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MODERN MATERIALS AND PROCESSING TECHNOLOGIES AS A FACTOR IN THE DEVELOPMENT OF THE AEROSPACE AND ROCKET INDUSTRIES

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Abstract. *The article examines the impact of modern structural materials' characteristics on the advancement of the aerospace and rocket industries. The growing role of ceramic materials with unique properties is emphasized: heat resistance, high hardness and strength; resistance to oxidation and corrosion; radio transparency; lower density compared to metals. It is often the case that they are indispensable in the manufacture of elements of rocket systems and defense industry products. However, technical ceramics belong to the category of difficult-to-machine materials, which complicates the processes of manufacturing critical products from them. Possible ways to improve the efficiency of manufacturing rocket antenna fairing - thin-walled shells of complex geometric shapes made of sitalls (a type of glass ceramics) are considered. Options for improving traditional technological processes for the manufacture of fairings using CNC machines for their mechanical processing are proposed. The use of additive SLS technology in the production of antenna fairings is substantiated. A variant of an improved technological process for manufacturing antenna fairings was presented.*

Keywords: *modern structural materials; technical ceramics; rocket antenna fairing made of glass-ceramics; blank production technology; grinding processes; machining quality and accuracy; additive technologies.*

1. Introduction

The rapid development of the aerospace and rocket industries is accompanied by the emergence of challenges that require the use of modern materials with the required properties to address them. This is possible through improved manufacturing technologies for critical components of products made from these materials, including those for aircraft.

Modern requirements for defense and aerospace products include strict adherence to quality, reliability, safety, and compliance with international standards. Key standards include AS/EN 9100 — an international standard for quality management systems for the aviation, space, and defense industries; and AS9145, which incorporates APQP (Advanced Product Quality Planning) and PPAP (Production Part Approval Process) methods used in the development of new products or modifications to existing ones.

Key requirements for defense (missiles, projectiles of various calibers) and aerospace industries products include the following:

• reliability and resistance to external influences, maintaining functionality under extreme conditions: force impacts, vibrations, temperature changes, humidity, electromagnetic interference;

• high precision and reliability of components – especially for satellites, launch vehicles, and navigation systems;

• compatibility with control and guidance systems – integration with digital platforms, GPS, and other navigation systems.

The capabilities and potential of modern rocket technology are linked to the technical level of the structural materials used. Most of these materials are difficult to machine. These include high-strength alloy steels, heat-resistant alloys based on nickel, titanium, tungsten, rare earth metals, composites [1–5] and non-metallic materials such as structural ceramics [6–8]. The latter possess unique properties and are increasingly replacing metals in the production of products in this class. The efficiency of using these materials depends on the level of processing technology used to manufacture products made from them, based on the principle of ensuring the necessary performance characteristics of rocket system components while minimizing costs.

2. Current state of research in the field of increasing the efficiency of the production of antenna fairings as an element of rocket systems

The structure of rocket systems includes ballistic missiles, launch vehicles, and sounding rockets. Each of these systems consists of four basic elements: a payload (a warhead for ballistic missiles); a propulsion system; a guidance and control system; and an overall structure. Space launch vehicles and sounding rockets are used to launch satellites into orbit and collect scientific data in the upper atmosphere. An example of the design of such a system is shown in Fig. 1.

A complex, spatially shaped nose cone is mounted on the rocket's nose, connected to a cylindrical body housing the rocket engine that provides thrust. The rocket system's surface is typically made of metal or composite materials with heat-absorbing or protective coatings.

The nose cones, which protect the seeker's antenna from aerodynamic pressure and heat, are the most critical components of the warhead of a modern rocket and most high-speed aircraft. Their primary purpose is to transmit radio frequency control signals with minimal loss and distortion under conditions of high thermal (heat flux density up to 32 MW/m^2) and force loads (excess pressure greater than 50 kPa) [9].

To perform their functions, antenna fairings must also be made of a radiotransparent material. Certain types of technical ceramics possess such properties, for example: pure oxide ceramics based on Al_2O_3, Si_2O_2, and ZrO_2; carbide ceramics based on SiC; nitride ceramics based on Si_3N_4; as well as quartz ceramics and glass ceramics – sitalls [10].

