DOI: 10.54254/2755-2721/70/20240975

Soft nanotechnology: Used as a functional coating on a nanostructured germicidal surface

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Abstract. Bacterial contamination has emerged as a significant threat to human health over the past century. Initially, antibiotics were seen as the solution to this problem, but their overuse has led to the development of drug resistance and the rise of "superbugs." These superbugs are resistant to most, if not all, conventional antibiotics, making them particularly difficult to treat. Interestingly, research has shown that the wings of dragonflies and cicadas possess natural nanopillar structures that are capable of inhibiting bacterial growth. These nanopillars puncture bacterial cell membranes, leading to bacterial death. This discovery has opened up new avenues for combating bacterial contamination. Recent advancements in soft nanotechnology have introduced innovative antibacterial coatings that are crucial for combating these antibiotic-resistant superbugs. These coatings work by mimicking the nanopillar structures found on the wings of dragonflies and cicadas. Understanding the interaction between bacteria and these nanoantibacterial coatings is essential for achieving effective bactericidal outcomes. Different bacteria require varying optimum aspect ratios, which can be achieved through various formation methods. Therefore, this paper elucidates the principles of soft nanocoating, with a focus on comparing aspect ratios obtained through different preparation techniques and, according to the different aspect ratio, determining the corresponding applicable sterilization scene. It also explores the practical application of nanostructure bactericidal surface coatings to address the growing threat of antibiotic resistance and enhance public health. Moreover, as an emerging field, this paper examines the challenges in soft nanocoating applications and the directions that can be improved in the future. The versatility and potential of soft nanotechnological coatings seems to apply to various industries, promising enhanced performance and safety standards. This is a crucial step towards creating a safer and healthier future for all.

Keywords: Soft Nanotechnology, Antibacterial Surfaces, Aspect Ratio, Functional Coatings

1. Introduction

With the rapid advancement of science and technology, nanotechnology has emerged as a pivotal force driving innovation across various sectors. Its versatility and applicability have sparked significant interest, particularly in materials science, medicine, and environmental conservation. Notably, nanotechnology has reshaped diagnostic procedures, treatment methodologies, and drug delivery systems, ushering in a new era of precision and efficacy.

Among its branches, soft nanotechnology stands out for its remarkable flexibility and cost-effectiveness, garnering attention for its potential applications. Of particular interest is its promise in coating technology, notably in the development of antibacterial coatings. This is especially true when it comes to biomimetic aspect ratio nanostructures on PET surfaces [1]. This study seeks to explore the feasibility of leveraging soft nanotechnology to create bactericidal surface coatings through nanostructure engineering.

The investigation entails theoretical analyses to gauge the viability and efficacy of soft nanotechnology in fabricating nanostructured surfaces with antibacterial properties. Additionally, it aims to address the challenges inherent in the manufacturing and implementation processes of soft nanotechnology, including evaluating various coating preparation methods and comparing their resultant aspect ratios.

Furthermore, this research endeavors to compare the performance of soft nanotechnology with existing state-of-the-art techniques in antimicrobial coating preparation. By doing so, it aims to provide insights into the advantages and limitations of soft nanotechnology in the realm of antibacterial coatings, thereby offering valuable guidance for future research and practical applications.

2. Definition and application of soft nanotechnology

2.1. Advanced bactericidal surface coating technology for nanostructures

Soft nanotechnology, a pioneering approach in the field of nanoscience, is revolutionizing the fabrication of functional coatings by harnessing the power of nanoscale materials and structures. One of the key players in this domain are metal nanoparticles, which have demonstrated potent interactions with viral or bacterial glycoproteins. These nanoparticles can penetrate infected cells and disrupt their genome, effectively halting replication processes and rendering various microorganisms inactive.

Non-enveloped viruses, in particular, are notably sensitive to metal particles. This sensitivity enhances their susceptibility to interaction with viral surfaces, making them prime targets for neutralization. Even enveloped viruses, which are typically more resistant, can have their outer envelopes neutralized through various chemical and physical methods, further expanding the scope of soft nanotechnology’s antimicrobial capabilities.

Research has also indicated that the physical structure of nanomaterials can compromise the integrity of microbial walls and membranes. This ability to disrupt these crucial structures provides another avenue for neutralizing harmful microorganisms [2].

