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RESTORATION OF ALUMINIUM ALLOY STRENGTH PROPERTIES BY COLD SPRAY AFTER CORROSION DAMAGE

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ABSTRACT

The paper presents the results of the research aimed at studying the strength properties of cold spray coatings for restoring aluminum alloys damaged by corrosion. The topicality of the research in the field of coating strength is determined by the reliability requirements for technical designs in operation. The practical relevance of the research is the development of an efficient technology for restoring aircraft components made of aluminum alloys, which is based on the cold spray method. The scientific novelty consists in studying the strength characteristics of the coating when powders are locally deposited on a damaged metal area. Corrosion lesions are considered as damages. To achieve the aims set, the results of fundamental research on the effect of cold spraying on the strength characteristics of the restored material are summarized; and metallographic studies, and mechanical tests of samples coated by cold spray are performed. The tests were carried out on samples made from aircraft alloy 1163RDTV and restored by cold spray after corrosion damage. As a result of the studies, the mechanical characteristics of the material restored by cold spray coating were obtained.

Keywords: aircraft, plane, corrosion damage, durability, fatigue, aluminum alloy, cold spray, functional coatings

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1. INTRODUCTION

Over the past 17 years, centers for the study of gas dynamic cold spray (CS) have emerged in the US, Germany, Canada, England, France, China, Japan and India, which shows the wide interest of the scientific community in this method. The analysis of publications on the gas dynamic cold spray method makes it possible us to distinguish the following main areas of research:

- gas dynamic regularities,
- laws governing the impact of particles on the surface,
- study of the properties of coatings;
- development of equipment for coating.

The main results of Russian studies aimed at studying the fundamental principles of the CS method are reflected in [1-9]. These works describe the generalized results of experimental and theoretical studies of the processes of acceleration of fine particles in supersonic nozzles, jets, their impact loading, erosion-adhesion transition, physical and chemical interaction at the contact boundary with the formation of bonds. Experimental settings and diagnostic methods are described. The structure and properties of coating materials are considered.

In work [10], methods for determining adhesion and cohesion properties of CS coatings were investigated. The data on adhesive and cohesive strength of coatings are presented. Spraying was performed on a DIMET-404 type installation. In their studies, the authors consider spraying on steel substrates only.

A survey of foreign studies [11-18] showed a fairly wide range of applied research aimed at studying the properties of coatings applied by the CS method on aluminum alloys. The works describe methods of crack retardation and restoration of mechanically modeled damages on the surface of sheet material, the results of reinforcing riveted joints, the corrosion properties of the coatings offered, the strength properties under cyclic loading.

In general, it can be concluded that most research results are obtained for spraying conditions with parameters provided by the experimental equipment. For aluminum alloys, there is insufficient data on the effect of the powder mixture composition and spraying conditions on the strength properties of coatings. When considering the methods of restoring metal products, the damage is modeled by mechanical milling of the material, which affects the strain-stress state of the surface in the area of the defect being modeled. In this case, the surface has properties that differ from the surface properties in the case of corrosion damage.

Thus, taking into account the current state of research and the prospects for their practical application, studies of the strength properties of materials with CS coatings are quite relevant. In particular, in [19, 21, 22], the authors show that for the aviation industry, research related to the restoration and protection of aircraft structures by the gas dynamic cold spray method for operational damages is of great importance. In this article, the authors present the results of studies on the strength properties of the aviation alloy of the 1163 series with a coating applied by the gas dynamic cold spray method in the corrosion area.

Purpose and objectives of the research

The main purpose of the research is to evaluate the effect of gas dynamic spray on the strength characteristics of the restored material and to find the optimal parameters of the process that characterize the quality of the coating according to the functional requirements established for it.

Optimization is carried out by varying the parameters included in the following main stages of the spraying process:

- preparation of the surface for spraying;
- composition of the powder mixture;
- mode and conditions of spraying;
- surface finishing.

The selection of the optimal combination of the parameters for each stage is the main objective of the research. The results are evaluated by the following tests: metallographic examinations, coating microhardness tests, mechanical tests of coated samples, corrosion tests. The general diagram of the studies is shown in Fig. 1.