Figure 1 - Example of the design of a large research rocket (payload up to 250 kg, flight range 400 km) [9]

Sitalls are produced by fine crystallization of glasses or melts of various compositions, occurring throughout the entire volume of the formed product. Their most important properties are a low coefficient of thermal expansion, low thermal conductivity, stable permittivity over a wide temperature range, high hardness, radio transparency, heat resistance (up to 1200°C), and corrosion resistance. In Ukraine, sitalls are widely used to produce rocket antenna fairings, ensuring reliable operation of products under extreme conditions due to their strength and performance characteristics.

A radio-transparent fairing is a body of revolution, a thin-walled shell of complex spatial shape (fig. 2).

Finished parts must meet requirements for mechanical strength, heat resistance, and radio technical properties [9–12], that is, prevent control signal distortion. This is ensured by the accuracy of the part's profile and wall thickness, as well as the specified characteristics of the product's surface layer—its structure, the absence of defects, and a certain roughness.

Existing workpiece technologies to produce complex-shaped ceramic products (usually slip casting or centrifugal casting) do not allow these requirements to be met without additional mechanical processing [10]. Therefore, the blank is subjected to multi-stage mechanical processing, namely grinding with diamond

Figure 2 – Left: aerodynamic fairings (Northrop Grumman). Right: Fairings used to protect the homing system of the reentry vehicles (American Technology & Research Industries) [9]

wheels, primarily in a metal bond, on both universal and specialized machines.

Mechanical processing of products of this class is very labor-intensive. This is due to the properties of the material itself, as well as the lack of technological advancement of the fairing design [10, 12]. Signs of lack of technological advancement: large dimensions of the product (maximum diameter – up to 500 mm, height – over 1000 mm); complex curvilinear profile of the contour of the inner surface of the part, variable along the length; the need for smooth mating of individual curved sections of the inner surface; the wall thickness of the finished product is 4.0 ± 0.03 mm with a wall thickness of the workpiece up to 20.0 mm, which can be variable along the length of the product; the specified deviation of the geometric dimensions of the contours along the length of the part per diameter is: internal ≤ 0.04 mm, external less than ± 0.1 mm; roughness of the treated surface no more than R_a = 2.0 μm; absence of a defective layer in the finished product due to mechanical processing.

However, given the properties of glass-ceramics (a combination of high hardness and brittleness), their abrasive machining at all stages of the manufacturing process (MP) — from rough grinding to diamond finishing of both shell surfaces — is accompanied by the formation of a defective layer, the depth of which, even after finishing operations, can reach 0.2–0.5 mm. This requires a combined hardening operation. The operation consists of removing the defective layer in a solution of concentrated acids, followed by hardening of the formed surfaces in liquid salts of chemical compounds (ion bombardment). This operation is environmentally harmful, labor-intensive, and expensive. Its duration is related to the depth of the defective layer formed after the fine grinding and diamond finishing operations, which occupy up to 70% of the total machining time.

Thus, the efficiency of machining ceramic rocket fairings using traditional technology depends on the following negative factors: hard and brittle workpiece material; complex curvilinear tool path; variable cutting depth caused by uneven allowance thickness along the length of the product; non-rigid processing system;

rapid and uneven tool wear; formation of a defective surface layer that must be removed after the combined hardening operation.

An analysis of existing rocket fairing manufacturing processes has revealed that their effectiveness depends on the workpiece production method. Maximizing the workpiece's configuration and dimensional accuracy to match the corresponding part parameters allows for the significant elimination of labor-intensive and costly machining operations. This is possible using modern 3D printing technologies.

3. Formulation of the purpose of the research

The research conducted demonstrates that the labor intensity of manufacturing thin-walled shells of complex spatial shapes made of glass-ceramics and sitalls, such as rocket antenna fairings, depends on the workpiece production method. The purpose of this article was to identify ways to improve the manufacturing efficiency of these parts through the implementation of modern technologies and processing methods.

