

Types of Production and Operational Defects of the Multilayer Glued Constructions and Polymer Composite Materials Products and Methods to Detect Them

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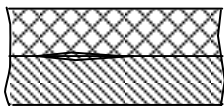
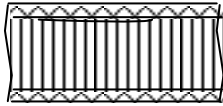
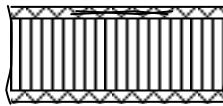
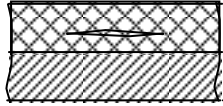
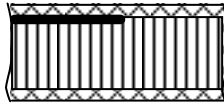
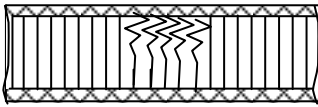
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Abstract. The types of defects of multilayer glued constructions and polymer composite materials (PCM) parts during their manufacturing and operation are shown. PCM defects are referred to seven different groups by the degree of their danger. The quantitative and qualitative indicators of defects are given and possible causes of their appearing are specified. Methods of detection of defects are specified.

1 Types of defects in multilayer glued constructions

Table 1 shows the most common types of defects in layered glued constructions, produced using the PCM, which may occur during their manufacturing and operation.

Table 1. Types of the defect in the glued construction manufactured with use of the PCMs

Defect designation	Schematic image
Nonglued areas in the layered, honeycomb, and other constructions with filler	 
Stratifications in the coverings and the units of the glued honeycomb and layered PCM constructions	 
Foreign inclusions (polymer films, paper, etc.) in the honeycomb constructions	
Honeycomb filler trample (loss of stability)	

Such defects are nonglued areas in the layered, honeycomb, and other constructions with filler, stratifications in the coverings and the units of the glued honeycomb and layered PCM constructions, foreign inclusions in the honeycomb constructions, honeycomb filler trample.

2. Groups of defects of products made from PCMs by the degree of their danger

The defects caused by a low degree of curing of polymer matrix (table 2) and deviations of material composition from standard parameters in the whole volume of an article are attributed to the first hazard group (the highest degree of hazard). Defects caused by undercuring of the matrix lead to a decrease in heat-resistance, to a sharp reduction of such operational characteristics as water- and moisture resistance, to a decrease in resistance to attacks of aggressive environments and also to a change of fracture nature of such material at static and dynamic fatigue loading. Deviations in chemical composition in a significant volume of components lead to essential changes in strength and elastic properties and worsen operational reliability. These changes in a different degree depend on the type of deformation (tension, compression, shift), nature of stressed state (one-axis, flat, volumetric), and also on duration and cyclicity of loading.

Exfoliations are ascribed to the second group of hazard. An influence of exfoliations on material properties depends significantly on the type of the stressed state. Exfoliations (as per se) practically do not influence on tension strength and elasticity modulus, whereas compression strength of exfoliated material may essentially decrease depending on occurrence depth and length of the exfoliation.

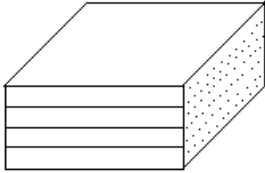
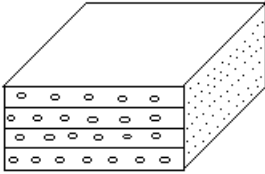
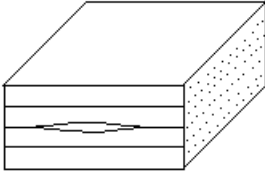
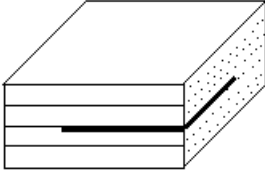
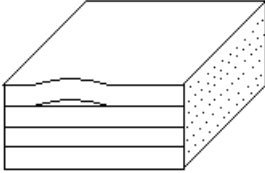
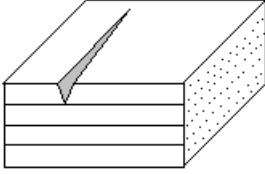
Cracks are attributed to the third hazard group of defects. Cracks create a high concentration of stresses, break integrity of a composite material by subjecting it and its separate elements to environmental attacks and may cause exfoliation of the material.