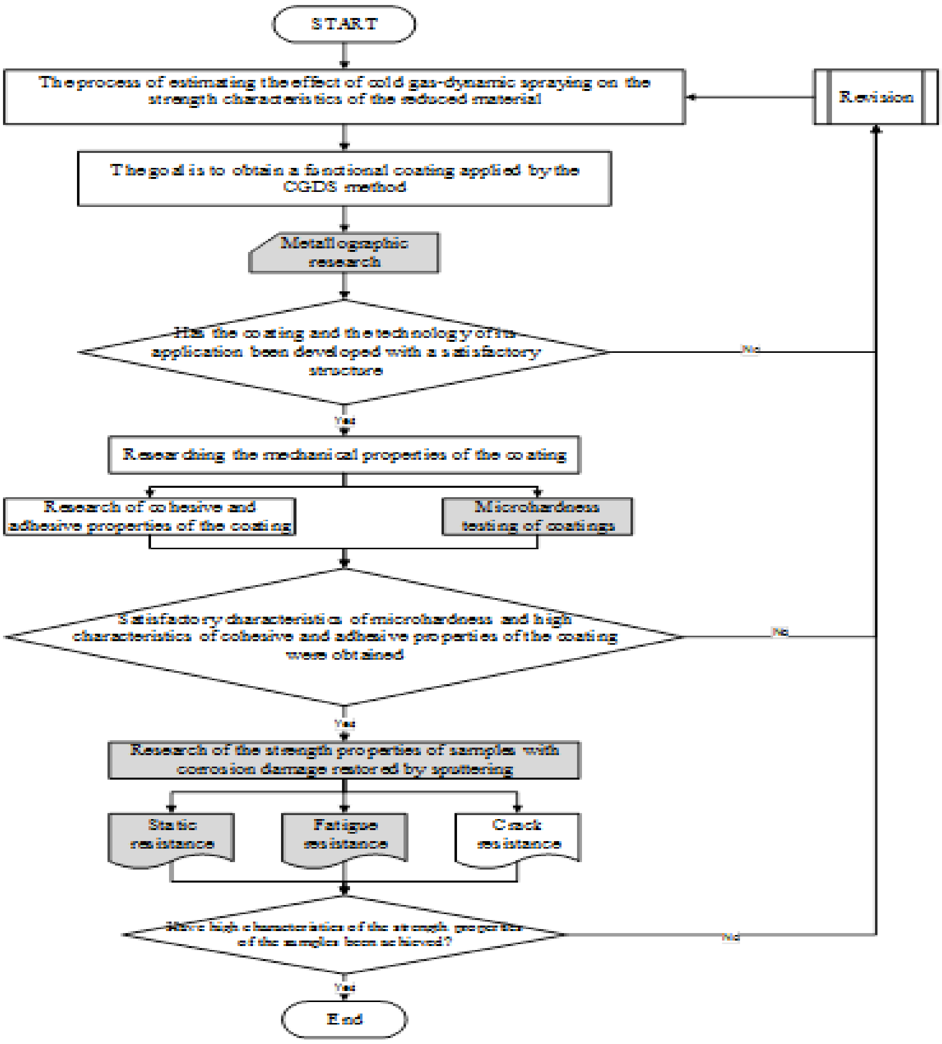

Figure 1 General diagram of the studies - described in this article

Experimental equipment

The samples were tested for static strength on a universal electromechanical installation Instron 3369. Its purpose is: testing of various materials and structures for tension-compression and bending; features and capabilities: registration of longitudinal and transverse deformations with mounted sensors or an optical extensometer; load recording with force gauges with a maximum load of 50 kN, 5 kN, 1 kN. The maximum load is 50 kN, the positioning resolution is 0.0625 μm, the load measurement accuracy is 0.5% of the measured value in the range from 1% to 100% of the rated power of the load sensor.

The fatigue test on the samples was performed on a universal servo-hydraulic test machine Instron-8801. The maximum load is 100 kN. Its purpose is: performing static, fatigue tests of materials and structures; testing for cracking resistance.

