Study of the microstructure of aramid fabrics for structural and protective organoplastics modified in a microwave electromagnetic field

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Abstract. The microstructure of samples of aramid fabric TSVM-DZh, subjected to the influence of the microwave electromagnetic field of an average power level with a frequency of 2450 MHz, was investigated. A significant change in the conditions of contact of individual filaments at the level of the interfibrillary bond of fibers, expressed in the integration of fibrils into agglomerates, filling gaps between the fibers with an increase in the interaction area and in the convergence of individual fibers, which improves the reliability of intermolecular bonds was established. The obtained results can be used as one of the mechanisms for increasing the strength characteristics of structural organoplastics and protective materials from aramid fabrics after microwave exposure.

1. Introduction

1.1. Status of the question
High strength and heat-resistant characteristics of fabrics based on aramid filaments determine their use as not only structural materials in aircraft construction, but also so-called “ballistic” materials used as personal protective equipment of the 1st and 2nd class for equipping EMERCOM employees and personnel working in extreme conditions, when possible emergencies, accompanied by mechanical damage of high-speed objects, exposure to high temperatures or liquids under pressure. One of the first such materials can be attributed to Kevlar, which was also used by the US Army during the Vietnam War. Good protective properties of aramid fabrics in combination with light weight and flexibility led to their widespread use in the army, aviation and navy [1-3]. In Russia, one of the most common ballistic materials based on aramid filaments are TSVM, Rusar and some other materials generally similar in properties [4-5]. Compared with metal and ceramic protective agents, aramid fabrics and composites based on them (organoplastics) are significantly lighter and provide flexibility and freedom of movement, can be worn secretly under outerwear, although, of course, they do not provide adequate protection in combat using automatic small arms.

Recently, due to its lightness and durability, organoplastics are finding more and more widespread use in aviation technology as structural materials and means of protection for responsible units (engines, control systems) from damaging factors [6–8].
However, aramid fabrics also have drawbacks associated with weak resistance to low-speed hard drummers [9, 10], weakening of the protective properties when wet, exposure to direct sunlight, significant armor effect, which leads to serious injuries. As a result, the design of elements of protective clothing is complicated by the introduction of water- and light-tight pockets or outer layers of fabric, the use of multilayer (20-30 layers) systems, which makes the protective kit heavier and reduces the mobility of a person.

1.2. Relevance of research
Studies to increase the strength of such fabrics are aimed at improving the technologies for obtaining the initial components and the formation of fabrics by optimizing weaving [11, 12]. This complicates the process, leads to an increase in material, labor and financial costs, and also leads to the need for restructuring or re-equipment of production, which lengthens the cycle of introducing new developments.

The increase in the number of local conflicts, as well as natural and man-made emergencies requires an increase in the protective characteristics of flexible materials and their reliability. Creating a unified methodology for the technological management of the formation of the required characteristics of materials by electromagnetic impact on the finished object without disturbing the existing technological cycle will allow designing optimal serial technological routes with minimum cost and high quality of products, solving the problem of import substitution especially in strategically important industries aimed at ensuring the security of the country and increase the competitiveness of products.

1.3. Statement of the problem
Composites based on aramid fibers are similar to structural glass and carbon plastics in terms of the structuring principle – a polymer matrix and multidirectional reinforcing fibers. Therefore, it is possible to apply the method of microwave exposure to the final product developed by us without modifying the existing technologies [13, 14]. However, this assumption requires experimental verification and theoretical justification. We have conducted experiments to study the effect of microwave electromagnetic field on the breaking strength of aramid filaments [15], during which it was found that microwave processing, with an average specific power, increases the axial breaking load on the TSVM-DJ filament by almost 2 times. It has also been obtained that, after exposure to a single-layer aramid fabric with a microwave electromagnetic field, the resistance of the last piercing by a cone with a corner at apex of 900 increases, both in dry and wet conditions, from 1.5 to 2 times, depending on the applied power density. The best results are achieved when exposed to the microwave electromagnetic field of average power density for 4-8 minutes.

The purpose of the research was to study the specific features of the structure of the TSVM-J fabric and the multilayer composite based on it at different magnifications to reveal the possible mechanism of the effect described above.

2. Research methods and equipment
We have studied the microstructure of the TSBM-DJ monolayer fabric, article 56319A in the initial state (control samples) and after modification in the microwave electromagnetic field. The experiments were carried out on a microwave installation "Zhuk-2-02" (LLC AgroEkoTech, Obinsk, Kaluga region), which allows you to adjust the intensity of the microwave electromagnetic field frequency of 2450 MHz by changing the distance to the object. Modification of the samples was carried out at an average power level with an exposure time of 4 minutes. Previously, in these modes, the best results were obtained for increasing the strength of aramid filaments and fabrics.

The appearance of the surface of the fabric samples was studied using an electron microscope MIRA II LMU (Tescan Ersay Holding, Czech Republic) in the Laboratory of Special-Purpose Materials of the Saratov State University named after N. G. Chernyshevsky.