Local zones with a raised content of fibers, matrix or pores belong to the fourth group of defects. The hazard degree of such defects depends, finally, on size, shape and arrangement of a defect.

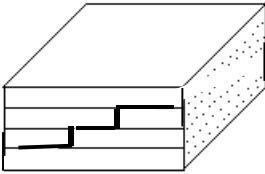
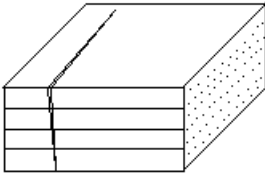
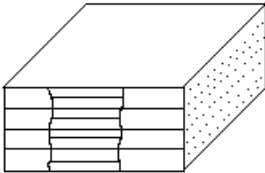
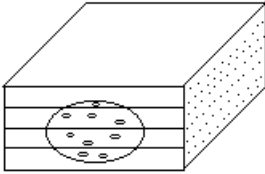
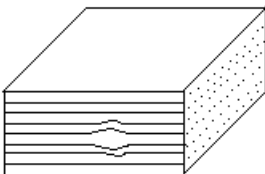
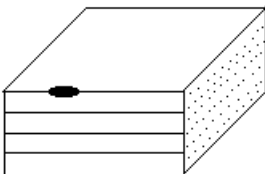
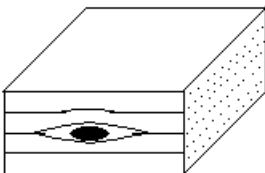
Folds, striae, cavities, foreign particles, crumples, joints and overlappings of reinforcing filler are ascribed to the fifth hazard group. Joints and overlappings basically influence on physical-mechanical characteristics through a change of material structure: an increase of reinforcement degree in an overlappings zone and its reduction - in a zone of a joint; their effect on mechanical properties is lower if they serve as stress concentrators. Crumples, folds, striae and foreign particles have a very similar effect on physical-mechanical properties of materials as they lead to a local curvature of fibers and to a change of material composition in a section throughout the defect. An influence of these defects on strength and elasticity increases with rising of reinforcement degree because the higher the fiber content, the higher number of material layers is affected by these defects.

Spalling of edges of holes and pockets, tearing of surface layers, chips and holes are included in the sixth hazard group because they are stress concentrators reducing load-bearing ability of materials. Researches showed that an influence of stress concentrators (in the form of holes) on strength of carbon-filled plastics decreases both with an increase in test time at long-term static loading and with a rise in rate of one-time static and dynamic deformation. The defects referred to the fiber curvature in the layer plane and to an insignificant deviation of the reinforcement angle from a preset value belong to the seventh hazard group. In most cases defects of such type are not comprehensive and curvatures or deviations of the reinforcement angle, as a rule, affect one or several layers of composite material only, and their dimensions are much less than dimensions of the construction component.

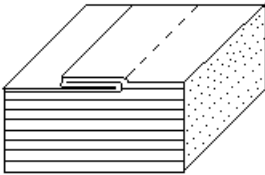
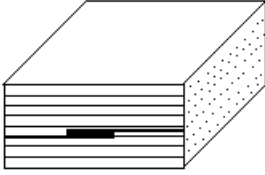
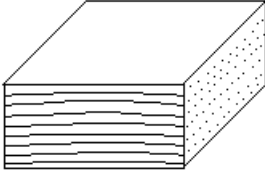
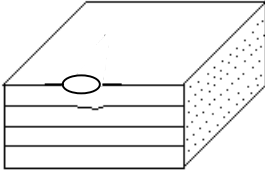
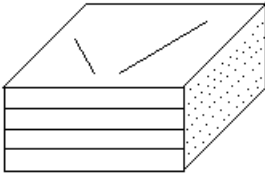
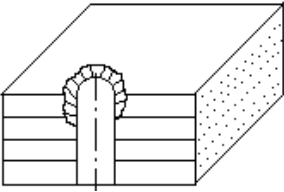
Table 2. Types of defects in parts and constructions made from PCM

