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Increasing the Fatigue Strength of Aluminum Alloy Parts Using Composite Coatings for Aerospace Engineering

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ABSTRACT

Aluminum alloys are widely used in many arears of engineering including aerospace engineering. Unfortunately, fatigue properties of aluminium alloys are not sufficient and their increase is very important scientific and practical task. The article is devoted to the studies of the Al_2O_3 composite coatings' effect on bending fatigue tests of aluminium specimens. Initially, the coatings were formed by converting the surface of aluminum alloy specimens by anodic-cathodic microarc treatment to a depth of 90-110 microns. Then the resulting coating was cladded with a "Cr-CrC" surface layer of 9-14 microns' thickness from the vapor phase. The clad layer filled the pores and cracks of the Al_2O_3 coating that formed after the microarc treatment. Based on the analysis of bending fatigue tests results, it is shown that the formed composite layer can be used as a reinforcing coating in aerospace engineering. The effectiveness of the developed coating depends on the part's section thickness and the level of its loading. In the case under consideration, with cyclic bending stresses of less than 95 MPa, the increase in fatigue strength was 1.75-1.8 times.

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Introduction

Modern aluminum alloys are widely used in many areas of technics, for example, in construction and transport [1-3]. Especially, aluminium has found application in aviation and aerospace engineering due to the combination of low weight and sufficiently high strength [4-6]. Moreover, aluminium is non-magnetic and characterized with excellent corrosion resistance. At present the volume of their use by weight is about 70% of the total mass of structural materials in aviation and aerospace [4]. Unfortunately, the fatigue strength of aluminium alloys is not sufficient. That is why some investigations are devoted to the determination of aluminium alloys fatigue properties at different loading conditions aiming the development of methods to increase fatigue strength [7-9]. However, the load value on the critical components for aerospace application and the requirements for their weight reduction are increasing. Therefore, research and development in the field of increasing the strength of aluminum alloy parts continues to be intensively conducted. Basically, these improvements include the following areas:

- Aluminum alloys compositions and methods of their preparation [10, 11].
- Designs and technologies for manufacturing aluminium parts [12, 13].
- Hardening of aluminum alloys both at the stage of manufacturing parts and at the final stages of processing [14,15].

Certain features of parts made of aluminum alloys for aviation and space technology include relatively small sections of parts. At the same time, the stress distribution in parts during cyclic bending loading takes place just in the surface areas. So, to improve the parts' performance a surface hardening of aluminum alloy can be the used by developing composite coatings on these surfaces.

One of the most effective methods of aluminum parts surface hardening can be attributed to the transformation of their surface layer by anode-cathode microarc treatment [14]. This method allows you to create a wear-resistant anticorrosive surface layer of Al_2O_3 to a depth of 70 microns to 300 microns. However, this layer is characterized by the presence of pores and cracks, which turn out to be stress concentrators under cyclic loads. As a result, the surface fatigue strength decreases, which contributes to the destruction of material from the inside in certain time, and the coating peels off.

The purpose of the research is to increase the fatigue strength of aerospace parts made of aluminum alloys by forming composite coatings.

Methodology

The research methodology included the following steps:

- Manufacturing aluminium alloy specimens;
- Anodic-cathode microarc treatment of specimen's surfaces;
- The analysis of the features of the Al_2O_3 coating;
- The choice of material for cladding Al_2O_3 coating;
- Carrying out comparative fatigue bending tests;
- Determination of correlation equations on the tests data;

- Analysis of results obtained.

Specimens were made of an aluminum alloy sheet (2024 type) with a thickness of 2.8 mm. After that, the surface layer was transformed into Al_2O_3 to a depth of 70...110 microns by anodic-cathode microarc treatment. As a specific feature of the treatment process the coatings were characterized with pores and cracks. To overcome this problem, it has been decided to clad the coating with high strength properties' material which, moreover, fill the surface pores and cracks of this coating. As well the proper cladding technology should be applied. The cladding layer thickness was in the range of 10...15 microns.

Comparative fatigue bending tests were carried out applying as-delivered specimens, specimens with Al_2O_3 coatings and ones with Al_2O_3 coatings cladded with a material having high strength properties.

