Influence of technological parameters of spraying on mechanical properties of gas-dynamic coatings

G V Moskvitin, M S Pugachev

Institute of Machine Science named by A.A.Blagonravov, Russian Academy of Sciences, 4 Maly Kharitonyevsky Street, Moscow, 101990, Russia

E-mail: Gvmoskovitin@yandex.ru

Abstract. A methodology for shear and tension “ring tear-off” tests of copper, aluminum, zinc and nickel coatings laid through gas-dynamic spraying has been considered. It has been shown that the shear and tension test methodology permits obtaining dependences of strength of the bond between the coatings and the substrate on their laying temperature. The cohesive strength tension tests of the copper, aluminum, and zinc coatings using the “ring tear-off” method have shown the minimal spread of the values (≤ 5%) at the brittle character of the coating failure, which enhances the plausibility of the obtained mechanical properties.

1. Introduction

By virtue of enhancing the quality of the surface of articles intended for various purposes, by laying various coatings, its resistance to failure under external loads can be increased. When exploiting an article, there always appear loads and their respective stresses, which act along the normal or tangent to the coating surface and result in its failure, the early breakdown of equipment or accidents. In order to avoid this, coatings are tested for their cohesive strength (cohesion) and the strength of the bond between the laid metal layer and the substrate (adhesion).

2. Conducting research and experiments

Copper, aluminum, zinc and nickel coatings were sprayed onto the surface of a 40X steel substrate using a DIMET-404 gas-dynamic installation. The coatings were formed from mechanical mixture of fine powders of metals (Cu, Al, Zn, Ni) and hard brittle particles of corundum (Al₂O₃) [1].

The coatings were laid from a distance of 10 mm from the installation nozzle edge to the substrate surface, the nozzle movement speed was 10 mm/sec. For each powder, a spraying temperature was selected taking into account its physic-mechanical properties and was in the range of 180–540°C.

The value of adhesion between the coating and the substrate was determined using the method of tearing the laid layer from the substrate during a shear test [2]. The coatings were loaded on an INSTRON universal servohydraulic test machine with recording a load-displacement diagram. A sample with a coating was installed in a matrix, and under a load (P, figure 1) at a constant movement speed 8×10⁻⁶ m/sec, it was pushed through until a dramatic drop in the resistance to the load; at that, the coating was displaced relative to the sample or displaced with failure.
Figure 1. Scheme to test the samples for shear adhesion.
Sample — 1; metal layer — 2; matrix — 3; casing — 4.

The limit of strength of the bond between the coating and the substrate was calculated according to the formula (1) [3]:

\[ \tau = \frac{P(\pi D h)^{-1}}{1} \] (1)

where \( P \) is the maximal load at the moment of failure — shear of the coating layer, N; \( h \) is the width of the coating belt, m; \( D \) is the sample diameter, m.

To test the cohesive strength of the coating, the samples had been made on the basis of an industrial standard that regulates tests of coatings laid using gas thermal methods [4]. A sample consisted of two symmetric parts combined by means of a centering bushing and fastened with a pin and nuts (figure 2).

Figure 2. Sample to perform the tension test of the coating using the “ring tear-off” method: 1 — sample parts, 2 — centering bushing, 3 — seal washer, 4 — nut, 5 — pin, 6 — coating.

The coating was laid onto the sample surface and then mechanically treated until the set thickness of the layer was obtained. After that, the pin was removed, and tails were screwed into each part in order to install the sample into the clips of the test machine. The appearance of the coating on the sample surface after the failure (Fig. 6) gave a name to the proposed methodology — a “ring tear-off method” [5].

The samples were tested on a universal servohydraulic testing machine made by SHIMADZU firm, at the maximal load of 50 kN. The load was applied at the constant speed of the actuator’s movement equal to \( 5 \times 10^6 \) m/sec. During the tension test, the data were registered in load-displacement coordinates (figure 3).
The main mechanical characteristics of the coating were determined according to the State Standard GOST 1497-84. The coating’s cohesive strength value was calculated in compliance with the following formula (2) [5]:

\[ \sigma_{coh} = \frac{P_{\text{max}}}{F} \]  \hspace{1cm} (2)

where \( P_{\text{max}} \) is the maximal load before the failure, N; \( F \) is the coating area, mm\(^2\).

The area of the sprayed metal layer was calculated as the difference between the area of the sample cross-section with and without the coating.

