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Machining of holes in a large hybrid structure during its assembly using modular equipment

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Abstract. The study aimed to examine a technology for machining holes with an automatic drilling machine during the assembly of a large hybrid structure (polymer composite material + metal) with the use of modular equipment. In order to analyze the process of hole machining in large structures during their assembly, a wing box model measuring 17,765x3050x438 mm was assembled to simulate a civil aircraft wing box—a test wing box. The used modular equipment provides a geometric position accuracy of 0.5 mm in hole machining. In order to machine holes using an automatic drilling machine, a hole machining map was created. This map details key hole parameters such as hole diameter, hole accuracy, hole center coordinates, and hole axis direction, as well as material layers. To align the automatic drilling machine with a large structure, the map of holes to be machined should be divided into areas (in the case of long parts, into subareas). It was found that the technology for machining holes with numerically controlled automatic drilling machines using a combination tool allows holes to be machined in large hybrid structures to their final diameter in one or two passes, ensuring a geometric position accuracy of 0.5 mm. The study of hole machining in large structures revealed that in order to achieve a geometric position accuracy of 0.5 mm in automatic hole machining, long parts should be divided into subsections of no longer than 1 m. The overall length of the reference zone for the automatic drilling machine was determined. The obtained results can be used to optimize hole machining in large structures in aviation, shipbuilding, and other industries.

Keywords: polymer composite material, mixed stack, large-sized structure, modular assembly technology, hole machining, automated drilling machine with numerical control

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МАШИНОСТРОЕНИЕ

Научная статья
УДК 629.735.3

Исследование процесса обработки отверстий в крупногабаритной конструкции со смешанными пакетами при сборке на модульном оборудовании

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Резюме. Цель работы – исследование технологии обработки отверстий, выполненных с помощью автоматизированной сверлильной машины, при сборке крупногабаритной конструкции со смешанными пакетами (полимерный композиционный материал + металл) на модульном оборудовании. Для исследования процесса обработки отверстий в крупногабаритной конструкции при сборке на модульном оборудовании был собран образец кессона габаритами 17765х3050х438 мм, имитирующий кессон крыла гражданского самолета – тестовый кессон. Используемое модульное оборудование обеспечивает достижение точности геометрического положения выполняемых отверстий 0,5 мм. Для обработки отверстий с помощью автоматизированной сверлильной машины была составлена карта обработки отверстий. В карте обработки отверстий отражены ключевые параметры отверстий, такие как диаметр отверстия, точность отверстия, координаты положения центра отверстия, направление оси отверстия, слои в пакете. Для привязки автоматизированной сверлильной машины к крупногабаритной конструкции карту обработки отверстий необходимо делить на зоны, а в случае длинномерных деталей – на подзоны. Выявлено, что технология обработки отверстий на автоматизированных сверлильных машинах с числовым программным управлением с помощью комбинированного инструмента позволяет обрабатывать отверстия окончательного диаметра за один-два перехода в крупногабаритных конструкциях со смешанными пакетами, обеспечивая точность геометрического положения рассверливаемого отверстия 0,5 мм. На основании полученных результатов по исследованию обработки отверстий в крупногабаритной конструкции выявлено, что для достижения точности геометрического положения выполняемых отверстий 0,5 мм длинномерные детали необходимо делить на подзоны длиной не более 1 м для автоматизированной обработки отверстий. Определен габаритный размер длины зоны привязки для автоматизированной сверлильной машины. Полученные результаты могут быть использованы для оптимизации технологических процессов при обработке отверстий в крупногабаритных конструкциях в авиационной, судостроительной и других отраслях промышленности.

Ключевые слова: полимерный композиционный материал, смешанный пакет, крупногабаритная конструкция, технология модульной сборки, обработка отверстий, автоматизированная сверлильная машина с числовым программным управлением

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INTRODUCTION

The current development of aviation is leading to the increasingly widespread use of polymer composite materials (PCM) in the structures of aerospace equipment [1, 2]. This is easily explained by a number of advantages offered by PCM structures[3] [3–5].

Alongside parts manufactured from PCM, parts made from metal alloys are also used. These are predominantly aluminum and titanium alloys. The joining of PCM parts with parts made from metal alloys is referred to as a mixed stack. The primary difficulty in joining such stacks with mechanical fastening elements (bolts, bolt-rivets) lies in the different requirements for the hole-making technology for these fasteners [6–16]. These differences are due to the dissimilar internal properties of the materials in the parts that make up the mixed stack. In most cases, the only feasible method for joining PCM+metal structures is the installation of fasteners into pre-machined holes of the final diameter.

The reliability of these joints depends primarily on the hole surface quality parameters and the accuracy of their geometric position in the parts being joined. Consequently, the process of hole machining in PCM parts and their structural combinations with metal parts requires special attention and constitutes a significant portion of the overall labor intensity of the assembly process [17–19].

The technology of hole production using automated CNC drilling machines allows for the machining of final diameter holes in one or two operations in large-sized structures with mixed stacks. This is achieved using combined tools, following a pre-programmed machining route to ensure the specified accuracy [20, 21].

OBJECTIVE

The objective of this work is to investigate the technology of hole machining using an automated drilling machine during the assembly of a large-sized structure with mixed stacks (PCM + metal) on modular equipment. This technology ensures the achievement of a geometric position accuracy of 0.5 mm for the machined holes.

MATERIALS AND METHODS

To study the hole machining process in a large-sized structure during its assembly on modular equipment, a wing box sample with dimensions of 17765 x 3050 x 438 mm was assembled. This sample, referred to as the test wing box (Fig. 1), simulates a civil aircraft wing box [22–24].

Holes with a diameter of 3.1 mm were initially made in the transverse frame parts. These holes will subsequently serve as reference holes and holes for the installation of temporary fasteners during further assembly operations (Fig. 2).

[3]Ivanov Yu.N., Chashchin N.S., Starodubtseva D.A., Isachenko A.S., Koval A.P., Zenin K.P., et al. *Design and manufacture of products from composite materials*: textbook. Irkutsk: Irkutsk National Research Technical University; 2023, 132 p. (In Russ.). EDN: ZCWNTJ./ Иванов Ю.Н., Чащин Н.С., Стародубцева Д.А., Исаченко А.С., Коваль А.П., Зенин К.П. [и др.]. Проектирование и производство изделий из композиционных материалов: учеб. пособ. Иркутск: ИрНИТУ, 2023. 132 с. EDN: ZCWNTJ.

