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Analysis of tearing test results for joining tips of metal-composite joints

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Abstract. *Designing highly loaded joints of metal-composite ends of aerospace engineering units meets the problem of assessing their bearing capacity, checking the adequacy of created mathematical calculation models to real testing results, and studying the dependence of the production technology of such joints on their final load-bearing capacity.*
The study of the dependence of the load-bearing capacity of "metal-composite" joints on the technology of their creation and the evaluation of the quality control process of combined joints with cylindrical trans-versal microelements and the adhesive bond between connecting parts was chosen as the goal of the research.
The joint of a flat metal tip with a carbon fiber part using transverse cylindrical pins and adhesive is considered as an object of research. Transversal pins of different diameters are inserted into the composite package. Various technological processes of preparing the surface of the metal part and pins for subsequent adhesive joining are considered in order to maximize the adhesion between the polymer binder and the metal elements of the joint. Al-so, for a more rational distribution of stiffness and corresponding stresses in the parts, the metal tip has a variable stepped thickness along the length of the joint.
As the results of the study, the theoretical failure load of the joints was evaluated and compared with the results of experimental tests. Also the technological process of preparing the surface of the metal part and the pins for further joining with the composite part is recommended, which ensures maximum adhesion between the joining parts.
A conclusion was made regarding the diameter of the pins and the shape of the profiled metal part, which ensure the maximum load-bearing capacity of the connection.
The types of joint failure were analyzed and conclusions were drawn regarding changes in the technology of surface preparation, the layout of the pins and the choice of their diameter.
As conclusions, recommendations were formulated regarding a certain technology for surface treatment of a metal part, which guarantees maximum adhesion between the metal part, pins and composite, and actual processes of quality control of "metal-composite" joints with transversal microelements were selected.

Keywords: *transversal fastening elements, "metal-composite" joint, micropins, adhesive, adhesion, tension test.*

Introduction

To evaluate the practical significance of the qualimetric model of quality management for technical processes of production preparation and the possibility of using the results obtained by means of the model, it is necessary to conduct experimental research of parameters for such processes at the conditions of experimental-industrial (prototype) production. The nomenclature of production processes of "metal+composite" joints in industrial conditions was investigated at two enterprises.

According to the results of many studies, scientists have established that the most relevant are overlapping type joints with a composite part thickness laying in the range of 3...7 mm. Such joints work mainly under shear load and small peeling-off loads. It is a combination of composite shells with metal bottoms and necks. The metal parts of such joints are most often made of titanium alloys, and the composite part is made of carbon fiber materials, which are bonded with various types of polymer matrices, often epoxy ones.

The second relevant type of joints is a combined bolted joint reinforced with transversal fasteners. They are

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designed to transmit bearing stresses and strains and reduce the influence of interlaminar shear.

References review. Analysis of main achievements in the field of estimation of structural-manufacturing solutions of joints with transversal z-pins

It is known that the issue of structural elements joining, especially in the field of aerospace engineering, is the most important, because joints make a large contribution to the total mass of structures and are very often cause its destruction. In the up-to-date scientific literature, a lot of attention is paid to the design of metal-composite joints. Thus, general engineering approaches to the design of both adhesive and joints of dissimilar parts using transversal microelements were considered in [1]. An overview of the possible practical implementation of such joints in the form of metal z-pins of different cross-section geometries, monolithic or separately manufactured micropins is considered in papers [2], [3]. In more detail, the practical issues of designing purely adhesive joints are shown in [4], [5], and numerical modeling of the stress-strain state of "metal-composite" adhesive joints is analyzed in [6]. The issue of surface treatment for adhesive joints by means of special mechanical surface treatment of joining parts is studied in [7]. In the sources [8], [9] special attention is paid to the issue of choosing modern structural adhesives and their application technology. Real quantitative parameters of the bearing capacity of lap joints can be obtained from the results of experimental tests. Test schemes and methods are considered in [10]–[12]. But the issue of researching the bearing capacity of combined metal-composite joints with transversal microelements and adhesive has not been fully explored yet. Also, the choice of surface treatment technology for metal and composite parts to ensure maximum adhesion between them, the choice of micropins location scheme, grounding the necessity of step profiling of parts along the joint length, and assessment of its overall quality are also relevant issues that require further analysis.

Materials and methods of research

The research was carried out both with the help of theoretical methods, i.e. by using the main statements of the mechanics of materials and structures, mechanics of reinforced materials, processing of experimental data, and with the help of experimental methods – tensile tests of lap joint specimens, methods of microstructural analysis of microsections of joint areas.

1. Selection parameters of metal-composite joints with transversal microelements and adhesive film

Joint load-bearing capacity was selected as the most actual property in the specific conditions of the enterprise's priority type of production and after analysis of all the most important relevant properties of joints. For its evaluation, specimens of joints with transversal fastening microelements allowing to transmit given load were designed.