4. Presentation of the main material

4.1 Traditional methods for increasing the efficiency of mechanical processing of sitall fairings

Analysis of the basic fairing machine option.

The performance characteristics of glass-ceramic components, especially rocket antenna fairings, depend on their manufacturing conditions, starting from the basic manufacturing process, from the workpiece production stages to the final step of the complex manufacturing process, namely, the combined hardening of the pre-machined surfaces.

Until recently, aircraft fairing grinding was performed on modernized lathes equipped with high-speed grinding aggregate heads and direct force copying systems (Fig. 3).

Due to the increased brittleness and hardness of glass-ceramics, their mechanical processing is difficult, and therefore, the grinding process is multi-stage [10, 12]. It includes roughing and finishing operations of grinding the inner and outer contours. This involves removing the main allowance of up to 8–10 mm per side, unevenly along the entire profile of the part. Machining is carried out using deep grinding (cutting depth of 0.5...1.5 mm), which is accompanied by the formation of a defective layer damaged by the machining due to insufficient accuracy of the fairing wall thickness, which is unacceptable.

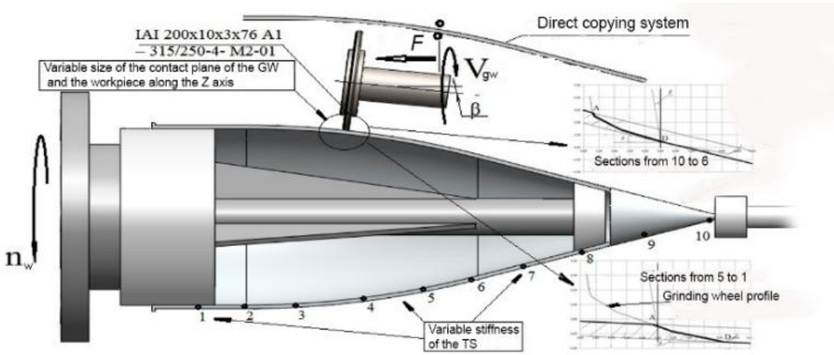

Figure 3 - Diagram of the external processing of the fairing using a representative part as an example [12]

The direct copying system does not ensure the required machining accuracy. It is significantly affected by the following factors: the accuracy of the grinding wheel installation relative to the copying device (performed by the machine operator); intensive wear of the grinding wheel and changes in its profile during operation, which requires dressing the tool during finish grinding; the high labor intensity of the internal grinding operation due to the complexity of the part profile; changing the diametrical dimensions of the internal cavity along the length of the part requires the sequential use of grinding wheels of at least three standard sizes, stopping the grinding process, and resetting the entire process system for machining with the next wheel.

The required machining accuracy of the product is achieved through the final diamond lapping of its surfaces. This part of the process is performed manually, requires many dimensional measurements, significant time investment, and highly skilled machine operators.

The sequence of stages to produce fairings from technical combined-defective glass-ceramic AC-418 (the structure of the original glass is Si_2O-Al_2O_3-Li_2O-TiO_2) is presented in Table 1.

To evaluate the effectiveness of the considered TP (see Table 1), an approximate calculation of the time spent on machining a representative part was performed. Initial data: the part (see Fig. 3) is a thin-walled shell of revolution (paraboloid of revolution) made of AC-418 sitall with dimensions: overall length L up to 750 mm, diameter of the cylindrical part of the product D_c = 200 mm, wall thickness of the product h = 4.0 ± 0.03 mm with a wall thickness of the workpiece h_w = 15.0...20.0 mm.

Table 1 - Generalized basic process for manufacturing sitall fairings

The technological process of manufacturing sitall fairings		
Workpiece production technology:	Machining of the workpiece:	Combined hardening of the machined surfaces:
- synthesis of the starting material (batch production); - production of the workpiece by centrifugal casting; - crystallization of the fairing material in the workpiece.	- sequential rough and finish diamond grinding of the internal and external surfaces of the workpiece; - diamond abrasive finishing of the ground surfaces.	- removal of defective layers caused by mechanical processing by chemical etching; - strengthening of component surfaces by ion bombardment.

up to 750 mm, diameter of the cylindrical part of the product D_c = 200 mm, wall thickness of the product h = 4.0 ± 0.03 mm with a wall thickness of the workpiece h_w = 15.0...20.0 mm.

