Analysis of the state and prospects of application of the plasma sputtering method for obtaining wear-resistant coatings

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Abstract. The analysis of the properties of structural materials according to the wear resistance criterion is carried out. The prospects for the application of the plasma spraying method for obtaining wear-resistant coatings are given. Practice shows that methods of increasing the wear resistance of parts by applying on them thin coatings of ceramic, cermet and other highly wear-resistant materials by surfacing, vapor deposition, detonation and plasma spraying are very effective.

1. Introduction

The most important performance indicator of the quality of a material is its wear resistance. If we analyze the properties of known structural materials, it turns out that the level of wear resistance of most of them is low. And as you know, the durability, reliability and efficiency of friction units are largely determined by their ability to resist wear. This explains the relevance of research in the direction of developing technologies that would improve the wear resistance of the working surfaces of parts that have small tolerances for final processing and are made of easily processed and cheap materials.

The literature gives many examples indicating the high-performance properties of coatings obtained by these methods. However, there is no information on a specific technology for obtaining such coatings either in the literature on this topic known to us, or in the practice of manufacturing friction units. If we consider wear resistance as the resistance of a material to separation under dry friction in a system of two solids, then the whole variety of friction patterns can ultimately be represented by five types of frictional interaction: elastic displacement, plastic deformation, cutting, adhesive interaction of the film surface, seizure accompanied by deep pulling out of the material. \cite{1,2}. Under certain conditions, these types of interaction can change the value of the contribution to the total friction force, passing from the predominant type to the accompanying one.

2. Research methods and results

Ordinary functioning of friction units is possible if the first, second and fourth types of interaction make a contribution to the magnitude of the frictional contact. The third and fifth types of interaction are
manifested as the main ones only in emergency situations and therefore, when designing a unit, friction should be minimized [3].

Table 1 shows the mechanical properties and wear resistance of some structural materials, as well as the properties of plasma-sprayed materials according to various literature sources. It is stimulating to note that despite the huge number of structural plasmatrons, feeders, power sources and types of powders, the properties of materials sprayed in the optimal mode are approximately at the same level, an order of magnitude or more inferior to the properties of compact materials, even substantiated the fundamental impossibility of obtaining other properties as an order of magnitude or more inferior to the properties of compact materials, even substantiated the fundamental impossibility of obtaining other properties associated with ultimately with a discrete nature of the solidification of particles during spraying, which is a distinctive feature of the method.

| Structural materials | \( \rho \), kg/m\(^3\) | \( \sigma_s \), kg/mm\(^2\) | \( H_v \), kg/mm\(^2\) | E-10\(^6\), kg/mm\(^2\) | \( \alpha \cdot 10^{-6}, \) l/deg | Relative wear resistance | Conditions of receiving |
|----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Beryllium            | 1850            | 40              | 320             | 30              | 12              | 44              | Sintering       |
| Tungsten             | 19300           | 100             | 250-400         | 36              | 7               | 60              | -               |
| Molybdenum           | 10200           | 50              | 250             | 32              | 5,5             | 40              | -               |
| SNGN-60              | 7700-7900       | 40              | 860             | 13.5            | 5.5             | 40              | Reflow at 1100 °C |
| Relit                | 16500           | 40              | 2500            | 72              | 4,5             | 330             | Casting         |
| NK-8                 | 14600           | 150             | 1200            | 55              | 4,5             | 30              | -               |
| Microlite            | 3960            | 9               | 2100            | 37,6            | 8,5             | 55              | -               |

| Plasma-sprayed materials | Be | W | Mo | Relit | WC+Co | \( Al_2O_3 \) | Zr\( O_2 \) |
|--------------------------|----|---|----|-------|-------|-----------------|--------------|
| Density, kg/m\(^3\)     | 1840 | 19250 | 10300 | 13000-15000 | 1400 | 2800-3200 | 5700 |
| Porosity, P              | 90% | 80-90% | 87-90% | 7-11% | 1-4% | 8-25% | 16-28% |
| Hardness, kg/mm\(^2\)   | 330-390 | 320-370 | 100-250 | 700 | 1000 | 640-800 |
| Strength, kg/m\(^2\)    | 2   | 4.4 | 4.3  | 2-10 | 9 | 4-11 | 0.4-0.8 |
| \( \alpha \cdot 10^{-6}, \) l/deg | -  | 2.7-3  | 3-3.5  | -  | -  | 8-8.5 | -  |

Table 1. Properties of some structural and plasma-sprayed materials.