The level of checking-up loading was estimated for composite article with the thickness 6 mm, width 60 mm, produced of composite with following parameters: reinforcing carbon UD tape – 02C300UAP/LY556, stacking sequence – [$0°_{10}$, $90°_{4}$, $\pm 45°_{8}$] (Fig. 1). According to the resting results composite package has following mechanical properties: ultimate strength at tension along 0° – 578 MPa; elasticity modulus at tension along 0° – 74 GPa. In accordance with original data checking-up value of loading is 208080 N. For further analysis one has to know shear strength and rigidity characteristics of joining elements (for the current case – for composite article, transversal pin and for adhesive substrate, if presented).

According to passport characteristics of binder LY556 interlaminar properties of composite package are

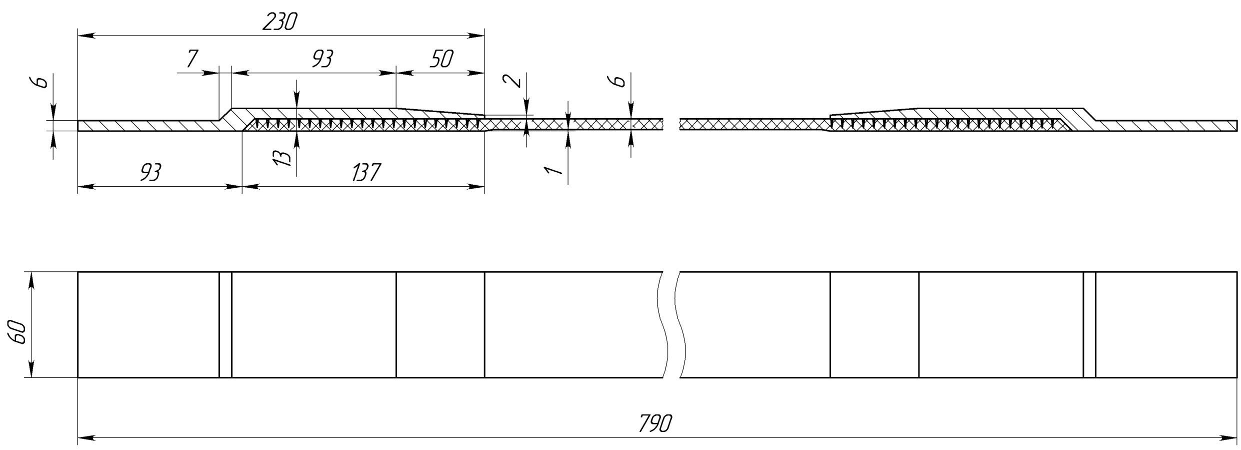

Fig. 1. Arrangement and dimensions of testing specimen

following: ultimate strength at interlaminar shear is 75.8 MPa; shear modulus of at interlaminar shear is 6150 MPa. In combined joint with adhesive substrate with the thickness 0.1 mm БФ-2 adhesive is used. It has shear strength 40 MPa, shear modulus – 3500 MPa.

Generalized scheme of specimen is shown on Fig. 1. Metal tips (flanges) are made of 30ХГСА steel (the thickness at zone of joining is 6 mm). Originally Ti-alloy tips were used but were replaced with stronger due to conditions of experiment. Generally, at comparative analysis one can use different tip materials at the left and right sides of a joint. In such case the failure happens at weakest link.

For correct selection of joint parameters analysis of joining layer with different composition was done. Following options were considered: pure adhesive joint, pinned joint (pins with diameter 1, 1.5 and 2 mm), combined «adhesive+pins». In the case of combined joining layer its strength depends both on adhesive properties, pin material and relative area of pins ν_{pin} with respect to entire composite area.

At selection of relative pins area ν_{pin} strength comparison of different methods of joining τ_{joint} (“pin”, “adhesive+pin”) with the strength of pure adhesive joint was done (Fig. 2). Analysis of these dependencies allows to make conclusion that the best variants of joining layer are those which permit us to realize maximum possible density of pins installation. According to results obtained by scientists in National Aerospace University “KhAI” the value of relative pins area has to be more than 7% (ν_{pin} ≥0.07). In such case efficiency of load transferring by pins will be more than adhesive film transfers.

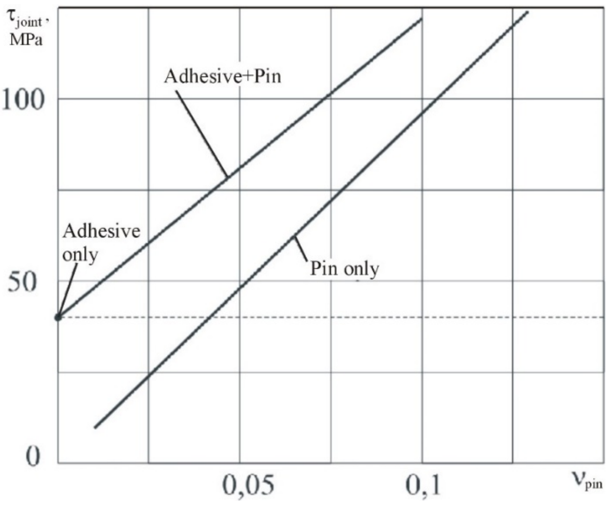

Fig. 2. Values of the reduced strength of “pinned”, “adhesive-pinned” joining layer and the strength of pure adhesive

Two possible schemes of pins arrangement were considered – tetragonal (Fig. 3, *a*) and chess (Fig. 3, *b*).