Hazard group	Type of defects	Defect pattern	Quantitative and qualitative indicators	Possible causes of defect formation
1	2	3	4	5
The first group	Low degree of binder curing at formation		Degree of polymerization lower than 95-98%	Deviation of component contents in binder from standard values. Non-observance of time-temperature conditions at formation
	Deviation of component contents in material from standard values throughout the whole volume of a part or within a significant share of its volume		Preset value of volume contents of matrix (V_m , %), fiber (V_f , %), and pores (V_p , %)	Deviation of prepreg composition from standard values, violation of prepreg storage time or conditions. Non-observance of conditions at formation
The second group	Exfoliation	a) Internal defect (the defect does not appear at the edge of the part) 	Shape and plane sizes, occurrence depth.	Ingress of adhesion preventing greases, films. Insufficient content of binder, high content of volatile components. Non-observance of conditions at formation: excessively enhanced temperature, high cooling rate, unregulated heat or mechanical effects. Low-quality of adhesion preventing coating on tool surface
		b) The defect appears at the edge of the part 		
		c) Subsurface defect 		
The third group	Crack	a) Surface crack 	Plane sizes of the defect. Damaged layers and crack direction. Location of the crack in the part	Non-observance of conditions at formation – high cooling rate. Excess of allowable mechanical loads in cases of removal of a part from tool, transportation and machining

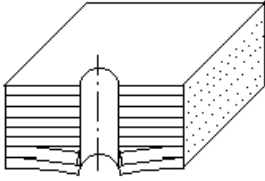
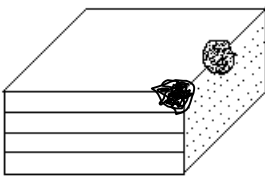
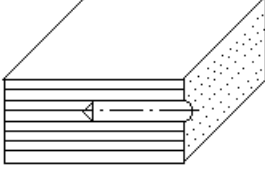
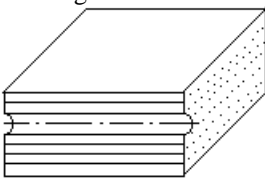
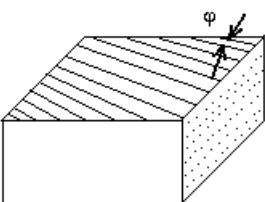
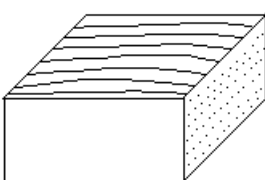
Continuation of Table 2

1	2	3	4	5
The third group	Crack	<p>b) Internal crack</p>  <p>c) Through-thickness crack</p> 	.	Impact loads in the course of operation
The fourth group	Local deviation of chemical composition from standard values	<p>a) Local area with an enhanced content of matrix or fibers</p>  <p>b) Local area with an enhanced content of pores</p> 	$V_m, \%$ $V_f, \%$ $V_p, \%$	<p>Non-uniform pressure at formation. Non-uniformity of rolling-on.</p> <p>Non-observance of conditions at formation: duration and value of the applied pressure, heating rate. Deviations of prepreg chemical composition from prescribed values</p>
The fifth group	Cavity		<p>Plane sizes of the defect.</p> <p>Occurrence depth</p>	Excess of allowable content of volatile components in prepreg. Non-observance of conditions at formation: heating rate, duration and value of the applied pressure
	Ingress of foreign particles	<p>a) Surface inclusion</p>  <p>b) Internal inclusion</p> 	<p>Plane sizes of the defect and thickness of an inclusion. Occurrence depth. Location and orientation of the defect in the part</p>	Ingress of foreign particles in the course of prepreg manufacture, cutting and lay out

