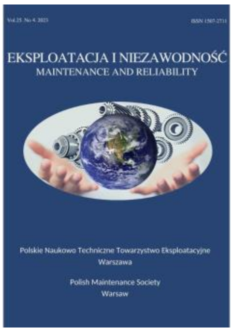

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An assessment of the reliability of CFRP composites used in nodes of friction after impact of UV-A impacts and thermal shocks

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Highlights

- For composites exposed to friction indicated areas of safe exploitation.
- Areas of the necessity of withdrawing composites from further exploitation are indicated.
- It is possible to observe a noticeable environmental impact upon the process of friction.
- Empirical functions of failure lead to the designation of critical values of probability.

Abstract

This article describes the results of tribological research into epoxy-based composites reinforced with carbon fiber. The composites were subjected to accelerated tests simulating a semi-annual influence of environmental conditions of an elevated temperature, precipitation in combination with an influence of UV-A radiation of 0.83 W/m^2 as well as cyclic thermal shocks causing a leap temperature difference of 116.5°C. The process of friction was conducted in conditions of dry friction and wet friction in the presence of water. The authors found a positive influence of a two-month impact of environmental conditions upon increasing wear resistance. They found a reduction in weight in conditions of friction with water. At the same time, a reliability analysis for the same boundary conditions showed an increased risk of critical composite damage. The article indicates areas of safe exploitation of composites and areas of the necessity of withdrawing composites from further exploitation under the assumed environmental and tribological loads.

Keywords

CFRP composites, aging, thermal shocks, reliability analysis, wear

1. Introduction

Starting with the design phase, through manufacture and finally the operation of the items, reliability aspects constitute one of fundamental issues [4]. Despite the difficulties caused by the construction of reliability models, engineering solutions are based on them due to economic issues, but first and foremost to issues resulting from the safety of people operating a given item [15]. This is particularly conspicuous in certain industry sectors, in which activities carried out by maintenance management departments, are performed according to the imposed service life regardless of the actual state of a given component. The sector in which preventive measures are obligatory is, among others, aeronautical industry.

Reliability is a probability of non-occurrence of interruptions and random failures in certain required conditions of enforced exploitation [e.g. 26, 30]. Reliability is an essential criterion for all machines used in technology. As a requirement

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considered in reliability with regard to a given item, it is essential to include, among others, working time [27], number of performed cycles [1, 16] or a covered distance [19], in which the operation of an item should not be affected by its failure. The item itself is regarded as a simple element or a complex system. When considering a case, it is necessary to determine whether the item is subject to an overhaul. If so, it is then regarded as a renewable element, otherwise it is considered non-renewable. In accordance with [23],the basic indicators of reliability are the failure function ***F(t),*** the reliability function ***R(t)*** and the probability density function ***f (t),*** which are continuous functions in time ***t*** for non-renewable items, whose failure occurred after a trouble-free operation time τ.

$$F(t) = P\{\tau < t\} \tag{1}$$

$$R(t) = P\{\tau \geq t\} = 1 - F(t) \tag{2}$$

$$f(t) = \frac{dF(t)}{dt} \tag{3}$$

However, the renewable element, in general, has four basic states: functioning (work), emergency repair (overhaul), preventive repair, reserve. Due to the skipping of the state of preventive repair and reserves, the recovery process of finite non-zero recovery time becomes a model of an exploitation process of the recovery element (Fig. 1).

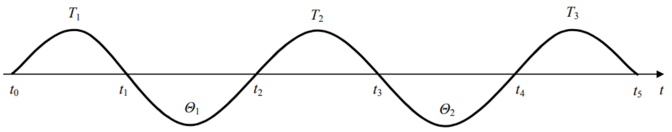

Fig. 1. An example of the recovery process with non-zero recovery time (on the basis of 22).