Spraying was made on an experimental CS unit developed at RAS SB ITAM. The spraying unit was positioned using a robotic 6-axis manipulator KUKA KR 16-2 (Germany).

For metallographic examinations, the following equipment was used:

- Automated cutting and grinding-polishing machines Presi (France);
- Microscope Zeiss, stereo and direct light with a set of filters.

For microhardness measurements, an automatic microhardness tester DuraScan 50 (Emco-Test, Austria) was used.

2. MATERIALS AND METHODS

The strength properties of alloy 1163RDTV alloy restored after corrosion damage by the gas dynamic cold spray method were studied to determine the optimum powder composition and included the following:

- spraying samples with various parameters of the spraying technology;
- metallographic examinations;
- mechanical tests of coated samples for strength;
- analysis of the results.

Spraying

The purpose is to obtain a coating for restoring the strength properties of an aluminum alloy with corrosion damage.

As samples for spraying, plates of sheet aluminum alloy 1163RDTV (105×25×2) mm in size were used. Corrosion damages were modeled in the form of surface corrosion with a depth of 10% and 20% of the thickness of the material. The corrosion damage was modeled on one side of the sample. The surface appearance of the sample in the corrosion area is shown in Fig. 2.

The sprayed material is ASD-1 aluminum powder with a spherical shape of particles. The average particle diameter was about 30 μm. In the experiments an axisymmetric supersonic nozzle was used with diameters of critical and output cross sections of 2.8 and 6.5 mm, respectively. The working gas was air. Spray modes are shown in Table 1. Fig. 3 presents a view of a sprayed sample.

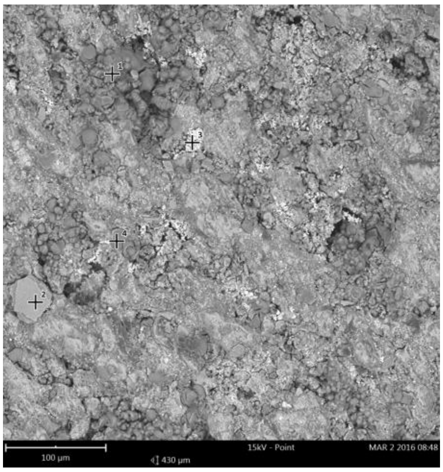

Figure 2 Surface appearance of the sample in the corrosion area

After the spraying, the superfluous coating layer was removed on the grinding wheel in three stages. At the first stage, preliminary removal of the superfluous layer was carried out. At the second stage, finishing the surface to the nominal thickness of the workpiece was performed. The third stage was final polishing of the surface (Fig. 4). After that, the workpieces were milled. After milling, the samples geometrically corresponded to proportional flat samples of type I according to GOST 1497-84 (foreign equivalents: ASTM E8-95a, EN10002) for tensile tests on static strength (Fig. 5) and proportional flat samples of type VII according to GOST 25.502-79 (foreign equivalents: ASTM E 466-82, AECMA Standard) for fatigue tests (Figure 6a). In addition, for fatigue tests, a non-standard sample was prepared without a hole and a fillet from the areas for gripping devices to the working part of the sample (Figure 6b).

For the convenience of identification, a three-level designation of sample groups in the format (*.**.*...*/*...*) was adopted, where

1. level (*) – surface condition:

- "a" group – clear samples with no corrosion;
- "b" group - samples with corrosion lesions;
- "c" group –samples restored after corrosion attacks.

2. level (**) –depth of the corrosion area:

- the depth of corrosion areas (thickness restored) in percent;

3. level (*...*/*...*) – spraying characteristics: composition of powder mixture/ spraying temperature mode in degrees Celsius.

Thus, for example, sample 103 will belong to a group of samples labeled **c.20.Al100/200**.

