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DISTINCTIVE FEATURES OF SLM TECHNOLOGY APPLICATION FOR MANUFACTURING OF LPRE COMPONENTS

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Abstract. In view of the growing competition in the modern market for rocket and space technology products, the issue of maximizing the cost reduction of the process of its production is urgent. In particular, the rocket engine is traditionally one of the costliest and technologically demanding rocket units, which basically reduces the problem of reducing the cost of rocket production to the development of new, more technologically advanced and less costly, approaches to manufacturing LPRE components. Thus, it is of increased interest to use a relatively young method for producing parts by layer-by-layer melting of thin layers of metal powder by exposing it to high-power laser radiation. This method is a part of the methods of additive technologies and is called SLM (Selective Laser Melting). In order to assess the influence of the main features of the production of components, the study of hydraulic channels manufactured with the additive SLM technology was carried out, and a load-bearing element of the fastening structure was manufactured which geometry was obtained by applying topological optimization methods. The aim of the work is to determine the main hydraulic characteristics of inner channels of typical LPRE's elements, as well as the limits of the technology applicability in terms of liquid-propellant rocket engines. The possibility of manufacturing elements, including hydraulic paths, was investigated: regeneratively cooled cylinders, throat inserts of a liquid-propellant engine, as well as experimental designs of film cooling rings were adapted to be produced by means of SLM. The possibility of producing thrust frame, the shape of which was obtained by the method of topological optimization, was investigated. Samples of designs of typical hydraulic channels, as well as the constituent elements of the design of the rocket engine chambers, were manufactured. The main hydraulic characteristics of the typical hydraulic channels, as well as the distinctive features of their production using the method of additive technologies SLM, were determined. The thrust frame, which geometry was obtained by means of topology optimization, was successfully manufactured.

Key words: ADDTITVE MANUFACTURING, SELECTIVE LASER MELTING, LRPE COMBUSTION CHAMBER, HYDRAULIC CHANNELS, FILM COOLING, THROAT INSERT, CYLINDER, CARRIER.

ОСОБЛИВОСТІ ВИКОРИСТАННЯ ТЕХНОЛОГІЇ ВИГОТОВЛЕННЯ SLM ДЛЯ КОМПОНЕНТІВ РРД

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Анотація. З огляду на зростання конкуренції на сучасному ринку виробів ракетно-космічної техніки, актуальним є питання максимального здешевлення процесу її виробництва. Зокрема, ракетний двигун традиційно є одним з найбільш витратних і технологічно вимогливих вузлів ракети, що в принципі, зводить задачу здешевлення ракетного виробництва до освоєння нових, більш технологічних і менш витратних, підходів до виготовлення компонентів РРД. Таким чином, являє підвищений інтерес використання відносно нового способу отримання деталей шляхом пошарового сплаву тонких шарів металевого порошку за допомогою впливу на нього потужного лазерного випромінювання. Такий спосіб є частиною методів адитивних технологій і називається SLM (Selective Laser Melting). Для оцінки впливу основних особливостей виробництва компонентів, проведено дослідження гідравлічних трактів, виготовлених методом адитивних технологій SLM, а також виготовлений силовий елемент конструкції кріплення, геометрія якого отримана шляхом застосування методів топологічної оптимізації. Метою роботи було визначення основних гідравлічних характеристик типових конструкцій елементів гідравлічних трактів, а також межі застосування технології в рамках побудови рідинних ракетних двигунів. Досліджено можливість виготовлення елементів, що включають в себе гідравлічні тракти: регенеративно-охолоджувальні циліндри, секції критичного перерізу РРД, а також дослідні конструкції поясів завісного охолодження. Досліджено можливість виробництва силового кріплення, форма якого отримана методом топологічної оптимізації. Виготовлені зразки конструкцій типових гідравлічних трактів, а також складові елементи конструкції камер РРД. Визначено основні гідравлічні характеристики типових конструкцій трактів, а також особливості їх отримання методом адитивних технологій SLM.