The presented progression of t1, t3, ... , t2k+1, ... is created by moments of successive failures, whereas progression t2, t4, ... , t2K, ...- by recovery moments. The two additional progressions of random variables - T1, T2, ... , Tk, ... and Θ1, Θ2, ... , Θk, ..., determine the working times and recovery times, respectively. The progressions form a stream of failures (damage) and a stream of recoveries.

In case the reliability of an element determines the reliability of the system, then it is right to state that the reliability structure of the system is determined [20]. In practice, the structures of the systems are divided into basic structures, i.e. serial, parallel and threshold, as well as mixed ones, obtained from a serial, parallel or threshold combination of subsystems which have basic structures. A serial reliability structure of a system is observed when a failure of any component causes failure of the entire system. Thus, an item is operational only when all its components are in good order. In the case of a parallel structure, the entire item is operational if at least one of its element is operational. A threshold structure is ascertained when at least some elements of the system are operational.

Composite materials are widely used in modern structures such as aircraft and spacecraft due to their high efficiency, resistance to high temperature, possibility to shape easily and low weight. Generally, with regard to composite materials, very often mathematical models such as Weibull analysis [21, 2, 18, 12] or Monte Carlo analysis [3, 28] are applied to assess reliability. Sometimes, less popular methods, for example Hasin or Tanaka [31], are used for determining the probability of an occurrence of damage. The above-mentioned methods are usually used in the reliability analysis of different properties of tested composites, typically structural properties, including mechanical strength, thermal resistance, or abrasive wear [9].

Many engineering items, whose durability is affected by the load type, number of cycles and their duration, is subjected to the Weibull distribution. The main parameters describing the 2-parameter Weibull distribution [19, 25, 29, 10], is the shape parameter α called the Weibull modulus and the scale parameter β, which is a characteristic parameter determined for the cumulative probability of failures at a level of 0.632 [24]. In the Weibull reliability model, the cumulative distribution function F(t) after its appropriate transformation of equation (1) is expressed as:

$$F(t) = 1 - exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \tag{4}$$

while the density of the failure function assumes a form:

$$f(t) = \begin{cases} 0, & t < 0 \\ \frac{\alpha}{\beta} t^{\alpha - 1} exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right], & t \geq 0 \end{cases} \tag{5}$$

Thus, returning to equation (2), the reliability of the technical item will be equal to

$$R(t) = 1 - F(t) = exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \tag{6}$$

Since the reliability coefficient is the probability of non-occurrence of failure at a certain time of using a given component. The reliability of strength (which may be a different material property) is the probability that a failure will not occur under a given load of a construction element. Therefore, it is assumed that the reliability of an item will be considered as a function of strength σ rather than a function of time. The cumulative distribution function in the form of a 2-parameter model will be as follows:

$$F(\sigma) = 1 - exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^{\alpha}\right] \tag{7}$$

The functions of failure and density of distribution undergo an analogical transformation. In the experimental part of this article, instead of mechanical stresses $\boldsymbol{\sigma}$, the authors introduced the loss of mass ***Um*** which is proper for the process of friction. Resistance to abrasion, apart from the resistance to mechanical stress, is an important atribute of construction materials

The reliability systems that are related to aviation, due to strict security requirements, are serial systems. One failure leads to a malfunction of the whole aircraft. Thus, both the presumptions and a very moment of their occurrence, making it possible to observe damage to composite parts, the external ones e.g. skin, as well as the internal ones, e.g. bulkheads, are an extremely important issue. The article attempts at determining these criteria with regard to carbon-epoxy composites, in which the damage is due to friction processes occurring on their surface. The authors used the Weibull distribution to determine the critical states. The data included in this article are a continuation of the research conducted at the University of Military Aviation in the Department of Airframe and Engine [11].