Within the framework of the accepted assumptions, this conclusion is correct, which is confirmed by the overwhelming majority of the results of determining the properties of sprayed materials, some of which are presented in table 1. Taking into account the established relationships between the strength characteristics of materials and their wear resistance, it can be argued that the possibilities for using sprayed coatings obtained within this method, as frictional or wear-resistant, are minimal, due to the low mechanical properties of the sprayed layers, and attempts to solve this problem by selecting any combination of initial powders and finding the traditional optimum in terms of current, distance, granulation, gas consumption, relative movement rates, etc. to fail.

This is the first important conclusion drawn from the analysis of the relationship between the strength characteristics of materials and their wear resistance. It is also confirmed by the fact that there is no information in the literature on the successful use of plasma-sprayed materials in friction units obtained by one-step spraying technology in air or in a controlled atmosphere; the field of application of sprayed materials having serious practical value, today, in essence, is limited only to heat-resistant, heat-protective and corrosion-resistant coatings based on \( W, Mo, Ni, Al_2O_3, ZrO_2 \), respectively; tests of molybdenum coatings sprayed by conventional technology as friction disc brakes and coatings based on \( Al_2O_3 \) as wear-resistant coatings did not give positive results.

Successful use of nickel-cobalt alloy steels as wear-resistant sprayed coatings is due solely to the operation of subsequent reflow. The properties of these coatings immediately after spraying do not
fundamentally differ from the properties of other sprayed materials and, therefore, this case goes beyond the scope of processes that limit the method of high-temperature spraying [4].

Consequently, without a qualitative improvement in the properties of plasma-sprayed coatings, their use to increase wear resistance in the overwhelming majority of practically important cases (under conditions of real specific loads and sliding velocities of a rubbing pair) is fundamentally impossible. What are the possible ways of such a qualitative improvement in the strength properties of coatings? In our opinion, today, there are 2 promising areas, effective to varying degrees:

1. Application of multi-operational technologies, including operations for the following high-temperature treatment: spraying and subsequent reflow; spraying and heat treatment.

2. More complete utilization of the heat contained in the applied material particles by increasing the compactness of the metallization jet, provided that inert atmospheres are used where necessary.

The prospects of the first of these directions are confirmed by the successes achieved in obtaining wear-resistant coatings by plasma spraying of alloys based on Ni-Cr-B-Si [5].

There are, however, significant difficulties that limit the possibilities of improving the quality of sprayed coatings by this group of techniques. These difficulties are as follows: the obligatory combination of a more refractory substrate with a less refractory coating; the need for uniformity of mechanophysical properties (thermal expansion coefficient, elastic modulus), which makes it possible to jointly heat up to temperatures close to the melting temperatures of the coating, the coated part, while not all materials allow prolonged heating to such high temperatures, due to irreversible changes in the chemical and phase composition, leading to a sharp deterioration in their properties.

In our opinion, the success in the creation of technologies for obtaining wear-resistant coatings by the plasma method will largely depend on the success in overcoming the listed difficulties.

The essence of the second direction of qualitative improvement of the properties of sprayed coatings is described in detail in [6]. Here we would like to dwell only briefly on some features of the method, the results obtained and the prospects for further research in this direction in relation to the problem of obtaining wear-resistant coatings.

The main difference of this method from the classical method of plasma spraying is that when spraying in a compact jet mode, it is possible to use the cumulative thermal effect of the deposited particles in order to create conditions for favorable thermodynamic and metallurgical reactions. Under certain conditions, the high-temperature region turns out to be localized in a thin surface layer of the coating, which makes it possible to almost completely eliminate the heating of the substrate and thereby make it possible to obtain high-strength coatings on materials with a significantly lower melting point and strongly differing in their physical and mechanical properties from similar properties of the applied cover. For example, it was possible to obtain Al oxide coatings containing from 80 to 90% of the α-phase on sintered aluminum alloy substrates. The coatings were tested for wear in a pair with sintered tungsten carbide and showed characteristics close to the wear resistance of a microlite.

