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FEATURES OF THE ADAPTATION OF 3DPRINTED REGENERATIVE COOLING CHANNELS OF THE LPRE THROAT INSERTS

For modern LPREs there is a general tendency to find new approaches to decrease manufacturing costs as well as increasing engine efficiency. This is grounded on the fact that classically, the design of LPRE components represents assemblies which consist of several complex parts joined together by means of specific technological processes. Particularly, throat inserts production often requires advanced machining of both inner wall and chamber jacket which are brazed to ensure the integrity of the obtained part. One of the possible ways to simplify the complex manufacturing technology of the throat inserts is the application of additive manufacturing methods. For instance, SLM (Selective Laser Melting) technology allows to partly exclude complex machining, welding and brazing from production cycle of the throat inserts. As a result, classically manufactured assembly transforms into single 3D-printed part and consequently, this has positive impact on system reliability while the time expenses reduce significantly.

The possibility of using the additive printing process for the manufacture of throat inserts of liquid-propellant rocket engines is investigated in this paper. A design was chosen for comparison based on the analysis of existing typical real designs of liquid-propellant rocket engines. The designs of the throat inserts are to be manufactured by means of SLM technology. Several 3D models with varying geometry features of cooling channels were designed. The obtained results made it possible to analyze new metal throat inserts of the liquid-propellant engines and compare them with those which were manufactured using traditionally used technologies. Comparative analysis allows us to study the main features of the SLM-manufacturing of the throat inserts of the liquid-propellant engine and propose the main ways of adaptation of the geometry of the cooling channels while taking into account the technological limitations of the chosen additive manufacturing method.

Key words: *additive manufacturing, selective laser melting, LRPE combustion chamber, hydraulic channels, throat insert.*

Для сучасних ЖРД існує загальна тенденція пошуку нових підходів до зниження виробничих витрат, а також підвищення ефективності двигунів. Це обумовлено тим, що класично конструкція компонентів ЖРД є агрегатом, що складаються з декількох складних частин, з'єднаних між собою за допомогою певних технологічних процесів. Зокрема, виготовлення секцій критичного перерізу часто потребує складної механічної обробки як внутрішньої стінки, так і сорочки камери, що припаюються для забезпечення цілісності отриманої деталі. Одним із можливих способів спрощення складної технології виготовлення секцій критичного перерізу є застосування адитивних методів виробництва. Наприклад, технологія SLM (Selective Laser Melting) дозволяє

частково виключити складну механічну обробку, зварювання та паяння із виробничого циклу секцій критичного перерізу. В результаті класично виготовлене складання перетворюється на одну деталь, надруковану на 3D-принтері, і, отже, це позитивно позначається на надійності системи, а тимчасові витрати значно скорочуються.

У даній роботі досліджується можливість застосування процесу адитивної друку для виготовлення секцій критичного перетину ЖРД. На підставі аналізу існуючих типових реальних конструкцій ЖРД була обрана конструкція для порівняння і виготовлення її адитивним методом SLM. Розроблено кілька 3D-моделей з різною геометрією охолоджуючих каналів. Отримані результати дозволили проаналізувати нові металеві деталі секцій критичного перетину ЖРД і порівняти їх з виготовленими по традиційно застосовуваних технологій. Аналіз порівняння, дозволяє вивчити основні особливості SLM-виготовлення секцій критичного перетину ЖРД і запропонувати основні способи адаптації геометрії з урахуванням технологічних обмежень адитивної друку.

Ключові слова: *адитивні технології, selective laser melting, камера жрд, гідравлічні тракти, секція критичного перерізу.*

Для современных ЖРД существует общая тенденция к поиску новых подходов к снижению производственных затрат, а также повышению эффективности двигателей. Это обосновано тем, что классически конструкция компонентов ЖРД представляет собой сборки, состоящие из нескольких сложных частей, соединенных между собой посредством определенных технологических процессов. В частности, изготовление секций критического сечения часто требует сложной механической обработки как внутренней стенки, так и рубашки камеры, которые припаиваются для обеспечения целостности полученной детали. Одним из возможных способов упрощения сложной технологии изготовления секций критического сечения является применение аддитивных методов производства. Например, технология SLM (SelectiveLaserMelting) позволяет частично исключить сложную механическую обработку, сварку и пайку из производственного цикла секций критического сечения. В результате классически изготовленная сборка превращается в одну деталь, напечатанную на 3D-принтере, и, следовательно, это положительно сказывается на надежности системы, а временные затраты значительно сокращаются.

