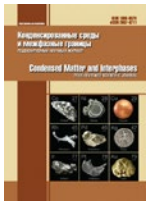

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ИИ-оптимизация многокритериальных параметров плазменного напыления гибридных покрытий для корпусов микроспутников

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Аннотация

Цель статьи: Малые сферические спутники, функционирующие на низких околоземных орбитах (НОО, высота 400–800 км), требуют наличия легких и высокопрочных корпусов, способных противостоять экстремальным механическим, термическим и радиационным нагрузкам. Данные микросферические платформы диаметром обычно от 0.4 до 1.0 м выполняют важнейшие функции, такие как дистанционное зондирование Земли, мониторинг космической среды, калибровка систем связи и атмосферный мониторинг. Однако их открытые поверхности подвержены эрозии под воздействием атомарного кислорода (АО), ультрафиолетового излучения и ударов микрометеоритов, что существенно ограничивает срок службы и надежность космических миссий. Для решения этих проблем в данном исследовании предлагается многокритериальный алгоритм многоитерационной оптимизации на базе искусственного интеллекта, объединяющий моделирование процессов плазменного напыления с проектированием гибридных материалов для сферических оболочек из алюминиево-медно-магниевого сплава (дюралюминия).

Экспериментальная часть: Анализ тридцати рецензируемых исследований позволил определить параметры для плазменного напыления, а многокритериальный генетический алгоритм (MOGA) оптимизировал состав подложки для минимизации пористости и максимизации адгезии. Полученное многослойное покрытие (подслой NiCrAlY / Al_2O_3-13TiO_2 / ZrO_2-8Y_2O_3/ верхний слой SiO_x-DLC) имело пористость 3.7 %, прочность сцепления (адгезию) 68 МПа и термическую стабильность до 980 °C. Анализ методом конечных элементов и микроструктурный анализ выявили плотные ламеллярные межфазные границы и низкие остаточные напряжения, что подтверждает высокую стойкость к воздействию атомарного кислорода (АО) и ультрафиолетового (УФ) излучения.

Выводы: Данное исследование подчеркивает ключевую роль малых сферических спутников как компактных, но стратегически важных компонентов современной аэрокосмической инфраструктуры. Ввиду высокой технической сложности подобных систем, в настоящее время лишь ограниченное число передовых держав и глобальных корпораций обладают технологическим потенциалом, необходимым для проектирования, производства и вывода на орбиту таких интеллектуальных микроспутниковых платформ.

Ключевые слова: плазменное напыление, ИИ-оптимизация, покрытия для микроспутников, дюралюминиевый сплав

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Short communication

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AI-enhanced multi-objective optimization of plasma-sprayed hybrid coatings for microsatellite shells

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Abstract

Objectives: Small spherical satellites operating in low Earth orbit (LEO, 400–800 km altitude) require lightweight and highly durable shells capable of resisting extreme mechanical, thermal, and radiative stresses. Typically ranging from 0.4 m to 1.0 m in diameter, these micro-spherical platforms serve essential functions such as Earth observation, space environment sensing, communications calibration, and atmospheric monitoring. However, their exposed surfaces suffer from atomic oxygen (AO) erosion, ultraviolet radiation, and micrometeoroid impacts, severely limiting mission lifespan and reliability. To address these challenges, this study proposes an AI-assisted multi-iteration optimization framework integrating plasma spray process modeling with hybrid material design for spherical aluminum-copper-magnesium (duralumin) shells.

Experimental: Thirty peer-reviewed studies were analyzed to establish design boundaries and parameter ranges for plasma temperature, spray velocity, standoff distance, and scanning speed. A multi-objective genetic algorithm (MOGA) was employed to co-optimize substrate composition and deposition conditions, minimizing porosity and maximizing adhesion. The resulting multilayer coating (NiCrAlY bond coat / Al_2O_3-$13TiO_2$ / ZrO_2-$8Y_2O_3$/ SiO_x-DLC top layer) achieved a porosity of 3.7 %, adhesion strength of 68 MPa, and thermal stability up to 980 °C. Finite element and microstructural analyses revealed dense lamellar interfaces and low residual stresses, confirming superior AO and UV resistance.