The results of the time calculation indicate the low effectiveness of the basic TP. The total machining time of the fairing is T_{Σ} = 49 hours. The time spent on the machining process itself, T_{mp}, does not exceed 52% of T_{Σ}, with 20% of this time spent by the worker. Auxiliary operations of the T_{ap} also require significant time. These include interpretational inspection of the product's geometric parameters. These are performed on special measuring machines outside the machine and require the worker to reposition the workpiece. The number of repositioning reaches 8–10 and can increase if there are significant discrepancies between the workpiece and part profiles.

Thus, the main problem with the efficient processing of thin-walled parts of this type is the lack of automation in processing and inspection, coupled with the significant influence of the subjective "human" factor on the result. This problem can be partially solved by using computer numerical control (CNC) machines for abrasive machining operations.

Using CNC machines in fairing manufacturing.

The efficiency of using CNC machines increases with the increasing complexity of the workpiece profile and the need to achieve high-quality, precision-machined surfaces. However, the grinding process for fairings is characterized by a rapid loss of tool dimensional accuracy due to intense wheel wear and dynamic instability of the system [10, 12]. Therefore, CNC machines must compensate for changes in workpiece allowances, deformations in the process system, temperature effects, machine errors during coordinate movement, and other factors.

Complete machines of fairings are possible using the STUDER series machines [13].

The machining process is preceded by the preparation of a control program. For this purpose, a 3D model of the workpiece is developed, considering its configuration and all specified dimensions, after which the program itself is written [14].

These machines are equipped with the following key components:

– a GE FANUC Series 16-T CNC system, which allows scanning of the internal and external profiles of the workpiece before machining, which is necessary for the automatic calculation of grinding allowance and the assignment of rational cutting parameters in accordance with the machining program;

– a specialized system for measuring and monitoring the dimensional accuracy, geometry, and surfaces of workpieces and parts, as well as mechanical machine components, using control sensors, measuring heads, and feeler gauges, as well as for monitoring and controlling machine operation, including grinding wheel balancing;

– adjustable vibration mounts for vibration damping, which increases machining accuracy;

– self-centering devices for mounting the workpiece on external and internal surfaces;

– a universal rotating grinding head for external and internal grinding, programmable for every 1.0° of rotation, and a device for adjusting the angle of the working elements;

– a set of diamond grinding wheels and a mechanism for their automatic change according to the program;

– a device for automatic dressing of the wheels as they wear out, controlled by the CNC system.

The machine's design, using a dedicated software subsystem, allows for the integration of machining and inspection operations directly on the machine for all stages of fairing grinding, significantly reducing the overall time required for its machining.

The results of the time analysis for implementing the TP option, compared to a traditional one, revealed the following. The CNC machining option reduces the time required for intermediate operations within the T_{Σ} structure as follows: auxiliary T_{ap} – by almost 14 times; finishing, as the most complex and critical operation, by 3 times. This reduces the overall fairing machining time by 3.3 times – from 49.0 hours to almost 15.0 hours, while maintaining the specified accuracy and quality of machining.

Based on the obtained results, it can be concluded that using CNC machines is rational for the machining of complex, thin-walled components, such as glass-ceramic rocket fairings. However, even in this case, the abrasive machining process results in the formation of a defective layer on the machined surfaces, which is unacceptable from the standpoint of ensuring the fairings' performance characteristics and requires a combined hardening operation.

The results of an analysis of existing manufacturing processes for large-size shell-type parts led to the conclusion that their effectiveness depends on the workpiece production method. Maximizing the configuration and dimensional accuracy of the workpiece to the corresponding part parameters allows for the significant elimination of labor-intensive and costly machining operations.

