Influence of operating conditions on the protective polyurethane coating for carbon fiber reinforced plastic blades of gas turbine engines

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Abstract. The article presents research results of protective coating, which is a two-component composition based on polyurethane, developed in Bauman Moscow State Technical University, in operating conditions. The influence of sea water and negative temperature on the properties of carbon fiber reinforced plastic with protective coatings, as well as resistance to erosion wear, was determined. It is shown that the developed coating has high performance properties and resistance to erosion wear compared to existing commercial coatings certified by Boeing, Pratt & Whitney and Airbus.

1. Introduction

The area of application of polymeric coatings, which are highly resistant to different aggressive media, thermal, and mechanical stresses, is increasing tear by year in modern aircraft construction [1-7]. Polyurethane (PU) coatings, the structure and the required target properties of which are achieved by target modification of the initial components, have currently become widespread [8-12]. Development of coatings is particularly acute for protecting gas turbine engine (GTE) blades against erosive wear, the general cause of which is the ingress into the object of sand and dust particles of various sizes flying in the airflow. Particle velocities and angles of incidence may vary depending on the ambient conditions and flight mode. Erosive wear is one of the major damaging factors of polymer composites [13-16], and of GTE blades made of carbon fiber reinforced plastic (CFRP) in particular. Furthermore, the use of coatings is significantly affected by water, which can lead to their premature destruction [17-19].

The purpose of this work is to study CFRPs with applied protective coatings (BMSTU) under operating conditions, as well as to carry out comparative tests of polyurethane coatings of different manufacturers with a developed protective composition to determine the resistance to erosion.

2. Materials and methods

The experimental samples were pressed carbon fiber plates based on CBX 300 carbon biaxial fabric (G. Angeloni, Italy) with fiber direction +45°/-45° and unidirectional carbon fabric UC 230 (Carbon Studio, Saint Petersburg, Russia) based on Toray T700 thread and epoxy resin EC 57 (Elantas, Italy) with
hardener W 61 (Elantas, Italy). The thickness of the plates was 3, 4 and 6 mm. The cure mode is 8h at 25°C and 6h at 80°C.

The resulting plates were cut into samples of 3x10x60mm for three-point bending testing, 6x10x50 mm – for short-beam shearing, and 4x100x100mm – for erosion resistance testing. The developed protective composition (unmodified and modified with a hydrophobic additive) was applied to some of the samples. Additionally, commercial coatings were applied to samples intended for erosion resistance tests, as shown in Table 1.

| Protective coating                      | Coating type                                         | Coating thickness, mm |
|-----------------------------------------|------------------------------------------------------|-----------------------|
| Coating made by BMSTU (Moscow, Russia)  | A two-component composition based on polyurethane    | 0.18                  |
| Modified coating made by BMSTU (Moscow, | Two-component composition based on polyurethane + 7%  | 0.18                  |
| Russia) 8681HS (3M™, USA)              | hydrophobic additive                                 |                       |
| 8B6A Laminar® X-500 (Akzo Nobel        | A two-component composition based on polyurethane    | 0.1                   |
| Aerospace Coatings, Netherlands)       |                                                      |                       |
| BT1-0 (reference)                      | A titanium alloy foil                                | 0.1                   |

Before applying the coatings, all carbon fiber samples were pre-cleaned with a Reoflex degreaser (Germany). Protective polyurethane film 8681HS, which is a one-sided scotch tape, was directly glued to the degreased surface of CFRP. Titanium foil was adhered to a carbon fiber sample using the 3M Scotch-Weil 9323 adhesive. Polyurethane compound 8B6A Laminar® X-500 was applied with a brush. Modified and unmodified composition of BMSTU, which is a two-component viscous polyurethane system, was diluted with P4 organic solvent (“Himtorgproekt” LLC, Moscow, Russia) at a ratio of 1:1 and applied by spraying with a spray gun.

Before the shearing and bending tests, some samples with and without developed coatings were kept in sea water for 16 days. At the time of exposure, the samples mass change was controlled. The mass change was determined by the formula:

$$\Delta m = \frac{m - m_0}{m_0} \times 100\%,$$

where $\Delta m$ is a quantitative measure of mass change expressed in percent; $m$ is the mass of the sample after the medium exposure; $m_0$ is the initial mass of the sample.