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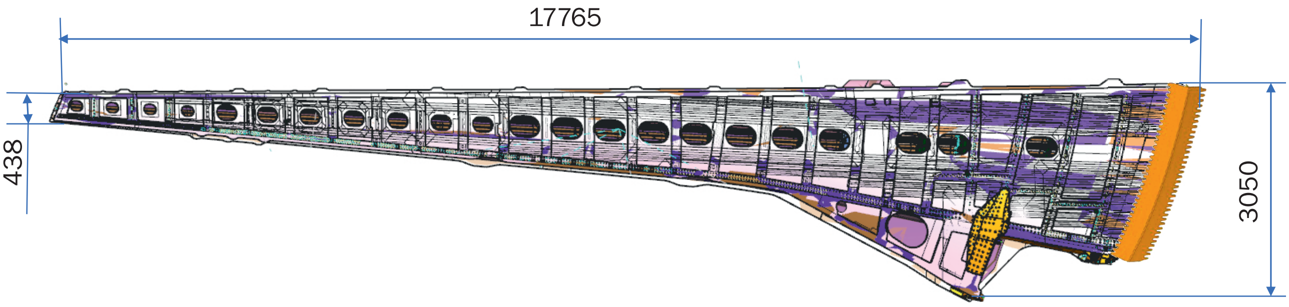
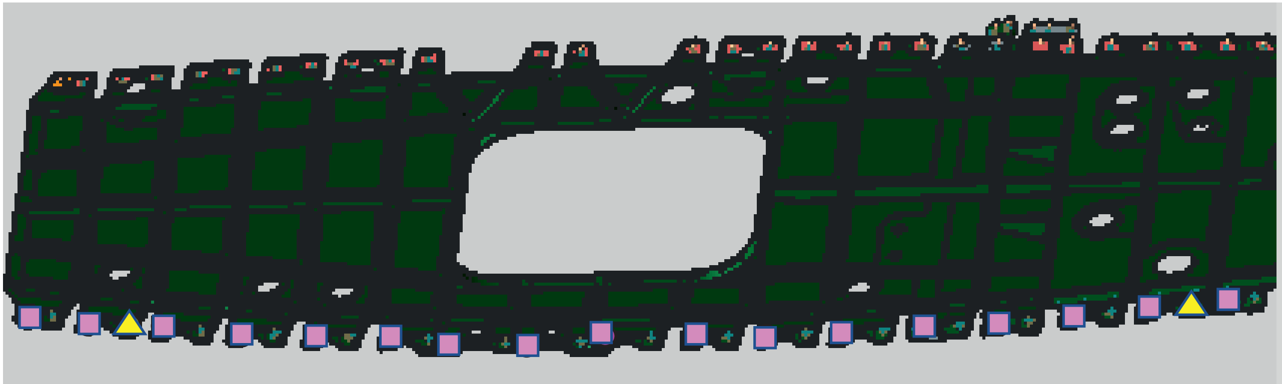


Fig. 1. *Test wing box*
Рис. 1. *Тестовый кессон*



△ – reference holes
□ – holes for the installation of temporary fasteners
△ – Базовые отверстия
□ – Отверстия для установки тех. крепежа

Fig. 2. *Example of a layout for reference holes and holes for temporary fasteners in a transverse frame part*
Рис. 2. *Пример схемы выполнения базовых отверстий и отверстий под технологический крепеж в поперечной детали кессона*

Through these holes, the holes were sequentially drilled–first into the upper panel and then into the lower panel–using manual power tools. Subsequently, they were drilled out from the side of the outer theoretical contour to the required diameter of 4 mm, and in the root zone, to a diameter of 6 mm. Then, temporary fasteners were installed in the corresponding holes.

Subsequently, all holes in the test wing box were drilled using an automated drilling machine (Fig. 3).

Fig. 3. *Automated drilling machine with numerical control*
Рис. 3. *Автоматизированный сверлильный станок с числовым программным управлением*

HOLE MACHINING MAP

A hole machining map was created for the test wing box, and the coordinates of the holes to be machined were defined (Fig. 4) to study the hole machining process in a large-sized structure with mixed stacks.

The hole machining map documents basic hole parameters, such as hole diameter, hole tolerance, the coordinates of the hole center position, the hole axis direction, and the layers within the stack. A fragment of the hole machining map is presented in Table 1.

Fig. 4. *Schematic diagram of the hole machining map for the test wing box*
Рис. 4. *Схематическая карта обработки отверстий в тестовом кессоне*

Table 1. A fragment of the hole machining map
Таблица 1. Фрагмент карты обработки отверстий

Point Number	Diameter, mm	The coordinates of the hole center position, mm			The hole axis direction			Stack
		X	Y	Z	X	Y	Z	
1	14	2337.03	-1390.28	-1963.71	0.2844	0.9061	0.3131	Ti+PCM+Ti+Al
2	14	2701.15	-1477.10	-2009.32	0.2235	0.9282	0.2974	Ti+PCM+Ti
3	14	2725.67	-1496.00	-2067.61	0.2106	0.9323	0.2941	Ti+PCM+Ti
4	14	3487.99	-1613.89	-1945.57	0.0973	0.9593	0.2650	Ti+PCM+Ti
5	14	3463.91	-1614.55	-2054.23	0.0868	0.9610	0.2625	Ti+PCM+Ti
...	...	...	...	...	...	...	...	...
15	7.94	4696.71	-1341.54	-3229.84	-0.0373	0.9748	0.2201	PCM+Al
16	12.7	5198.63	-1306.25	-3491.97	-0.0876	0.9743	0.2075	PCM+Ti+Al
17	12.7	5204.49	-1304.43	-3462.70	-0.0949	0.9740	0.2058	PCM+Ti+Al
...	...	...	...	...	...	...	...	...
47	7.94	4969.03	-1177.54	-3948.35	-0.0730	0.9770	0.2002	Ti+PCM
48	7.94	5059.48	-1156.67	-4023.91	-0.0715	0.9768	0.2017	Ti+PCM

REFERENCING

For the automated machining of holes, the CNC drilling machine must be referenced to base geometric elements, which define the position and rotation angles of the drilling spindle.

When machining holes in large-sized structures, the traditional method of positioning the CNC drilling machine from the origin of a single theoretical coordinate system cannot be implemented for two reasons:

a) It does not account for the actual position of the structural elements;

b) As the spindle moves away from the machine's "zero" point, the magnitude of the tool positioning error at the drilling point accumulates. Consequently, the total error may exceed the specified positional tolerance for the hole.

To minimize the tool positioning error at the drilling point, the structure being machined is divided into separate sections – hole machining zones – each with its own local coordinate system that accounts for local specificities. As a result of this division of the large-sized structure, the spindle position error accumulates only within each individual hole machining zone, and the accumulated error within a zone is guaranteed to remain within the hole's positional tolerance.

One method to create a coordinate system within a local hole machining zone is to align three specially selected points (the actual point cloud) in the zone with three corresponding theoretical points (the theoretical point cloud). This allows the machine to "enter" the local coordinate system of the hole machining zone.

The process of moving and rotating the actual point cloud to achieve its best (optimal) alignment with the theoretical point cloud is called roto-translation (from the English words "rotation" and "translation").

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The roto-translation process requires at least three points, each with its own specific geometric requirements:

Master – Defines the coordinate origin (zero). This is a point (hole) with the most stringent accuracy requirements.

Slave – Defines the direction of the coordinate system's X-axis, i.e., the Slave point lies on the OX axis.

Roto – Defines the rotation angle of the coordinate system plane relative to the defined axis above, i.e., the Roto point does *not* lie on the OX axis but lies on the XOZ plane.

By sequentially performing the roto-translation process, the drilling head – and consequently the CNC drilling machine – is referenced to a group of holes within the machining zone on the assembled wing box.

HOLE MACHINING ZONES

Following the logic above, the hole machining map is divided into hole machining zones (Fig. 5). For each zone, the coordinates of the reference holes are added to the coordinates of the holes to be machined (Table 2).

For ease of use, the first two digits of the zone numbering correspond to the number of the rib located within that zone. The rear spar and the traverse beam have their own numbering (Table 2).