2. Methodology of research

2.1. Material

In order to manufacture the composite the authors used epoxy resin L 285 along with the dedicated hardeners H 286 and H 287. The ratio of the resin to the hardeners combined in equal parts was 100:40. The reinforcement was carbon fibre fabric GG 280 P/T. The carbon fabric, 280 g/m^2 in weight (ISO 4605 [6]), was characterized by a weave 2x2 Twill (ISO 2113 [5]) and supersaturation of 220 g/m^2. The epoxy resin LG 285 is certified by the German Luftfahrt-Bundesamt. The ten-layer composite was manufactured by means of the pressing method, using the pressing pressure of 2.5 MPa on a hydraulic press PDM - 50S Mecamaq. The composite sheets were allowed to cure for 7 days, and then the test samples sized 100x15mm, in accordance with the resin manufacturer's instructions [14], underwent heating at 80^{o}C for twenty-four hours in a climatic chamber WKL 64/40 Weisstechnik. The manufactured samples were exposed to different environmental operating factors, such as UV-A radiation at an increased temperature, humidity as well as temperature shocks. The choice of environmental factors was determined by real environmental loads that affect aircraft skin during operations.

2.2. Environmental conditions

The influence of atmospheric conditions on the abrasive wear of composites can be very complex and depends on several factors, such as the composite's composition, its structure, the testing conditions, including the type of exposure to atmospheric conditions. Therefore, it is crucial to determine how different environmental conditions affect the behavior of composites in the context of tribology to assess their operational properties in various frictional components.

In accelerated tests, two types of environmental conditions affecting a composite used in aviation were simulated. The first environment was based on the impact of UV-A radiation, increased temperature and precipitation. The parameters were selected on the basis of climatic data of the spring and summer of warm temperate climate [13, 17]. A simulation of a six-month exploitation time was conducted in accordance with PN-EN ISO 4892-1 [7] and PN-EN ISO 4892-3 [8] norms. For this purpose, an accelerated weathering tester, UV QUV/SPRAY/RP Q - Lab Corporation, was used. The light source was UV-A 340 lamps, simulating daylight [8]. The value of the intensity of radiation was 0.83 W/m^2, the weathering time equalled 500h, the cycle length of the exposure time was 4h, the length of condensation of water vapour cycle equalled 4h and the temperatures during exposure and condensation were 60°C and 50°C, respectively. The parameters were selected on the basis of experiments and observations included in the research. The time of accelerated weathering, corresponding to two, four and six months of exposure to climatic conditions was successively: 167 h, 334 h and 500 h of the weathering tester operation.

The second environment of accelerated tests was based on assumptions of sudden temperature changes on the surface of composites used in the construction of aircraft operating on the route for half a year of daily exploitation in the hottest months of the year. The values corresponding to these parameters were as follows: flight time of 1 hour in one direction, number of flights during one day 2, waiting time at the airport equal to 0.5 h, time of the aircraft staying at the altitude of 11km - 0.5 h, temperature of aircraft skin at the airport and at the altitude of 11km assumed between +60°C and -56.5°C (the difference in temperature was 116.5°C). The simulation of thermal shocks for 728 cycles was conducted in a chamber for thermal shocks Shock Event T/60/V2 Weisstechnik.

2.3. Abrasive wear

The measure of wear during the conducted investigations was a loss in the composite weight. The very process of abrasion (Fig. 2) in a reciprocating motion was carried out under dry and wet friction conditions in a direct contact with water, using a linear tribometer - the Taber Linear Abraser. The anti-sample was an abrasive material, 6.5 mm in diameter and gradation 200. It was pressed against the material surface with a weight of 1,850g. The anti-sample surface, in accordance with the manufacturer's recommendations, was recovered every 100 cycles of abrasion. The frequency of movement of an anti-sample in the sample was 1.25Hz. The length of the abrasive path in one cycle equalled 177.8 mm. The loss of weight measured with regard to the state prior to abrasion was monitored at predefined intervals of 100, 300, 600 and 1,000 abrasion cycles. For this purpose, an analytic laboratory balance Excellence XSE205DU/M Mettler Toledo was used.