Виготовлений елемент силового кріплення, конструкція якого отримана методом топологічної оптимізації.
Ключові слова: АДИТИВНІ ТЕХНОЛОГІЇ, SELECTIVE LASER MELTING, КАМЕРА ЖРД, ГІДРАВЛІЧНІ ТРАКТИ, ЗАВІСНЕ ОХОЛОДЖЕННЯ, СЕКЦІЯ КРИТИЧНОГО ПЕРЕРІЗУ, ЦИЛІНДР, КРОНШТЕЙН.

ОСОБЕННОСТИ ПРИМЕНЕНИЯ ТЕХНОЛОГИИ ИЗГОТОВЛЕНИЯ SLM ДЛЯ КОМПОНЕНТОВ ЖРД

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Аннотация. Ввиду возрастающей конкуренции на современном рынке изделий ракетно-космической техники, актуальным является вопрос максимального удешевления процесса ее производства. В частности, ракетный двигатель традиционно является одним из наиболее затратных и технологически требовательных узлов ракеты, что в принципе, сводит задачу удешевления ракетного производства к освоению новых, более технологичных и менее затратных, подходов изготовления компонентов ЖРД. Таким образом, представляет повышенный интерес использование относительно нового способа получения деталей путем послойного сплавления тонких слоев металлического порошка посредством воздействия на него мощного лазерного излучения. Такой способ является частью методов аддитивных технологий и называется SLM (Selective Laser Melting). Для оценки влияния основных особенностей производства компонентов, проведено исследование гидравлических трактов, изготовленных методом аддитивных технологий SLM, а также изготовлен силовой элемент конструкции крепления, геометрия которого получена путем применения методов топологической оптимизации. Целью работы было определение основных гидравлических характеристик типовых конструкций элементов гидравлических трактов, а также границы применимости технологии в рамках построения жидкостных ракетных двигателей. Исследована возможность изготовления элементов, включающих в себя гидравлические тракты: регенеративно-охлаждаемые цилиндры, секции критического сечения ЖРД, а также опытные конструкции поясов завесного охлаждения. Исследована возможность производства крепежного элемента, форма которого получена методом топологической оптимизации. Изготовлены образцы конструкций типовых гидравлических трактов, а также составляющие элементы конструкции камер ЖРД. Определены основные гидравлические характеристики типовых конструкций трактов, а также особенности их получения методом аддитивных технологий SLM. Изготовлен крепежный элемент, конструкция которого получена методом топологической оптимизации.
Ключевые слова: АДДИТИВНЫЕ ТЕХНОЛОГИИ, SELECTIVE LASER MELTING, КАМЕРА ЖРД, ГИДРАВЛИЧЕСКИЕ ТРАКТЫ, ЗАВЕСНОЕ ОХЛАЖДЕНИЕ, СЕКЦИЯ КРИТИЧЕСКОГО СЕЧЕНИЯ, ЦИЛИНДР, КРОНШТЕЙН.

Introduction

The most complex and advanced technologies are traditionally used while designing and manufacturing of liquid-propellant rocket engines. It is quite difficult and sometimes even impossible to create relevant designs without these technologies. Moreover, work products obtained using these technological processes not infrequently are expensive and also the manufacturing process is demanding and time-consuming. [1, 2, 3]. Thus, in order to cheaper the LPRE production, it would be worthwhile to search for new approaches towards manufacturing of designed parts. One of the means which can significantly increase the manufacturing of the LPRE designs is appliance of alternative ways of production and design of the constituent elements. In particular, using additive manufacturing has a range advantages for solving complex technical problems. In this work SLM (Selective Laser Melting) process is considered as the main way of manufacturing LPRE combustion chamber components.

The process consists in sequential layer-by-layer melting of powder material by means of powerful laser radiation and allows: to obtain parts with complex geometry, internal cavities and cooling channels; to exclude the manufacture of complex equipment and devices due to the absence of the need to use a number of technological processes; reduce the weight of the resulting product and, in some cases, replace a complex assembly unit with one part;

reduce manufacturing costs due to the insignificant effect of the number of manufactured parts on the duration of their production. [4, 5].