Required value of relative increment (spacing) of pins location can be estimated by means of following dependencies:

– for the case sown on the Fig. 3, *a*:

$$\bar{t} = \sqrt{\frac{\pi}{4\nu_{pin}}}\,; \tag{1}$$

– for the case sown on the Fig. 3, *b*:

$$\bar{t} = \sqrt{\frac{\pi}{2\nu_{pin}}}\,. \tag{2}$$

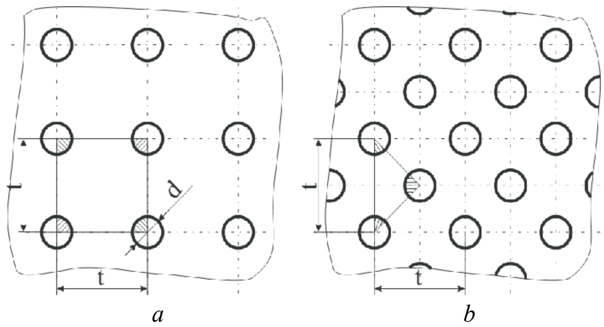

Fig. 3. Arrangement schemes of pins installation: *a* – tetragonal; *b* – chess

Following results were obtained after analysis: to guaranty relative pins area to be not less than 7 % the spacing between them by tetragonal scheme has to be not more than 3.35 of diameter; for the case of chess arrangement – not more than 4.74 of diameter. Thus, tetragonal pins arrangement can’t satisfy the solution of the problem formulated. Since pins were produced from the wire with diameters 1, 1.5 and 2 mm and joint width is 60 mm, then following variants of fastening pins arrangement were suggested: for the diameter 1 mm – spacing is 5 mm (relative spacing 5, that is slightly more than necessary); for the diameter 1.5 mm – spacing is 6 mm (relative spacing 4); for diameter 2 mm – spacing is 7 mm (relative spacing 3.5).

Table 1 shows values of reduced strength of joining layer, minimal quantity of pins rows (i.e. minimal joint length) at the condition of uniform load transferring by each row, and maximum quantity of rows (i.e. maximum joint length), which leads to increasing of joint load bearing capacity.

The values in the fifth column of Table 1 indicate the maximum load the joint can withstand. The low value of the load is associated with a significant difference in the stiffness of joining articles, namely, the steel flange is 2.7 times stiffer than the composite part. Assuming that the original thickness can’t be changed and that it is technologically not expedient to profile the composite part, it was decided to gradually reduce the thickness of the flange with a direct (stepped) bevel. During design, taking into account the requirements for the unification of equipment, typical specimens and design documentation were developed. 30 specimens were produced (10 pieces for each size of the fastening pin).

The tests were conducted under controlled conditions. The obtained values of the real bearing capacity and corresponding theoretical values given in Table 2.

Table 1. Estimation of joint parameters

Arrangement and parameters of joining layer	Reduced strength of joining layer, MPa	Minimal quantity of rows (quantity of pins in a row) / joint length, mm	Maximum quantity of rows / joint length, mm	Maximum original (theoretical) load bearing capacity, N
Adhesive, δ_{adh} = 0.1 mm	40	– / 86.7	– / 120	44210
Pin Ø 1 mm, increment 5 × 5 mm, chess scheme	60.3	23 (11 by 12 in a row and 12 by 11 in a row) / 57.5	37 / 92.5	54324
Pin Ø 1.5 mm, increment 6 × 6 mm, chess scheme	94.3	13 (6 by 10 in a row and 7 by 9 in arow) / 39	35 / 105	79841
Pin Ø 2 mm, increment 7 × 7 mm, chess scheme	123.1	9 (5 by 8 in a row and 4 by 7 in a row) / 31.5	23 / 80.5	101068
Adhesive + Pin Ø 1 mm, increment 5 × 5 mm, chess scheme	91.5	15 (8 by 12 in a row and 7 by 11 in a row) / 37.5	37 / 92.5	83980
Adhesive + Pin Ø 1,5 mm, increment 6 × 6 mm, chess scheme	120.5	10 (5 by 10 in a row and 5 by 9 in a row) / 30	29 / 87	103308
Adhesive + Pin Ø 2 mm, increment 7 × 7 mm, chess scheme	145	10 (5 by 8 in a row and 5 by 7) / 35	24 / 84	120932

Modes of joints failure were different. Until the moment of failure, the tensile diagram was close to linear. It should be noted that the bearing capacity was calculated using a simplified method without considering temperature loads. These thermal stresses can reach 30...50 % of the strength limit of the composite package. With great probability, it should be assumed that the difference between the predicted bearing capacity and the experimentally obtained one can be partially explained by the lack of consideration of temperature stresses. In the future, the assessment of the thermal linear expansion coefficients of the composite package should be included in the mandatory list of tests.