In the specific domain of nanobactericidal surface coatings, soft nanotechnology stands out prominently. By leveraging the unique properties of nanostructures, such as nanoparticles, it is possible to construct coatings endowed with potent antibacterial functionalities. These nanostructures operate at the microscopic level, effectively rupturing bacterial cell membranes and eradicating bacteria, thus achieving significant antibacterial effects.

Advanced soft nanotechnology takes this a step further by allowing precise control and optimization of antibacterial efficacy. By modulating the shape, size, and density of nanostructures, scientists can fine-tune the antibacterial properties of these coatings, maximizing their effectiveness while minimizing potential side effects. This level of control is a testament to the power and potential of soft nanotechnology, and its role in shaping the future of functional coatings and beyond.

2.2. Application of soft nanotechnology in functional coatings

Past research highlights the widespread application of soft nanotechnology in functional coatings, particularly in the development of nanobactericidal surface coatings. Scientists have made significant strides in inhibiting and eliminating various strains of bacteria by tailoring nanostructures within coatings [3]. These findings underscore the importance of embracing soft nanotechnology in the creation of antibacterial surface coatings, paving the way for further refinement and progress.

Soft nanotechnology refers to the manipulation of soft matter, such as polymers, gels, and biomolecules, at the nanoscale, to create novel structures and functions. Soft nanotechnology offers a promising avenue for advancing nanobactericidal surface coatings, which are coatings that can kill or prevent the growth of bacteria on surfaces. By leveraging the principles and advantages of soft nanotechnology, such as self-assembly, flexibility, and biocompatibility, and building upon previous research, the field can drive innovation in the preparation and application of antibacterial coatings. For example, soft nanotechnology can be used to design and fabricate nanostructured coatings that can release antibacterial agents, such as silver or copper nanoparticles, in a controlled manner, or that can mimic the natural antibacterial properties of biological surfaces, such as lotus leaves or shark skin [4]. This innovative approach holds the potential to yield more reliable and effective solutions for combating bacterial contamination on surfaces, thereby contributing to enhanced hygiene and safety standards in various settings, such as healthcare, food, and water. Overall, the integration of soft nanotechnology into the development of nanobactericidal coatings represents a significant step forward in the fields of surface engineering and antimicrobial technology.

3. Method and manufacturing feasibility of soft nanotechnology in coating preparation

3.1. Overview of the methods for preparing soft nanocoatings

Soft nanotechnology is a branch of nanoscience that deals with the synthesis and application of nanoscale materials that have soft or flexible properties, such as polymers, gels, and liquids. One of the main challenges in soft nanotechnology is to fabricate soft nanocoatings that can modify the surface properties of various substrates, such as metals, ceramics, glass, and plastics. Soft nanocoatings can provide enhanced functionalities, such as self-healing, anti-fouling, anti-corrosion, anti-wear, and anti-reflective properties, depending on the composition and structure of the nanomaterials used. There are several methods for preparing soft nanocoatings, each with its own advantages and disadvantages. Some of the most common methods are plasma spraying (Plasma Spraying), electron beam physical vapor deposition (EB-PVD), sol-gel method (Sol-Gel), immersion coating method (Dipping Coating), electrophoretic deposition (Electrophoretic Deposition) and others.

3.2. Different process methods for evaluating the coating preparation

Plasma Spraying: This method uses an ionized gas, or plasma, as a heat source to melt or semi-melt the coating materials, which are usually in the form of powders or wires. The molten or semi-molten materials are then sprayed onto the substrate surface at high speed, forming a coating layer. This method can produce coatings with high adhesion, high density, and high hardness, as well as enhance the surface properties of the substrate, such as wear resistance, corrosion resistance, and high-temperature oxidation resistance. However, this method also has some drawbacks, such as high cost, high energy consumption, high noise, and high thermal stress on the substrate. Moreover, this method is not suitable for coating materials that are sensitive to high temperatures or oxidation, such as organic polymers or biological materials [6].

EB-PVD (Electron Beam Physical Vapor Deposition): This method involves evaporating the coating materials onto the substrate surface using a high-speed electron beam, which is generated by a high-voltage power supply. The electron beam heats up the coating materials, which are usually in the form of ingots or pellets, in a vacuum chamber, causing them to vaporize and condense on the substrate surface, forming a dense and uniform coating layer. This method can produce coatings with high purity, low porosity, and low stress, as well as control the microstructure and crystal orientation of the coating materials. However, this method also has some limitations, such as its high cost, low deposition rate, and complex equipment. Furthermore, this method is not suitable for coating materials that have low vapor pressure or a high melting point, such as ceramics or metals.