Table 1 Spraying modes

Item no	Sample code	Powder composition	Temperature mode	Conditional depth of corrosion	Group code
1	103	Aluminum 100%	200° C	20 %	c.20.Al100/200
2	104	Aluminum 100%	300° C	20 %	c.20.Al100/300
3	105	Aluminum 85% Zinc 15 %	200° C	20 %	c.20.Al85Zn15/200
4	107	Aluminum 100%	200° C	10 %	c.10.Al100/200

5	108	Aluminum 100%	200° C	10 %	c.10.Al100/200
6	110	Aluminum 100%	200° C	10 %	c.10.Al100/200
7	111	Aluminum 100%	200° C	10 %	c.10.Al100/200

Figure 3 Appearance of the blank with a restored area after corrosion attack

Figure 4 Appearance of the blank after surface machining

Figure 5 Appearance of the blank after milling for static tests

Figure 6 Appearance of the sample after milling for fatigue tests

Metallographic examinations

The aim is to study the structure of the coating to select the optimum ratios of the powder composition, spraying mode, application method and surface treatment.

Microhardness tests

The purpose is to evaluate the plasticity properties of the coating.

The microhardness of the coatings was investigated on transverse sections by 10 equidistant measurements along a straight line. The average values of the microhardness $HV_{0.1}$ were calculated from the measurements.

Mechanical tests of samples for strength

The purpose is to evaluate the strength properties of an aluminum alloy recovered after a corrosion attack.

Tensile tests were performed under static and cyclic loading.

The calculations of the mechanical characteristics and the construction of the load-displacement and strain-stress dependencies for each sample were performed automatically using the Instron Bluehill software. Tests for static tensile strength are regulated by standards GOST 1497-84, GOST 11701-84 (foreign equivalents: ASTM E8-95a, EN10002).

In the fatigue tests, the samples were loaded with a zero-to-tension stress sinusoidal cycle ($R = 0$) with a frequency $f = 5$ Hz and a maximum load σ_{max}^{gross} = 135 MPa. Fatigue tests are regulated by standard GOST 25.502-79 (foreign equivalents: ASTM E 466-82, AECMA Standard).

Tests for corrosion resistance of the coating

The purpose of the tests is to evaluate the corrosion resistance of the coating for the selected method of its application and treatment based on the analysis of corrosion kinetics processes.

These tests are in the process of pre-test preparation.

3. RESULTS & DISCUSSION

Tensile tests under static loading

The change in the mechanical characteristics of the restored aluminum alloy as a function of the powder mixture and the spraying mode was estimated from the change in the deformation curve with respect to the equivalent curve obtained for samples with no corrosion. Earlier the authors analyzing the results of group “a” (standard samples) samples tests for the studied material (alloy 1163RDTV) obtained mechanical characteristics and plotted the material deformation curve, which were presented in [19, 20].

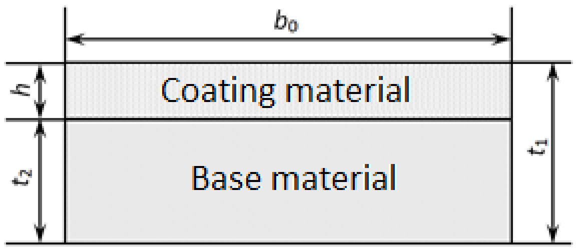

Figure 7 Cross-section of the working part of the samples

$F_1 = b_0t_1$, $F_2 = b_0t_2$, $F = b_0h$; where b_0 is the width of the working part of the sample; t_1 is the thickness of the coated sample, t_2 is the thickness of the base material, h is the depth of the corrosion area

For the restored samples, the total cross-section of sample F_1 will be considered in the form of two sectors: a sector of the base material with a cross-sectional area F_2 and a sector of the restored cross-section F. That is, $F_1 = F + F_2$.

In the process of testing the recovered samples, cracking of the applied coating occurs followed by delamination (Fig. 8). Fig. 9 shows the surface of the sample and the inner surface of the detached coating. A similar structure of the surfaces represented suggests that the powder particles attached to the surface of the substrate remain on it, and the destruction of the coating occurs at a distance from the substrate. Thus, it can be assumed that under the considered loading, the destruction occurs in the coating itself and the adhesion properties are higher than the cohesive ones.

