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Plasma treatment for producing hydrophobic and hydrophilic coatings on fabric surfaces

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This study examines the formation of hydrophilic and superhydrophobic surfaces using atmospheric-pressure plasma jets, with a particular emphasis on developing durable waterproof coatings for textile materials. The effects of plasma treatment on the structural and chemical properties of the substrates were analyzed, along with the influence of key technological parameters such as discharge power and the composition of the plasma-forming gas. Argon (Ar) was used as the primary plasma gas, while hexamethyldisiloxane (HMDSO) vapor served as the precursor for hydrophobic coating formation. Surface hydrophilicity was evaluated after one and ten treatment cycles using Ar plasma at a flow rate of 40 mL/s and a discharge power of 200 W. Superhydrophobic coatings were produced under similar plasma conditions, with a gas mixture of Ar + HMDSO introduced at 20 mL/min. Contact angle measurements were performed to assess changes in wettability and to quantify the hydrophilic or superhydrophobic character of the treated surfaces. The results demonstrate that plasma treatment enables effective tuning of surface hydrophobicity and that the resulting coatings exhibit stable performance when exposed to various liquids.

Keywords: surface treatments, liquid-solid interfaces, superhydrophobic, hydrophilic, fabric.
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1. Introduction

In recent years, plasma technologies have attracted increasing attention due to their numerous advantages. Unlike traditional surface modification methods, plasma treatment does not require the use of liquid reagents and does not generate wastewater, making it an environmentally friendly approach. Moreover, the application of non-polymerizing plasma enhances the adhesion properties of materials and increases their hydrophilicity [1].

Significant advancements in atmospheric-pressure plasma processing technologies [2] have opened new opportunities for industrial implementation, making such processes more competitive compared to vacuum plasma methods [3]. These improvements enable processing under conditions typical of standard production equipment, without the need for vacuum generation or the use of expensive reactive gases such as argon or carbon tetrafluoride [4-8].

The application of plasma technologies allows for targeted modification of surface characteristics, including adhesion, surface energy, and wettability. However, despite substantial progress in atmospheric-pressure plasma (APP) treatment [9], the development of effective methodologies based on a single plasma source remains a critical challenge. Most studies to date have focused on individual aspects of surface modification, highlighting the need for a comprehensive approach to understanding the mechanisms that regulate surface properties. Controlling surface wettability plays a key role in various technological processes, including textile production [10-12], packaging materials [13], biomedical hydrophobic coatings [14-16], and filtration systems [17]. One of the most promising surface modification methods is atmospheric-pressure plasma jet treatment, which enables changes in material hydrophilicity and hydrophobicity without the use of aggressive chemical reagents [18-20]. This method is characterized by high efficiency, the ability to achieve localized effects, and environmental safety.

Despite the active development of this field, several challenges remain, including the durability of the obtained coatings [21-27], the optimization of processing parameters, and the adaptation of the technology for industrial applications. This study investigates the mechanisms of hydrophobic and hydrophilic surface formation using atmospheric-pressure plasma jets, evaluates the effects of treatment conditions on fabric properties, and analyzes the stability of modified materials under external influences. The results obtained may contribute to the development of innovative functional coatings for various industrial applications.

2. Experimental section

The experimental setup designed for the study of hydrophilic and superhydrophobic coatings obtained using a plasma jet based on a high-frequency discharge at atmospheric pressure is schematically presented in Figure 1. The formation of the plasma flow was carried out using an RF generator, which provided a discharge between a copper conductor, insulated with quartz glass, and a grounded copper plate. A quartz tube with a length of 100 mm, an inner diameter of 3 mm, and an outer diameter of 10 mm was used for plasma generation. The power source was a high-frequency generator Seren-R 301 operating at a frequency of 13.56 MHz. Argon (Ar) was used as the main gas supplied to the system, while hexamethyldisiloxane (Purity: ≥99.0%) was used as the precursor. Since HMDSO is in a liquid state at room temperature, its dosing was performed through a bubbler. Gas flow regulation was ensured by a mass flow controller.

