Al₅, FeAl, Fe₃Al, which have a lower hardness, are formed in the region adjacent to the steel substrate.

Figure 4. Microstructure of the intermetallic layer at the steel–aluminum interface in samples № 2 (a); № 5 (b); № 6 (c) and a sample made by the arc surfacing process (d).

Designation of samples according to Table 2.

The thickness of the formed intermetallic layers in all samples is in the range from 1 to 3 μm, which is 3-4 times less than in the FGLC samples made by the authors of [15] by arc surfacing (Fig. 4). This is due to the lower heating temperatures of the interface reached during frictional surfacing as compared with arc surfacing process. This limits the diffusion interaction between aluminum and iron. In addition, one should not exclude the influence of the mechanical effect exerted by the rotating rod on the intermetallic layer during frictional surfacing process. The consequence of this process is crushing and grinding of intermetallic compounds forming a thin layer.

Thus, the use of the friction surfacing process makes it possible to obtain FGLC samples with a continuous layer of intermetallic compounds of the Fe-Al system of different stoichiometric composition with a thickness of no more than 3 μm, which allows us to expect high values of the adhesion strength of the surface aluminum layer to the steel substrate.

4. Conclusions
1) The fundamental possibility of using the friction surfacing process to obtain functional-gradient layered compositions for tribotechnical purposes based on structural steels with working layers of aluminum-matrix CM is shown.
2) The influence of technological parameters of the frictional surfacing process: the rotation frequency of the rod, the longitudinal linear velocity of the rod movement and the method of the substrate surface preparation on the possibility of obtaining and the features of the formation of the deposited layer is determined.
3) It has been established that the use of the tinning process or the absence of preparation of the substrate surface does not allow the formation of a weld in the range of rod rotation frequency from 1400 to 2160 rpm. At the same time, the combination of mechanical and chemical preparation method of the substrate surface leads to the formation of a weld between the substrate and the deposited layer even at the minimum (82 mm/min) of the tested values of the longitudinal linear velocity of the rod.
4) It was found that due to low heating temperatures, as well as mechanical impact during frictional surfacing, the intermetallic layer formed at the interface of the FGLC samples is characterized by a
thickness 3-4 times less than that on the samples obtained by the arc surfacing process (1-3 μm versus 4-10 μm).

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