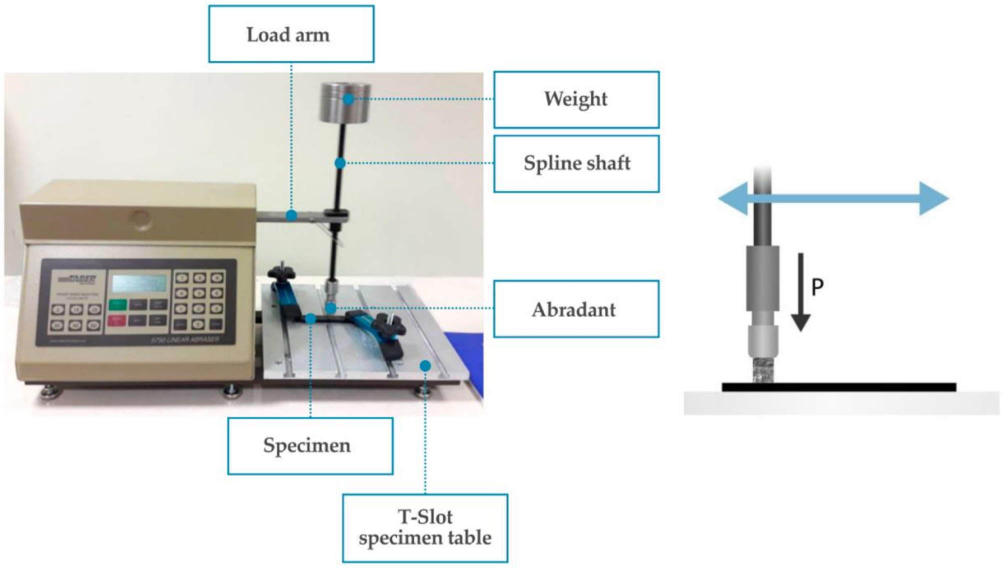

Fig. 2. The Taber Linear Abraser model 5750 (based on [29, 30]).

3. Reliability analysis

The reliability analysis was carried out on the basis of the results of the study to assess the impact of operating conditions on tribological properties, which was described in detail in article [11]. A reliability analysis was performed using the Weibull distribution, among other things, due to the fact that the results are not inherent in a normal distribution. Also a good matching to the regression function for the Weibull distribution was shown (Tab. 1 and Fig. 3, 4), resulting from a linear form of function (7), probability of the occurrence of weight loss ***Um***.

$$lnln\left(\frac{1}{1-p}\right) = ln(Um) \tag{8}$$

The equation includes probability ***p***, successively for each result, taking another i-th place in the ranking created in a given group of results, amounting to ***n*** for a combination of variable factors (environment, exposure time and type of friction), calculated in accordance with equation:

$$p = \frac{i - 0.5}{n} \tag{9}$$

The approximated functions concern the probability distribution of maintaining high wear resistance, characterized by weight loss during the progression of the friction process. Adjusting the approximated function is very high (R^2 mostly reaches 1), which allows using these functions to interpolate the results of the findings with regard to the values of variable factors used in experimental research, underlying their designation.

Tab. 1. Regression functions Y = aX + b and the coefficients of determination R^2 of the Weibull s linear distribution function as a weight loss after the processes of friction of composites, due to the impact of many months of adverse environmental conditions.

Type of friction	Number of months	UV-A		Thermal shocks	
		Y = a*X + b	R^2	Y = a*X + b	R^2
dry	0	Y = 1.304 * X + 6.070	0.952	Y = 1.304 * X + 6.070	0.952
	2	Y = 1.750 * X + 6.186	0.960	Y = 1.717 * X + 6.752	0.972
	4	Y = 2.047 * X + 8.231	0.978	Y = 1.443 * X + 5.354	0.983
	6	Y = 2.055 * X + 7.600	0.956	Y = 2.106 * X + 8.876	0.983
wet	0	Y = 1.141 * X + 2.455	0.979	Y = 1.141 * X + 2.455	0.979
	2	Y = 1.032 * X + 2.558	0.964	Y = 1.118 * X + 3.807	0.966
	4	Y = 1.106 * X + 3.346	0.918	Y = 1.001 * X + 3.258	0.962
	6	Y = 1.228 * X + 4.486	0.837	Y = 1.608 * X + 5.353	0.949