It should be noted that at present, the study of rapid prototyping or 3D printing technology is receiving increased attention [6, 7]. However, the complexity of the implementation of this technology is due to the lack of statistical data on the use of SLM technology in the manufacturing of elements of liquid-propellant rocket engines, in particular, there are no standards regulating the quality system. In addition, the characteristics and quality of the obtained products directly depends on many factors: like the printer itself, the quality of the powder, etc., which creates additional problems.

Thus, taking into account the advantages of the SLM process, the ability of introducing it for the manufacture of LPRE chamber components was considered. Despite the obvious advantages, it is important to assess the technology's limits of applicability, which are restricted by the specific requirements of the aerospace industry.

Formulation of a problem

The objects of the study were the typical elements of the LPRE design. On the basis of the equipment of FlightControl Propulsion [8], these elements were manufactured and experimentally tested with the identification of the features of the SLM technology appliance. The limits of applicability of the technology within the framework of the liquid-propellant rocket engines design were studied, and the influence of the technology on the main hydraulic characteristics of typical hydraulic channel designs was determined.

Solution of the problem

The solution of the problem was obtained based on experimental study of the specimens of typical LPRE elements which were manufactured using SLM technology.

Experimental study

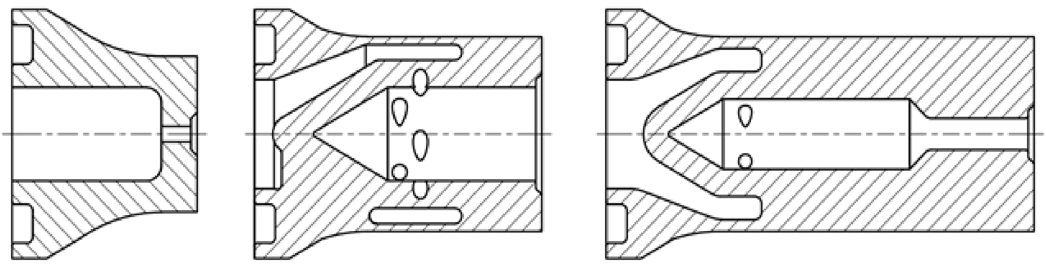
Typical elements that compose the rocket engine chambers are injectors, nozzles, collectors, as well as cooling channels of the housings. In order to study the features of the application of additive manufacturing technology, samples of typical designs were made: orifices, centrifugal opened and closed injectors (see Fig. 1) [6]. Being one of the most important, hydraulic repeatability was chosen as the main purpose of research. For the designs of liquid-propellant engine flow paths, a scatter of 5% can be considered as satisfactory repeatability of hydraulic characteristics.

Figure 1 – Manufactured specimens

Orifices

The range of application of the orifices for LRPE designs is immense: bypass openings of the collectors, straightening devices, component bypass openings, etc. Since geometrically, in comparison with other geometrical figures, cross-sectional area of the circle is the largest, provided that the hydraulic diameters are equal, it was of particular interest to determine the smallest diameter of the manufactured orifice, at which the flow characteristic from sample to sample would change within 5%. For this purpose, 88 samples of injectors of various sizes were 3D-printed (see Table 1). The determination of the mass flow rates was carried out by the weight method, in which, a liquid with a set inlet pressure is passed through the flow path of the research object for a certain amount of time. Flowing through the hydraulic channel of the object, the liquid fills a measuring container, which is weighed after filling. For each instance of the injector, the hydraulic tests with a set inlet pressure was repeated at least three times. The weight of the moistened measuring container is taken into account each time before a new experiment.

The analysis of the obtained experimental data allowed to determine that the minimum diameter of the 3D-printed orifices, at which the dispersion of the hydraulic characteristics would lie in the range of 5% (see Table 1), is ⌀1 mm.