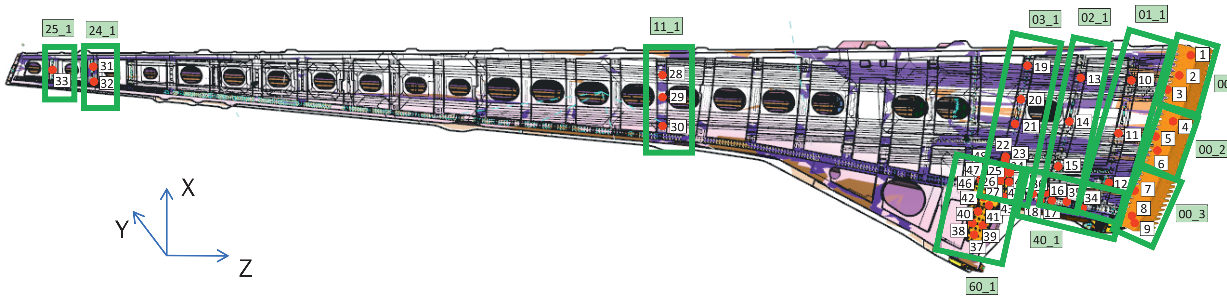


Fig. 5. *Schematic diagram of the hole machining zones in the test wing box*
Рис. 5. *Схема расположения зон обработки отверстий в тестовом кессоне*

Table 2. A fragment of the hole machining map with zone division
Таблица 2. Фрагмент схемы обработки отверстий с разделением по зонам

Zone Number	Point Number	Functionality	Diameter, mm	The coordinates of the hole center position, mm			Stack
				X	Y	Z	
00_2	104	Master	5	3265.10	-1592.38	-2057.63	Ti+PCM+Ti
	105	Slave	5	3740.25	-1634.93	-2048.73	Ti+PCM+Ti
	106	Roto	5	3150.67	-1607.83	-1960.13	Ti+PCM+Ti
	4	Обработка	**14**	3487.99	-1613.89	-1945.57	Ti+PCM+Ti
	5	Обработка	**14**	3463.91	-1614.55	-2054.23	Ti+PCM+Ti
	6	Обработка	**14**	3511.03	-1603.75	-1995.61	Ti+PCM+Ti
11_1	119	Master	5	6015.33	-444.71	-8641.05	PCM+Al
	120	Slave	5	6312.93	-466.99	-8596.64	PCM+Al
	121	Roto	5	5824.57	-426.06	8456.11	PCM
	28	Обработка	**6.35**	6119.39	-365.90	-8902.64	PCM+Al
	29	Обработка	**6.35**	6412.90	-391.02	-8783.49	PCM+Al
	30	Обработка	**6.35**	6693.07	-395.42	-8666.88	PCM+Al
40_1	128	Master	5	5014.13	-1446.23	-2648.28	PCM+Ti
	129	Slave	5	5260.88	-1233.99	-3528.08	PCM+Ti
	130	Roto	5	5197.39	-1324.61	-3120.77	PCM+Ti
	34	Обработка	**14.29**	5089.93	-1413.38	-2761.27	PCM+Ti
	35	Обработка	**14.29**	5133.97	-1346.73	-3048.69	PCM+Ti
	36	Обработка	**14.29**	5198.34	-1283.36	-3318.83	PCM+Ti

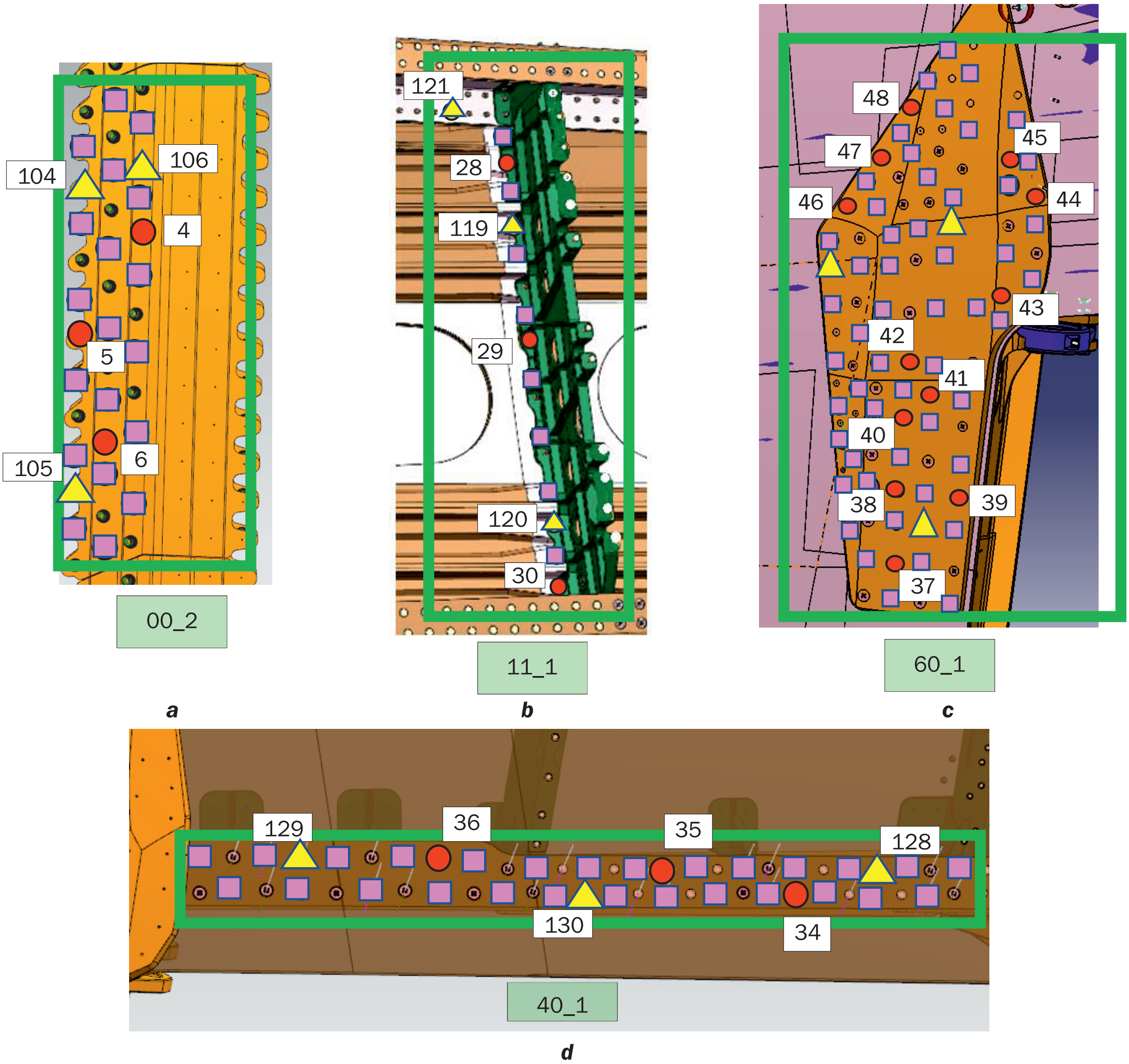
Since during assembly, parts can be displaced relative to each other and relative to their theoretical position, it is necessary to determine the actual position of each part. This means that for each part (with a potential displacement), the roto-translation operation must be performed, and it must be designated as a separate zone.

The arrangement of reference holes, holes for temporary fasteners, as well as holes to be machined in typical zones is shown in Fig. 6.

EXPERIMENTAL PLAN

The sequence of actions for investigating the hole machining process during assembly on modular equipment:

1. Position the assembled test wing box for drilling using an automated CNC drilling machine (Fig. 7).



– reference holes
– holes for the installation of temporary fasteners
– holes to be machined

– Базовые отверстия
– Отверстия для установки тех. крепежа
– Отверстия для сверления

Fig. 6. *Typical hole machining zones in the test wing box: a – for rib 0 splice plate; b – for ribs; c – for the traverse beam; d – for the rear spar cap*

Рис. 6. *Типовые зоны обработки отверстий в тестовом кессоне: a – для накладок бортовой нервюры; b – для нервюр; c – для балки траверсы; d – для пояса заднего лонжерона*