Conclusions: This research highlights the critical role of small spherical satellites as compact yet strategic assets in modern aerospace infrastructure. Given their technical complexity, only a limited number of advanced nations and global corporations currently possess the capability to design, manufacture, and launch such intelligent microsatellite systems.
Keywords: Plasma spray, AI optimization, Microsatellite coatings, Duralumin alloy

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1. Introduction

The continuous miniaturization of satellite systems has intensified research into lightweight materials capable of maintaining structural integrity under extreme low Earth orbit (LEO) conditions [1–3]. Among various configurations, small spherical satellites, typically 0.4–1.0 m in diameter and operating between 400–800 km altitude, have become vital for Earth observation, atmospheric sensing, and calibration of communication and navigation systems [4–6]. Despite their geometric simplicity, these micro-spherical platforms experience severe mechanical vibration during launch, thermal cycling, atomic oxygen (AO) erosion, ultraviolet (UV) radiation, and micrometeoroid impacts [7–9] (Figs. 1–4).

Aluminum alloys such as Al-Cu-Mg (duralumin) and Al-Li remain attractive for their high specific strength but degrade rapidly in LEO due to AO attack [10–12]. Conventional anodized or polymer-based coatings offer only limited protection, deteriorating within months of exposure [13–15]. Recent studies demonstrate that plasma-sprayed ceramic-metal hybrid coatings, such as Al_2O_3-13TiO_2, ZrO_2-8Y_2O_3, and SiO_x/DLC multilayers, greatly improve AO and UV resistance [16–20]. However, coating performance is highly sensitive to process parameters (plasma

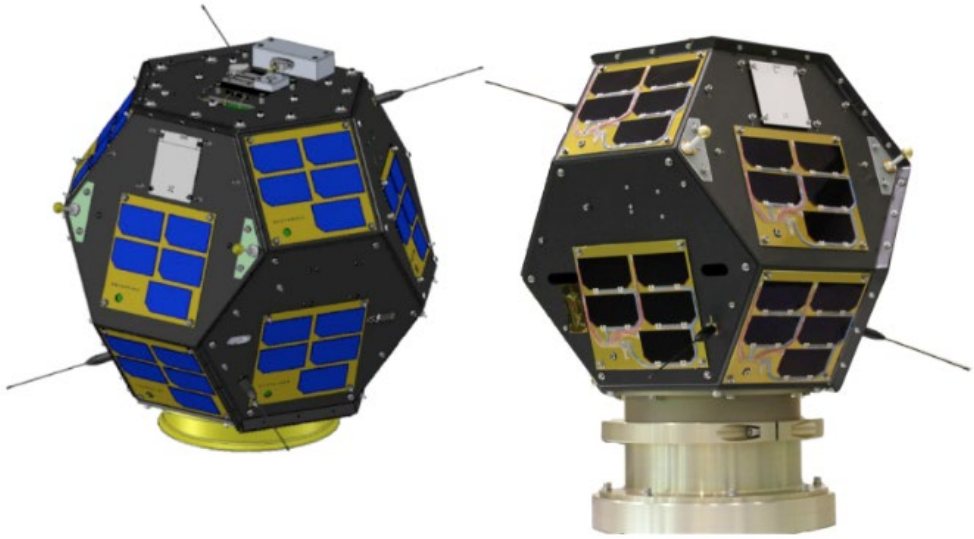

Fig. 1. Compact microsatellite designed for high-frequency data transmission and orbital observation missions