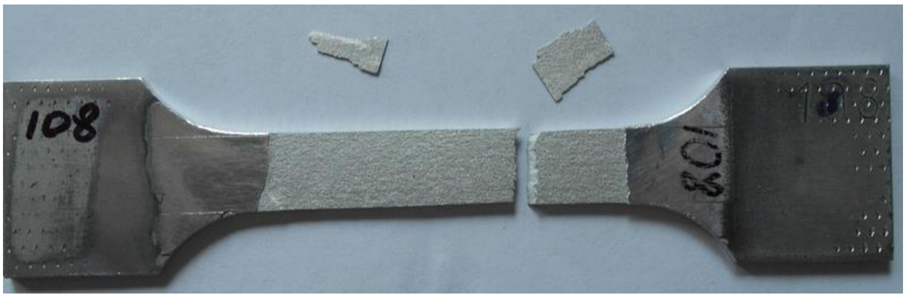

Figure 8 Appearance of the sample after destruction in the tensile test

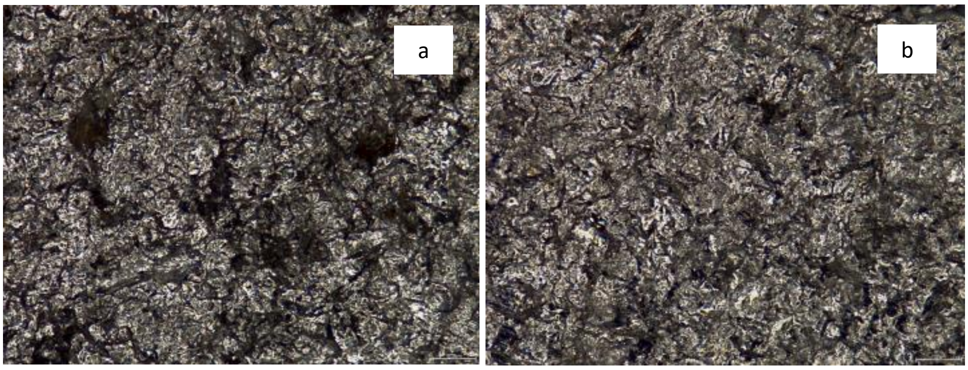

Figure 9 Surface of the sample after destruction (a) and inner surface of the detached coating (b). Image magnification 300$^{\times}$

Observations show that the cracking of the coating occurs at stresses close to the value of the material elastic limit. Therefore, one should take into account the fact that after the cracking, the coating is excluded from calculations, and the values of the mechanical characteristics of the material calculated for the cross-section F_1 (with the exception of the relative elongation) must be recalculated taking into account the depth of the corrosion area, that is, the cross-section F_2 (Fig. 7). This phenomenon was discussed in greater detail by the authors in [20]. We will consider the fragment of the deformation diagram when the coating still perceives the load. This fragment of the deformation diagram corresponds to the elastic range, and the properties of the material obey Hooke's law. Fig. 10 shows the deformation diagrams obtained for cross-section F_1. Table 2 shows the numerical values of the effective modulus of elasticity and the elastic limit. The effective modulus of elasticity is the value obtained when testing a coated sample, assuming that in the loading process in the restored sample, before the cracking begins, a strain level occurs that is common both for the coating layer and for the strip of material.