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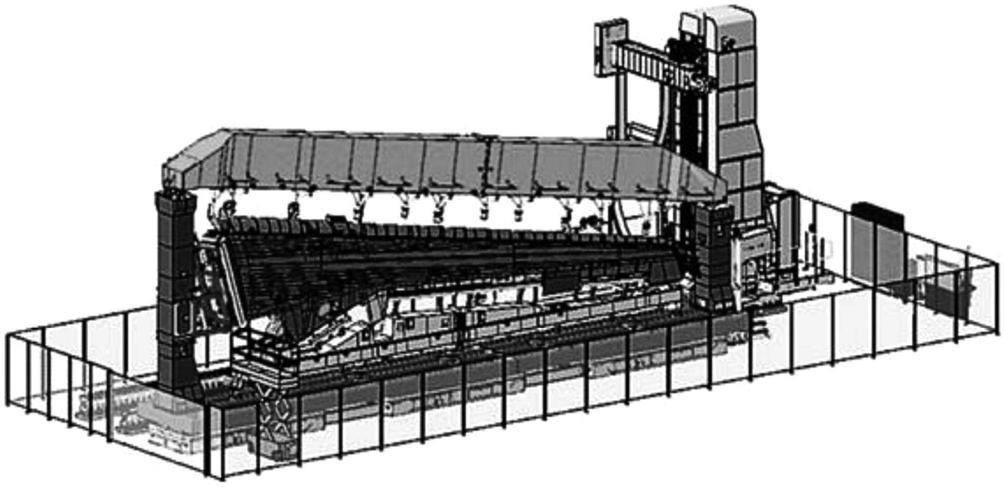

Fig. 7. *Hole machining on an automated drilling machine with numerical control*
Рис. 7. *Обработка отверстий на автоматизированном сверлильном станке с числовым программным управлением*

2. Machine the holes using a pre-prepared hole machining program with specified operating parameters, employing either a combination drill (drill with countersink) or a drill and a combination reamer (reamer and countersink).

3. Measure the position of the machined holes relative to the part edge on the frame elements (Fig. 8).

4. Analyze the results.

Experiment on Determining the Dimensions of the Reference Zone for Long-Measuring Parts. Based on the results of the investigation into hole machining in the large-sized structure, and in accordance with the methodology described above, it follows that to achieve a geometric position accuracy of the machined holes of 0.5 mm, long-measuring parts must be divided into sub-zones for hole machining.

Samples for the Investigation. In studying the hole machining technology for the large-sized structure to determine the overall length of the reference zone, samples used were ribs No. 1, 2, and 3, which are long-measuring parts. These ribs were divided into sub-zones according to Table 3.

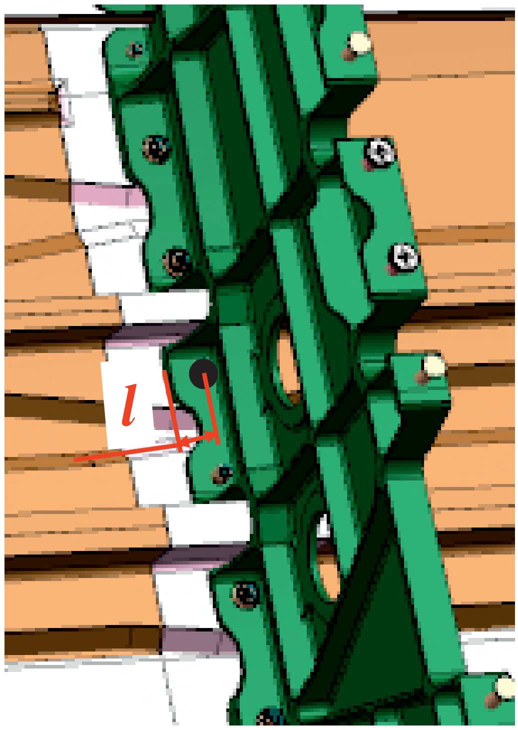

Fig. 8. *Minimum distance from hole to part edge (l)*
Рис. 8. *Минимальное расстояние от отверстия до обреза детали (l)*

Based on the data from Table 1, a new hole machining map was created (Table 4).

Table 3. Zoning of long-measuring ribs
Таблица 3. Деление на зоны длинномерных нервюр

Rib Number	Number of Zones	Length of zone, mm
3	1	1500
2	2	1200; 1050
1	3	900; 800; 700

Table 4. Hole machining map with zone division for determining the reference zone length dimensions
Таблица 4. Карта обработки отверстий с разбивкой на зоны для определения габаритного размера длины зоны

Zone Number	Point Number	Functionality	Diameter, mm	The coordinates of the hole center position, mm			Stack
				X	Y	Z	
03_1	101	Master	5	3522.61	-1060.62	-4063.80	PCM+Al
	102	Slave	5	4689.81	-1183.83	-3942.30	PCM+Al
	103	Roto	5	3298.19	-1033.07	-3987.10	PCM
	1	Machining	7.94	3392.85	-1030.09	-4074.10	PCM+Al
	2	Machining	7.94	3652.73	-1087.68	-4051.37	PCM+Al
	3	Machining	7.94	3779.77	-1110.26	-4039.38	PCM+Al
	4	Machining	7.94	3908.82	-1129.50	-4027.44	PCM+Al
	5	Machining	7.94	4058.24	-1147.91	-4012.23	PCM+Al
	6	Machining	7.94	4191.04	-1161.56	-3995.52	PCM+Al
	7	Machining	7.94	4310.00	-1171.08	-3980.64	PCM+Al
	8	Machining	7.94	4426.28	-1176.81	-3971.32	PCM+Al
	9	Machining	7.94	4557.11	-1181.68	-3956.56	PCM+Al
	10	Machining	7.94	4818.89	-1183.65	-3927.25	PCM+Al
02_1	104	Master	5	3143.06	-1175.24	-3391.10	PCM+Al
	105	Slave	5	3767.98	-1295.00	-3331.62	PCM+Al
	106	Roto	5	2922.09	-1157.23	-3268.92	PCM
	11	Machining	7.94	3077.33	-1157.31	-3397.81	PCM+Al
	12	Machining	7.94	3337.73	-1221.49	-3373.51	PCM+Al
	13	Machining	7.94	3464.88	-1247.01	-3362.01	PCM+Al
	14	Machining	7.94	3593.40	-1269.45	-3349.78	PCM+Al
	15	Machining	7.94	3728.55	-1289.55	-3336.50	PCM+Al
	16	Machining	7.94	3862.83	-1306.20	-3322.55	PCM+Al
	17	Machining	7.94	3992.94	-1319.30	-3308.36	PCM+Al
02_2	107	Master	5	4376.12	-1340.72	-3267.06	PCM+Al
	108	Slave	5	5020.24	-1327.56	-3191.65	PCM+Al
	106	Roto	5	2922.09	-1157.23	-3268.92	PCM
	18	Machining	7.94	4112.51	-1328.35	-3296.54	PCM+Al
	19	Machining	7.94	4243.57	-1335.85	-3282.10	PCM+Al
	20	Machining	7.94	4507.62	-1343.05	-3251.26	PCM+Al
	21	Machining	7.94	4634.15	-1342.46	-3237.64	PCM+Al
	22	Machining	7.94	4750.95	-1341.28	-3218.58	PCM+Al
	23	Machining	7.94	4891.38	-1334.75	-3207.23	PCM+Al
01_1	109	Master	5	2889.36	-1327.69	-2706.56	PCM+Al
	110	Slave	5	3353.53	-1427.38	-2664.52	PCM+Al
	111	Roto	5	2556.72	-1290.32	-2547.76	PCM
	24	Machining	7.94	2758.59	-1290.97	-2718.28	PCM+Al
	25	Machining	7.94	2958.48	-1345.45	-2700.45	PCM+Al
	26	Machining	7.94	3088.72	-1376.07	-2688.63	PCM+Al
	27	Machining	7.94	3221.49	-1403.53	-2676.69	PCM+Al
	28	Machining	7.94	3466.81	-1445.32	-2653.37	PCM+Al
01_2	112	Master	5	3685.00	-1473.20	-2631.07	PCM+Al
	113	Slave	5	4125.23	-1505.03	-2583.02	PCM+Al
	111	Roto	5	2556.72	-1290.32	-2547.76	PCM
	29	Machining	7.94	3586.83	-1461.93	-2640.44	PCM+Al
	30	Machining	7.94	3795.31	-1484.10	-2619.48	PCM+Al
	31	Machining	7.94	3926.36	-1494.48	-2605.22	PCM+Al
	32	Machining	7.94	4058.98	-1502.23	-2590.36	PCM+Al
01_3	114	Master	5	4383.41	-1509.60	-2554.67	PCM+Al
	115	Slave	5	4770.51	-1499.63	-2509.12	PCM+Al
	111	Roto	5	2556.72	-1290.32	-2547.76	PCM
	33	Machining	7.94	4254.17	-1508.61	-2568.58	PCM+Al
	34	Machining	7.94	4508.37	-1508.76	-2539.31	PCM+Al
	35	Machining	7.94	4890.39	-1492.78	-2494.64	PCM+Al