Structures of coatings made of Al₂O₃ with additives of magnesium and chromium oxides, zirconium samples obtained in the mode of a non-compact and compact jet show that in the latter case, the structure of the material is characterized by the absence of layering, typical for plasma coatings, with a small number of dead-end pores. By comparing some of the obtained etched structures with the atlas of microlite microstructures, it was possible to establish their identity. Other properties of alumina coatings and wear test results when paired with other materials are shown in Table 2.

### Table 2. Properties of plasma sputtered alumina coatings in compact jet mode.

| Original structure | Microhardness coverings | Phase structure | Porosity, % | Diameter blocks, micron | Surface cleanliness class |
|--------------------|-------------------------|----------------|-------------|-------------------------|-------------------------|
| Al₂C₂ 99.99%       | 2200                    | α - Al₃O₃ - 95 | 9.4         | 11.4                    | 11-12                   |
| Al₂O₃ +1.5+2%      | 2400                    | α - Al₃O₃ - 96 | 7.65        | 14.8                    | 11-12                   |
| Cr₂O₃              |                         |                |             |                         |                         |
Al₂O₃ +1%MgO 2100 a – Al₂O₃-93-96% 6.25 7.2 11-12 -
Al₂O₃ +1%MgO +3% ZrO₂ 2100 AlMgO₄-3-5% 4.4 5 10-12 -
CM -322 2182 x – Al₂O₃-98% 4.7 1-3 10-11 -

| Sample | Counterbody | Friction coefficient | Pressure, kg/cm² | Speed, m/s | Phase composition | E=ΔH/T |
|--------|-------------|----------------------|------------------|------------|-------------------|--------|
| Al₂O₃  | Al₂O₃       | 0.127-0.133          | 2.7              | 0.5-0.8    | γ – Al₂O₃         | 10⁻²   |
| Al₂O₃  | Steel 2X13  | 0.24-0.44            | 5-14             | 0.5-0.8    | 70-100%           | 10⁻³   |
| Al₂O₃  | Cast iron ZhCHKh | 0.33-0.39      | 32              | 0.5-0.8    | γ – Al₂O₃         | 10⁻⁷   |
|        | + 0.5Cr₂O₃  |                      |                  |            | 90% α –          |        |
|        | + 0.7MgO    |                      |                  |            | Al₂O₃             |        |
|        | + 0.5BeO    |                      |                  |            |                   |        |

Analysis of the results obtained allows a more optimistic assessment of the capabilities of the plasma spraying method in order to obtain wear-resistant coatings. The creation of the required temperature regime in the macro-volumes of the coating formation region (determined experimentally so far) allows bringing the mechanical characteristics of the sprayed layers to a level close to the corresponding characteristics of compact materials [7].

The data available on the structure, strength, and wear resistance of ceramics sprayed in a compact jet mode indicate the identity of the listed properties and properties of sintered ceramics. Thus, the possibility of obtaining plasma-sprayed materials with the properties of known structural materials, including the property of wear resistance, has been proved in principle. At the same time, all the advantages of the economic nature of the plasma method, considered at the beginning of the article, are preserved.

Further studies related to the second of the listed areas of qualitative improvement of the properties of sprayed coatings should be carried out in order to study the conditions for obtaining wear-resistant coatings on a Monolit-type installation from other materials, both homogeneous (metal, ceramic) and composite (cermet). The main task of these studies is to find a correct quantitative description of the relationship between the deposition conditions and the values of nonstationary temperature fields in the forming coating and substrate [8].

3. Conclusion

The possibilities of using plasma-sprayed coatings obtained within the framework of the traditional "classical" method of high-temperature spraying as wear-resistant are minimal, due to the low strength properties of these coatings.

Progress in this matter can be achieved in 2 ways: 1) through the use of multi-operational technologies for obtaining sprayed coatings, which necessarily include the operations of subsequent high-temperature processing; 2) by improving the existing plasma spraying process by making the most complete use of the heat contained in the deposited material particles during the formation of coatings on the substrate.

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