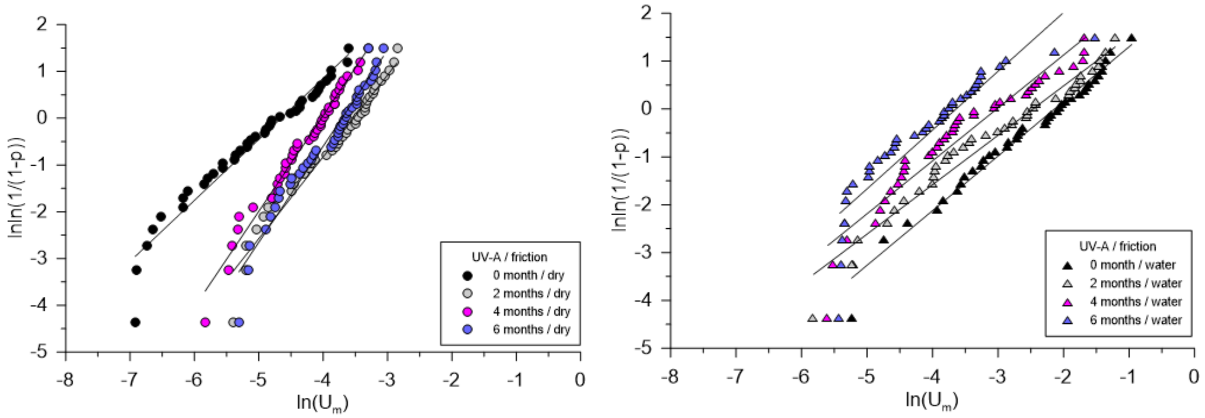

Fig. 3. Results of approximation of the probability of the behaviour of the resistance to composites' wear subjected to the influence of UV-A radiation and then dry friction and friction with water presence.

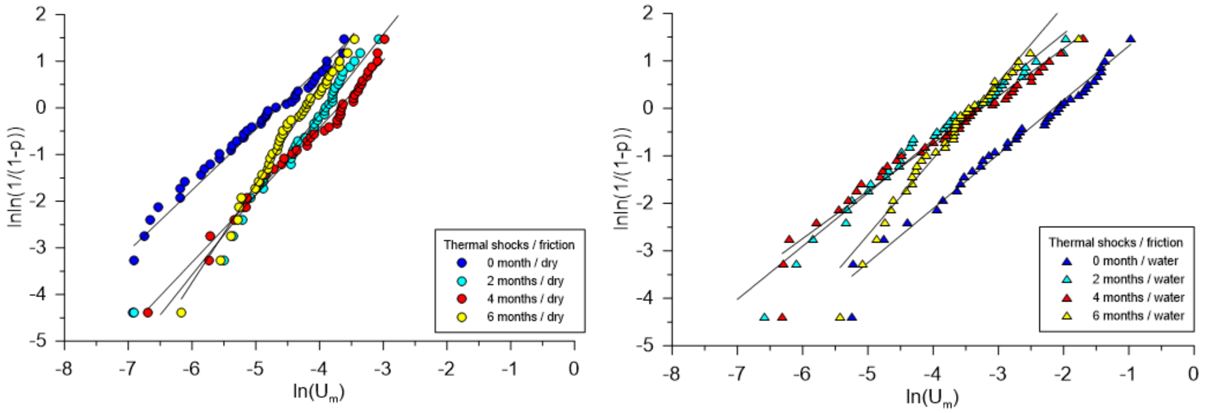

Fig. 4. Results of approximation of the probability distribution of the behaviour of resistance to composites' wear subjected to the influence of thermal shocks and then dry friction and friction with water presence.