Results and Discussion

An analysis of the structure features of the Al_2O_3 coating formed by anodic-cathode microarc treatment on aluminum alloy samples with a thickness of 2.8 mm showed the following (Figure 1):

- As-treated structure is characterized with presence of defective layer (Figure 1a) which must be removed for improving surface properties;
- The surface hardness of the Al_2O_3 coating, with a thickness of 90...110 microns, after removal of the defective layer was 11…13 GPA and it increased up to 17...19 GPA at the boundary with the base material (Figure 1b);
- Al_2O_3 coatings formed by anode-cathode microarc treatment, even after removing the surface defective layer, are characterized by the presence of protrusions and depressions of different sizes which is proved by surface topography (Figure 1c,d). In addition, pores and cracks are observed almost throughout the entire cross-section, and which in some cases extend almost to the entire depth of the coating. Moreover, the number of pores decreases towards the boundary with the base material.

Taking into account the above-mentioned features of Al_2O_3 coatings formed by anodic-cathode microarc treatment on aluminum alloy samples, it was necessary to develop a method for creating a clad layer that would eliminate defects in the coating. A high-strength "Cr-CrC" coating deposited in a protective medium on the surface sample from the vapor-phase was adopted as the basic method. This made it possible to fill the pores and cracks in the coating, providing high adhesive properties.

The thickness of the "Cr-CrC" layer cladding the surface of the Al_2O_3 coating was 10...15 microns. Subsequent analysis of the surface layer structure proved the filling surface pores by "Cr-CrC" cladding and the penetration of "Cr-CrC" to the entire depth of cracks in the Al_2O_3 coating (Figure 2).

Comparative fatigue tests of bending samples were carried out at bending stresses of 30...300 MPa. As a result of processing the results obtained, the parameters of the regression equations LgN from Lgσ were determined, corresponding to the inclined sections of the fatigue curves with a 50% probability of non-destruction: for the as-obtained material specimens

$LgN=13.8218-4Lg\sigma$,

for specimens with Al_2O_3 coating formed by anodic-cathode microarc treatment

$LgN=9.9685-2.16Lg\sigma$,

for specimens with Al_2O_3 coatings additionally cladded with "Cr-CrC"
$LgN=16.2341-4.97Lg\sigma$,

The fatigue curves of the specimens are shown in Figure. 3.

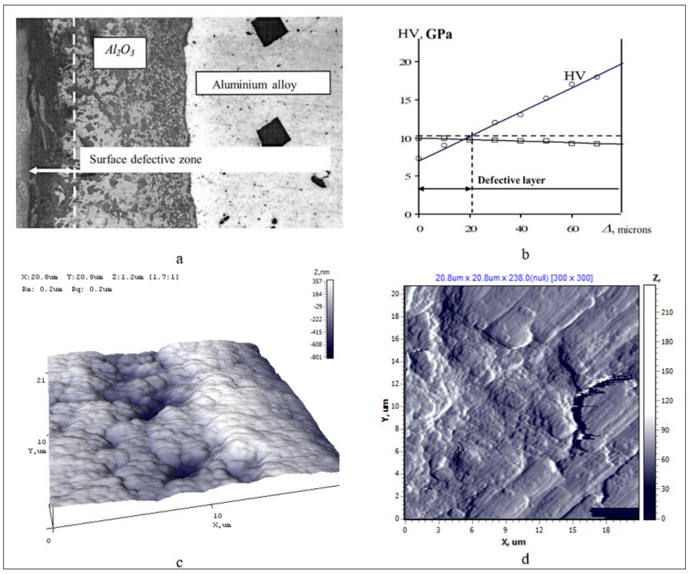

Figure 1: Typical Structure of the Coating formed by Cathode-Anode Microarc Treatment (a), hardness changes through the depth of the Coating (b) and topography of the coating surface before (c) and after (d) removal of the defective layer

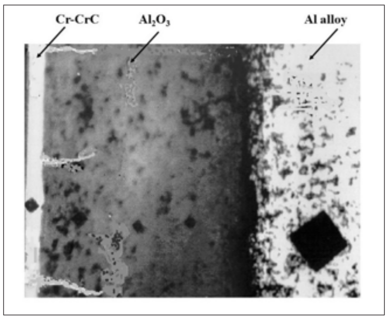

Figure 2: Microstructure of the Al_2O_3 Coating Cladded with "Cr-CrC" Compound

The analysis of the fatigue curves of the obtained data showed the following. At the loading levels corresponding to σ1 = 95 MPa and σ2 = 125 MPa, the average values of the number of cycles N1 and N2 of operating time were determined with a 50% probability of non-destruction of the samples, which turned out to be equal, respectively:

- In the absence of coatings, $N1A= 8.1\cdot10^5$ cycles, $N2A = 2.7\cdot10^5$ cycles;
- For samples with Al_2O_3 coatings, $N1O = 4.9\cdot10^5$ cycles, $N_{2O} = 2.7\cdot10^5$ cycles;
- For samples with Al2O3 coatings cladded with "Cr-CrC", $N1X = =2.5\cdot10^6$ cycles, $N2X = 6.8\cdot10^5$ cycles.

