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Application of FMEA for Assessment of the Polymer Composite Materials Quality

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Abstract. The paper is devoted to developing a methodology for failure mode and effects analysis on the example of assessment of defects that occur during production and operation of polymer composite materials and industrial products from them. The paper uses the Ishikawa method to illustrate and further analyze the cause of defects in reinforced polymer composite material. The Ishikawa diagram was constructed and analyzed using the method of causal analysis. The types and consequences of failures and defects for polymer composite materials are analyzed. For each type of defect, the value of the priority number of risks is calculated. For the most critical defect, measures to reduce potential defects are proposed. Suggestions for improving the detected defective zones in the structures of polymer composites in the analysis process are given.

Keywords: FMEA, product innovation, quality control, defect, polymer composite material, method Ishikawa, economic productivity.

1 Introduction

All defects in composite materials are divided into two major classes [1]: manufacturing defects that occur in structures or in the process of their manufacture, manufacturing component components, and operational damage that occurs during operation.

According to the degree of danger, the first group includes defects associated with a low degree of curing of the polymer matrix and deviations in the material composition from the entire volume of the normalized values [2]. They lead to a decrease in heat resistance of the material, a sharp deterioration of performance characteristics such as water and moisture resistance, to reduce the resistance of the material to aggressive environments, and changes like material destruction under static and dynamic fatigue loads. Deviations in the composition of a significant amount of material lead to significant changes in the characteristics of strength, elasticity, and operational reliability [3]. These changes depend to varying degrees on the type of deformation (tension, compression, shear), the nature of the stress state (uniaxial, flat, volumetric), as well as the duration and cyclicity of the load.

The second group includes delamination [4] (Figure 1).

Manufacturing and operational defects and damage of composite materials are presented in Table 1.

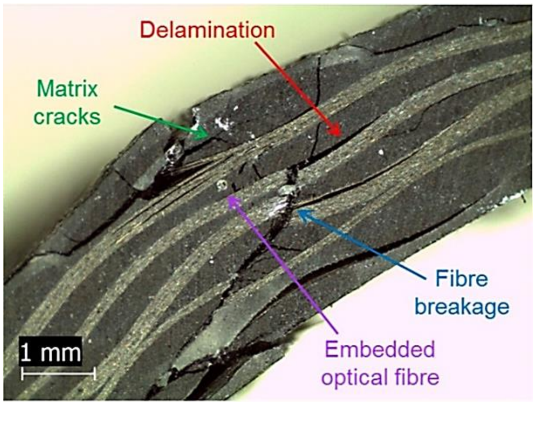

Figure 1 – Delamination in defective composite material [5]

The effect of delamination on the material properties significantly depends on the type of stress state. The tensile strength and modulus of elasticity of the delamination in its pure form are practically not affected. Simultaneously, the compressive strength of the delamination material can be significantly reduced depending on the depth and length of the delamination.

Table 1 – Manufacturing and operational defects and damage of composite materials

Defects and Damages in Composite Structures	Microdefects	Defects of reinforcing fibers
		Matrix defects in the intervals between the elementary fibers
		Defects at the “matrix – fiber” interface
	Minidefects	Twisting the fibers
		Curvature of fibers
		Fiber misorientation
		Different degrees of fiber tension
		Small risks, scratches, dents
		Unreinforced binder areas
		Breakage of individual threads, bundles, or groups of elementary fibers
		Depletion of binder in separate sections of threads or bundles
		Dimensional rejects of composite material blanks
		Dimensional rejects of workpieces during processing
		Chips
	Macrodefects	Cracks and notches that cross the layers inward (through and not through)
		Sinks and dents on the surface of composite material
		Impact defects (not visible, visible not through, though)
		Delamination, bulging, non-adhesion, air micro-connections (open, closed, multi-storey)
		Buckling of the structure
		Overlapping layers or turns of reinforcing material
		Foreign microinclusions
		Significant scratches with a depth of more than one elementary layer of composite material
		Formation of folds of reinforcing material with an influx of binder (internal, surface)
		Local decrease in adhesive strength between layers of composite material
	Operational damage	Mechanical wear
		Fatigue wear
		Aging
		Combat damage
		Emergency damage
		Damage from improper and negligent maintenance
		Other damage

The third group of defects is cracking [6]. Cracks create a high concentration of stresses, disrupt the integrity of the composite, and can lead to delamination of the material.

The fourth group of defects includes local areas with high fiber content, matrix, and pores [7]. The degree of danger of these defects ultimately depends on the defect’s size, shape, and location.