Table 2. Joint load bearing capacity

Pin diameter, mm	Theoretically estimated load bearing capacity, kN	Real load bearing capacity, kN	Relative difference, %
1	116.6	75	–35.6
1.5	147.2	102.4	–30.4
2	174.8	127.4	–27.1

To increase the load-bearing capacity of a joint, it is suggested to use a stepped change in the thickness of the metal tip. The effectiveness of this approach is demonstrated on the example of a joint with pins Ø 2 mm. The steps have constant width and height. The calculation results are shown in the table 3.

According to Table 3, the efficiency of using a stepped form of a metal article is high, but there is a stabilization of the load-bearing capacity (provided that the length of the joint is constant). So, in this case, it is not advisable to make more than four thickness transitions, because there is no significant increase in bearing capacity, and there are problems with the bearing of the hole wall by the pin at the zone of the thin part of the metal article.

Table 3. Load bearing capacity of stepped flange tip calculated analytically

Quantity of steps	Step length, mm	Step height, mm	Load bearing capacity, kN	Relative growth of load bearing capacity, %*
2	65	3	168.7	+39.4
3	43.3	2	198.3	+63.9
4	32.5	1.5	202.3	+67.2

* comparison with original load bearing capacity 120.9 kN

In general, the achieved bearing capacity of the joint based on “adhesive+pin” joining layer with pins (having diameters of 1, 1.5 and 2 mm) is 36, 49.2 and 61.3 % of the bearing capacity of the composite part, respectively. This result is explained by the high load concentration along the joint and the negative effect of temperature stresses. Stepped profiling of a metal part allows to increase the bearing capacity by 60...70 % on average. In this case, the bearing capacity of the joint on pins with a diameter of 2 mm will reach 97.3 % of the bearing capacity of the composite part. To further increase the load-bearing capacity of the joint, one can change the composition (composite stacking angles, adhesive and other parameters) of the joining layer along the joint.

Studying microstructure of polymeric composite at zone of transversal micropins embedding

In some of the studied specimens following failure mode was observed: pulling out of micropins from composite article and failure of reinforcing fibers in definite layers. To determine the reasons of this mode of failure auxiliary study of the microstructure of polymeric composites in the zone of transversal fastening micropins installation was carried out, microsections were prepared. The scheme of specimen cutting to make representative microsections is shown in Fig. 4.

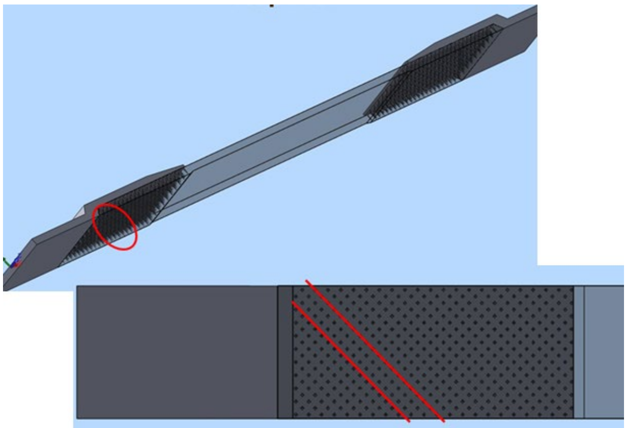

Fig. 4. The scheme of microsections cutting to study composite microstructure with embedded transversal micropins

To estimate influence of transversal fastening micropins on carbon plastic structure analysis of composite internal microstructure after testing loading was conducted. Analysis of microstructure was done by means of stereoscopic microscope МБС-9.

Pictures of specimens' microstructure are shown on the Fig. 5–7.

Microstructural analysis allows to make following conclusions:

– there is a slight violation of the flatness of the layers when introducing transversal fastening elements;

– there are no noticeable zones of carbon fibers failure, which are potentially possible during introducing micropins to the composite reinforcement grid;

–the bending of carbon fibers is observed in the zone of transversal fastening micropins embedding;

– in some areas local delamination of fibers from the binder is observed.

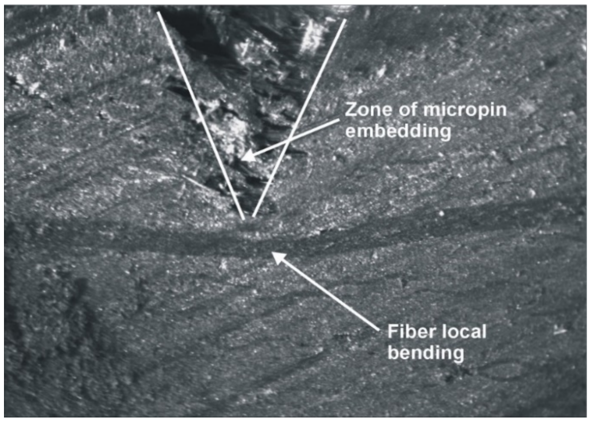

Fig. 5. Carbon plastic microstructure at zone of transversal micropin embedding Micropin was pulled out during testing loading, magnification – ×28