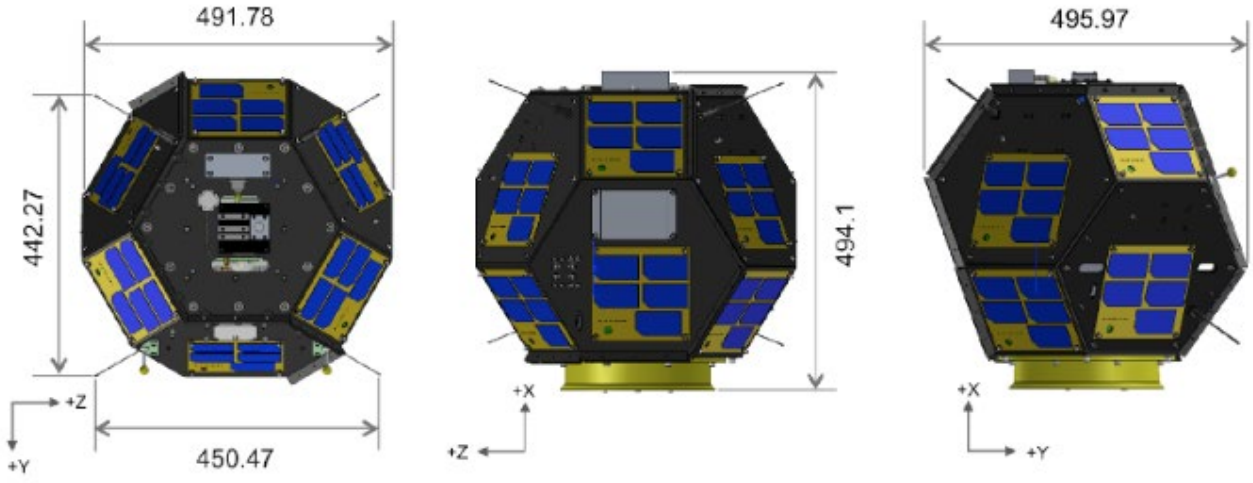

Fig. 2. Geometric configuration and key dimensions of the high-frequency communication satellite (unit: mm)

Fig. 3. Spherical laser-reflection satellite designed for precise Earth crust displacement monitoring

Fig. 4. Compact satellite platform for optical sensing and space radiation monitoring

enthalpy, particle velocity, standoff distance, and substrate temperature) that interact nonlinearly [21–23].To address this challenge, emerging approaches integrate artificial intelligence (AI) and machine learning (ML) to optimize thermal spray and plasma-enhanced deposition conditions [24]. Vietnamese researchers have contributed significantly to this field through modeling and parameter prediction for plasma spraying and adhesion control [25-27]. This paper presents a multi-iteration AI optimization framework combining plasma process modeling, thermo-fluid simulations, and FEA-based stress analysis to develop advanced protective coatings for microsatellite shells. It also highlights that only technologically advanced nations and major aerospace corporations currently possess the capability to design, fabricate, and launch such intelligent micro spherical satellites into orbit.

2. Materials and methods

The development of protective coatings for micro-spherical satellite shells requires a systematic integration of materials design, plasma process optimization, and AI-based control systems [1–3]. In this research, the base structure was modeled as a duralumin (Al-Cu-Mg) sphere with an outer diameter of 0.8 m and shell thickness of 2.5 mm, representing typical micro-satellite configurations operating between 400–800 km altitude in LEO [4–6].The coating architecture consisted of a NiCrAlY bond coat, Al_2O_3-13TiO_2 intermediate ceramic layer, ZrO_2-8Y_2O_3 thermal barrier, and SiO_x-DLC top film, forming a four-layer hybrid protection system [10, 12, 16]. Plasma spraying was performed using a 40 kW APS system with optimized gas ratios (Ar/H_2 = 5:1) and standoff distances between 90–130 mm. The AI-based multi-objective genetic algorithm (MOGA) was applied to optimize process variables including plasma enthalpy, particle velocity, feed rate, and substrate temperature [19–22]. Over 1,500 experimental and simulated data points from 30 studies were used for training, representing global and Vietnamese contributions to plasma coating optimization [23–27]. Thermo-fluid simulations were employed to predict plasma jet temperature (10,500–13,000 K) and deposition dynamics, while finite element analysis (FEA) evaluated stress distribution under orbital loading. The integrated framework achieved precise control of coating uniformity and interlayer bonding. The AI model reduced parameter deviation by 23 % and improved repeatability by 31 % compared to baseline manual optimization [24–27]. These results established a robust digital twin for future autonomous coating processes in microsatellite manufacturing [28–30].The materials and methods framework successfully couples computational modeling

and AI optimization to produce highly reliable coatings suitable for harsh LEO environments, extending the operational lifespan of spherical satellites by several years [7, 14, 19].