The fifth group includes folds, swirls, shells, foreign inclusions, joints, and overlaps of reinforcing filler [8]. Joints and overlaps mainly affect the physical and mechanical characteristics due to changes in the composition of the material.

Particularly, an increase in the degree of reinforcement in the overlap zone and a decrease in the butt zone, and to a lesser extent, affect mechanics stress concentrators. Folds, swirls, and foreign inclusions have a very similar effect on the physical and mechanical properties of the material, as they lead to the local curvature of the fibers and changes in the composition of the material in the cross-section of the defect. The effect of these defects on the strength and elasticity increases with increasing degrees of reinforcement of the material because these defects affect more layers of material [9].

The sixth group consists of chips, cuts, and holes, concentrating stresses [10]. Studies show [11] that the effect of stress concentrators in the form of spots on the strength of carbon plastics decreases both with prolonged static load over the test duration and with the increasing speed of one-time static and dynamic deformation. Increasing the test temperature also leads to a decrease in the effective stress concentration of carbon fiber with a complex scheme of reinforcement [12].

The seventh group includes defects associated with the curvature of the fibers of the plane of the layers, with a slight deviation of the reinforcement angle from the specified value [13]. In most cases, defects of this type are not large-scale, and the curvature or deviation of the reinforcement angle, as a rule, affect only one or more layers of the composite. Their size is much smaller than the size of the structural element.

Quality control of polymer composite materials (PCM) products must be carried out throughout their life cycle [14]. The life cycle of PCM parts consists of four main stages: design, production, operation (including repair), and utilization (including recycling) [15].

The rule of 10 times A illustrates the cost of eliminating defects. Feigenbaum [16]. The cost of correcting the defect increases ten times at each subsequent stage of the product life cycle:

$$1:10:100:1000$$

1000 monetary units – the necessary operating costs,
100 monetary units – the necessary costs of production,
10 monetary units – the necessary costs in preparing for production,
1 monetary unit – the necessary costs for the design of the product.

In this regard, the actual task is analyzing and assessment the types and consequences of defects that occur during the manufacturing and operation of polymer composite materials and industrial products from them according to the FMEA.

The main application of FMEA is to improve product design (service characteristics) and its manufacturing and operation (service delivery) processes [17]. The analysis can be applied concerning newly created products (services) and processes and existing ones [18].

2 Research Methodology

The research object is defects of PCM and their evaluation by FMEA (Figure 2).

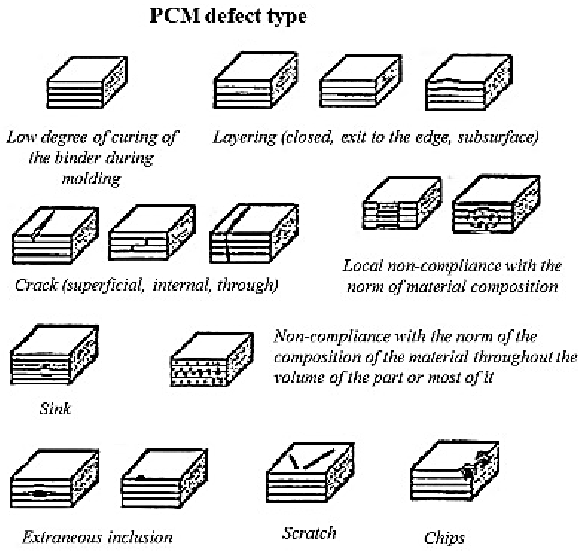

Figure 2 – Different polymer composite material defects, including the research object

Stages of FMEA included:

1) construction of structural component, functional and flow models of the object of analysis;

2) research models. During the study of models are determined:

– potential defects of each of the elements of the component model of the object. Such defects are usually associated either with the failure of the functional element (its destruction and breakage), with the incorrect performance of its valuable functions (failure of accuracy and performance), or with harmful functions of the element. It is also necessary to consider potential defects during transportation, storage, and external conditions (humidity, pressure, temperature).

– potential causes of defects. Ishikawa diagrams, constructed for each object's functions with the appearance of defects, can be used for detection.

– potential consequences of consumer defects. Since each of the considered defects can cause a chain of failures in the object, the analysis of the consequences uses structural and flow models of the object.