Based on the regression function, in each case, the authors determined shape parameters ***α*** of the Weibull model, corresponding to the values of directional coefficients ***a*** of the regression function. At ***a*** =1, the Weibull distribution becomes an exponential distribution. Besides, the authors established the scale parameters ***ß***, corresponding to the intersection of the regression function with the OY axis, and thus values ***b*** of the regression function. In this way, it was possible to obtain the failure function ***F(Um)*** and the reliability function ***R(Um)m*** which, in the basic approach, are expressed with functions:

$$F(Um) = 1 - exp\left[-\left(\frac{Um}{ß}\right)^{\alpha}\right] \tag{10}$$

$$R(Um) = 1 - \left\{1 - exp\left[-\left(\frac{Um}{ß}\right)^{\alpha}\right]\right\} = exp\left[-\left(\frac{Um}{ß}\right)^{\alpha}\right] \tag{11}$$

At the same time, the value of the shape parameter ***α*** corresponds to abrasive wear ***Um*** for the value of the cumulative probability of damage resulting from the adopted Weibull distribution, namely for: *pf = 1- 1/e ≈ 0.632* (namely *lnln(1/pf) = -0.779*). In this way, the readings for the composites which were not subjected to exploitation in adverse environmental conditions were adopted as a critical value ***Um0***. In conditions of dry friction, *Um0* is equal to *0.00524 g*, whereas in conditions with the presence of water, *Um0* equals 0.05881 g. Based on the experimental research and surface microscopic observations, it appears that this loss of weight in the majority of examined cases corresponds to the destruction of the outer resin layer and the first symptoms of fibers chipping in the first reinforcement layer (Fig. 5). The photographs were taken by means of an optical microscope GX53 with a camera Olympus Corporation no. SC180.

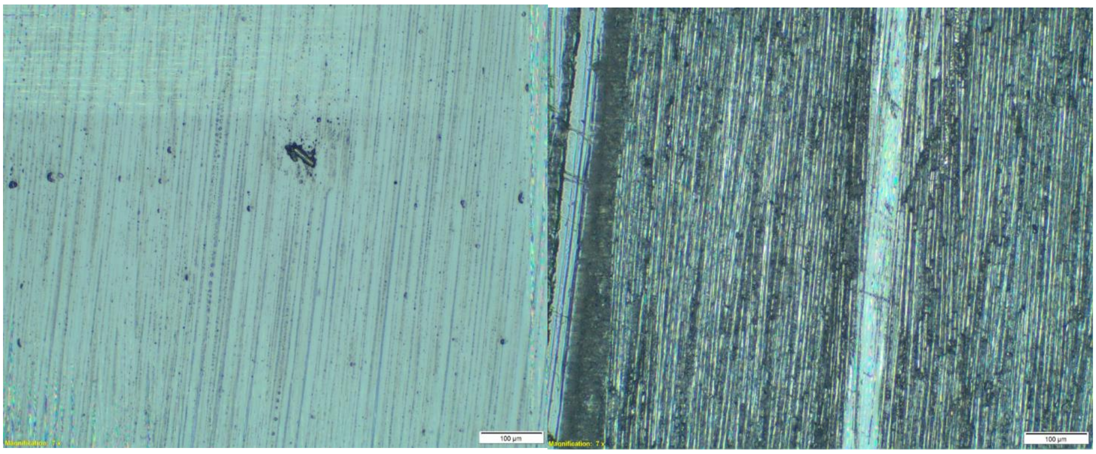

Fig. 5. Composite sample image before and after an initial period of friction, corresponding to achieving critical values Um0.

After exceeding the value ***Um0*** in a given process of friction, the emerging composite destruction is so severe that the composite should no longer be exploited under the occurrence of friction processes. The composite material must be replaced or repaired. Basing these assumptions on the results of experimental research, it was possible to obtain real failure functions ***F (Um)*** as well as deduction areas regarding further exploitation of composites exposed to abrasion (Fig. 6 and 7).