Continuation of Table 2

1	2	3	4	5
The fifth group	Fold	<p>a) Surface fold</p>  <p>b) Internal fold</p> 	Plane sizes of the fold and occurrence depth. Location of the defective zone in the part	Prepreg folds. Formation of a fold at lay up of a stack and rolling on of prepreg. Insufficient stack compaction in the course of preforming. Non-uniform application of pressure
	Stria		Amplitude and wavelength. Plane sizes of a stria. Orientation and number of layers affected with the stria	Prepreg striae. Formation of striae in the course of lay up of a stack. Non-uniform stack compaction in the course of impregnation, preforming and formation
	Crumple		Crumple dimensions: depth, width, length. Orientation of the crumple in the part.	Defects of tool surface. Joints of substrates, absorbing and separating layers. Foreign particles and particles of auxiliary materials on tool surface. Mechanical actions during operation
	Scratch		Scratch dimensions: depth, width, length. Orientation of the scratch in the part	Carelessness at removal of the part from toll, at transportation, storage and machining. Mechanical actions during operation
The sixth group	Spalling of edges of holes and pockets		Plane sizes of the defect. Depth of the defect	Incorrect tool sharpening. Violation of machining conditions

Continuation of Table 2

1	2	3	4	5
The sixth group	Tearing of surface layers		Plane sizes of the defect. Depth of the defect	Absence of pressing or insufficient pressing of the substrate material. Incorrect tool sharpening. Violation of machining conditions – excessive feeding of tool
	Chips		Defect dimensions: depth, width, length. Location on the part	Carelessness at removal of the part from toll, transportation, storage and machining. Mechanical actions during operation
	Hole	<p>a) Blind hole</p>  <p>b) Through hole</p> 	Hole depth and diameter. Location in the part. Diameter, location in the part	Carelessness at machining and lay-up of a stack
The seventh group	Deviation of the reinforcement angle		Deviation of the reinforcement angle from a prescribed value. Numbers and quantity of layers	Incorrect cutting and lay-up of a stack
	Distortion of fibers within the layer plane		Amplitude and wavelength or angle. Orientation of damaged layers. Plane sizes of defects	Curvature of fibers in prepreg. Distortion of prepregs at lay out or formation

3 Stages of generation of defects in the course of production process

Complexity of PCM composition, variety of types of reinforcing fillers, various techniques for prepregs manufacture and formation of parts cause a significant variety of defects [1]. For example, at the stage of manufacture of yarn prepregs the following defects may arise: incorrect composition of components, moving apart and twisting of yarns, formations of local non-impregnated areas, leaks out of binder, joints and overlaps of separate yarns, different density of yarn lay out in prepregs caused by increased or lowered density

of preliminary yarn lay out resulting in variations of thickness of prepreg monolayers. At the stage of production of fabric prepregs such defects as local leaks out of binder, incorrect composition of components, displacement of fabric texture and folding caused by action of interlayer may appear alongside with defects caused by the used fabric: broken warp thread, web sagging, accumulated fluff, increased moisture content, etc.

The following most typical defects may arise at the stage of cutting (if high-quality prepreg is used and conditions of its storage are not violated): deviation of cutting angle from prescribed values, undercutting of separate threads, texture distortions at removal of a template, deformation of cut pieces at transportation, moving apart of the cutting line from the template outline, distortion of filler structure in the cut area.

A number of defects caused by non-observance of layout angle, displacement of the layout zone, distortion of prepreg structure in the layer plane (fiber curvature), formation of prepreg waviness because of a non-uniform tension at the lay-up and changes of the rolling-on force (which may lead to fold formation) may arise at the stage of stack lay-up. At this stage some small pieces of separating material and foreign particles adhered to prepreg may ingress between layers. Also the order of the lay-up of layers may be violated and the rolling-on roller may be overheated. The possibility of defect formation at the stage of lay up of thick-walled parts is especially high taking into consideration a large number of layers and an intensive decreases of substrate stiffness with each laid-up layer.

At the stage of formation of a part the following defects may arise: folds and fiber curvature caused by consolidation and displacement of material; incorrect material composition; leaks out of binder or shrinkages caused by a non-uniform temperature field; crumples caused by foreign particles on the surface of external layers, handling marks on tools, joints of separating layers (films), substrate or absorbing layers; exfoliations and cracks caused by internal stresses in material arising at heat treatment or at cooling of the part or at a careless removal of the part from the tool.