3. Results and discussion
Micrographs of samples at different magnifications are shown in figures 1 - 3. It can be seen that with a small magnification (field of view - 2.02 mm) there are no differences in the structure of the woven fabric layer. It may be noted a somewhat dimmer, matt appearance of the treated sample (figure 1). With a larger increase in the field of view of 330.7 microns, separate fibers extending from the filament become noticeable. At the same time, there are significantly more such fibers on the control sample than on the treated sample. This suggests that during the action of the microwave electromagnetic field, a certain consolidation of fibers into bundles in the structure of the filaments occurred. This statement is confirmed by the appearance of agglomerates on the surface of filaments, apparently formed by deformed fibers. With a larger increase in the field of view of 65.9 - 66.13 micrometers (figure 2), the differences in the structure of the filaments and fibers of the fabric become more noticeable. Separate fibers and microfibrill filaments are clearly visible on the surface of the filaments of the control sample, connecting the filaments to each other only at separate points. Also microagglomerates of organic structures are noted, possibly environmental pollution placed on the surface of individual fibers and not simultaneously connected with several fibers. Thus, it is possible to note only the macromechanical connection of the threads among themselves in the process of weaving the fabric, which determines the strength and other operational parameters of the control sample. The surface of the filaments of the treated fabric sample is covered with a sufficiently dense layer of agglomerates, connected simultaneously with several filaments, which are also close to each other, being in close contact. The presence of agglomerates connecting the filaments most likely determines additional points of contact between the filaments and the occurrence of sufficiently strong bonds, which generally contributes to an increase in the interaction regions of the filaments at the intermolecular level. This interaction contributes to the increased strength of the fabric, complementing the purely mechanical contact formed by weaving. The noted features are even more pronounced with a large increase in the surface of the tissue in the field of view of 33.07 μm (figure 4).

On the surface of the filaments of the control sample of tissue there is a large number of randomly located separated misoriented fibers and microfibrils. It is not possible to identify any reliable areas of contact of the fibers of one filament with a neighboring thread. Between the filaments there are significant gaps with sizes greater than 10 microns.

On the surface of the filaments of the treated fabric sample, there are agglomerates of fibers and individual fibers tightly adjacent to it. In this case, the filaments are very close together (5 μm or less), which promotes the contact of the agglomerates with several adjacent filaments. Virtually the entire filament has a coating formed by fibers complexed into agglomerate.

The obtained micrographs can be taken as the rationale for the next mechanism to increase the strength of aramid filaments and fabrics after exposure to a microwave electromagnetic field. Studies [4, 5] found that the structural unit of aramid fibers are rigid macromolecules or their aggregates - fibrils. The high strength and rigidity of such fibers under tension are due to the high degree of orientation of the macromolecules along the fiber axis and the high dissociation energy of chemical bonds.

The difference in the stress state of neighboring structural elements causes shear stresses in the boundary region between the fibers forming the filament. As a result, uniaxial stretching of the fiber is accompanied by the growth of interfibrillary cracks along the direction of the tensile force.
The splitting of the filaments and the separation of the fibers apparently occurs already at the stage of weaving the fabric and is accompanied by the simultaneous breaking of some of the most intense fiber fragments, their exit to the surface of the filament and twisting into spiral-shaped formations under the action of stress relaxation. As a result, the fabric perceives loads with a smaller number of solid filaments and a smaller number of fibers in each filament. Thus it can be concluded that each filament takes an external load individually. As a result, after breaking the first group of fibers during loading, the load is perceived by the next bundle of fibrils, etc., until the remaining fibers are unable to resist the tensile load, and the filament breaks. There is a catastrophic total destruction, accompanied by intensive splitting and fluffing of the filaments and damage to the tissue. The effect of the microwave electromagnetic field most likely contributes to an increase in the number of interfibrillar bonds at the level of macromolecules. As a result, as the load grows, the conditions for joint rather than separate
operation of the fibers forming the filament are made. The weakening of the structure of the above-
mentioned cracks is leveled in this case by the described action of interfiber structures formed in the
microwave electromagnetic field and additional fibril bonds, as well as the formation of agglomerates
of separated fibers due to their destruction in the electromagnetic field, filling the space between the
filaments and entering into surface contact on macromechanical and physical level of intermolecular
interaction. The ongoing residual dehydration of the fibers and, as a result, of the filaments leads to their
partial shortening and convergence, which facilitates the interaction with the agglomerates of the fibers
and contributes to the formation of stronger bonds in the structure of the fabric.

Figure 2. The surface of aramid fibers in the field of view is 65.9 - 66.13 microns. Control sample (a),
treated sample (b)
Figure 3. The surface of aramid filaments in the field of view is 33.17-33.07 microns. Control sample (a), treated sample (b)

4. Conclusion
Thus, processing in the microwave electromagnetic field causes a certain restructuring of the composite structure based on aramid fabric, which can be called a kind of "quasi-structuring." This change in the structure allows creating conditions for increasing the resilience of external influences, in particular, by
increasing the tensile strength of individual filaments and the puncture resistance of the woven structure. Processing of aramid fabrics in the microwave electromagnetic field, therefore, allows to improve the operational, in particular, protective characteristics of the elements of light armor, without making changes of existing technologies for the synthesis of fibers, weaving filaments and the formation of fabric.

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