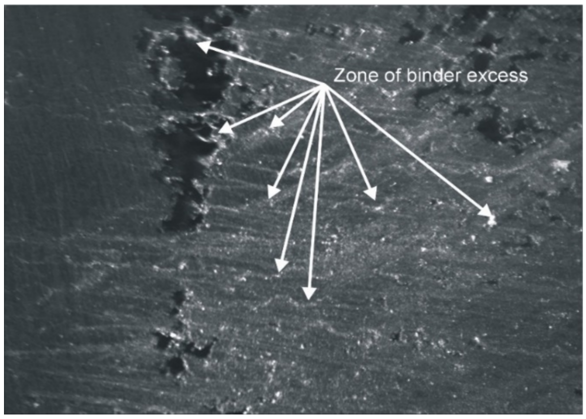

Fig. 6. Microstructure of carbon plastic at zone of transversal micropin embedding, magnification – x28

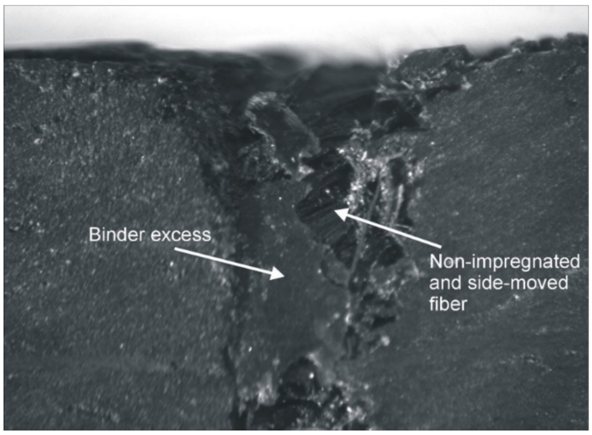

Fig. 7. Microstructure of composite at zone of transversal micropin embedding, magnification – x28

In order to study the continuity of the contact of binder and metal micropins specimens with longitudinal and transverse bonding of the composite and metal wire were used. The microstructure was analyzed by means of ZEISS NEOPHOT 21 microscope, which allows you to expand the magnification range.

The study was conducted in two stages:

– on the first stage the microstructure of the joint boundary between the binder and the metal before loading;

– on the second one – after loading.

As a result of the study, it was found that the violation of the joint continuity between two components and the separation of the reinforcement fibers wasn't observed on most specimens. But after testing violation of adhesive bonds was observed on this border (Fig. 8). In recorded cases the zones of adhesive bonding failure are located near the micro-indentations on the surface of the metal wire.

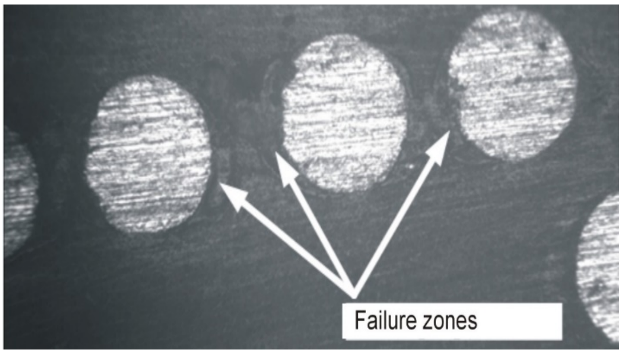

Fig. 8. Microstructure of carbon plastic with longitudinal reinforcing wires, magnification ×125

These results show the necessity of research directed to adhesive strength increasing at the interface binder-metal surface by means of technological methods.

Thus, these studies of specimens' microstructure allow us to draw the following conclusions:

– distortion (curvature) of reinforcement fibers in the range of relative spacing of cylindrical micripins equal to 3.5...5.0 and tetragonal structure of pins location is observed, but this distortion has no critical character for the joint load-bearing capacity;

– non-uniform binder distribution in the studied cross-sections of the specimens is observed, i.e. in some places there is the excess of binder, in some – non-impregnated fibers were found. This situation can be determined by two factors: insufficient viscosity of the binder or insufficient and non-uniform pressing during composite package layers impregnation.

It is possible to reduce or exclude mentioned deviations from the recommended values by means of keeping strict control of the operation modes during joint mounting.

3. Studying method of adhesive strength increasing

Determination of adhesion strength is a rather complex task, the solution of which is considered in [4]–[6]. Nowadays the lack of a unified approach to the theory of adhesion is explained by the complexity and variety of phenomena occurring at the boundary of the phase distribution (Fig. 8).

Their analysis shows that the number of significant factors affecting adhesive strength and directly related to joints design can include:

– processes of preliminary preparation of micro-fasteners surfaces;

– composition of coating;

– technology of coating application.

– renovation of the surfaces of adhesive contact, i.e. removing contaminations, oxides, films from these surfaces;

– increasing area of adhesive contact between metal and composite;

– application of intermediate layer (substrates) of materials which have elevated adhesion to both exact metal and exact composite.