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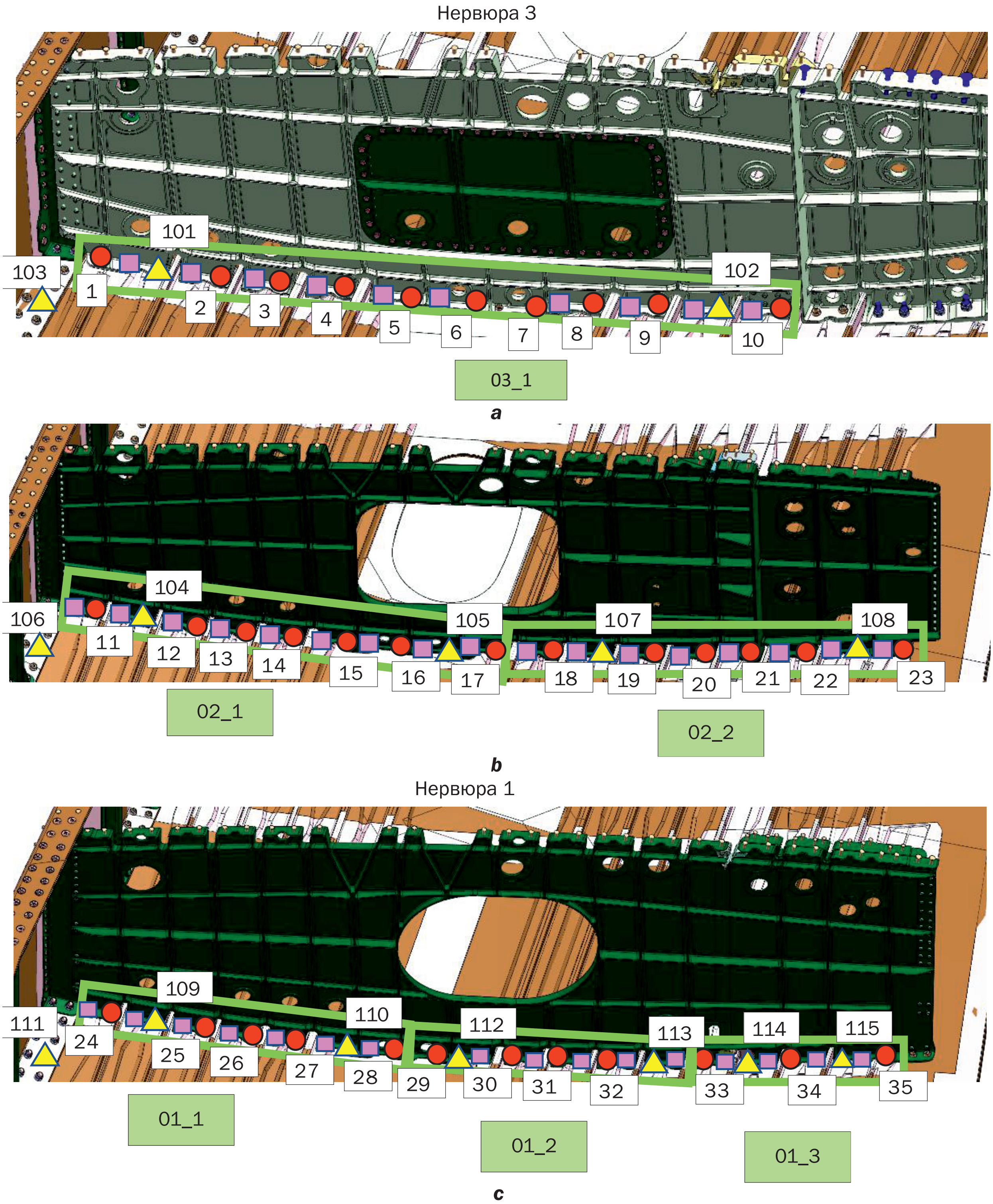
The layout of reference holes, holes for temporary fasteners, and holes to be machined for wing box rib-type parts is shown in Fig. 9.

Sequence of actions for the investigation to determine the overall length dimension of the reference zone for long parts:



△ – reference holes
□ – holes for the installation of temporary fasteners
● – holes to be machined

△ – Базовые отверстия
□ – Отверстия для установки тех. крепежа
● – Отверстия для сверления

Fig. 9. *Layout of holes in the hole machining zones for wing box rib-type parts: a – rib 3; b – rib 2; c – rib 1*

Рис. 9. *Расположение отверстий в зонах обработки отверстий для деталей типа нервюры кессона: a – нервюра 3; b – нервюра 2; c – нервюра 1*

1. Machine the reference holes and holes for temporary fasteners in the samples (ribs) according to the layout of holes in the hole machining zones (see Fig. 9).
2. Install the temporary fasteners according to the layout (see Fig. 9).
3. Perform hole machining using a pre-prepared hole machining program.
4. Measure the distance from the hole center to the rib edge (see Fig. 8).
5. Analyze the results.

The measurement of the position of the machined holes relative to the parts' edges was carried out using a vernier caliper (GOST 166-89[4]).

RESEARCH RESULTS

During the experiment, the values of the positional deviations of the machined holes in each zone of the investigated ribs were determined.

Fig. 10 shows the actual positional deviations of the machined holes from the edges of the frame parts.

Analysis of the obtained deviations of the actual position of the machined holes from the theoretical position leads to the conclusion that points No. 10-15, 20-21, 23-25 do not meet the specified requirements. These points belong to ribs 1, 2, and 3. These ribs are long parts that can have their own deformations. Consequently, these parts require additional division into sub-zones.

Results of the Investigation on Determining the Reference Zone Dimensions for Long-Measuring Parts. During the experiment, the values of the positional deviations of the machined holes in each zone of the investigated ribs were determined.

Fig. 11 shows the actual positional deviations of the machined holes from the rib edge.

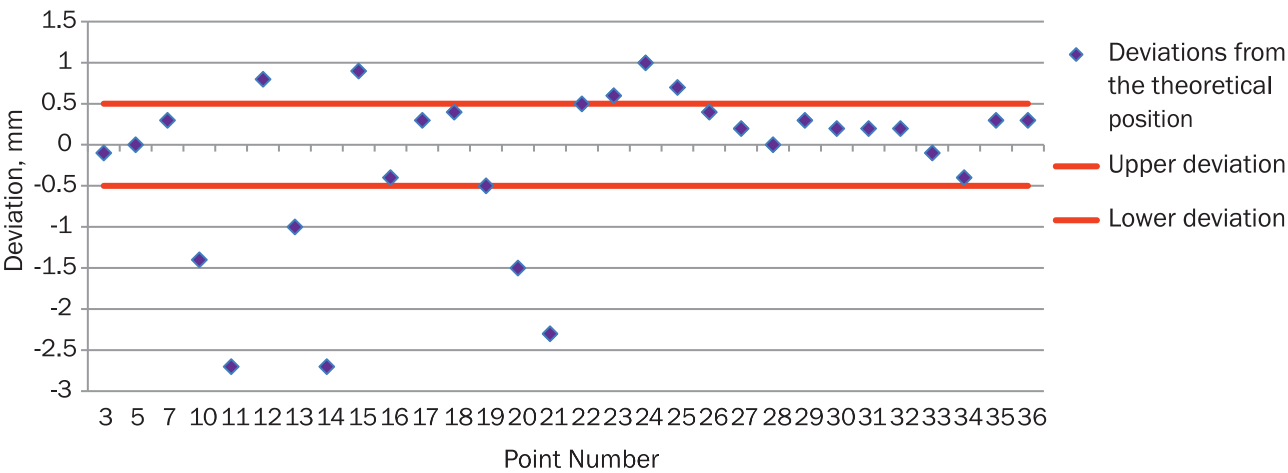


Fig. 10. *Actual positional deviations of the machined holes from the edges of the frame parts*
Рис. 10. *Фактические отклонения положения обработанных отверстий от обрезов деталей каркаса*