Shearing and bending tests at three-point bending were performed on the Zwick Roell Z10 universal testing machine (Zwick Gmb H&Co. KG, Germany). The loading rate was 10 mm/min. Testing temperature is +25 °C and -50°C.

The bending strength $\tau_M$ (MPa) was determined according to the formula:

$$\tau_M = \frac{3F_{\text{max}}}{4bh},$$

where $F_{\text{max}}$ is the load corresponding to the destruction of the sample, $b$ is the sample width, $h$ is the sample thickness.

The bending strength $\sigma_s$ (MPa) was determined according to the formula:

$$\sigma_s = \frac{3F_{\text{max}}}{2bh^2},$$

where $F_{\text{max}}$ is the load corresponding to the destruction of the sample, $b$ is the sample width, $h$ is the sample thickness, and $l$ is the distance between the supports.

The bending elasticity modulus $E_b$ was calculated according to the formula:

$$E_b = \frac{0.21 \Delta P L^3}{bh^3 \Delta \omega},$$

where $\Delta P$ is the pressure difference, $L$ is the length of the sample, $b$ is the sample width, $h$ is the sample thickness, and $\Delta \omega$ is the angular deflection.
where $\Delta \omega$ is the difference in the deflections $\omega'$ and $\omega''$, $\Delta F$ is the increment of load in the elastic section of the load corresponding to the change in the deflection $\Delta \omega$.

To determine the erosion resistance of the coatings indicated in Table 1, an erosion installation of supersonic deposition based on the particle accelerator "Dimet" was used. The distance from the output of the supersonic nozzle cutoff to a sample was 25 mm. Tests of each coating were carried out in steps. Before the start of the tests and in the intervals between the steps (after the next dose of sand ended in the pneumatic accelerator bunker), a portion of quartz sand was measured using electronic scales, which was filled into the receiving bunker of the pneumatic accelerator. Sand particles were picked up by a stream of compressed dried air and accelerated in the expanding nozzle to a speed of 340 m/s. After the bunker ran out of sand, the surface condition of the samples was monitored visually and photographed. The tests were carried out until holes developed in the coatings. Wear resistance of the coating was evaluated by the total mass of the used sand, which caused the formation of the hole.

3. Results and discussion

Figure 1 shows the dependence of changes in the mass of CFRP samples on the time of exposure in seawater.

![Figure 1](image)

Figure 1. Changes in the mass of CFRP samples after exposure to the sea water: 1 - samples without coating; 2 - samples with modified coating; 3 - samples with unmodified coating.

As can be seen from the figure, the change in the mass of samples occurs along the saturation curve. CFRP samples with an unmodified polyurethane coating demonstrate a higher rate of water absorption at the initial stage of the experiment (up to 100 hours) than CFRPs with a modified coating and without it. After 384 hours of exposure in seawater, uncoated CFRPs have a water absorption of 0.3%, CFRPs with unmodified coating – 0.4%, with modified coating – 0.5% relative to the mass of the non-swollen sample. It should be noted that all CFRP water absorption indicators have low values comparable to those for non-reinforced thermoset matrices.

Table 2 shows how the CFRP shear strength changes depending on the test conditions.

| Type of coating          | The exposure time in seawater, h | Test temperature, °C | Shear strength, MPa |
|-------------------------|---------------------------------|----------------------|--------------------|
| Without coating         | 0                               | 25                   | 66±2               |
| Without coating         | 0                               | -50                  | 67±2               |
| Without coating         | 384                             | -50                  | 68±6               |
| With unmodified coating | 384                             | -50                  | 78±6               |
| With modified coating   | 384                             | -50                  | 57±8               |
The table shows that the shear strength of CFRPs is almost independent of the test temperatures and exposure in water. The obtained values are comparable to the data spread. Slightly different values of shear strength obtained for CFRPs with coatings are probably associated with an increased methodological error.

Table 3 shows how the bending strength and modulus of elasticity of CFRP samples change depending on the test conditions.