Technological processes which match to above-mention factors are following: degreasing and etching metal surfaces by special agents, stripping, abrasive grinding and polishing (sandblasting), application to joining surfaces special elastic adhesives.

The goal of conducted studies is comparative estimation of technologies for increasing adhesion of "metal+composite" joints. For determination degree of adhesion of composite to metal steel wire with diameter 0.25 mm was used. Carbon fiber were impregnated by means of binder based on compound К-153, epoxy resin ЕД-20 and hardener PEPA (12 %).

The method of adhesive strength between metal wire and carbon composite was the following. A piece of wire, one end of which was clamped in special grip, was co-cured with composite package on definite length L. After polymerization this package was installed to tearing machine and wire was pulled out from composite with reading the pulling out force value N. Testing of 8–10 specimens with the same structure was conducted. Following options of wire surface preparation before co-curing with composite were realized: degreasing in acetone, abrasive grinding and wiping with a cotton. Variant of metal coatings considered is oxide film and adhesive БФ-2. Results of experimental testing after wire pulling out are shown in Table 4.

Analysis of experimental results allows you to make following conclusions:

– abrasive removing of oxide films and other contaminants from metal surfaces with consequent surface stripping totally increase adhesive strength between binder and steel surface. Average increasing of relative force of pin pull out is more than 3% at quite low coefficient of variation 2.2…7.9;

– application of intermediate layer between wet composite and metal article (БФ-2, БФ-2 + К153 + + 8% PEPA) increases adhesive strength in 1,13…1.32 times;

– significantly worse experimental results were obtained for cases of joining metal tip surface with wet composite without application of auxiliary adhesive layer.

Table 4. The part of general protocol of testing for estimation adhesive strength of “metal+composite” joints

Nb.	Operations of surface preparation	Composition of a coating	L, mm	N, N	N/L, N/mm	Variation coefficient, %
1	Degreasing in acetone, cleaning in water, wiping with cotton	Oxide film	2.0	60.4	30.2	7.9
			4.0	72.1	18.0	7.8
			6.0	72.2	12.0	10.6
			8.0	78.3	9.78	9.5
			12.0	80.0	6.67	6.8
			16.0	82.2	5.14	7.4
			20.0	92.3	4.61	5.9
2	Degreasing in acetone, cleaning in water, wiping with cotton	БФ-2 +К153 +8% PEPA	2.0	67.9	34.0	20.3
			3.0	92.9	31.0	10.9
			4.0	94.6	23.7	6.9
3	Stripping, cleaning in water, wiping with cotton	БФ-2	2.0	61.3	30.6	7.6
			3.0	72.0	24.0	12.9
			4.0	82.0	20.5	12.1
			8.0	60.3	7.5	6.3
4	Abrasive grinding, degreasing in acetone, wiping with cotton	No coating	2.0	46.2	31.1	2.2
			3.0	54.8	28.3	6.9
			4.0	57.4	14.4	4.9
			5.0	62.4	15.5	4.8
5		3	2.0	62.6	31.3	7.3
			3.0	85.5	28.5	12.6
			4.0	81.7	20.4	2.1
			5.0	99.0	20.0	5.8
6	Degreasing in benzene Б-70, wiping with cotton, stripping, cleaning in water	1	2.0	16.5	8.2	4.3
			4.0	25.3	8.3	6.3
			6.0	30.2	5.0	18.8
			8.0	34.2	4.5	3.5
			12.0	43.8	3.6	8.0

4. Results of mechanical testing

Considering previous conclusions developed for research-industrial tension tests the butch of metal-composite lapped specimens (made of carbon 02C300UAP and binder Araldite LY556) and composite structure $[0_5/90_5/+45_4/-45_4]$ was produced. Testing was conducted on tearing machine “ZD-10/90” with crosshead movement rate 2 mm/min. Appearance of representative specimen is shown on the Fig. 9.

Special attention has to be paid to types (modes) of specimens failure:

– composite failure in regular zone of a joint without visible damages in non-regular zone of a joint;

– the same but with partial pulling out of pins from metal tip;

– delamination inside of composite package due to poor interlaminar shear strength;

– separation of composite package from metal tip surface with (or without) pulling out of cylindrical pins from holes in metal tip;

– combination of above-mentioned failure modes.

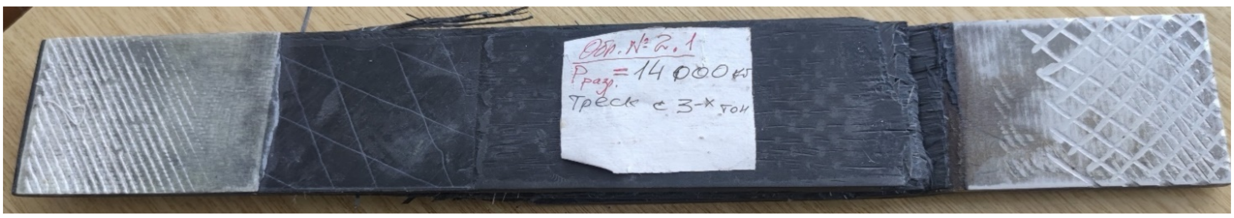

Fig. 9. Visual top view on specimen after testing

A typical example of separation of entire composite package from metal tip is shown on Fig. 10. This fact is evidence of poor strength of joining micropins with metal tip and poor adhesive contact of composite with metal tip.