– the ability to control the appearance of defects. It is determined whether the defect can be detected due to the measures provided in the object of control and diagnosis;

3) expert analysis of models. The following parameters are defined (Figure 3):

– the parameter of the severity of the consequences of the consumer S. It is an expert assessment, which is usually given on a 10-point scale; the highest score is given for cases where the consequences of the defect lead to legal liability;

Factor S	Factor O	Factor D
1 - very low (almost no problems)	1 – very low	1 - almost immediately the effect will be detected
2 - low (problems are solved by the employee)	2 – low	2 - very good detection
3 - not very serious	3 - not very low	3 - good
4 - below average	4 - below average	4 - moderately good
5 – average	5 – average	5 - moderate
6 - above average	6 - above average	6 - weak
7 - quite high	7 - close to average	7 - very weak
8 – high	8 – high	8 - bad
9 - very high	9 - very high	9 – very bad
10 - catastrophic (danger to people)	10 – 100%	10 - almost impossible to determine

After receiving expert assessments S, O, D calculate the priority number of PCR risk according to the formula: $\mathbf{PCR = S \cdot O \cdot D}$

Figure 3 – Assessment of PCM defects

– defect frequency parameter O – it is also an expert assessment, which is given on a 10-point scale; the highest score is given when the estimate of the frequency of occurrence is 1/4 and above;

– defect detection probability parameter D – like the previous parameters, it is a 10-point expert assessment; the highest score is given for hidden defects that cannot be detected before the consequences;

– consumer risk parameter PNR (priority number of risk). It is defined as the product S x O x D (Figure 3). This parameter shows what relationship to each other is currently the causes of defects. Defects with the highest risk priority factor (PNR is greater, or 100–120) must be eliminated in the first place.

The assessment of factors S, P, and D are assessed on the qualimetric scales presented in Figure 3.

3 Results and discussion

An analysis of the types and consequences of failures was performed to assess PCM defects discussed above. For each type of defect, the value of the priority number of risks is calculated. For the most critical defect, measures to reduce potential losses are proposed.

To obtain the results, it was not the potential failures considered but those determined from PCM defect statistics analysis.

Due to the structural analysis at different scale levels, the actual material is accumulated, which allows obtaining initial data for structural-parametric modeling:

– determining the values of the effective characteristics of all components of the composite;

– estimates which of these components and at what load will be destroyed in the first place;

– quantitative assessment of the impact of stress concentrators on the growth of the main crack.

Structural modeling allows to describe in general the dynamics of the destruction process but does not give numerical estimates of the obtained models. Among the many parametric models used to describe the behavior of polymeric composite materials under load, the theory of percolation is becoming more widespread. It allows finding a correlation between the corresponding geometric (e.g., considering the scheme of filler, the effect of thickness, and defects) and physical characteristics.

3.1 Construction of the Ishikawa diagram on the example of a defect in the carbon fiber-filled PTFE-composite

The occurrence of the defect of the PCM based on polytetrafluoroethylene and carbon fibers [19] was analyzed.

The practical methodology of the Ishikawa method is illustrated in Figure 4.

First, a macrostructural analysis of the polymer composite was performed. A visual study of the surfaces of the studied samples showed the heterogeneity of the distribution of carbon fiber in the matrix of the polymer (a), the spotted structure (b), and the presence of cracks (c).

During the wear tests, an increase in the temperature in the friction zone up to 200 °C was noted, which led to the sample set with the counter body. It is due to the material's low physical and mechanical properties (low density, uneven distribution of carbon fiber in the matrix), which confirms the results of further tests.

Secondly, tests were conducted to determine carbon fiber-filled PTFE composite's physical, mechanical, and tribotechnical characteristics. The mechanical tests showed that all samples have a low elongation at break (30-100 %). It is usually a consequence of poor mixing of the source components – coagulated fiber in the composition matrix.

Third, the Ishikawa diagram was constructed using a step-by-step algorithm of the causal analysis method. The causes of defects were divided into six key positions – man, method, material, mechanisms, control, and environment. The most significant causes of this problem were identified in low-skilled workers and in violation of mixing technology.

3.2 Drawing up a protocol for FMEA of PCM defects

For the priority number of risks, a critical limit (PNR_{cr}) should be set in advance from 100 to 125. Reducing PNR_{cr} corresponds to the creation of higher quality and reliable products.

Next, we need to make a list of defects for which the value of PNR exceeds PNR_{cr}. For such defects, it is necessary to recommend ways to eliminate and prevent them, and therefore, general methods to improve the effectiveness of polymer composite materials.

The protocol of the analysis of types, causes, and consequences of polymer composites is given in Table 2.

3.3 Quality control of products from PCM

The use of modern non-destructive testing methods at all stages of the product life cycle eliminates the lack and increases the durability of parts with PCM (Figure 5).

At the design stage, control the technical documentation to produce parts. There are input, interoperative, and output quality control at the production stage. At input, control has checked the quality of the used raw materials.