The load rigidity was estimated as the ratio of the limit of the elastic region of the stress-displacement diagram (line segment BC, figure 3) to its respective displacement (line segment AC, figure 3).

3. Research and test results

After the shear tests of the copper coating, the substrate surface contained coating residues, which covered less than 50\% of its initial area, which permits interpreting the results as the strength of the bond between the coating and the substrate. A regular texture of red-colored dots can be seen on the substrate surface, and after having sheared the copper coating laid at a temperature of 540°C, on the sample, along the layer borders, there are continuous spots of copper up to 1.8 mm wide, wherein shear strips (figure 4) can be seen. The adhesion between the copper coating and the steel substrate depends on the spraying temperature and achieves the maximal value of 50 MPa at a temperature of 540°C (figure 5).

![Figure 3. Tension test diagram for the aluminum coating.](image)

After the shear test, the surfaces of the sample substrates with the laid aluminum and zinc coating have shown presence of the continuous layer of the laid metal on the surfaces across the whole area of
the substrate, which permits interpreting the test results as the cohesive strength of the coating after the shear test.

After having been sprayed at an air flow temperature of up to 360°C, the zinc coating’s cohesive strength amounts to 35 MPa; an increase of the air flow temperature up to the maximum is accompanied by a decrease in the cohesive strength of the metal down to 14 MPa (figure 5).

The metal’s cohesive strength of the aluminum coating does not practically depend on the spraying temperature and amounts to 27 MPa in average (figure 5). The obtained dependence of the cohesive strength on the spraying temperature is rather consistent with the regularities of the changes in the structure and properties of the coating revealed using metallo-physical research methods [6–8].

![Figure 5. Coating shear test results: aluminum (1), zinc (2) and copper (3).](image)

When considering the results obtained through the shear test of the laid copper, aluminum and zinc coating layer, it should be noted that this method permits revealing the regularities of changes in the strength of the bond between the coating and the substrate as well as of the cohesive strength of the coating metal depending on the technological parameters of spraying. Such tests have to be recommended and used for researches into the mechanical characteristics of coatings laid by means of gas-dynamic spraying.

As a result of the tests of the copper, aluminum, nickel and zinc coatings for their cohesive strength using the “ring tear-off” method, clear dependences of this characteristic on the spraying temperature have been revealed (table 1).

If the spraying temperature rises, the cohesive strength of the aluminum coating is accompanied by a dramatic decrease; at the same time, the coating rigidity decreases and its plasticity grows.

A similar dependence of the cohesive strength on the spraying temperature is traced for the copper coating.

The obtained dependence of the change in the cohesive strength of the copper and aluminum coating on the spraying temperature is rather consistent with the changes in the structure obtained using metallo-physical research methods [9].

The increase in the spraying temperature of the zinc coating does not practically influence the cohesive strength of the coating metal and is accompanied by a decrease in the rigidity and an increase in the plasticity.
Table 1. “Ring tear-off” test results

| Metal for spraying | Spraying temperature, °C | Coating strength, MPa | Elongation, mm | Rigidity, MPa/mm |
|--------------------|--------------------------|-----------------------|----------------|-----------------|
| Aluminum           | 180                      | 181                   | 0.1            | 1894            |
|                    | 270                      | 108                   | 0.145          | 746             |
|                    | 360                      | 82                    | 0.144          | 573             |
|                    | 540                      | 53                    | 0.146          | 362             |
| Zinc               | 270                      | 91                    | 0.135          | 681             |
|                    | 450                      | 95                    | 0.160          | 594             |
| Nickel             | 360                      | 64                    | 0.044          | 1695            |
|                    | 540                      | 72                    | 0.152          | 473             |
| Copper             | 180                      | 165                   | 0.091          | 2375            |
|                    | 270                      | 100                   | 0.134          | 751             |
|                    | 360                      | 90                    | 0.158          | 576             |
|                    | 540                      | 86                    | 0.148          | 585             |

The rise in the spraying temperature of the nickel coating is accompanied by an increase in the cohesive strength and plasticity, and its rigidity decreases significantly.

Figure 6. Failure surface of the copper (a), aluminum (b), zinc (c), and nickel (d) coatings.
Both a research of the sample surface after the coating failure and the appearance of the test diagrams show that the failure is brittle (figure 3 and figure 6).