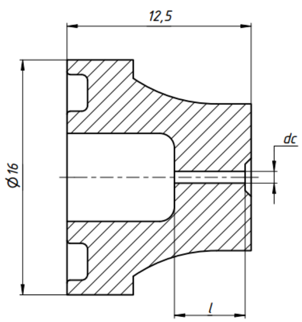
Specimen 1 Specimen 2 Specimen 3

Figure 2 – The design of the manufactured specimens

Tangential holes

Tangential holes are one of the most common examples of hydraulic paths for liquid-propellant rocket engines. It is practically impossible to imagine the high-quality operation of devices for creating film flows without tangential holes, such as centrifugal injectors and film cooling rings of liquid-propellant engine chambers [9]. In order to determine the hydraulic characteristics, as well as ensure the future design of reliable elements, samples of tangential hole rings with different geometric cross-sectional shapes, as well as in a certain range of unit sizes, were designed and manufactured using the SLM technology (see Fig. 3, Table 2).

Table 1 – Unit sizes of the manufactured orifices

	d_c, mm	l/d_c	Quantity, pcs
	0.5	1	5
	0.5	2	5
	0.5	6	4
	0.6	1	5
	0.6	2	4
	0.6	6	5
	0.8	0.5	5
	0.8	1	4
	0.8	2	5
	0.8	6	5
	1	0.5	5
	1	1	5
	1	2	5
	1	6	5

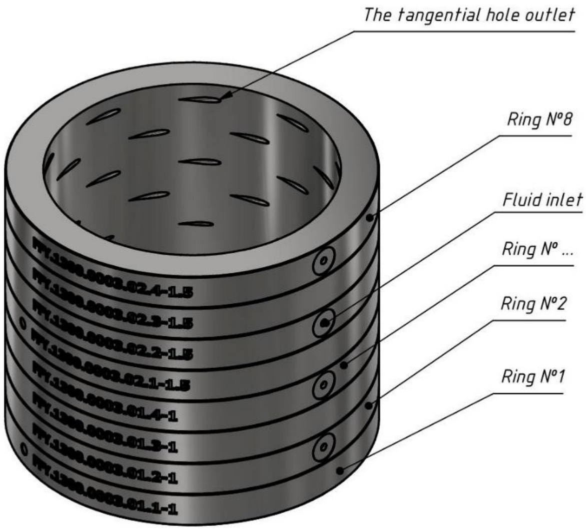


Figure 3 – The pilot design model for tangential holes study

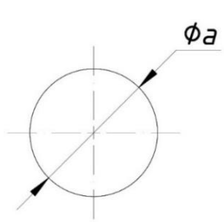
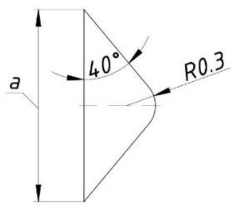
Four identical samples were made for each unit size (designated by the characters O1 ... 3, T1 ... 3, E1 ... 3 and D1 ... 3 for each cross-sectional shape respectively). The inlet pressure $p_{вх}$ was kept constant. The obtained average values of mass flow rates for the manufactured samples are shown in the Table 3. The average mass flow rate was determined as

$$\dot{m}_{cp} = \frac{1}{n}\sum_{i=1}^{n}\dot{m}_i^p,\ kg/s$$

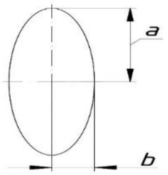
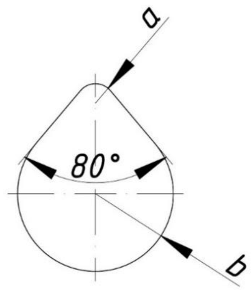
where $\dot{m}_i^p$ – is the mass flow rate of each ring with tangential holes with inlet pressure p;

n = 4 – number of rings with holes of the same size and shape.