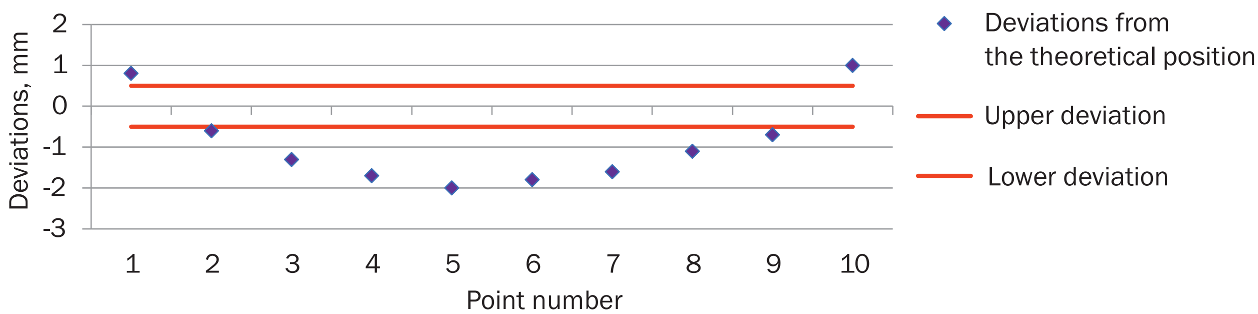


Fig. 11*. (Beginning of the drawing)*
Рис. 11. *(Начало рисунка)*

[4]GOST 166-89. Vernier callipers. Specifications. Introduced on January 1, 1991; valid until January 1, 1996. Moscow: Gosstandart, 1991. / ГОСТ 166-89. Штангенциркули. Технические условия. Введ. 01.01.91; срок действия до 01.01.96. М.: Госстандарт, 1991.

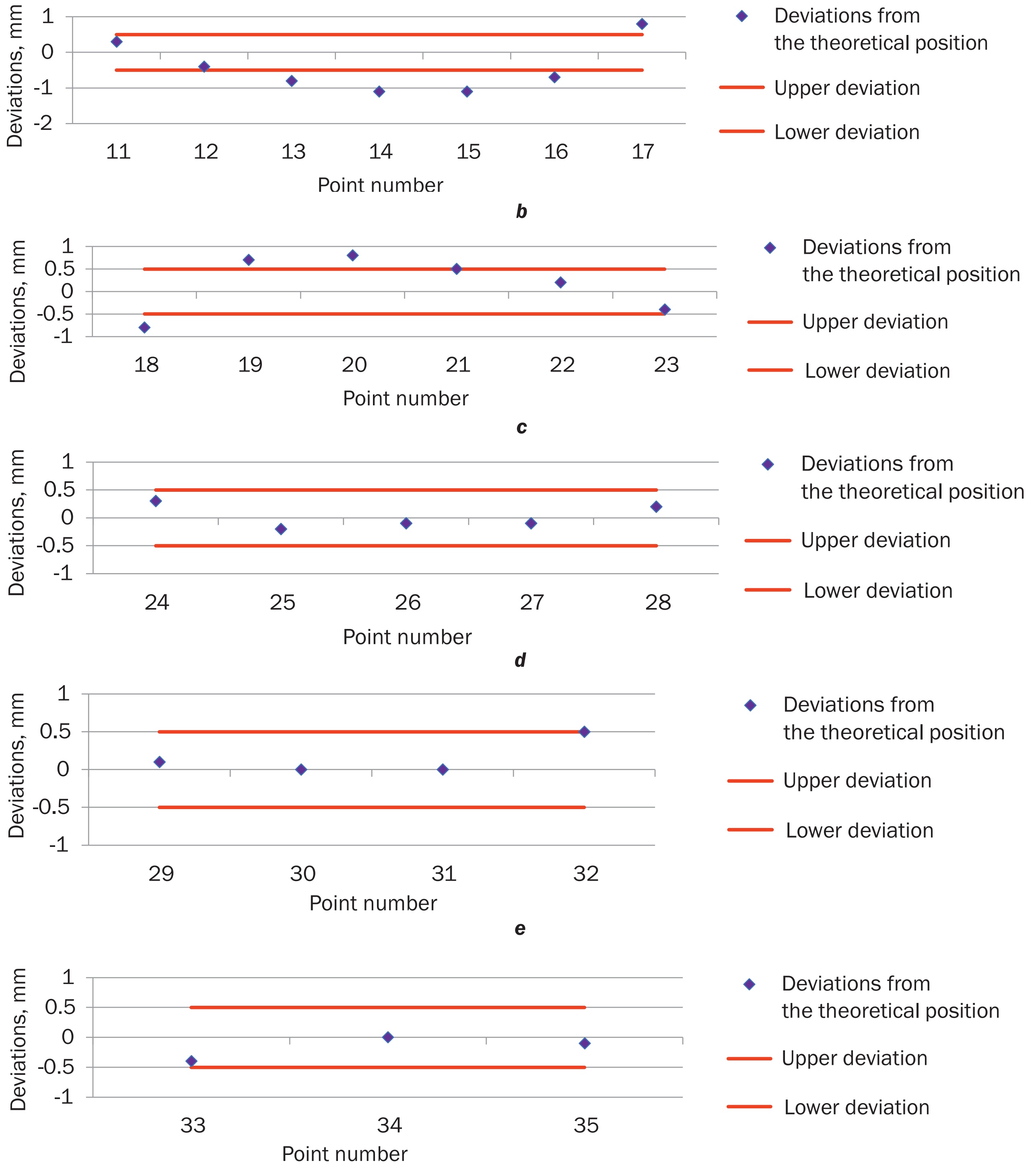


Fig. 11. Actual positional deviations of machined holes from the edges: a – for the zone length of 1500 mm; b – for the zone length of 1200 mm; c – for the zone length of 1050 mm; d – for the zone length of 900 mm; e – for the zone length of 800 mm; F – for the zone length of 700 mm

Рис. 11. *Фактические отклонения положения обработанных отверстий от обрезов: a – для зоны длиной 1500 мм; b – для зоны длиной 1200 мм; c – для зоны длиной 1050 мм; d – для зоны длиной 900 мм; e – для зоны длиной длиной 800 мм; f – для зоны длиной 700 мм*

Based on the analysis of the results obtained, it can be concluded that to achieve a hole positioning accuracy of 0.5 mm, the length of the subzone should not exceed 1 m.

CONCLUSION

It has been established that the hole machining technology using automated CNC drilling machines allows for the machining of final diameter holes in one or two operations in large-sized structures with mixed stacks. This is achieved using combined tools and a pre-programmed hole machining route, ensuring the geometric position accuracy of the machined hole.

Based on experimental research, it has been determined that to ensure a geometric position accuracy of holes of 0.5 mm, long parts must be divided into sub-zones with a length not exceeding 1 m.

The obtained results can be used to optimize technological processes in the aerospace, shipbuilding, and other industries.