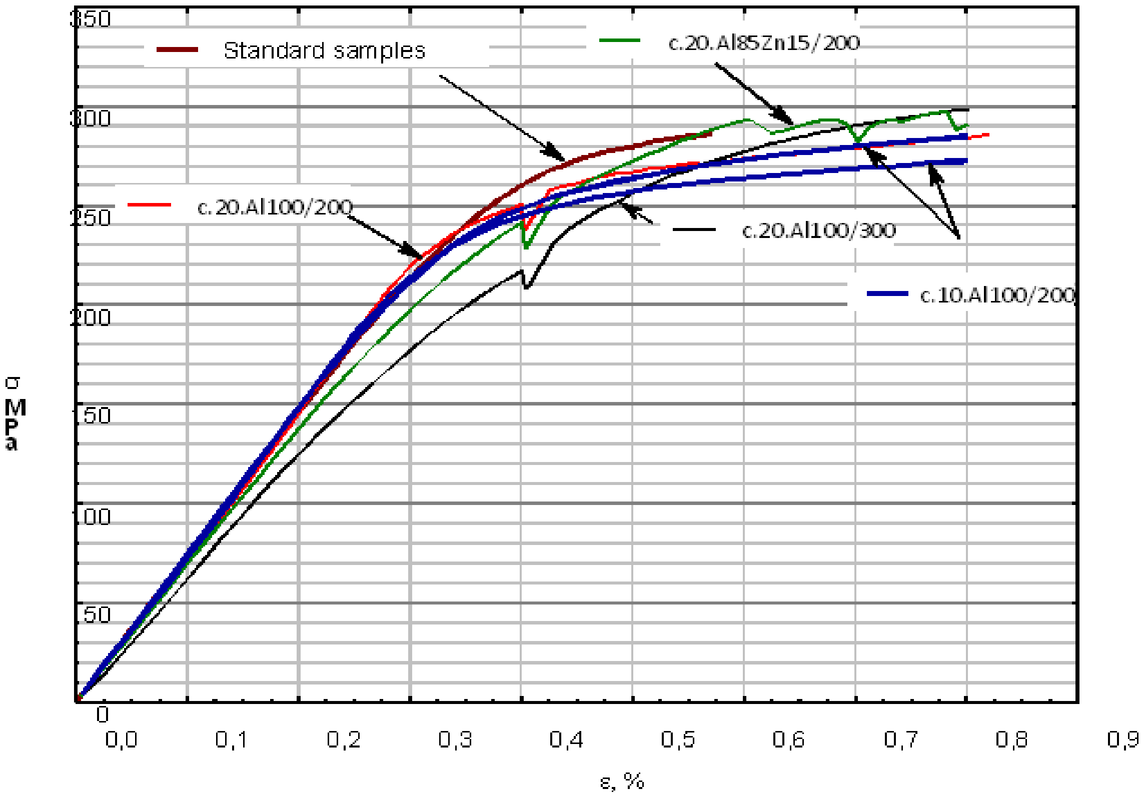

Figure 10 Fragment of deformation diagrams of group “a” (standard samples) samples and restored samples

Table 2 Mechanical characteristics of grade 1163RDTV alloy recovered after a corrosion attack

Material property studied	Sample group			
	c.20.Al100/200	**c.20.Al100/300**	**c.20.Al85Zn15/200**	**c.10.Al100/200**
Effective modulus of elasticity E_{ef}, MPa	70696,7	62174,3	69452,2	74238,6
Elastic limit $\sigma_{0,001}$, MPa ($\varepsilon_{res} = 0{,}001\%$)	233,869	147,929	146,359	193,65

Three spraying modes were considered. The composition of the powder and the temperature were varied. At the first stage, tests were performed on samples with a restoration depth of 20% of the plate thickness. The best result was achieved for a powder mixture of 100% aluminum and a temperature of 200° C (CS parameters *Al100/200*). At the second stage, tests were performed on samples with a restoration depth of 20% with the selected spraying parameters.

It is evident from the deformation diagrams that during the stretching of the samples, the applied coating destructs when the sample is deformed within 0.275-0.3%, the upper limit of which corresponds to a stress level close to the value of the elastic limit of the base material. When comparing the modulus of elasticity of the material in question (Fig. 10) in the diagram and the effective modulus of elasticity obtained for the restored sample, a good agreement is found with the depth of corrosion area of both 10% and 20%. The obtained values of the effective modulus of elasticity are close to the boundaries of the 95% confidence interval. Thus, one can talk about restoring the characteristics of the static strength of 1163RDT aluminum alloy with corrosion depth of up to 20% in the elastic range of the deformation diagram.

For the selected spraying parameters, the average microhardness of the coating was determined, which was 61.3 $HV_{0.1}$. For the base metal, the average microhardness is 144.6 $HV_{0.1}$.