Table 2 – Shapes and sizes of the cross-section areas of tangential holes specimens

№	a, *mm*	$F = \frac{\pi \cdot a^2}{4}, mm^2$	
O1	1	0.79	
O2	1.5	1.77	
O3	2	3.14	
№	**a, *mm***	**F, mm^2**	
T1	1.93	0.79	
T2	2.9	1.77	
T3	3.87	3.14	

The end of the table 2

<table>
<tr><th>№</th><th>a, mm</th><th>b, mm</th><th>F, mm^2</th><td rowspan="4">
</td></tr>
<tr><td>E1</td><td>0.83</td><td>0.3</td><td>0.79</td></tr>
<tr><td>E2</td><td>1.17</td><td>0.5</td><td>1.77</td></tr>
<tr><td>E3</td><td>1.67</td><td>0.6</td><td>3.14</td></tr>
<tr><th>№</th><th>a, mm</th><th>b, mm</th><th>F, mm^2</th><td rowspan="4">
</td></tr>
<tr><td>D1</td><td>0.07</td><td>0.48</td><td>0.79</td></tr>
<tr><td>D2</td><td>0.11</td><td>0.72</td><td>1.77</td></tr>
<tr><td>D3</td><td>0.14</td><td>0.95</td><td>3.14</td></tr>
</table>

Results of tangential holes hydraulic tests

Table 4 shows the deviations of the obtained flow rates from the average values presented in the table 3.

The deviation δ of the average mass flow rate from the average value was determined by the formula:

$$\delta = \left|\frac{\dot{m}_i - \dot{m}_{cp}}{\dot{m}_{cp}}\right| \cdot 100\%$$

Table 3 – The average values of the mass flow rate

$P_{вх}$, *kgf/cm*^{2}	$\dot{m}_{cp}$, kg/s											
	O1	**O2**	**O3**	**T1**	**T2**	**T3**	**E1**	**E2**	**E3**	**D1**	**D2**	**D3**
1	0.045	0.121	0.240	0.049	0.128	0.241	0.036	0.115	0.219	0.052	0.138	0.233
3	0.079	0.216	0.421	0.087	0.240	0.438	0.063	0.222	0.394	0.091	0.241	0.409
5	0.102	0.280	0.542	0.116	0.316	0.566	0.082	0.290	0.519	0.118	0.312	0.529
10	0.145	0.398	0.763	0.169	0.459	0.805	0.118	0.433	0.751	0.170	0.443	0.745
15	0.178	0.489	0.926	0.213	0.566	0.987	0.146	0.533	0.918	0.210	0.542	0.904

Table 4 – The maximum obtained values of the deviations of the mass flow rates from the average value

$P_{вх}$, kgf/cm^2	δ, %											
	O1	**O2**	**O3**	**T1**	**T2**	**T3**	**E1**	**E2**	**E3**	**D1**	**D2**	**D3**
1	**6.67**	**7.63**	0.73	**5.15**	**11.11**	**10.37**	**5.56**	4.12	1.71	**16.5**	0.72	1.94
3	**6.67**	2.20	1.01	**6.36**	4.58	0.63	4.35	**7.66**	**5.77**	**16.02**	0.52	1.77
5	**6.86**	2.33	1.06	2.80	3.56	0.88	2.75	**6.46**	4.24	**15.92**	0.96	1.61
10	**7.40**	2.45	0.88	4.59	2.45	0.81	2.76	2.08	2.33	**16.59**	0.79	1.88
15	**6.74**	2.35	0.97	**7.29**	2.78	0.76	3.25	2.30	2.4	**16.57**	0.78	1.91

As can be seen from the Table 4, satisfactory repeatability was obtained for the most of the specimens. It should be noted that the 3D printing was carried out on different printers: EOS 400 and Sisma 300 (parts material Inconel 718). Other things being equal, specimens printed on Sisma 300 printer had better hydraulic repeatability. Figure 4 shows the hydraulic testing process of E1 type samples with a water inlet pressure of 5 kgf/cm^2.