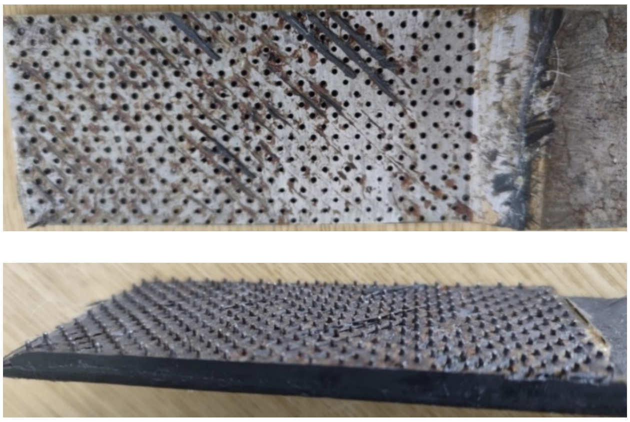

Fig. 10. Appearance of delaminated entire composite package (figure below) from metal tip (figure above). All cylindrical micropins are pulled out fully from metal tip

The cylindrical microelements in this example were inserted to the holes with tight fit, but the degree of tightness was insufficient. To exclude such a failure mode, it is necessary to strictly control the force of micropins pulling out from the holes or use welding to joint them to metal tip.

In this case, the metal tip was made of aluminum alloy and micropins are made of steel wire. This combination doesn't allow to use welding.

An example of failure at interlaminar delamination of a composite package is shown in Fig. 11. It is clearly visible (at angle view) that micropins are not pulled out in the thicker part of the metal tip (due to deeper contact with a hole), but in the thinner part they are pulled out. Interlaminar delamination has occurred due to interlaminar shear, i.e due to inappropriately selected structure of composite package and weak interlaminar adhesion.

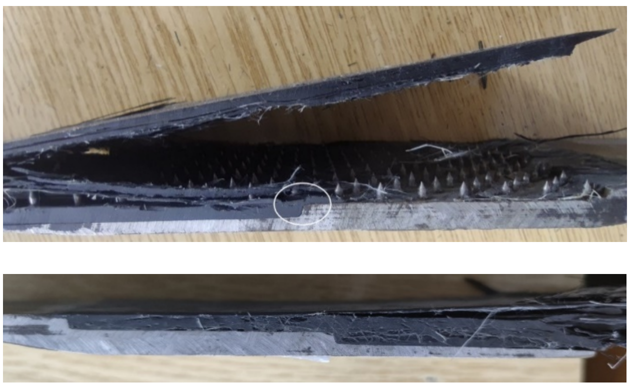

Fig. 11. An example of interlaminar failure mode of composite package at stepped metal article realization (above). White oval shows the location of metal article thickness changing. Side view on the joint is shown below

Another typical example of interlaminar delamination can be observed at stepped tip thickness variation, it is shown on Fig. 12.

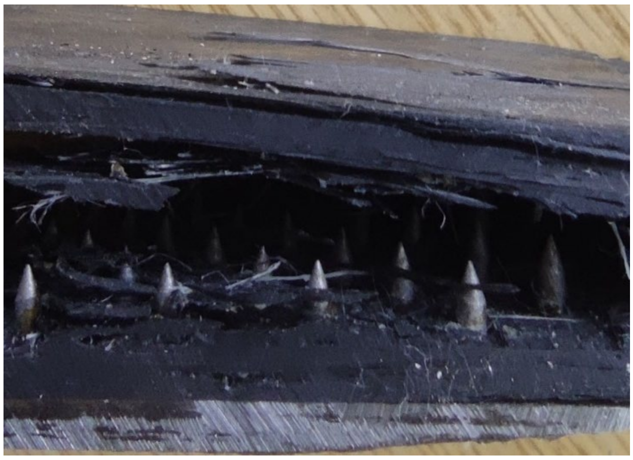

Fig. 12. Interlaminar delamination of composite attached to the articles with the stepped thickness changing. Specimen is prepared for analysis along the line where testing load was applied

One can see in this picture that interlaminar delamination mostly can be observed at zones of prepreg layer having staking angle of ±45° with respect to the direction of loading. It is necessary to note that the shape of inserted micripins is quite correct and their arrangement isn't violated. Moreover, delamination of composite package occurs by several different surfaces (not by the single one). This is quite desirable behavior from the strength point of view.

Failure of composite package at regular zone of joint near the edge of metal tip is shown on Fig. 13.