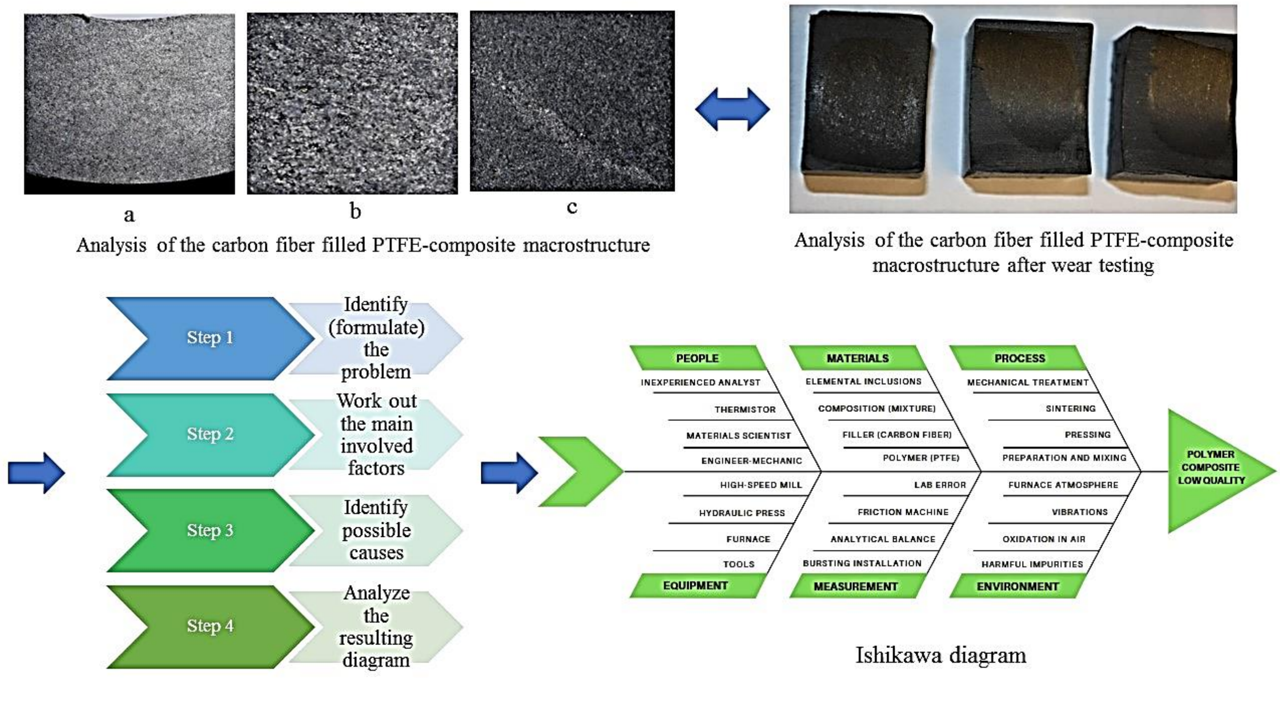

Figure 4 – The detailed practical methodology for the construction of Ishikawa diagram

Table 2 – Protocol for analysis of types, causes, and consequences of defects of polymer composites.

Defect type	Consequences of the defect	Rank "S", ball	The cause of the defect	Rank "O", ball	Defect detection measures	Rank "D", ball	RNR, ball
Low degree of curing of the binder during molding	It leads to significant changes in the characteristics of strength, elasticity, and operational reliability	7	Deviation from the norm in the binder. Non-compliance with the temperature-hour mode of formation	4	The degree of polymerization is less than 95-98 %	4	112
Non-compliance with the norm of the composition of the material throughout the volume of the part or most of it	It leads to significant changes in the characteristics of strength, elasticity, and operational reliability	7	Deviation of the composition of the prepreg from the norm, violation of the terms or conditions of storage. Non-compliance with the formation regime	4	Set volumetric values of matrix (V%), fibers (V%)	4	112
Layering	It leads to significant changes in the characteristics of strength, elasticity, and operational reliability	7	Getting anti-adhesive lubricants, films. Insufficient content of volatile binders. Violation of the mode of formation: increased temperature, high cooling rate, unregulated thermal or mechanical effects. The poor anti-adhesive coating on the surface of the equipment	4	It is determined visually by the shape and size in the plan, the depth of occurrence	4	112
Crack	Destruction of details	9	Violation of the forming mode, high cooling rate. There is a predominance of permissible mechanical loads when removing a part by tooling and transportation. Impact during operation	3	It was determined visually. The size of the defect in the plan. It affected layers and the direction of cracks on the part.	3	81
Sink	Affect the physical and mechanical properties of the material, as they lead to the local curvature of the fibers and changes in the composition of the material in the cross-section of the defect	7	Increased content of volatile elements in the prepreg. Violation of the modes of formation: the heating rate, time, value, applied pressure	5	The size of the defect in the plan. Depth of occurrence	3	105
Extraneous inclusion	Affect the physical and mechanical properties of the material, as they lead to the local curvature of the fibers and changes in the composition of the material in the cross-section of the defect	5	Getting foreign materials in the manufacture of prepreg, when it is exposed calculations	4	Dimensions in plan and thickness of inclusion. Depth of occurrence. Location and orientation of the area on the details	4	80
Local non-compliance with the norm of material composition	Destruction of details	9	An uneasy grip when molded. Uncertainty of rolling	3	Determined visually. The size of the defect in the plan. Affected layers and direction of cracks on the part	3	81
	A local area with a shift in the matrix of abo fibers	9		3		3	81
	Local area with pore space	9	Failure to comply with the applied fall heating rate's forming mode, time, and magnitude. Deflection of prepreg content	4		3	91