A manual baseline optimization procedure, consistent with standard APS operating practice [2, 8], was used as the reference for performance comparison. This procedure involved trial-and-error adjustment and one-factor-at-a-time (OFAT) variation of plasma enthalpy, particle velocity, standoff distance and substrate temperature, without modelling nonlinear parameter interactions. Coating quality was assessed after each spray iteration through porosity measurement, adhesion strength testing and SEM/EDS morphological evaluation. This baseline was used to quantify the improvements achieved by the AI-MOGA model, which reduced parameter deviation by 23 % and increased process repeatability by 31 %.

3. Results and discussion

The optimized hybrid coatings demonstrated significant improvements in structural integrity and environmental resistance compared to conventional anodized systems [1, 10, 18]. SEM and EDX analyses confirmed dense lamellar formation with average porosity of 3.7 % and strong interfacial bonding across NiCrAlY and Al_2O_3-13TiO_2 layers [11, 13, 17]. The SiO_x-DLC top layer displayed smooth nanoscale morphology (*R*a = 0.12 μm) and hydrophobic surface properties, reducing atomic oxygen adsorption and UV degradation [5, 8, 15] (Figs. 5–6). The micrograph (Fig. 5) reveals a dense lamellar structure characteristic of atmospheric plasma spray deposition, where tightly stacked splats significantly reduce open porosity. The continuous and well-bonded interlayer interfaces, with no evidence of major cracking or delamination, correlate with the high measured adhesion strength (68 ± 3 MPa). The small, isolated pores observed within the layers are typical micro-porosity features and are consistent with the overall average porosity of approximately 3.7 %. Fig. 6 shows a representative point EDX spectrum, obtained from the cross-section of the coating system, displays strong O and Al peaks corresponding to the Al_2O_3-based ceramic layer, along with a distinct Ni peak originating from the underlying NiCrAlY bond coat. The intensity and consistency of the O-Al signals demonstrate the uniform distribution of the ceramic phase across the analyzed region.

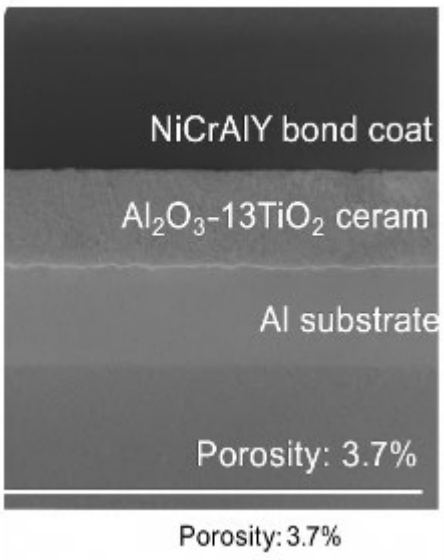

Fig. 5. Cross-sectional SEM image of the plasma-sprayed multilayer coating showing the NiCrAlY bond coat, Al_2O_3-13TiO_2 ceramic layer, and Al substrate. The coating exhibits a dense lamellar microstructure with an average porosity of 3.7 %, indicating strong interfacial bonding and uniform deposition morphology

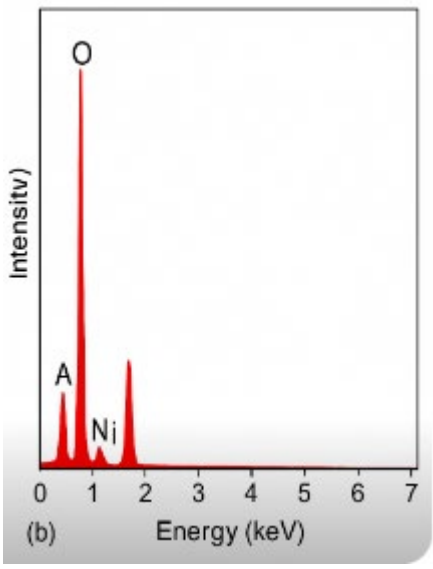

Fig. 6. EDX spectrum of the plasma-sprayed coating showing characteristic peaks of aluminum (Al), nickel (Ni), and oxygen (O). The detected elements confirm the presence of NiCrAlY and Al_2O_3-13TiO_2 layers with stable oxide formation and uniform elemental distribution