The analysis of the fatigue curves shown in Figure. 3 showed that the effect of the formed composite coatings is most significant at bending stresses close to and below the bending endurance limit, i.e. σ ≤ 95 MPa. At high values, tensile and compressive stresses approach the zone of low-cycle fatigue strength, where this effect is insignificant.

Thus, at cyclic bending stresses at σ ≤ 95 MPa:

- The formation of anode-cathode microarc treatment of Al_2O_3 coatings led to a decrease in the limited endurance limit when bending the base material by 1.75-1.8 times, due to the presence of pores and cracks in the most stressed surface layer.
- Deposition of the "Cr-CrC" cladding layer on the surface of Al_2O_3 made it possible to increase the limited endurance limit during cyclic loading of uncoated aluminum alloy samples by 1.3-1.4 times. In comparison with Al_2O_3 coatings, the limited bending endurance limit increases by 2.4-2.5 times, which is due to two factors.
- The "Cr-CrC" compound filled the surface pores and cracks in the Al_2O_3 coating, eliminating the stress concentrators associated with them.
- Due to different coefficients of thermal expansion in the coating, when it is cooled after surface cladding with "Cr-CrC", residual compressive stresses arise, which allows for bending cyclic stresses to significantly increase the service life of parts compared with parts made of aluminum alloys.
- The presence of residual compressive stresses was confirmed by the results of the analysis of deflections of thin samples on which "Cr-CrC" was deposited only on one of the side surfaces coated with Al_2O_3.

The results of the heating effect's studies to a temperature of 380-420 ° C, further exposure at this temperature and cooling in a natural environment at room temperature of specimens with Al_2O_3 coatings, as well as these coatings cladded using the above-mentioned "Cr-CrC" technology, on their fatigue strength showed the following.

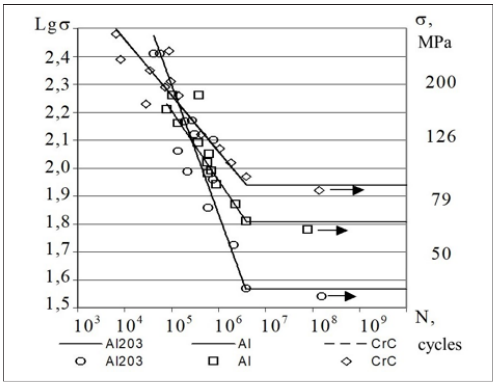

Figure 3: Fatigue Curves of as-obtained Specimens (without any coatings) (°), with Al2O3 Coatings (□) and Al_2O_3 Coatings Cladded with "Cr-CrC" (◊)

Additional heat treatment led to the removal of internal compressive stresses created by the anodic-cathode microarc treatment of the Al_2O_3 coating. As a result, the influence of surface defects on fatigue characteristics increased by more than 5 times compared to the starting material, and by 3.45 times compared to non-heat-treated samples coated with Al_2O_3. Also, the average number of operating cycles before failure decreased and the dispersion of test results increased significantly.

When analyzing the results obtained, it is necessary to take into account that the influence of the considered composite coating significantly depends not only on the level of cyclic stresses, but also on the thickness of the section of the part.

Conclusion

The formation of anodic-cathode microarc Al_2O_3 coatings on thin-walled aluminum alloys parts for aerospace equipment with increased wear-resistant and anticorrosive properties under cyclic loading conditions leads to a decrease in fatigue strength due to the presence of pores and cracks. As a result, the penetration of an aggressive medium to the base material after a certain time and its destruction takes place.

Cladding of the Al_2O_3 coating with a "Cr-CrC" compound from the vapor phase provides filling pores and cracks. This allows not only reliably isolate the aluminum alloy base from the aggressive environment, but also significantly increase the fatigue life of the part. In the case under consideration, with cyclic bending stresses of less than 95 MPa, the increase in bending fatigue for specimens of 2.8 mm thickness was 1.75-1.8 times.

The effectiveness of using the above composite coating significantly depends on parts thickness, bending stresses and geometric parameters of the part section. However, it can be effectively used in combination with a technically reasonable choice of geometric parameters to significantly increase the service life and corrosion resistance of parts.

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