Sol-Gel: This method utilizes easily hydrolyzed precursors and water-reactive precursors in a solvent, such as water, alcohol, or acetone, to form a sol, which is a colloidal suspension of nanosized particles. The sol is then applied to the surface of the substrate, either by dipping, spraying, spinning, or brushing, forming a thin and wet film. Upon drying and heat treatment, the sol transforms into a gel, which is a solid network of interconnected nanoparticles, ultimately forming a uniform and transparent coating layer. This method can produce coatings with low cost, low temperature, and high versatility, as well as tailor the chemical composition and structure of the coating materials. However, this method also has some challenges, such as long processing time, cracking and peeling of the coating layer, and difficulty in controlling the thickness and uniformity of the coating layer. Moreover, this method is not suitable for coating materials that are insoluble or unstable in the solvent, such as metals or carbon [5].

Dipping Coating: This method involves immersing the substrate into a liquid, which contains the coating materials, such as polymers, solvents, additives, and fillers. The liquid adheres to the substrate surface due to surface tension and capillary forces, forming a wet film. Upon drying and curing, the liquid solidifies, forming a coating layer. This method can produce coatings with low cost, simple equipment, and high compatibility, as well as adjust the viscosity and concentration of the liquid. However, this method also has some drawbacks, such as low deposition rate, low coating quality, and high environmental impact. Furthermore, this method is not suitable for coating materials that are volatile or reactive in the liquid, such as organic solvents or acids.

Electrophoretic Deposition: This method deploys an electric field to drive charged particles, such as nanoparticles, nanotubes, or nanowires, onto the substrate surface, which is usually immersed in a liquid medium, such as water or organic solvent. The electric field induces electrophoresis, which is the movement of charged particles under the influence of an electric field, and electrostatic attraction, which is the attraction between particles with opposite charges. The charged particles accumulate on the substrate surface, forming a dense and compact coating layer. This method can produce coatings with high efficiency, high quality, and high flexibility, as well as control the thickness and composition of the coating layer. However, this method also has some challenges, such as the high voltage requirement, complex medium preparation, and limited coating area. Moreover, this method is not suitable for coating materials that are neutral or poorly dispersed in the liquid medium, such as metals or ceramics.

These methods offer diverse approaches to achieving desired coating properties, catering to various applications and substrate materials [6].

3.3. Compare the efficiency and feasibility of these methods

Plasma Spraying and EB-PVD techniques excel in applying coatings over large surface areas, making them ideal for complex geometries and diverse substrates. These methods can produce coatings with high performance and durability, as well as modify the surface properties of the substrates. However, these methods also have high cost and energy consumption, as well as require sophisticated equipment and skilled operators. Moreover, these methods are not suitable for coating materials that are sensitive to high temperatures or oxidation, such as organic polymers or biological materials.

On the other hand, Sol-Gel and Dipping Coating methods specialize in producing thin film coatings characterized by exceptional uniformity and transparency, suitable for optical and electronic applications where precision is paramount. These methods can produce coatings with low costs and low temperatures, as well as tailor the chemical composition and structure of the coating materials. However, these methods also have a long processing time, cracking and peeling of the coating layer, and difficulty in controlling the thickness and uniformity of the coating layer. Moreover, these methods are not suitable for coating materials that are insoluble or unstable in the solvent, such as metals or carbon.

Electrophoretic Deposition stands out for its efficiency in depositing coatings while offering precise control over thickness and composition, making it a preferred choice for achieving tailored coating properties. This method can produce coatings with high quality and flexibility, as well as apply coatings on various substrates and shapes. However, this method also has a high voltage requirement, complex medium preparation, and a limited coating area. Moreover, this method is not suitable for coating materials that are neutral or poorly dispersed in the liquid medium, such as metals or ceramics.