В данной работе исследуется возможность применения процесса аддитивной печати для изготовления секций критического сечения ЖРД. На основании анализа существующих типовых реальных конструкций ЖРД была выбрана конструкция для сравнения и изготовления ее аддитивным методом SLM. Разработано несколько 3D-моделей с различной геометрией охлаждающих каналов. Полученные результаты позволили проанализировать новые металлические детали секций критического сечения ЖРД и сравнить их с изготовленными по традиционно применяемым технологиям. Анализ сравнения, позволяет изучить основные особенности SLM-изготовления секций критического сечения ЖРД и предложить основные способы адаптации геометрии с учетом технологических ограничений аддитивной печати.

Ключевые слова: *аддитивные технологии, selectivelasermelting, камера жрд, гидравлические тракты, секция критического сечения.*

Introduction. Typically, there are a number of components which consist of LPRE, for instance, turbopump units sensors, valves, combustion chambers. Wherein the cost of the later is often more than 50% of the total cost of the engine itself. This due to the fact that for the manufacturing of the classical combustion chamber design, a number of complex technological processes is applied. The examples of the processes are stamping, milling, rotary drawing, brazing, different types of welding, assembling and heat treatment which follows each production stage as well as obligatory control of the obtained parts. This leads to significant increasing of the labor intensity and the need of the special costly equipment. Therefore, for the modern rocketry, particularly for LPRE, it is of increased interest to search for solutions in order to reduce the cost of production of chambers, as well as increase their efficiency. One of the possible means is application of the additive manufacturing technology for LPRE regenerative cooling channels production. Particularly, it is known that throat is subjected to the maximum thermal loads while operation and often requires intensification of the heat transfer from the wall towards coolant. For instance, these are the artificial roughness performed on the surface of the inner wall of the cooling channels, coolant velocity incrementation by means of the decreasing the number of channels which leads to the necessity of spiral channels performing, etc. The described design features are complex to be performed with classical means of manufacturing. In turn, there is no complication of the additive manufacturing technology as well as manufacturing cost in case of the fulfilling of the requirements mentioned above. In this paper the possibility of the application of SLM technology for throat inserts manufacturing is studied, the main features of the manufacturing process are described and the recommendations are given in order to obtain the successful instances of the 3D-printed geometry adaptation of the LPRE regenerative cooling channels.

Statement of the problem. With the aim of the introduction of the additive manufacturing means for LPRE parts production the task was set: to design and SLM-manufacture low-thrust LPRE throat inserts with regard to the technological restrictions and following all the specific requirements of the aerospace field.

Design description.

The characteristics of the throat insert are represented in the table 1 and were chosen as the initial data for designing.LPRE throat is usually one of the most thermally loaded areas and for that reason is manufactured with regenerative cooling channels with the significant intensification of the heat transfer from the “hot” wall towards liquid to ensure the reliable operation of the engine.As a result of the preliminary cooling analysis, it was designed several variants of the cooling channels which differ from each other by the width, spiral angle, ribs thickness, etc. The following materials were considered as the main for the manufacturing: austenitic stainless steels as AISI 316L, 12X18H10T or 12X21H5T, nickel-chromium alloys as Inconel 718 and Haynes 230.

Table 1

The main characteristics of the LPRE throat insert

Parameter	Value	Units
Propellant components		
fuel	unsymmetrical dimethylhydrazine	-
oxidizer	nitrogen tetroxide	-
Oxidizer/fuel mixture ratio, k_m	2.25	-
Combustion chamber pressure, p_c	20	kgf/cm^2
Throat diameter, d_{thr}	29	mm

The choice took into account the heat stability and heat resistance of the material, as well as the presence of metal powder required for SLM production. According to the complex of the described characteristics, **Haynes 230** is the best material, which ensures the reliable operation of the part up to 1100 °C, while the 3D printed material is not inferior in properties to the classical one.