4.2 Possibilities of implementing additive technologies to produce antenna fairings from sitall

Additive manufacturing technologies for ceramic products offer significant opportunities for creating complex ceramic shells [15, 16]. Each method is based on the gradual deposition of material or its layer-by-layer formation in accordance with a 3D model of the product.

One of the most common methods is SLS (Selective Laser Sintering) [17-19]. SLS operates by sintering polymer powders of various ceramic components with a laser beam. These powders are applied layer by layer onto a special platform, and each layer is bonded with a liquid binder. After the process is complete, the resulting product undergoes a stage of removing the remaining binder and subsequent heat treatment in a furnace to achieve the desired density and strength.

The advantage of SLS technology is that other methods, which involve applying materials during wet molding [17], require heat treatment. This leads to chipping and cracking in thin-walled ceramic parts such as antenna fairings.

A schematic diagram of a part printed using SLS is shown in Figure 4.

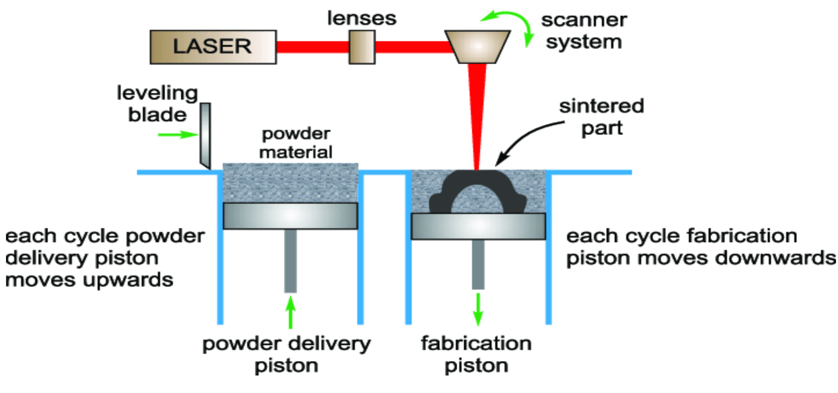

Figure 4 – Schematic diagram of the SLS method [20]

The main advantage of using additive manufacturing is its ability to solve the problem of workpiece production, where the profile of a workpiece obtained using conventional methods differeds significantly from the final product profile. This necessitated multi-stage machining (primarily abrasive machining with diamond tools), which resulted in the formation of a defective layer that must be removed during a combined hardening operation on the machined surfaces.

Additive manufacturing eliminates grinding operations, leaving only finishing operations for high-quality surfaces. This is because even with low material deposition rates during part formation, the surface quality obtained in an SLS machine will not always meet the requirements of the final product.

Based on the above, it is possible to develop an updated process for manufacturing parts such as antenna fairings from glass-ceramics using additive manufacturing as follows (Table 2).

Table 2 – Structure of the production process for manufacturing fairings from AC-418 sitall using SLS technology

Fairing manufacturing process		
Workpiece production technology:	Machining of the workpiece:	Combined hardening of machined surfaces:
- high-precision, high-quality workpiece production using SLS; - heat treatment of the workpiece to eliminate internal defects. .	- abrasive surface treatment (finishing operations – diamond finishing or lapping) to ensure the required precision and quality of the product (accompanied by the formation of a defective layer of shallow depth and rational structure).	- removal of the layer damaged by treatment with chemical etching; - hardening of the component surfaces by ion bombardment.

A comparison of two manufacturing processes for fairings made of AC-418 sitalls (basic traditional and using SLS technology) reveals the following advantages of additive manufacturing.

• The SLS method eliminates the need for traditional, consumable workpiece production technology.

• Knowing the material deposition rate during product formation on the SLS machine and the dimensions of the representative part, the total workpiece production time can be estimated at 7.5 hours.

• The precision and quality of the product surfaces formed under such conditions allow for the complete elimination of rough and fine grinding operations, leaving only the finishing abrasive operation if necessary.