Fatigue tests

Fatigue tests were performed for two types of samples: with a stress raiser in the form of a central hole (Fig. 11, 12a) and a non-standard sample (Fig. 12b).

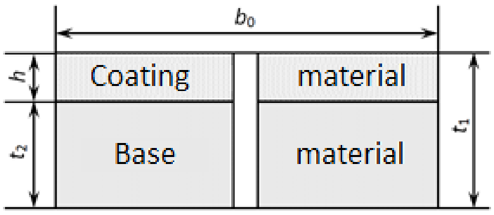

Figure 11 Cross-section of the working part of the sample with a central hole

$F_1 = b_0t_1$, $F_2 = b_0t_2$, $F = b_0h$; where b_0 is the width of the working part of the sample; t_1 is the thickness of the coated sample, t_2 is the thickness of the base material, h is the depth of the corrosion area

It should be noted that for both samples a high sensitivity of the coating to stress concentration was revealed. The non-standard sample without a hole withstood 100,000 loading cycles. Then the tests were stopped. During the tests, the coating was destroyed in the transverse direction of the sample in the transition area of the thickness from corrosion to the material (Fig. 12b).

The test results for the sample with a hole were compared with the data obtained earlier and presented in [23] (without taking into account a number of differences in conditions and test modes). In Fig. 14 it is shown that the longevity characteristic increased by 1.67 times in comparison with the sample not restored after corrosion. The longevity value of the sample restored after corrosion was 58985 cycles and is within the 95% confidence range for the basic fatigue curve obtained for the aluminum alloy. Fig. 13 shows a fragment of the section made in the longitudinal direction after the tests. After application of the cyclic load, a certain micro-peeling of the coating from the substrate was observed.

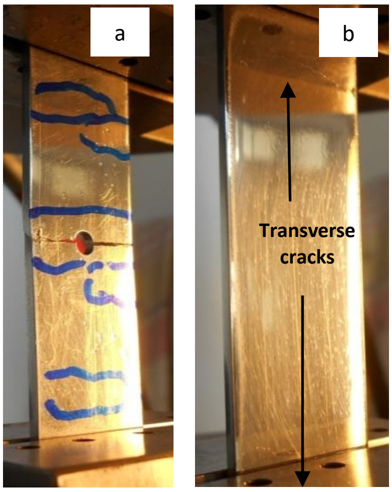

Figure 12 Appearance of the samples after the fatigue tests

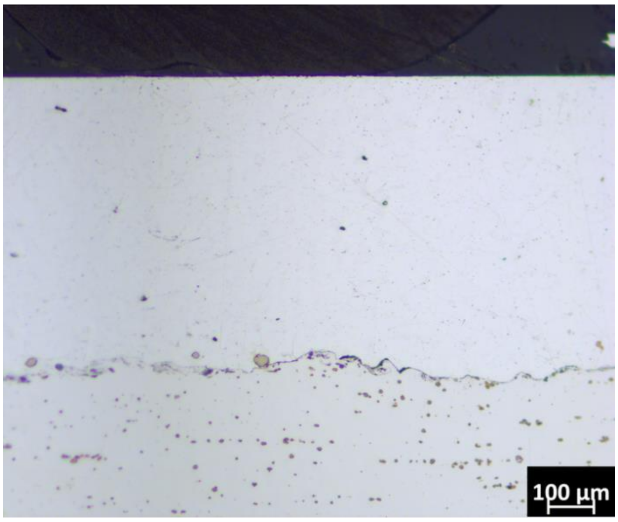

Figure 13 Fragment of the longitudinal section after the tests

However, the tests showed that, despite the multifocal destruction of the CS coating, the fatigue life of the restored sample increases. The results obtained suggest that the gas dynamic cold spray method for restoring corroded aluminum alloys is promising, provided that the stress concentration does not increase local stresses above the elastic limit of the material.