Throat insert classical design represents assembly unit, which includes the following parts: the inner wall and the jacket [1, 2, 3].On the inner wall the milled channels are performed on which the jacket is installed. Then, both parts are joined together by means of brazing which requires costly equipment as well as deep knowledge of the complex technological process. [2, 3, 4]. In some cases, when the cooling system fails to withstand significant thermal loads, it is possible to intensify heat transfer between the hot wall and the coolant by means of performing regenerative cooling channels spiral (to increase the coolant speed in channels by decreasing their number). Such complex geometry requires milling machine application with the following obligatory control of the geometry parameters of the part. There is always an instrumental uncertainty for machining process which influence significantly on an inner wall thickness while manufacturing. Moreover, there is a need for a special equipment for the component inlet as well as reliable measuring system while carrying out the hydraulic testing. In the process of the manufacturing in terms of brazing, there always a necessity in heat treatment in order to lower the internal stress after the brazing. Furthermore, all brazing seams are subjected to the obligatory quality control.

Solution to the problem.

The main problem of the SLM additive manufacturing technology is the necessity of the adaptation of the initial "classical" design geometry of the cooling channels, as there is a need in building self-supported surfaces in the inner cavities. Another problem is the study of the limits with acceptable hydraulic repeatability of the cooling channels along with the even distribution of the coolant among the channels.

Based on the experience of previous work, the following restrictions were chosen: the minimum linear dimension of the channelw was 1 mm, the minimum wall thickness was 0.4 mm. The manufacturing of the parts was carried out on two 3D-printers: EOS M400 и Sisma 300. All the work on SLM manufacturing of the specimens along with the study of the features of the 3D-printed LPRE throat inserts were performed on the FlightControl Propulsion equipment. Not only does the chosen technology allow to exclude the necessity in milling and brazing, but also allows not to produce special devices for hydraulic testings of the obtained parts. In this case all the complex necessary cavities, which provide the input and output of the component, can be integrated as a single piece in the part. Another advantage of the SLM-manufactured parts is that the geometric parameters have relatively small discrepancy, which implies on their geometric repeatability. The main advantage of the 3D-printed design is in its integrity: the known designs of the sophisticated LPRE units can be transformed into a single part. In this case, the manufacturing time mainly depends on the 3D-printing time and is less than the time which should be spent while manufacturing by classical means of production.With SLM-technology it is possible to realize virtually any cooling channels configuration. According to [1], one of the possible ways of the intensification of the heat transfer is obligatory turbulization of the flow with special turbulizers (see Fig. 1).

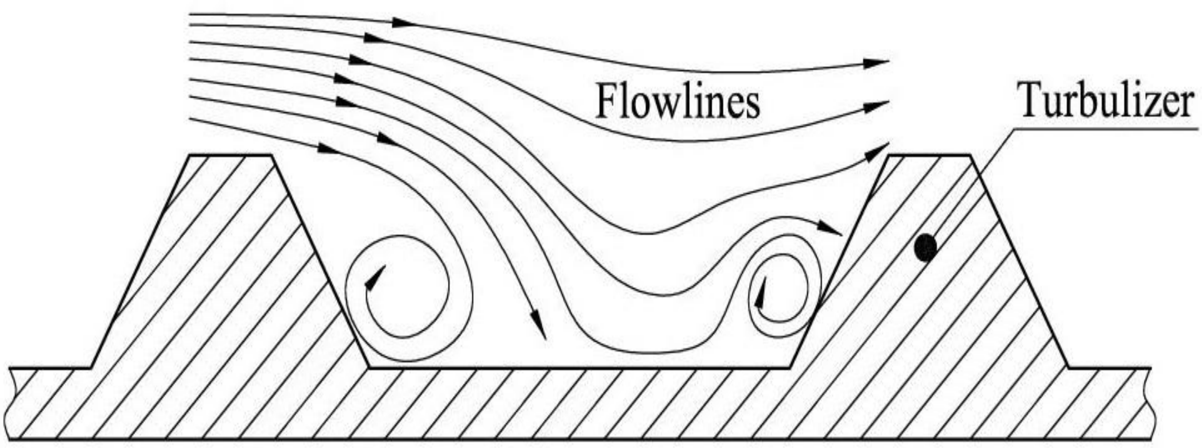

Figure 1. Flow turbulizer

Such design elements represent great complexity for "classical" manufacturing, but not for SLM-technology.