In the process of interoperation control, it is necessary to control the correctness and accuracy of compliance with technological regimes, assess their reliability, manufacturability, and design. Finished products are subject to initial control. At this stage, check the compliance of finished products to the specified requirements.

Input control of raw materials used and output control of finished products can be continuous or selective. A continuous control, each production unit (raw materials) is checked. Continuous control is used in conditions of exceptionally high requirements for the level of quality of products, in which it is unacceptable to pass defects into further production or operation due to significant losses (material and labor). Also, it may be in cases where the number of parts is insufficient to obtain samples or samples risks of the manufacturer and the consumer, and if technological process (equipment) does not provide stability of quality of the made details.

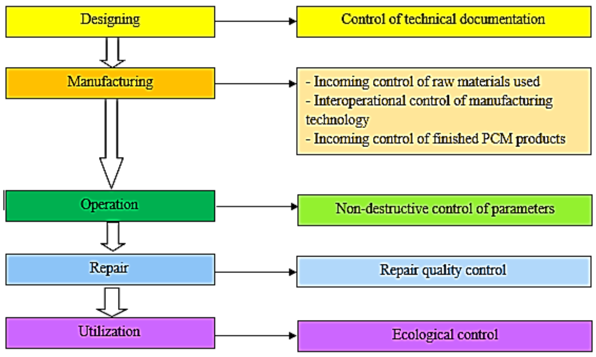

Figure 5 – Methods of quality control at different stages of the life cycle of PCM parts

In the case of selective control, only a specific part of the products (sample) is subject to inspection. Selective control gives a good result in the presence of a stable and well-established technological process of manufacturing parts.

At the stage of operation and repair of products with PKM and methods of visual diagnostics, the most widely used are various non-destructive testing methods. Depending on the physical nature of the signal used and the nature of its interaction with matter, these methods are divided into acoustic, eddy current, dielectric, thermal, and radiometric.

Disassembly, sorting, reusability assessment, and recycling are performed at the disposal stage. Most environmental indicators are monitored (safety of utilization).

4 Conclusions

FMEA is effective in reliability and in creating fault-tolerant systems that any developer should have. This method can allow developers to reduce the risk of critical situations. FMEA also increases product safety and, importantly, is easy to learn.

As a result of the application of the developed FMEA-methodology for the analysis of types and consequences of defects of polymer composites in operation, it was defined:

– the highest value of the priority number of risk (PNR) is 112. It corresponds to the low degree of curing of the binder during molding and non-compliance with the norm of the composition of the material throughout the part or most of it and delamination.

– reduction of PNR for the defect «Low degree of curing of the binder during molding» is possible due to the improvement and automation of control systems of the degree of polymerization less than 95-98 %.

– reducing PNR for the defect «Material composition norms for the entire volume of the part or most of it» is possible by controlling the set value of the volumetric value of the matrix and fibers.

– reducing PNR for the defect «Layering» is possible due to the improvement of mechanical and automated programs.

The paper tested Ishikawa's method to identify the cause of defects in low-quality carbon fiber PTFE-composite, which was divided into six key positions – man, method, material, mechanisms, control, and environment. The most significant causes of this problem were identified in low-skilled workers and in violation of mixing technology.

The task of ensuring high quality, reliability, and competitiveness of PCM products for industrial use, operating in harsh production conditions, cannot be successfully solved without effective modern control methods at all stages of the production cycle and life of this type of technical product. In this case, each step corresponds to its control methods, which are divided by quantitative, qualitative, and alternative characteristics.

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