Table 1. The brief theory and characteristics of the different methods

Method	Theory	Characteristic
Plasma Spraying	The solid powder is melted by plasma flame and sprayed onto the substrate surface	Suitable for large area coating, but the nanostructure control is relatively difficult
EB-PVD	The material is evaporated and deposited onto the substrate surface by an electron beam	Provides a uniform sheet coating with a high aspect ratio for high-precision applications
Sol-Gel	The dissolved metal precursor is used to form a gel, which is then heat-treated to form a coating	With high aspect ratio control ability, suitable for complex structures and multi-layer coatings
Dipping Coating	The substrate is soaked in a solution containing the material to form a coating	simple and easy, suitable for the preparation of some simple coatings, but the aspect ratio control is relatively simple
Electrophoretic Deposition	An electric field is used to deposit charged particles onto the electrode surface to form a coating	Uniform deposition of nanoparticles, suitable for complex shapes and high efficiency coating preparation

3.4. Compare the resulting aspect ratios of these methods

Coatings produced through Plasma Spraying and Electron Beam Physical Vapor Deposition (EB-PVD) are known for their high aspect ratio. This characteristic is a measure of the length to width ratio of a structure, and in the case of these coatings, it translates to superior strength and wear resistance. These properties make them ideal for applications in industries such as aerospace and automotive, where durability and longevity are paramount.

On the other hand, coatings derived from Sol-Gel and Dipping Coating methods typically possess a lower aspect ratio. While they may not offer the same level of strength and wear resistance, they excel in optical and electronic applications due to their uniformity. The smooth, even surface created by these methods allows for precise control over light transmission and reflection, making them ideal for applications such as optical lenses and electronic displays.

Electrophoretic Deposition (EPD) strikes a balance between these extremes. This method offers moderate aspect ratios, which provide a good balance of strength and uniformity. In addition, EPD is known for its excellent sealing properties and film formation capabilities. This makes it a versatile choice for a wide range of applications, from corrosion protection in automotive parts to the creation of high-quality ceramic films for electronic devices.

In conclusion, the choice of coating method depends on the specific requirements of the application. Whether it’s the high strength of Plasma Spraying and EB-PVD, the optical precision of Sol-Gel and Dipping Coating, or the versatility of EPD, each method offers unique advantages that can be leveraged to meet the demands of various industries. Understanding these principles is crucial for the development and application of effective coating solutions.

4. Practical applications of nanostructured bactericidal surface coatings and performance comparison

4.1. Challenges and limitations in practical application

There are indeed significant challenges and limitations in the practical application of nanostructures. Firstly, the high cost and technical complexity of the preparation process hinder widespread adoption. The need for advanced equipment and technologies escalates production expenses and restricts large-scale implementation. Secondly, ensuring the stability and durability of nanomaterials poses a considerable challenge, with certain nanostructures susceptible to degradation or failure over time [7].

This limitation compromises their long-term effectiveness in various applications. Moreover, guaranteeing the safety and biocompatibility of nanomaterials is crucial to preventing adverse effects on human health and the environment. These factors underscore the necessity for comprehensive assessment and mitigation strategies to address the challenges associated with nanostructure applications.

4.2. Effect of soft nanotechnology on the bactericidal surface properties of nanostructures

Soft nanotechnology is instrumental in optimizing bactericidal surface coatings on nanostructures, offering precise control over shape, size, and density. This control enhances coating stability, reliability, and antibacterial efficacy by tailoring nanostructures to disrupt bacterial cell membranes effectively.

Moreover, soft nanotechnology improves biocompatibility, reducing health risks associated with nanomaterial usage. Ensuring compatibility with biological systems prevents adverse reactions, bolstering coating effectiveness and safety.

This technology finds diverse applications, from medical devices preventing infections to food packaging preserving freshness and preventing contamination. Ultimately, soft nanotechnology holds promise for addressing public health and food safety challenges by reducing bacterial contamination threats.

In essence, soft nanotechnology's ability to enhance bactericidal surface coatings on nanostructures presents a compelling solution to combat bacterial contamination effectively, promising a safer and healthier future.

4.3. Expected properties of soft-nanotechnology coatings

Soft nanotechnological coatings are highly esteemed for their multifaceted benefits, including potent antimicrobial properties, exceptional stability, and robust biocompatibility. Crafted with precision through soft nanotechnology, these coatings exhibit unparalleled effectiveness in combating bacteria. Their remarkable durability and resilience ensure prolonged efficacy even in harsh environments, providing dependable protection against corrosion and wear [8]. Moreover, their biocompatibility and safe nature make them suitable for a wide array of applications, from medical devices to food packaging, instilling confidence in their reliability [9]. This amalgamation of attributes highlights the versatility and potential of soft nanotechnological coatings across various industries, promising enhanced performance and safety standards.