However, despite the described advantages, SLM-technology limits the geometrical shape to be printed. Thus, starting from specific length, the horizontal surfaces should be "supported" with special supporting elements. According to [1], there is a limitation on the length of the "unsupported" horizontal surface while building SLM-process: the maximum length is limited with 1 mm. Otherwise, the metal layers distort under the influence of the thermal loads and prevent new layer from the proper recoating. Because of that, there is a division on self-supported surfaces (45° - limit value for self-supported surfaces) and those, which require supporting structures. Moreover, the roughness of the 3D-printed surfaces significantly depends on the surface angle during the printing. The lesser the angle of the downward oriented surface, the rougher this surface is. The described dependence is called the stair-step-effect and is one of the distinctive features of the SLM-technology (see Fig. 2, 3) [5, 6]. In terms of hydraulic, rougher surface means that larger friction loss takes place so more inlet pressure needed for ensuring the required mass flow rate through the cooling channels while operation.

All of the above features must be taken into account when designing new parts or adapting existing technical solutions for the use of SLM technology.

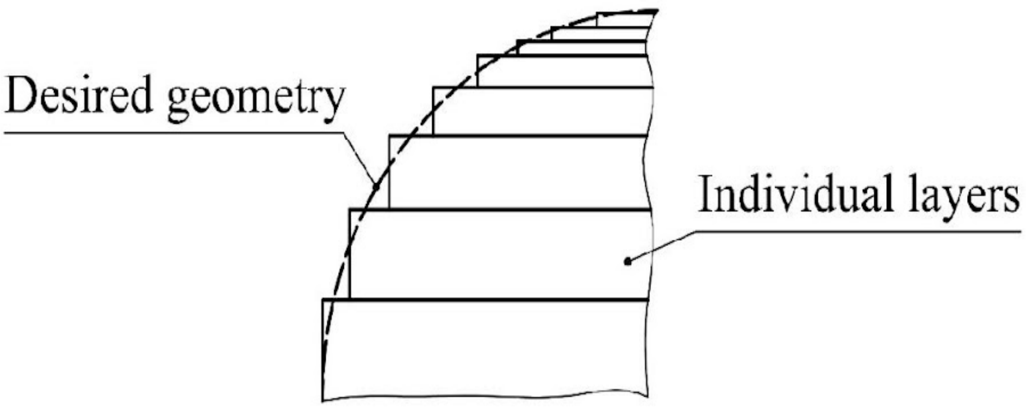

Fig. 2. Stair-step-effect

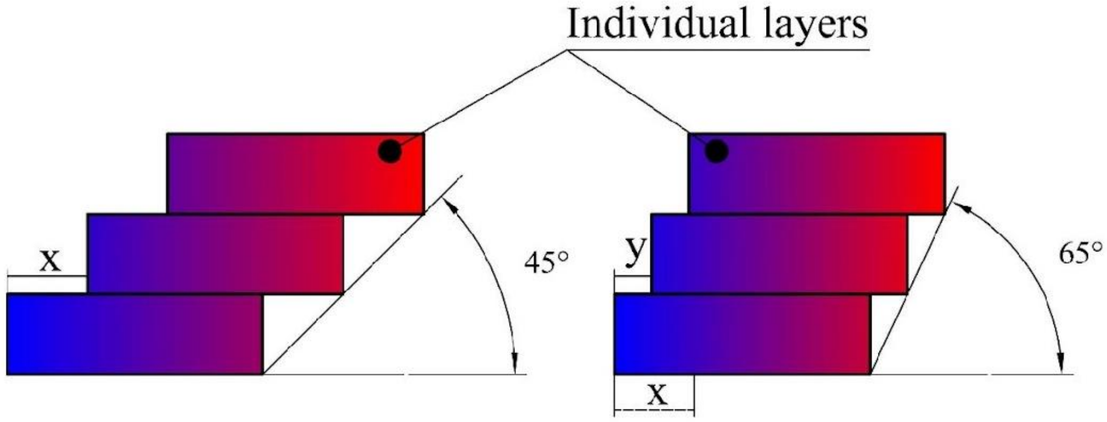

Fig. 3. Dependency on the surface angle inclination on the intensity of the stair-step-effect

The adaptation of the initial design is carried out based on the analysis of the unsupported surfaces creation. As the initial step, the orientation of the part during the building process was chosen. The orientation of the axis of symmetry of the part during printing is chosen collinear to the vector of the printing direction. However, the initial configuration of the cooling channels does not allow to print the part without application of the supporting elements inside.