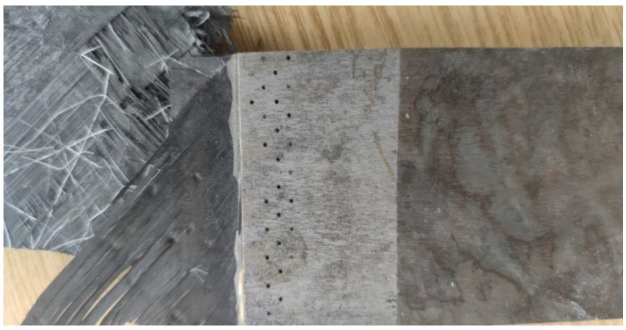

Fig. 13. Typical failure mode of composite package at regular zone neighboring with metal tip. One can catch that several micropins are pulled out fully from metal tip at the rows closest to composite article (black holes)

Failure of connections between metal tips and first three rows of micropins at chess pins arrangement is quite understandable from theoretical considerations, i.e. maximum shear strength occurs at this zone. Failure of composite in regular zone are defined mainly by not very rationally selected composites stacking sequence.

Top view on delaminated part of composite package is shown on Fig. 14.

Fig. 14. Top view on delaminated part of composite package

It can be seen from the Fig.14 that delamination has happened along surfaces of layers applying angle of 45º with the line of tension load application. Several rows of pins were pulled out from the holes in metal tip (more light color designates side surfaces of cylindrical pins). But the most quantity of pins was pulled out from a composite package. Black color in holes means track of pulled out pins. From the two sides of holes less dark extended zones can be observed. These slot-like zones or poor contact between pin and composite appear due to definite bending of reinforcing fibers which envelope pins from side surfaces. The shape and dimensions of these zones (even at chess pins arrangement) define design requirement to diameter of pins. But technological difficulties restrict installation pins with diameter less then 0.5…0.8 mm. It should be expected, that this contradiction can be solved by means of development of controllable 3D-processes for creation thin but strong rods.

Conclusions

1. Results of research-industrial implementation of above-mentioned developments have shown necessity of considering variants of technological process chain at the stage of structural-manufacturing solutions qualimetric analysis. This chain has to be directed to increasing adhesion of joining mediums and checking-up of these processes. The most suitable for exact conditions of implementation is the process of joining metal surfaces sandblasting with consequent cleaning and application of intermediate layer of following mixture – adhesive БФ-2 +К153 + 8%PEPA – to both metal and composite joining surfaces.

2. The most load bearing capacity at failure can be ensured at chess micropins arrangement due to their higher specific volume fraction in composite comparing with rectangular pins arrangement.

3. It was found that the most actual processes of quality control are ones developed for joints with cylindrical micropins with 2 mm in diameter inserted with tight fit to metal part, moreover this option guaranties the maximum adhesive strength of joining surfaces.

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Аналіз результатів випробувань на руйнування з'єднань метало-композитних закінцівок

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Анотація. *При проектуванні високонавантажених з'єднань метало-композитних закінцівок агрегатів аерокосмічної техніки виникає проблема оцінки їх несучої здатності, перевірки адекватності створених математичних моделей розрахунку реальним результатам випробувань та вивчення залежності технології виробництва таких з'єднань на їх остаточну несучу здатність. Мета: У якості мети дослідження обрано вивчення залежності несучої здатності з'єднань "метал-композит" від технології їх створення та оцінка процесу контролю якості комбінованих з'єднань з циліндричними трансверсальними мікроелементами та адгезійним зв'язком між з'єднувальними деталями. У якості об'єкта дослідження розглядаються з'єднання плаского металевої закінцівки з деталлю з вуглепластику за допомогою трансверсальних циліндричних штифтів та клею. Трансверсальні штифти різного діаметру впроваджені у пакет композиту. Розглядаються різні технологічні процеси підготовки поверхні металевої деталі та штифтів для подальшого склеювання з метою максимального підвищення адгезії між полімерним сполучним та металевими елементами з'єднання. Також для більш раціонального роз-поділу жорсткості та відповідних напружень у деталях металева закінцівка має змінну товщину за довжиною з'єднання. У якості результатів дослідження оцінено теоретичне руйнівне навантаження з'єднань та порівняно з результатами експериментальних випробувань. Також рекомендовано технологічний процес підготовки поверхні металевої деталі та штифтів для подальшого з'єднання з композитною деталлю, який забезпечує максимальну адгезію між з'єднувальними деталями. Зроблено висновок щодо діаметру штифтів та форми профільованої металевої деталі, які забезпечують максимальну несучу здатність з'єднання. Проаналізовано типи руйнування з'єднань та зроблено висновки щодо змін у технології підготовки поверхонь, схеми розташування штифтів та вибору їх діаметру. У якості висновків сформульовано рекомендації щодо певної технології обробки поверхні металевої деталі, яка гарантує максимальну адгезію між металевою деталлю, штифтами та композитом та обрано актуальні процеси контролю якості з'єднань "метал-композит" з трансверсальними мікроелементами.*

Ключові слова: *трансверсальні кріпильні елементи, з'єднання "метал-композит", мікроштифти, клей, адгезія, випробування на розтягування.*