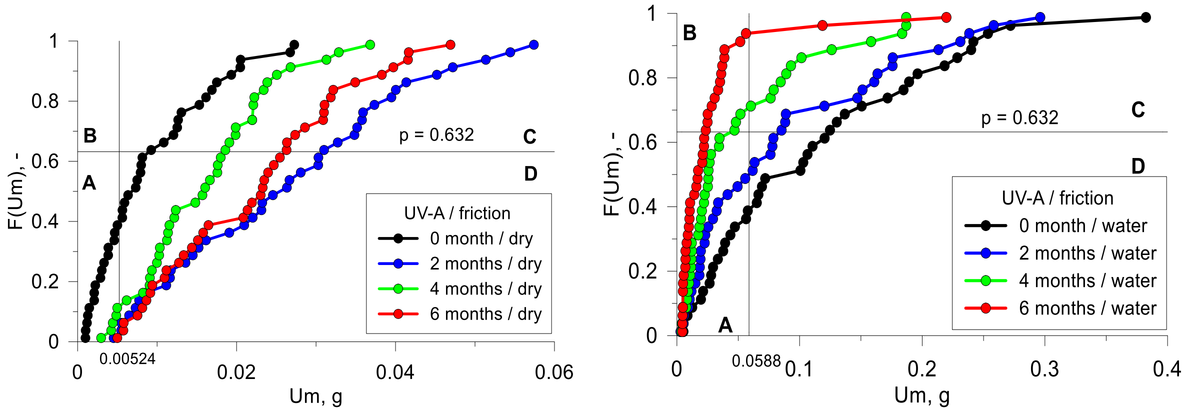

Fig. 6. Empirical failure function of a composite exposed to UV-A radiation.

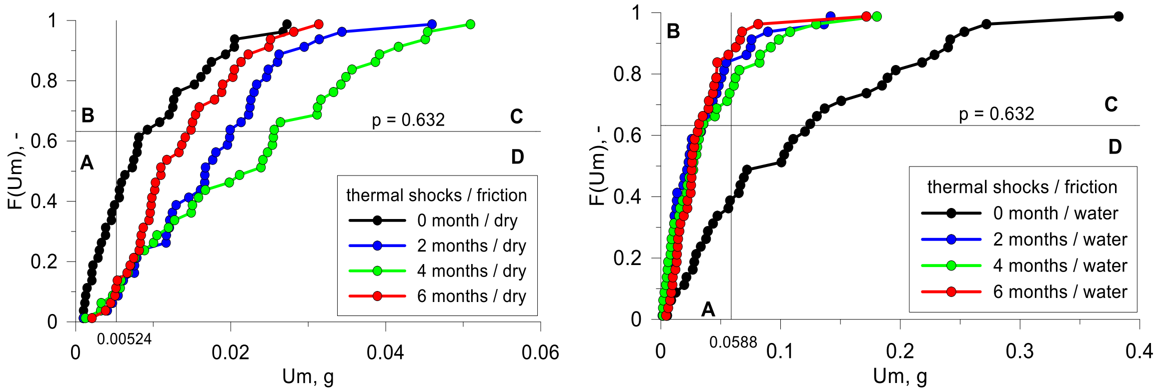

Fig. 7. Empirical failure function of a composite exposed to the influence of thermal shocks.

4. Conclusions

Previous studies indicate that complex environmental conditions can influence the tribological properties of composite materials. High atmospheric humidity can lead to water absorption by the polymer matrix in the composite, altering its physical, chemical, and tribological properties. This may result in reduced frictional strength, increased friction coefficient, and higher material wear. Additionally, ambient temperature during operation can affect the chemical reactions between composite components during friction, potentially altering their structure and tribological properties (elevated temperature may decrease the wear resistance of polymer composites). Furthermore, the presence of various gases and pollutants in the atmosphere can react with composite components, leading to the formation of lubricating substances or changes in the surface layers of the composite, ultimately affecting its wear behavior.