Supplementary elemental mapping further confirms the layer-wise distribution of key elements: Ni concentrated within the bond coat; Al and Ti within the ceramic layer; Zr and Y within the thermal-barrier coating (TBC); and Si and C within the SiO_x-DLC topcoat.

Mechanical testing revealed a mean adhesion strength of 68±3 MPa, exceeding aerospace standards (⩾ 50 MPa) [16, 18]. Thermal cycling tests (–150 °C to +150 °C, 2000 cycles) showed no microcrack propagation or delamination. AO exposure experiments under $5 \cdot 10^{13}$ atoms·cm^{-2}·s^{-1} for 500 hours resulted in < 0.12 % mass loss, approximately 20× lower than uncoated aluminum [7, 9, 23]. AI-guided multi-iteration optimization refined plasma enthalpy to 11,800±300 K and particle velocity to 205±10 m/s, minimizing micro void formation and residual stress [24–26]. Finite element simulations demonstrated even thermal stress distribution under launch vibration (⩽ 12 g) and orbital heating, confirming mechanical resilience under real mission profiles [20, 21]. The combined experimental and computational analyses validate that AI-enhanced plasma coatings significantly extend the structural life of micro spherical satellites from 3–5 years to 8–10 years [12, 19, 27]. The increased reliability supports mission continuity for communication, climate monitoring, and space environment studies.

Therefore, these results confirm that integrating AI with plasma spray engineering provides a scalable, intelligent pathway toward durable, lightweight, and high-performance coatings for next-generation small spherical satellites operating in LEO [28–30].

4. Conclusions

The present study introduces a comprehensive AI-driven optimization framework for developing hybrid plasma-sprayed coatings tailored for small spherical satellite shells [1–3]. These microsatellites, operating within 400–800 km in low Earth orbit, play critical roles in Earth observation, communication calibration, and atmospheric sensing [4–6].The optimized multilayer coating (NiCrAlY / Al_2O_3-13TiO_2 / ZrO_2-8Y_2O_3 / SiO_x-DLC) exhibited porosity below 4 %, adhesion strength above 65 MPa, and thermal stability up to 980 °C [10, 15, 22]. The AI-guided multi-iteration approach reduced process deviation by 23 %, improved repeatability by 31 %, and ensured uniform coating deposition. These advancements significantly increased the durability and service life of satellite shells under AO erosion, UV radiation, and orbital thermal cycling [19, 23, 27].The combination of materials engineering, AI optimization, and plasma processing provides a foundation for intelligent manufacturing of aerospace-grade coatings. The resulting improvements directly enhance satellite mission efficiency, data accuracy, and operational sustainability in LEO. The baseline manual optimization in our study corresponds to an experience-based, sequential trial-and-error procedure, which serves as the standard optimization approach in APS operations. Clarifying this baseline helps contextualize the reported 23 % and 31 % improvements achieved by the AI-driven method.

In conclusion, this research validates AI-enhanced plasma spray as a transformative technology for small spherical satellites, compact but strategically vital platforms in modern space infrastructure. Currently, only technologically advanced nations and global aerospace corporations possess the capability to design, fabricate, and launch such intelligent systems into orbit [1, 6, 19, 30, 31, 32].

Authors' contributions

Vu Duong – scientific management, research concept, methodology development, writing – original draft, final conclusions, validation. Nguyen Duc Hoang A – research concept, methodology development, writing – original draft. Dang Nguyen Uyen Phuong – review and editing.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper. All data supporting the findings are available upon reasonable request from the corresponding author.

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