Figure 4 – The process of the hydraulic testing of a specimen

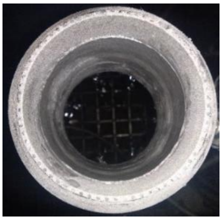
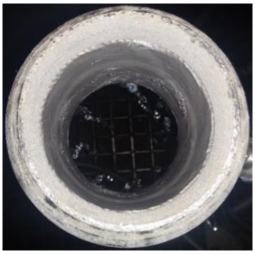
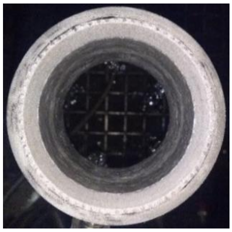
Film cooling rings

The film cooling rings are important elements of the internal cooling of the rocket engine combustion chamber. With the help of the ring a thin coolant film is formed on the surface of the gas wall of the chamber. The coolant film takes the heat flux from high-temperature combustion products, evaporates and then forms a protective low-temperature gas layer near the wall. Usually for manufacturing of the film cooling rings by means of classical production methods, there is an array of technological processes needed as the design of the film cooling consists of a large number of parts. For instance, these processes are: a precise adjustment, welding, and sometimes soldering. It was decided to design and manufacture samples of typical designs of film cooling rings using SLM technology, which geometry was adapted for 3D printing as a single part.

Results of hydraulic tests of the film cooling

According to the test results, pilot designs of film cooling rings shown satisfactory performance in various range of flow rates as well as internal flow path configurations. During operation of all samples, a thin uniform liquid film was formed, which remained stable over the entire surface of the inner wall. Thus, the fact was established that it is possible to successfully use 3D-printed film cooling rings in the designs of LPRE chambers instead of classical welded structures. Photos of the testing of the film cooling rings are shown in the table 5.

Table 5 – The results of the hydraulic testing of the film cooling specimens

36 g/s				
123 g/s				

Regenerative cooling channels

Of particular interest was the possibility of manufacturing throat inserts and cylinders, which are usually the main components of the LPRE chamber body. First of all, based on the technological limitations of 3D printer (which mainly allows to manufacture unsupported horizontal surfaces up to 1 mm) the possibility of adapting the geometry was examined. The data obtained earlier on the minimum sizes of the hydraulic channels of the internal paths was taken into account in order to ensure the hydraulic characteristics to be in the range of acceptable hydraulic repeatability. The hydraulic characteristics of the throat inserts and cylinders of various configurations were obtained for the subsequent collection of statistics and the possibility of predicting the hydraulic characteristics of the following designs. Figure 5 shows the manufactured sample of the throat insert.

Figure 5 – LPRE throat insert specimen

Four samples of the throat insert with the same geometry of the flow channels were manufactured. Table 6 shows two modes in which the tests were carried out.

Table 6 – Main operating modes and expected pressure drops

Mode	Mass flow rate, kg/s	Expected pressure drops, kgf/cm^2
Mode 1	0.620	17.2±4.6
Mode 2	0.295	3.9

The resulting inlet pressure deviations from the mean value are presented in the Table 7. The pressure deviations were determined by the formula:

$$\delta = \left|\frac{\Delta p_{ср} - \Delta p_{пр}}{\Delta p_{пр}}\right| \cdot 100\%$$

where $\Delta p_{пр}$ – is the value of the pressure drop expected for the particular design.

Table 7 – Deviations of pressure drops from expected

	№1	№2	№3	№4	№1	№2	№3	№4
m, *kg/s*	0.295				0.62			
$\Delta p_{пр}$, *kgf/cm²*	3.9				17.2±4.6			
Δp, *kgf/cm²*	7.368	8.26	9.431	8.448	30.227	31.504	40.058	36.516
	7.369	8.256	9.431	8.448	30.204	31.54	40.054	36.484
	7.374	8.255	9.43	8.452	30.23	31.54	40.054	36.45
$\Delta p_{ср}$, *kgf/cm²*	7.37	8.26	9.43	8.45	30.22	31.53	40.06	36.48
δ, %	89.0	111.7	141.8	116.6	75.7	83.3	132.9	112.1

Cylinders

In order to determine the possibility of manufacturing the LPRE cylinder design using additive technologies, 3 samples with different configurations of the flow channels were manufactured (see Fig. 6, Table 8)

Figure 6 – 3D-printed specimen of the LPRE cylinder

In the table 8:
Π – channel cross-section perimeter, *mm*;
F – channel cross-sectional area, *mm*^{2};
d_e – equivalent (hydraulic) diameter.

$$d_e = \frac{4 \cdot F}{\Pi}, mm$$

The tests were also carried out for two operating modes shown in the Table 9. The results of the hydraulic tests in the form of the obtained inlet pressure deviations from the mean value are presented in the Table 10.