The publication presents the mass loss factor of the composite during abrasive wear testing. It is considered a direct measure of material wear and allows evaluating the course of the process while maintaining the same input factors in the study (such as load or number of cycles). Comparing the results with reference samples helps define the influence of variable factors (e.g., the addition of modifiers in the composite composition or different exposure times to environmental factors) on the abrasive wear process.

An analysis of empirical functions of composites failure leads to the designation of exact critical values of probability and weight loss, responsible for being used in given areas of operation. The conducted reliability analysis proves that safe exploitation is possible until the emergence of a weight loss on the surface of friction, equal to 0.00524 g and 0.0588 g, respectively, in conditions of dry friction and conditions with the presence of water, conducted in accordance with the experiment described in the article. Overall, proportionally it is possible to assume weight loss for a given surface unit of the occurrence of the friction process. In the described experiment, the area of friction equalled 577.85 mm^2 (88.9*6.5). Thus, for each 1 mm^2 of surface, the weight loss of the CFRP composite should not exceed $0.9*10^{-6}$g and $0.1*10^{-4}$ g, respectively. At the same time, the probability of damage at the level of 0.632 must not be exceeded. The table below (Tab. 2) juxtaposes the numerical values of the critical probabilities of the emergence of damage as well as loss of weight with regard to the conditions of conducting the experiment, and to 1 mm^2 of the surface. Their achievement is possible during exploitation burdened with risk. After exceeding any of the values specified in Table. 2, adequately to the operating conditions, the composite should be withdrawn from further use.

Tab. 2. Critical values of weight loss Um and the probability of damage F (Um), defining risk-burdened exploitation in conditions of unfavourable environmental conditions.

Type of friction	Number of months	UV-A			Thermal shocks		
		risk Um (exp.)	risk Um (1 mm^2)	risk F(Um)	risk Um (exp.)	risk Um (1 mm^2)	risk F(Um)
dry	0	0.00945 g	$1.6*10^{-5}$ g/mm^2	0.632	0.0092 g	$1.6*10^{-5}$ g/mm^2	0.632
	2	0.03096 g	$5.4*10^{-5}$ g/mm^2	0.632	0.0198 g	$3.4*10^{-4}$ g/mm^2	0.632
	4	0.01848 g	$3.2*10^{-5}$ g/mm^2	0.632	0.0257 g	$4.4*10^{-5}$ g/mm^2	0.632
	6	0.02635 g	$4.6*10^{-5}$ g/mm^2	0.632	0.0147 g	$2.5*10^{-5}$ g/mm^2	0.632
wet	0	0.1252 g	$2.2*10^{-4}$ g/mm^2	0.632	0.1245 g	$2.2*10^{-4}$ g/mm^2	0.632
	2	0.0852 g	$1.5*10^{-4}$ g/mm^2	0.632	0.0588 g	$0.1*10^{-4}$ g/mm^2	0.730
	4	0.0588 g	$0.1*10^{-4}$ g/mm^2	0.711	0.0588 g	$0.1*10^{-4}$ g/mm^2	0.837
	6	0.0588 g	$0.1*10^{-4}$ g/mm^2	0.935	0.0588 g	$0.1*10^{-4}$ g/mm^2	0.872

Both in the case of impact of thermal shocks and UV-A radiation, it is possible to observe a noticeable environmental impact upon the process of friction in the presence of water. Already after a two-month exposure, there is an increase in the probability of critical damage to a composite, despite a clearly positive influence upon raising resistance to wear (lower weight loss). Thus, as long as the results of standard tests allow an observation of obtaining favourable results of investigations with regard to the occurrence of physical changes, in terms of estimating the exploitational risk, the probability of permanent damage to the composite becomes increased. This points to the necessity to verify the results of experimental investigations conducted in a standard way. The example, included in this article, is a basis to conclude that the analysis of changes in the properties of CFRP composite materials should be enriched with a reliability analysis that allows an evaluation of the emergence of risk of damage. The reliability analysis strengthens an interpretation of test results, accurately pointing to areas requiring further analyses or at least caution in their utilitarian use.

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