• The fairing machining time is reduced to one hour when forming a defective layer with a favorable structure and shallow depth (due to gentle machining conditions at low cutting forces), which will reduce the time of the combined operation of the operation of the part.

• The total time spent on manufacturing the fairing will not exceed 10.0 hours, with lower costs for equipment and reorganization of production.

5. Conclusions

This article examines the manufacturing processes for complex-shaped shells made from difficult-to-machine materials, using a sitall-based rocket nose cone as an example. The need to improve existing manufacturing technologies for this class of components is substantiated.

This paper also includes:

1. The physical and mechanical properties of difficult-to-machine structural materials used to manufacture rocket system components, including nose cone antenna fairing, are examined.

2. The priority of using various ceramic materials for the manufacture of rocket and aerospace components, including rocket nose cone radomes, is confirmed.

3. The basic manufacturing process for the sitall nose antenna fairing is analyzed.

4. It is established and confirmed that the labor intensity of sitall nose cone manufacturing depends on the workpiece production method.

5. The need to use CNC machines to improve the efficiency of machining the sitall antenna fairing is substantiated.

6. The potential effectiveness of using additive manufacturing techniques in antenna fairing production is analyzed.

7. A rational method for blank production using additive manufacturing is presented – using SLS technology, which allows for minimizing subsequent machining requirements for the antenna fairing.

8. An improved technological process for manufacturing antenna fairing using SLS technology is presented.

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СУЧАСНІ МАТЕРІАЛИ І ТЕХНОЛОГІЇ ЇХ ОБРОБЛЯННЯ ЯК ФАКТОР РОЗВИТКУ АЕРОКОСМІЧНОЇ ТА РАКЕТНОЇ ПРОМИСЛОВОСТЕЙ

Анотація. *У статті розглядається вплив характеристик сучасних конструкційних матеріалів на розвиток аерокосмічної та ракетної промисловості. Підкреслюється зростаюча роль використання керамічних матеріалів, що мають унікальні властивості: термостійкість; високі твердість та міцність; стійкість до окислення та корозії; радіопрозорість; меншу щільність проти металів. Однак технічні кераміки відносяться до категорії важкооброблюваних* *матеріалів, що ускладнює процеси виготовлення відповідальних виробів з них, в тому числі головних обтічників ракет, літальних апаратів (ЛА). Обтічники ЛА - тонкостінні складно-профільні оболонки, до яких пред'являються підвищені вимоги щодо точності геометричних розмірів і форми, а також якості поверхонь. Вони виробляються з радіопрозорих крихких неметалевих матеріалів, в тому числі з різновиду склокераміки – ситалів. Сучасні заготівельні технології (здебільшого це шлікерна технологія або відцентрове литво) не дозволяють забезпечити точність форми виробу і потрібну якість його поверхонь на етапі отримання заготовки. Тому виріб піддається трудомісткій багатоетапній механічній обробці, а саме операціям чорнового і чистового шліфування алмазними інструментами, які супроводжуються крихким руйнуванням оброблюваного матеріалу і формуванням порушеного обробкою дефектного шару. Це є неприпустимим з точки зору забезпечення експлуатаційних характеристик обтічників і передбачає наявність заключної операції - комбінованого зміцнення порушеного обробкою шару. Запропоновано варіанти вдосконалення традиційних технологічних процесів виготовлення обтічників за рахунок використання для їх механічної обробки верстатів з ЧПК, що дозволяє підвищити продуктивність операцій абразивного оброблення. Встановлено, що максимальне наближення конфігурації і точності розмірів заготовки до відповідних параметрів деталі дозволяє у значній мірі відмовитися від трудомістких і витратних операцій механічної обробки. Це можливо за рахунок використання сучасних 3D-технологій друку. Виходячи з цього, обґрунтовано використання адитивної технології SLS при виробництві головних антенних обтічників ракет і представлений варіант удосконаленого технологічного процесу їх виготовлення.*

Ключові слова: *сучасні конструкційні матеріали; технічна кераміка; антенні обтічники ракет із ситалів; заготівельні технології; процеси шліфування виробів; якість і точність обробки; адитивні технології.*