Such defects as chips, scratches, handling marks, spalling in the machined area, tearing of surface layers and formation of cracks caused by tool action are possibly at stages of transportation, storage and machining.

It is known that the recommended upper limit of working temperature for materials with a thermosetting matrix corresponds to 95-98 % of conversion degree of reaction-active groups. In this case the level of glass transition temperature typical for this material and corresponding heat resistance of this material is ensured. Violation in composition and mass shares of binder components, incorrect conditions of formation, for example, considerable variations of the rate of temperature growth, insufficient heating temperature, interruption of the formation process and shortening of formation time lead, as a rule, to a decrease in polymerization degree and heat resistance and to a sharp reduction in the level of structural and operational characteristics. For example, interruption of the formation process of KMU-3I and KMU-4e carbon-filled plastics after 0.5, 1.0, 2.0 and 3.0 hours upon attainment of a preset temperature level and the subsequent continuation of the formation process in 2-3 days leads to a decrease in compression strength of KMU-4e carbon-filled plastics by 13 % and 20 % at room temperature and at 150°C respectively. The maximum decrease in strength took place in case of interruption of the formation process within the first two hours.

Thus, defects of PCM should be distinguished depending on their origin (arisen at the stage of manufacturing, storage, transportation or operation), on their location in parts (on surface, internal or appeared at the edge of a part), occurrence depth, opening degree and plane sizes of these structural non-uniformities (macro-defects – over 60-100 microns in size which usually are localized in parts, and micro-defects – smaller than 60-100 microns in size which are, as a rule, distributed in the whole volume of material or in its considerable share). For example, plane size of a pore (micro-defect) is

less than 100 microns, but that of such air inclusion as cavity (macro-defect) – more than 100 microns.

4 Methods for detection of defects

Acoustic, radiation (X-ray), thermal, radio wave, optical and other techniques of nondestructive testing are applied to detect macro-defects in PCM constructions. Acoustic control methods are most widely used since they allow one to solve almost all key problems of nondestructive testing. Defectoscopy methods (echo-pulse, shadow, impedance and velocimetric methods, forced oscillation, free oscillation, reverberation technique, etc.) allow one to detect various holes, exfoliations, cracks, cavities, foreign inclusions, spalling of hole and pocket edges, and also tearing of surface layers caused by machining and assembly of PCM parts [2].

Detection of internal defects of PCM structures is possible by 3-dimensional optic-acoustic microscopy based on the echo-pulse defectoscopy implemented due to laser-initiated ultrasound. An acoustic microscope allows one to study internal structure of material in the tested zone and to detect folds, striae, deviations of reinforcement angle, curvature of fibers in the layer plane and other distortions of macrostructure.

Such surface defects of PCM parts and components as crumples, scratches, spalling of hole and pocket edges, chips, and also internal defects appearing at the surface of parts can be detected by visual-optical method and in certain cases by the luminescent technique. Surface irregularities and the depth of surface damages of PCM parts can be estimated with the help of roughness instruments and profilographs.

Detection of micro-scale defects and definition (or an estimation) of PCM properties directly in a part or in a construction without their destruction is possible by diagnostics methods based on correlation between acoustic characteristics of the material and its physical and mechanical properties, since acoustic properties (rate of propagation and attenuation of ultrasonic vibrations, spectral characteristics of signals passed through the studied zone, etc.) and various physical and mechanical properties of materials (density, porosity, elastic and strength characteristics, etc.) depend on the PCM structure produced in the course of part formation [3]. Diagnostics methods allow one to define with a rather high degree of precision such characteristics as porosity (volume content of pores), degree of binder curing at formation (conversion degree of reactive groups in PCM matrix), material composition and its density (in case it is defined by the ratio of the main components of PCM, i.e. by matrix and reinforcing filler but not by porosity), elastic and strength properties, direction of the primary orientation of filler and other similar characteristics of materials.

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