4.4. Performance comparison with the state-of-the-art technology

Soft nanotechnology coatings offer several advantages over state-of-the-art technologies. Firstly, they provide more efficient antibacterial properties and longer stability by precisely regulating nanostructure characteristics, contrasting traditional sterilization methods with their limitations. Secondly, these coatings exhibit better biocompatibility and safety, meeting material safety requirements in medical devices and food packaging. However, their high cost due to advanced materials and technologies is a drawback compared to some advanced alternatives [10]. Additionally, as a relatively new technology, the technical maturity of nanostructured bactericidal coatings may not match extensively verified advanced technologies, leading to uncertainty in performance stability [11]. Moreover, while effective in specific scenarios, their limited applicability compared to state-of-the-art technologies necessitates further research for practical application validation.

5. Conclusion

In the domain of nanostructured bactericidal surface coatings, soft nanotechnology exhibits remarkable promise. By crafting nanostructures with a focus on their aspect ratio, soft nanotechnology achieves efficient bacteria eradication, resulting in potent antibacterial surface coatings. These nanostructures disrupt bacterial cell membranes at the microscopic level, effectively eliminating bacteria and ensuring antibacterial efficacy. Soft nanotechnology enables precise control and optimization of antibacterial effects through modulation of nanostructure shape, size, and density. Future research can further explore soft nanotechnology's potential in nanostructured bactericidal coatings across diverse fields. Investigations may concentrate on enhancing antibacterial efficacy and stability by refining the regulation of nanostructures, offering applications in medical devices, food packaging, and beyond. In summary, soft nanotechnology opens new avenues for research and application in nanobactericidal coatings, heralding more reliable solutions for advancing antibacterial coating technologies.

References

[1] Roy, A., Patil, D., Yarlagadda, P. K., & Chatterjee, K. (2023). Cooperative stiffening of flexible high aspect ratio nanostructures impart mechanobactericidal activity to soft substrates. Journal of Colloid and Interface Science, 652, 2127-2138.
[2] Galdiero, S., Falanga, A., Vitiello, M., Cantisani, M., Marra, V., & Galdiero, M. (2011). Silver nanoparticles as potential antiviral agents. Molecules, 16(10), 8894-8918.
[3] Ivanova, E. P., Hasan, J., Webb, H. K., Truong, V. K., Watson, G. S., Watson, J. A., ... & Crawford, R. J. (2012). Natural bactericidal surfaces: mechanical rupture of Pseudomonas aeruginosa cells by cicada wings. Small, 8(16), 2489.
[4] Huan, Y., Wu, K., Li, C., Liao, H., Debliquy, M., & Zhang, C. (2020). Micro-nano structured functional coatings deposited by liquid plasma spraying. Journal of Advanced Ceramics, 9, 517-534.
[5] PENG Xia-wen, ZENG Xiao-jun, ZHANG Xiao-feng, TIAN Wei. A Review of Preparation, Properties and Applications of Functional Nano-Coatings[J]. Materials Protection, 2023, 56(5): 16-30
[6] Amirtharaj Mosas, K. K., Chandrasekar, A. R., Dasan, A., Pakseresht, A., & Galusek, D. (2022). Recent Advancements in Materials and Coatings for Biomedical Implants. Gels (Basel, Switzerland), 8(5), 323.
[7] Quintão, C. C. R., Camargo, L. S. A., Brandão, H. M., Saraiva, N. Z., & Munk, M. (2022). Challenges in the use of nanostructures as carriers of nucleic acids in clinical practice. Einstein (Sao Paulo, Brazil), 20, eRB5898.
[8] Schubert, J., & Chanana, M. (2018). Coating Matters: Review on Colloidal Stability of Nanoparticles with Biocompatible Coatings in Biological Media, Living Cells and Organisms. Current medicinal chemistry, 25(35), 4553–4586.
[9] Basavegowda, N., & Baek, K. H. (2022). Combination Strategies of Different Antimicrobials: An Efficient and Alternative Tool for Pathogen Inactivation. Biomedicines, 10(9), 2219.
[10] Zhu, Q., Chua, M. H., Ong, P. J., Lee, J. J. C., Chin, K. L. O., Wang, S., ... & Loh, X. J. (2022). Recent advances in nanotechnology-based functional coatings for the built environment. Materials Today Advances, 15, 100270.
[11] Rutala, W. A., & Weber, D. J. (2015). Disinfection, Sterilization, and Control of Hospital Waste. Mandell, Douglas, and Bennett's Principles and Practice of Infectious Diseases, 3294–3309.e4.