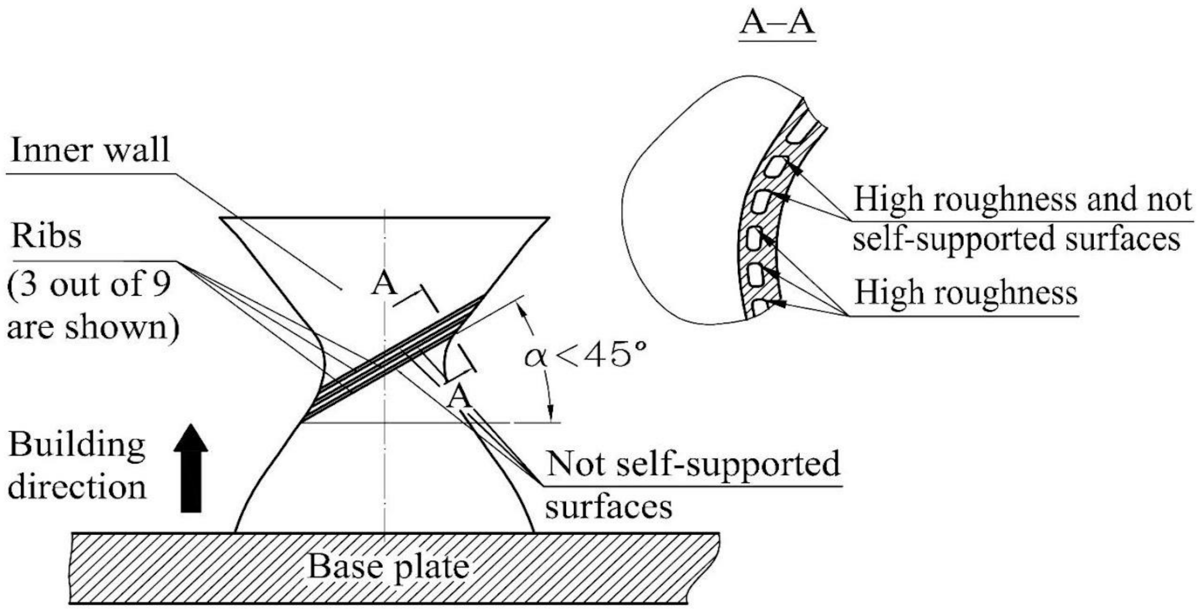

Fig. 4. Printing orientation of the specimens

For this reason, the adaptation of the channels' geometry was performed. The second angle of the rib γ was introduced. This angle can be called the compound angle (see Fig. 5). This angle regulates the incline of the printing surface relative to the base plate of the 3D-printer. It allows to ensure the printablity of the part and to decrease the roughness of the obtained surfaces. The varying area of the γ depends on technological restriction of the SLM-process and calculates for each case individually.