The “ring tear-off” estimate of the coatings’ cohesive strength shows a low spread of the values. The mean deviation of the results in the series of the samples is 0.5 to 5%, which is very important if there is a brittle failure.

4. Conclusions
As a result of the shear test, the determination of the coating’s mechanical properties has permitted obtaining the dependence of strength of the bond between the coating and the substrate on the spraying temperature; at that, if the coating’s adhesion exceeds the cohesive strength of the laid metal layer, the methodology permits estimating the cohesive strength through a shear test.

As the spraying temperature rises, the adhesion between the copper coating and the steel substrate increases and achieves the maximal value of 50 MPa at a temperature of 540°C. The maximal cohesive strength of the aluminum- and zinc-based coatings amounts to 30 and 35 MPa respectively and decreases, as the spraying temperature rises.

The “ring tear-off” determination of the coating’s mechanical properties permits researching their dependence on the technological parameters of spraying.

The maximal values of the coatings’ cohesive strength have amounted to: 181 MPa for aluminum, 165 MPa for copper, 72 MPa for nickel, 95 MPa for zinc; the strength of the aluminum and copper coatings decreases, as the coating laying temperature rises; on the contrary, the strength increases for nickel and does not change for zinc.

The “ring tear-off” method provides a highly credible estimate of the coatings’ cohesive strength.

References
[1] Dimet. Primenenie tekhnikii i oborudovaniya [Dimet. Application of technology and equipment] (electronic resource) Available at: http://www.dimet-r.narod.ru/ (accessed 30 June 2019)

[2] Methodological manual 1987 Opredenenie prochnosti scepeleniya gazotermicheskikh pokrytij s osnovoj [Determination of adhesion strength of thermal coatings with the base] (Moscow: VNIINMASH) [In Russian]

[3] Arkhipov V E, Landarski A F, Melshanov A F, Moskvitin G V, Pugachev M S 2011 Svojstva mednyh pokrytij, nanesyonnyh gazodinamicheskim napyleniem [Properties of copper coatings applied by gas-dynamic spraying] Uprochnayushchie tekhnologii i pokrytiya [Hardening technologies and coatings] 9 17-23 [In Russian]

[4] Xasui A, Morigaki O 1985 Naplavka i naplyenie [Surfacing and spraying] Gerevod s yaponskogo V.N. Popova pod red. V.S. Stepina, N.G. Shesternina [translation from Japanese by V. N. Popov edited by V.S. Stepin, N.G. Shesterkin] p 240 [In Russian]

[5] Arkhipov V E, Landarski A F, Moskvitin G V, Pugachev M S 2019 Ocenka kogezionnoj prochnosti gazodinamicheskikh pokrytij [Assessment of cohesive strength of gas-dynamic coatings] Vestnik mashinostroeniya [Bulletin of mechanical engineering] 4 64-70 [In Russian]

[6] Arkhipov V E, Landarski A F, Melshanov A F, Moskvitin G V, Pugachev M S 2015 Tekhnologicheskie osobennosti gazodinamicheskogo naneseniya pokrytij [Technological features of gas-dynamic coating] Vestnik mashinostroeniya [Bulletin of mechanical engineering] 9 64-70 [In Russian]

[7] Arkhipov V E, Landarski A F, Moskvitin G V, Pugachev M S, Falaleev N S 2016 Svojstva alyuminij – cinkovogo pokrytija, nanesyonogo gazodinamicheskim napyleniem [Properties of aluminum-zinc coating applied by gas-dynamic spraying] Uprochnayushchie tekhnologii i pokrytiya [Hardening technologies and coatings] 6 28-34 [In Russian]
[8] Arkhipov V E, Dubrovina A A, Kuksenova L I, Landarski A F, Moskvitin G V, Pugachev M S 2015 Struktura i svojstva pokrytij, nanesennyh gazodinamicheskikh napyleniem [Structure and properties of coatings deposited gas-dynamic spraying] Uprochnyayushchie tekhnologii i pokrytiya [Hardening technologies and coatings] 4 18-24 [In Russian]

[9] Arkhipov V E, Landarski A F, Moskvitin G V, Pugachev M S 2017 Gazodinamicheskoe napylenie: struktura i svojstva pokrytij [Gas-dynamic spraying: structure and properties of coatings] (Moscow: KRASAND) p 240 [In Russian]