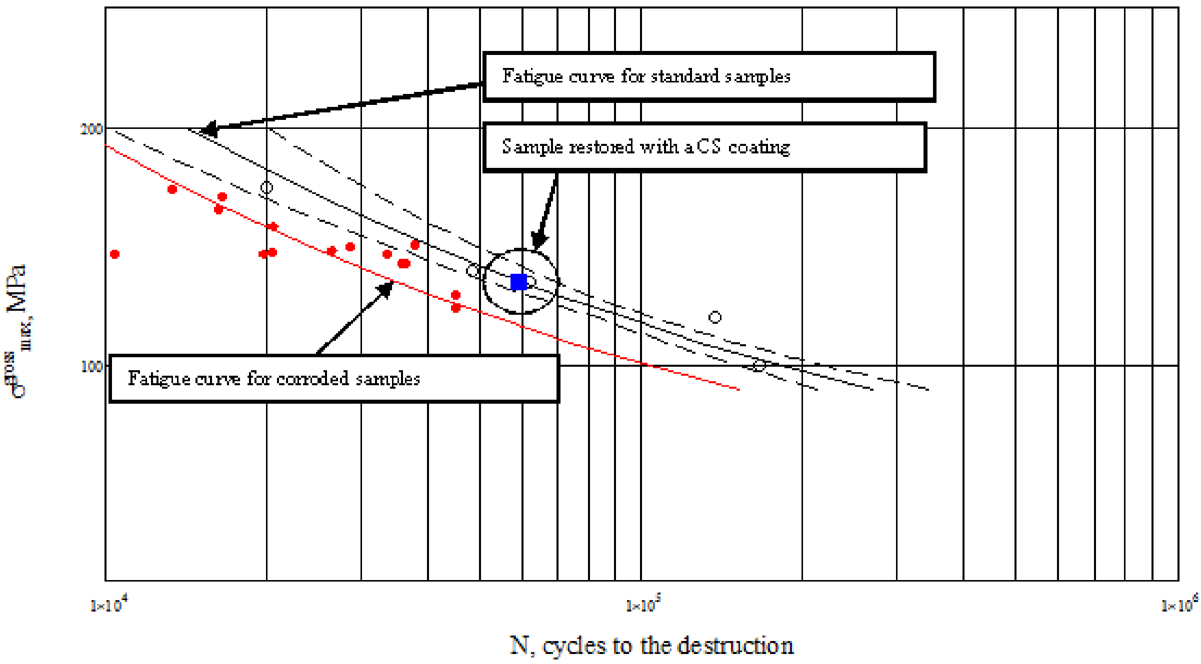

Figure 14 Fatigue life curves obtained during tensile tests of samples of the strip type with a central hole (type VII, see GOST 25.502-79) in various initial states [23] and the test result for the corroded sample restored with a CS coating

4. CONCLUSION

Preliminary studies of static strength and fatigue were performed for samples made of the 1163 series structural aluminum alloy restored by the gas dynamic cold spray method after a corrosion attack.

As a result of the researches, knowledge was gained of the strength properties of the 1163 series material with a coating applied by the gas dynamic cold spray method. Optimum spraying parameters were determined, and the dependencies were established between the spraying modes considered, the composition of the powder mixture and the coating properties studied.

The analysis of the results of experimental studies has shown that with the considered coating spraying mode, there is no complete restoration of the static strength characteristics. Yet the restoration of corrosion damage by the CS method increases the static strength characteristics of the sample in the elastic range of the deformation diagram. The best result of the static tests was a satisfactory coincidence of the linear portion of the deformation diagram for a sample restored from corrosion damage by the CS method and a standard “clear” sample with Al100/200 spraying parameters. The fatigue tests showed high sensitivity of a CS coating to the stress concentration, which should be taken into account when preparing the surface for spraying. Further research is required. Nevertheless, for a coated sample, the number of cycles before the destruction increases as compared with a sample not restored after a corrosion attack.

The authors believe that the gas dynamic cold spray (Cold Spray) method is a promising advanced method of restoring elements of corroded aircraft structures under operating conditions that makes it possible to restore the strength characteristics of the damaged structural element, and with the appropriate method of protecting the coating from the environmental effects, to decrease the regularity of repair and restoration works and to improve the reliability of the aircraft structures in general.

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