References

1. Kiva D.S. Stages of development and beginning of extensive use of polymer composite materials in passenger and transport aircraft structures (1970-1995). *Aerospace and technology*. 2014;6:5-16. (In Russ.).

2. Konstantinov A.S. Polymer composites effectiveness in design and producing of special loading equipment for ramp aircrafts. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences.* 2012;14(4):633-638. (In Russ.).

3. Molchanov B.I., Gudimov M.M. Properties of carbon fiber composites and their application areas. *Aviation Industry*. 1997. No. 3-4. P. 58–60. (In Russ.). EDN: ZPNNSF.

4. Fokin I.V., Sturov A.A., Ivanov Yu.N. Development prospects of composite materials in the 21st century. In: *Aviamashinostroenie i transport Sibiri: sbornik statej XV Vserossijskoj nauchno-tekhnicheskoj konferencii = Aircraft Engineering and Transport of Siberia: collected articles of the 15th All-Russian scientific and technical conference*. 22 December 2020, Irkutsk. Irkutsk: Irkutsk National Research Technical University; 2021, p. 208-211. (In Russ.). EDN: HLNMMU.

5. Le Tri Vinh, Koltsov V.P., Starodubtseva D.A. Simulating residual stresses formed in the technological sequence of shot-impact treatment–flap-wheel trimming. *iPolytech Journal*. 2024;28(2):202-213. (In Russ.). https://doi.org/10.21285/1814-3520-2024-2-202-213. EDN: QAHLRO.

6. Balla O.M. Processing fine holes in packages of dissimilar materials. *Aviation Industry*. 2013;4:27-30. (In Russ.). EDN: SDJAIV.

7. Garrick R. Drilling advanced aircraft structures with PCD (Poly–Crystalline Diamond) drills. *SAE Technical Papers*. 2007. https://doi.org/10.4271/2007-01-3893.

8. Ivanov Y.N., Chashhin N.S., Sultanova A.R. A study of cutting forces when drilling CFRP/Ti stacks. *Journal of Physics: Conference Series: Advances in Composites Science and Technologies*. 2021;1990(1):012035. https://doi.org/10.1088/1742-6596/1990/1/012035. EDN: QQRKSV.

9. Ivanov Y.N., Chashchin N.S., Pashkov A.A. A study of cryogenic cooling when reaming holes in CFRP/Ti/Al Stacks. In: *International Conference on Industrial Engineering: Proceedings of the 7th International Conference on Industrial Engineering*. 17–21 May 2021, Sochi. Chelyabinsk: Springer; 2022, vol. 2, p. 650-656. https://doi.org/10.1007/978-3-030-85230-6_77. EDN: CHYTQA.

10. Ivanov Yu.N. Drilling the holes in the mixed packets. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences.* 2014;16(1-5):1402-1406. (In Russ.). EDN: TJFAFL.

11. Ivanov Yu.N., Klantsova K.S., Chashchin N.S., Pyatykh A.S., Matlygin G.V., Isachenko A.S. A study of the influence of lubricating and cooling technological means on the accuracy and quality of processed holes in aviation materials. *Systems. Methods. Technologies*. 2025;3:29-36. https://doi.org/10.18324/2077-5415-2025-3-29-36.

12. Kayihan M., Karaguzel U., Bakkal M. Process design and experimental study on drilling operations of a hybrid aluminum/carbon fiber reinforced polymer/titanium composite. *Materials and Manufacturing Processes*. 2024;39(11):1630-1637. https://doi.org/10.1080/10426914.2024.2368547.

13. Garrick R.M., Bunting J.A. *PCD drill for composite materials*. Patent US, no. 7575401; 2004.

14. Shyha I., Soo S.L., Aspinwall D.K., Bradley S., Dawson S., Pretorius C.J. Drilling of titanium/CFRP/aluminium stacks. *Key Engineering Materials*. 2010;447-448:624-633. https://doi.org/10.4028/www.scientific.net/KEM.447-448.624. EDN: ODWSJD.

15. Tsao C.C. Investigation into the effects of drilling parameters on delamination by various step–core drills. *Journal of materials processing technology*. 2008;206(1-3):405-411. https://doi.org/10.1016/j.jmatprotec.2007.12.057. EDN: KLUTCR.

16. Xu Jinyang, Mkaddem A., Mansori M.E. Recent advances in drilling hybrid FRP/Ti composite: a state–of–the–art review. *Composite Structures*. 2016;135(1):316-338. https://doi.org/10.1016/j.compstruct.2015.09.028.

17. Zavatskaya T.V., Krotenko A.E., Ivanov Yu.N. Hole drilling and testing in titanium alloy-carbon fiber reinforced plastic stacks. *Zhiznennyj cikl konstrukcionnyh materialov: sbornik statej XII Vserossijskoj nauchno-tekhnicheskoj konferencii = Life cycle of structural materials: collected articles of the 12th All-Russian scientific and technical conference*. 6 June 2022, Irkutsk. Irkutsk: Irkutsk National Research Technical University; 2022, p. 209-215. (In Russ.). EDN: CVDQBN.

18. Fokin I.V., Sturov A.A., Ivanov Yu.N. Study of the problem of mechanical processing of parts made of composite material. In: *Shestye Kolachyovskie chteniya: materialy VI Vserossijskoj molodezhnoj nauchno-prakticheskoj konferencii, posvyashchyonnoj pervomu poletu cheloveka v kosmos = Sixth Kolachev Readings: Proceedings of the 6th All-Russian Youth Scientific and Practical Conference dedicated to the first human space flight*. 9 April 2021, Moscow. Moscow: OOO “Nauchno-izdatel’skij centr Infra-M”; 2021, vol. 6, p. 71-73. (In Russ.). EDN: ICULLJ.

19. Sultanova A.R., Gromashev A.G. Preparing holes in mixed packages for MC-21 aircraft wing structures joints. *Aviation Industry*. 2021;1:30-35. (In Russ.). EDN: MFOUKE.
20. Mueller–Hummel P., Atarsia A., Wiemann A. One shot – dry – drilling of composites/titanium/aluminium hybrid stacked materials in IT8 quality. In: *AeroTech Congress & Exhibition*. 2013. https://doi.org/10.4271/2013-01-2337.
21. Prokopchik S.V. On approaches to automated calculation of optimal cutting modes during single-tool machining on drilling machines. In: *Issledovaniya i razrabotki v oblasti mashinostroeniya, energetiki i upravleniya: materialy XII Mezhdunarodnoj nauchno-tekhnicheskoj konferencii studentov, magistrantov i molodyh uchenyh = Research and development in mechanical engineering, power engineering and control: Proceeding of the 12th International scientific and technical conference of students, postgraduates and young scientists*. 26–27 April 2012, Gomel'. Gomel': Sukhoi State Technical University of Gomel; 2012, p. 22-25. (In Russ.). EDN: VKXGRY.
22. Gromashev A.G., Sultanova A.R., Masokhin E.V. Modular principle of aircraft structures assembly and appropriate assembly equipment. *Aviation Industry*. 2021;3-4:58-65. (In Russ.). EDN: KFFMJU.
23. Gromashev A.G., Gaidansky A.I., Ulyanov A.V., Tretyakov A.V., Reznichenko D.V., Masokhin E.V., Sultanova A.R. *Method for modular assembly of an aircraft splice rib for connecting wing consoles to the center section and a device for implementing the method*. Patent RF, no. 2749432; 2021. (In Russ.).
24. Gromashev A.G., Gaidansky A.I., Ulyanov A.V., Tretyakov A.V., Reznichenko D.V., Masokhin E.V., Danilova O.L., Sultanova A.R. *Method for modular assembly of an aircraft wing console box with parts made of carbon polymer composite materials and metals and an assembly line with devices for implementing the method.* Patent RF, no. 2774870; 2023. (In Russ.).