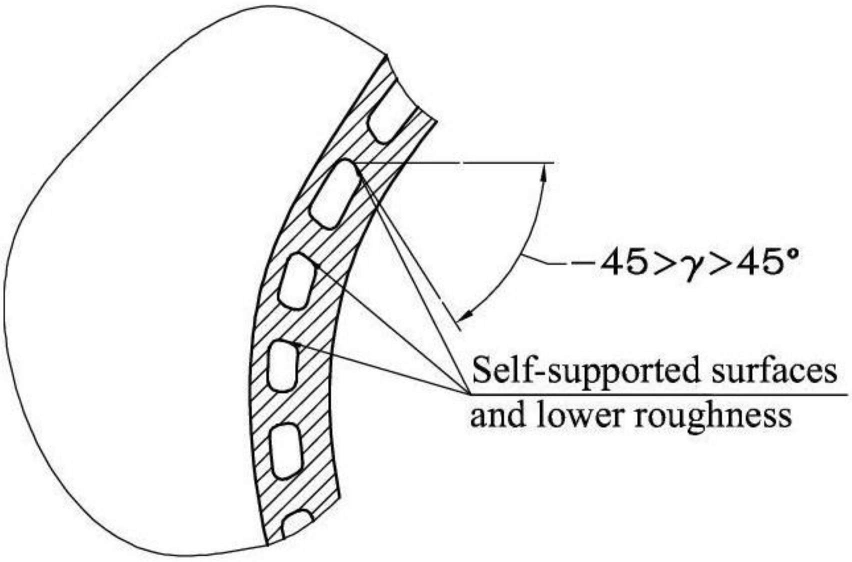

Fig. 5. Compound angle in the throat insert specimen

The following is recommended for the geometry adaptation of the throat inserts of the LPRE with regard to the technological restrictions of the SLM-process:

1. To introduce additional, compound angle γ, which is defining from the point of view of 3D printing of self-supporting surfaces;
2. To limit the maximum height of the cooling channels in the throat area up to 1 mm on condition that spiral angle does not meet the self-supporting surface-angle requirements.
3. If possible, add fillets of the surfaces of the ribs of the cooling channels with the inner and outer walls, since this reduces the amount of overhanging surface.
4. Decrease the inner wall thickness in order to increase cooling system efficiency. Recommended minimum thickness of the wall for SLM parts is 0.4 mm.
5. Provide technological orifices for powder removal during post-printing operations.

Results. As a result of the experimental study of the technology 2 specimens of the throat inserts were successfully 3D-printed. Two variants of the design were manufactured.The first variant remains geometric parameters which are the same as for the milled design.The second variant was manufactured with the purpose of studying the boundaries of the application of the SLM-technology.The comparison of the main geometric parameters of the specimes is shown in the table 2.

Table 2

Geometric parameters of the specimes

Specimen	Number of ribs	Ribs thickness	Inner wall thickness
Variant 1	9	1.25 mm	0.7...1.5 mm
Variant 2	22	0.4 mm	0.4 mm

The manufactured parts allowed to obtain sufficient information about the main features of the SLM-process. The second variant was created on the edge of the technological abilities of the 3D-printer as the thickness of the wall and ribs is extremely small. The comparison of the manufactured specimens is depicted in the Figure 6 (variant 1 is on the left, variant 2 is on the right).

Fig. 6. The comparison of the obtained specimens.

The possibility of polishing the additively manufactured surface of the profile “hot” wall was also tested. As a result, the required surface quality was achieved, which did not differ from the polished surfaces of traditionally used materials. In order to investigate the possibility of manufacturing special turbulizators, a channel with artificial roughness was successfully performed (see Fig. 6, the part on the left).

Conclusions. The results of the experimental study of the SLM-manufacturing of the LPRE throat inserts allows to make the following conclusions:

- the application of the SLM-technology allows to significantly increase the reliability of the obtained parts. This is due to the exclusion of such labor-intensive technological processes as brazing, milling, stamping, etc. from the manufacturing cycle of the throat inserts.
- SLM technology allows to reduce manufacturing time significantly. The manufacturing time of the 3D-printed throat inserts is 168 hours, whereas the manufacturing time of the design by means of the “classical” technologies approximately 330 hours.
- for SLM technology, an increase in the number of parts produced at a time does not mean a proportional increase in production time. In this case, the manufacturing time per part increases insignificantly.
- quality of the 3D printed parts shows, that the roughness of the obtained surfaces significantly depends on their angle during the printing process, which must be taken into account while designing of the 3D-models.
- adaptation of the designed part for SLM technology must first be carried out based on the analysis of unsupported surfaces in the product and is a mandatory preparatory operation.

All work on the study of the possibility of manufacturing the throat inserts was carried out by FlightControl Propulsion in the period from 2018 to 2020. It should be noted that due to the peculiarities of SLM technology, the adaptation of the geometry of the internal channels of the throat inserts is a complex engineering problem, which was solved by FlightControl Propulsion. The results of the study were successfully implemented in the chamber of the ML250 engine, designed for the lunar lander "Blue Ghost" by Firefly Aerospace, a member of the NASA "Artemis" program.

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