Based on the results of manufacturing and further hydraulic tests of throat inserts and cylinders (see Fig. 7, 8), the features of adapting the geometry of existing designs to technological limitations in SLM-manufacturing of parts were determined. It can also be seen from Table 10 that the smallest deviation from the expected pressure drop took place for the version with a circular cross-sectional shape, which is explained by the maximum hydraulic diameter d_e among the manufactured samples.

Table 8 – Geometric parameters of the cross-sections of the cylinder cooling channels

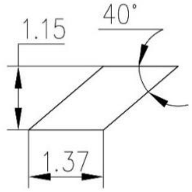
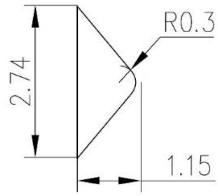
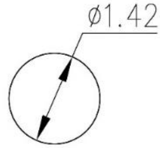
№	Channels quantity n, pcs.	F, mm^2	П, mm	d_e, mm	Cross-section.
1	44	1.47…1.6	5.97	0.98…1.07	
23	44	1.56	6.23	1	
3	44	1.6	4.4	1.42	

Figure 7 – Hydraulic testing process of the 3D-printed specimen of the cylinder

Figure 8 – Hydraulic testing process of the 3D-printed specimen of the throat insert

Thrust frame

A special form of the structural element of the thrust frame was created. Since 3D printing technology allows to obtain elements with unique properties and geometry, it was decided to carry out topological optimization of the existing thrust frame. The figure 9 shows the original design of the thrust frame.

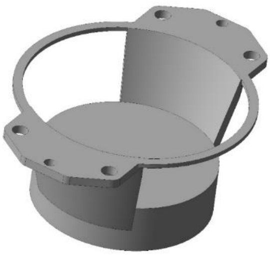


Figure 9 – The initial geometry of the thrust frame

Initially, the thrust frame was a thick-walled structure milled from sheet metal. Although the thrust frame fulfills the task, it has significant weight. Thus, the new geometry obtained by means of topological optimization methods both performs the task and reduction of weight ~ 50% takes place compared to the original one. Topologically optimized geometry of the thrust frame is shown in the Fig. 10. A photography of the printed thrust frame for attaching the LPRE chamber is shown in the Fig. 11.

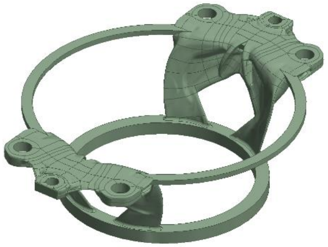


Figure 10 – Optimized geometry of the thrust frame

Figure 11 – 3D-printed thrust frame installed on the mixing head

Scientific novelty

This work presents for the first time the results of the experimental studies of the prototypes of liquid-propellant rocket engine components manufactured with SLM (Selective Laser Melting). The features of application of the SLM manufacturing technology for LPRE components are revealed, namely:

- the determination of the main hydraulic characteristics of typical design of elements of hydraulic channels, as well as the limits of applicability of the technology within the framework of the liquid-propellant rocket engines, was studied;

- the possibility of manufacturing of the elements including hydraulic channels, was investigated: regeneratively cooled cylinders, throat inserts of a liquid-propellant engine, as well as experimental designs of film cooling rings were manufactured for this purpose;

- the possibility of producing a thrust frame, which shape was obtained by the method of topological optimization, was studied.

- the main hydraulic characteristics of the typical design of SLM-manufactured cooling channels were determined.

Conclusion

The application of additive technologies, in particular SLM, has significant potential in the aerospace industry. Thanks to the work done, it is possible to determine the main boundaries for ensuring the minimum dimensions of acceptable hydraulic channels for the elements of liquid fuel rocket engines, successfully adapt existing technical solutions, and create parts with unique geometry and mass characteristics, which cannot be achieved using classical methods of manufacturing of liquid fuel rocket engines.

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