Список источников

1. Кива Д.С. Этапы становления и начала развернутого применения полимерных композиционных материалов в конструкциях пассажирских и транспортных самолетов (1970–1995 гг.) // Авиационно-космическая техника и технология. 2014. № 6. С. 5–16.
2. Константинов А.С. Эффективность применения полимерных композиционных материалов при проектировании и изготовлении специальной погрузочной оснастки для грузовых рамповых самолетов // Известия Самарского научного центра Российской академии наук. 2012. Т. 14. № 4. С. 633–638.
3. Молчанов Б.И., Гудимов М.М. Свойства углепластиков и области их применения // Авиационная промышленность. 1997. № 3-4. С. 58–60. EDN: ZPNNSF.
4. Фокин И.В., Стуров А.А., Иванов Ю.Н. Перспективы развития композиционных материалов в XXI веке // Авиамашиностроение и транспорт Сибири: сб. ст. XV Всерос. науч.-техн. конф. (г. Иркутск, 22 декабря 2020 г.). Иркутск: ИрНИТУ, 2021. С. 208–211. EDN: HLNMMU.
5. Ле Чи Винь, Кольцов В.П., Стародубцева Д.А. Моделирование процесса формирования остаточных напряжений при выполнении технологической последовательности «дробеударная обработка – зачистка лепестковым кругом» // iPolytech Journal. 2024. Т. 28. № 2. С. 202–213. https://doi.org/10.21285/1814-3520-2024-2-202-213. EDN: QAHLRO.
6. Балла О.М. Обработка точных отверстий в пакетах из разнородных материалов // Авиационная промышленность. 2013. № 4. С. 27–30. EDN: SDJAIV.
7. Garrick R. Drilling advanced aircraft structures with PCD (Poly–Crystalline Diamond) drills // SAE Technical Papers. 2007. https://doi.org/10.4271/2007-01-3893.
8. Ivanov Y.N., Chashhin N.S., Sultanova A.R. A study of cutting forces when drilling CFRP/Ti stacks // Journal of Physics: Conference Series: Advances in Composites Science and Technologies. 2021. Vol. 1990. Iss. 1. P. 012035. https://doi.org/10.1088/1742-6596/1990/1/012035. EDN: QQRKSV.
9. Ivanov Y.N., Chashchin N.S., Pashkov A.A. A study of cryogenic cooling when reaming holes in CFRP/Ti/Al Stacks // International Conference on Industrial Engineering: Proceedings of the 7th International Conference on Industrial Engineering (Sochi, 17–21 May 2021). Chelyabinsk: Springer, 2022. Vol. 2. P. 650–656. https://doi.org/10.1007/978-3-030-85230-6_77. EDN: CHYTQA.
10. Иванов Ю.Н. Сверление отверстий в смешанных пакетах // Известия Самарского научного центра Российской академии наук. 2014. Т. 16. № 1-5. С. 1402–1406. EDN: TJFAFL.
11. Иванов Ю.Н., Кланцова К.С., Чащин Н.С., Пятых А.С., Матлыгин Г.В., Исаченко А.С. Исследование влияния смазочно-охлаждающих технологических средств на точность и качество обрабатываемых отверстий в авиационных материалах // Системы. Методы. Технологии. 2025. № 3. С. 29–36. https://doi.org/10.18324/2077-5415-2025-3-29-36.
12. Kayihan M., Karaguzel U., Bakkal M. Process design and experimental study on drilling operations of a hybrid aluminum/carbon fiber reinforced polymer/titanium composite // Materials and Manufacturing Processes. 2024. Vol. 39. Iss. 11. P. 1630–1637. https://doi.org/10.1080/10426914.2024.2368547.
13. Patent no. 7575401, United States of America, B1. PCD drill for composite materials / R.M. Garrick, J.A. Bunting. Publ. 18.11.2004.
14. Shyha I., Soo S.L., Aspinwall D.K., Bradley S., Dawson S., Pretorius C.J. Drilling of titanium/CFRP/aluminium stacks // Key Engineering Materials. 2010. Vol. 447-448. P. 624–633. https://doi.org/10.4028/www.scientific.net/KEM.447-448.624. EDN: ODWSJD.

15. Tsao C.C. Investigation into the effects of drilling parameters on delamination by various step–core drills // Journal of materials processing technology. 2008. Vol. 206. Iss. 1-3. P. 405–411. https://doi.org/10.1016/j.jmatprotec.2007.12.057. EDN: KLUTCR.
16. Xu Jinyang, Mkaddem A., Mansori M.E. Recent advances in drilling hybrid FRP/Ti composite: a state–of–the–art review // Composite Structures. 2016. Vol. 135. Iss. 1. P. 316–338. https://doi.org/10.1016/j.compstruct.2015.09.028.
17. Завацкая Т.В., Кротенко А.Е., Иванов Ю.Н. Сверление и контроль отверстий в пакетах «титановый сплав-углепластик» // Жизненный цикл конструкционных материалов: сб. ст. XII Всерос. науч.-техн. конф. (г. Иркутск, 6 июня 2022 г.). Иркутск: ИрНИТУ, 2022. С. 209–215. EDN: CVDQBN.
18. Фокин И.В., Стуров А.А., Иванов Ю.Н. Исследование проблемы механической обработки деталей из композиционного материала // Шестые Колачёвские чтения: матер. VI Всерос. молодеж. Науч.-практ. конф., посвящ. первому полету человека в космос (г. Москва, 9 апреля 2021 г.). М.: ООО «Научно-издательский центр Инфра-М», 2021. Т. 6. С. 71–73. EDN: ICULLJ.
19. Султанова А.Р., Громашев А.Г. Подготовка отверстий в смешанных пакетах для выполнения соединений деталей крыла самолета МС-21 // Авиационная промышленность. 2021. № 1. С. 30–35. EDN: MFOUKE.
20. Mueller–Hummel P., Atarsia A., Wiemann A. One shot – dry – drilling of composites/titanium/aluminium hybrid stacked materials in IT8 quality // AeroTech Congress & Exhibition. 2013. https://doi.org/10.4271/2013-01-2337.
21. Прокопчик С.В. О подходах к автоматизированному расчету оптимальных режимов резания при одноинструментальной обработке на сверлильных станках // Исследования и разработки в области машиностроения, энергетики и управления: матер. XII Междунар. науч.-техн. конф. студентов, магистрантов и молодых ученых (г. Гомель, 26–27 апреля 2012 г). Гомель: ГГТУ им. П.О. Сухого, 2012. С. 22–25. EDN: VKXGRY.
22. Громашев А.Г., Султанова А.Р., Масохин Е.В. Модульный принцип сборки авиационных конструкций и оборудование для его реализации // Авиационная промышленность. 2021. № 3-4. С. 58–65. EDN: KFFMJU.
23. Пат. № 2749432, Российская Федерация, С1. Способ модульной сборки стыковой нервюры самолета для соединения консолей крыла с центропланом и устройство для осуществления способа / А.Г. Громашев, А.И. Гайданский, А.В. Ульянов, А.В. Третьяков, Д.В. Резниченко, Е.В. Масохин, А.Р. Султанова; заявитель и патентообладатель АО «АэроКомпозит». Заявл. 10.01.2020; опубл. 10.06.2021.
24. Пат. № 2774870, Российская Федерация, С1. Способ модульной сборки кессона консоли крыла самолета с деталями из углеродных полимерных композиционных материалов и металлов и сборочная линия с устройствами для осуществления способа / А.Г. Громашев, А.И. Гайданский, А.В. Ульянов, А.В. Третьяков, Д.В. Резниченко, Е.В. Масохин, О.Л. Данилова, А.Р. Султанова; заявитель и патентообладатель АО «АэроКомпозит». Заявл. 17.09.2021; опубл. 22.06.2023.

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Conflict of interests

The authors declare no conflict of interests.

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