Table 3. Bending strength and modulus of elasticity of CFRP samples with or without a protective coating before and after exposure to seawater and tested at different temperatures.

| Type of coating                  | The exposure time in seawater, h | Test temperature, °C | Bending strength, MPa | Modulus of elasticity, GPa |
|---------------------------------|---------------------------------|----------------------|-----------------------|---------------------------|
| Without coating                 | 0                               | 25                   | 1326±57               | 77±3                      |
| Without coating                 | 0                               | -50                  | 1405±93               | 92±4                      |
| Without coating                 | 384                             | -50                  | 1196±36               | 76±3                      |
| With unmodified coating         | 384                             | -50                  | 1647±42               | 69±3                      |
| With modified coating           | 384                             | -50                  | 1665±140              | 75±3                      |

The table shows that the bending strength of uncoated CFRPs at -50°C tends to increase (by 6% of the initial strength). Exposure in seawater with subsequent testing at -50°C, on the contrary, leads to a reduction in bending strength of CFRPs by 10%. Bending strength of coated CFRPs at -50°C after exposure to water increases by 25%. Such an increase in the strength of coated materials requires further research. The modulus of elasticity of the studied CFRPs does not depend much on the conditions of the combined action of water and negative temperature. It should be noted that after exposure to water and low temperature on coated CFRPs with protective compounds, the modulus of elasticity remains at the level of the modulus values for control samples. An increased (by 20%) value of the elastic modulus for non-swollen CFRP samples is associated with a lower test temperature.

Figure 2 shows photographs of the working area of the sample with the coating based on the polyurethane film 3M 8681 HS with the thickness of 0.36 mm at various stages of the test. It is seen in the photographs that the destruction of polyurethane film is accompanied by a process of its heat softening or even melting. The destruction occurs at the first seconds of testing and gradually progresses to the holes in the coating, which occurred at a mass of the used sand of 152g.
Figure 2. Photographs of the working area of the carbon fiber samples with the coating 8681 HS (3M™)

Figure 3 shows photographs of the working area of the CFRP sample with a titanium coating of BT1-0 grade. It can be observed that the destruction starts with a foil "swelling" process. It is most likely that low heat resistance of the adhesive (Tg=80°C) caused the onset of destruction of the sample according to the mechanism of overheating and spalling from the surface of CFRP. A through hole appeared at the supply of 27g of sand.

Figure 3. Photographs of working area of carbon fiber samples coated with the titanium foil of BT1-0 grade

Figure 4 shows photographs of the working area of the sample with the coating developed in BMSTU. It is clearly seen that the coating remains intact without signs of wear for a relatively long time. Only point individual foci of the internal structure changed, presumably connected with the possible local heat destruction which appeared during the tests. Penetrative destruction occurred when 710g of abrasive was consumed. Signs of volumetric thermal damage were not found during the experiment until the last moment.

Figure 4. Photographs of the working area with the polyurethane coating of BMSTU

Polyurethane conductive coating AkzoNobel Aerospace Coatings 8B6A Laminar® X-500 showed a relatively low resistance: only 3g of sand was required for the formation of a hole. A mechanism of brittle fracture of the coating was observed.

Upon impact of sand particles with the carbon fiber target at supersonic speeds all studied analogues demonstrated processes of materials destruction associated with the surface heating. Thus, the destruction mechanisms caused by insufficient heat resistance of materials were identified both in the case of the titanium foil delamination from carbon fiber substrate, and during the process of 3M
8681 HS coating melting. During the destruction, initially transparent coating became slightly clouded and did not delaminate from the CFRP sample.

4. Conclusion
The research of CFRPs strength in conditions of low temperatures and exposure to sea water showed that the shear strength remains almost unchanged for all studied samples. Increased strength values were shown by CFRPs with protective compositions applied to them. The bending strength of coated CFRPs at -50°C after exposure to water increased by 25%. At the same time, the modulus of elasticity remains almost unchanged. In addition, the developed coatings have shown the greatest resistance to abrasive wear. With a coating thickness of 0.18mm, 710g of sand was required for a through hole formation. The foreign film coating 3M 8681 HS received through destruction from the action of 152g of sand with a coating thickness of 0.36mm.

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