Main provision: In this study, hydrophilic and hydrophobic coatings were formed using a radio-frequency discharge method at atmospheric pressure. An analysis of their wetting properties was performed, and the dynamics of changes in coating characteristics during operation were examined. At a fixed power of the setup, the degree of hydrophilicity and hydrophobicity was tested in various experimental cycles, and the stability of the coatings on fabrics was evaluated under exposure to different types of liquids.

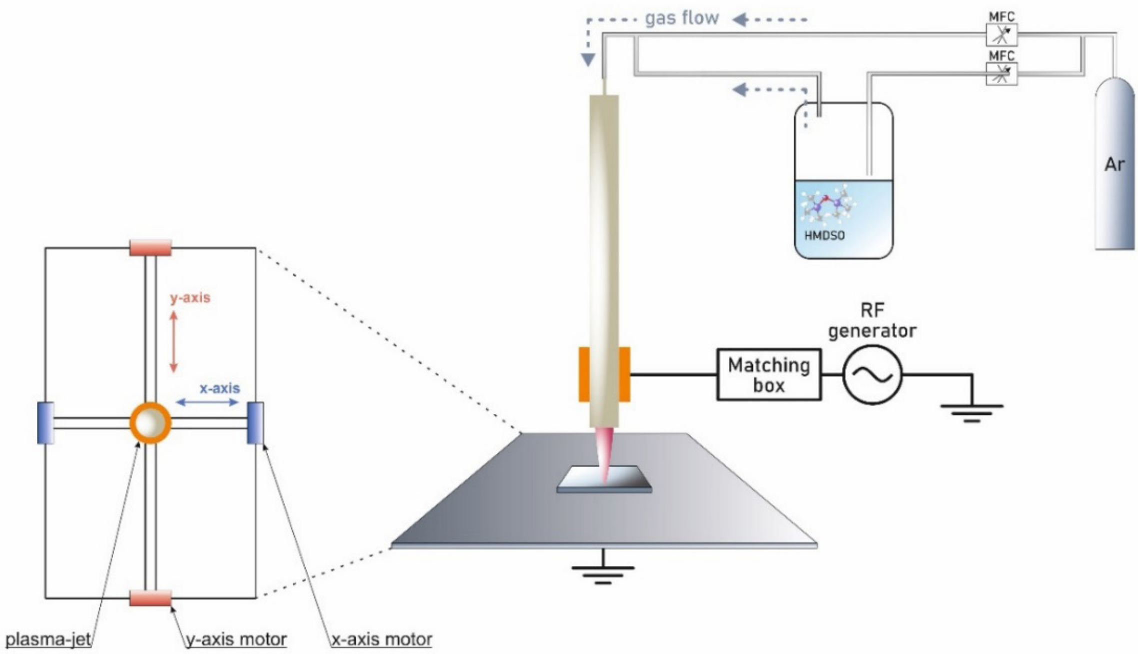

Figure 1 – Scheme of experimental setup.

3. Results an discussion

Experiments were conducted to determine the optimal conditions for the formation of hydrophilic and superhydrophobic coatings. In the initial stage, argon (Ar) was used as the sole gas medium to obtain hydrophilic surfaces. The dependence of the contact angle on the number of plasma treatment cycles was studied under the following parameters: a discharge power of 200 W, a pulse frequency of 1000 Hz, an Ar flow rate of 40 cm³/s, and a number of cycles ranging from 1 to 10. Figure 2a presents a graph of the relationship between the number of cycles and the contact angle. It was established that as the number of cycles increased, the treated surface exhibited more pronounced hydrophilic properties. This can be explained by the fact that prolonged exposure to argon plasma enhances hydrophilicity due to the removal of organic contaminants, surface activation, and an increase in the concentration of polar functional groups resulting from interactions with active plasma species.

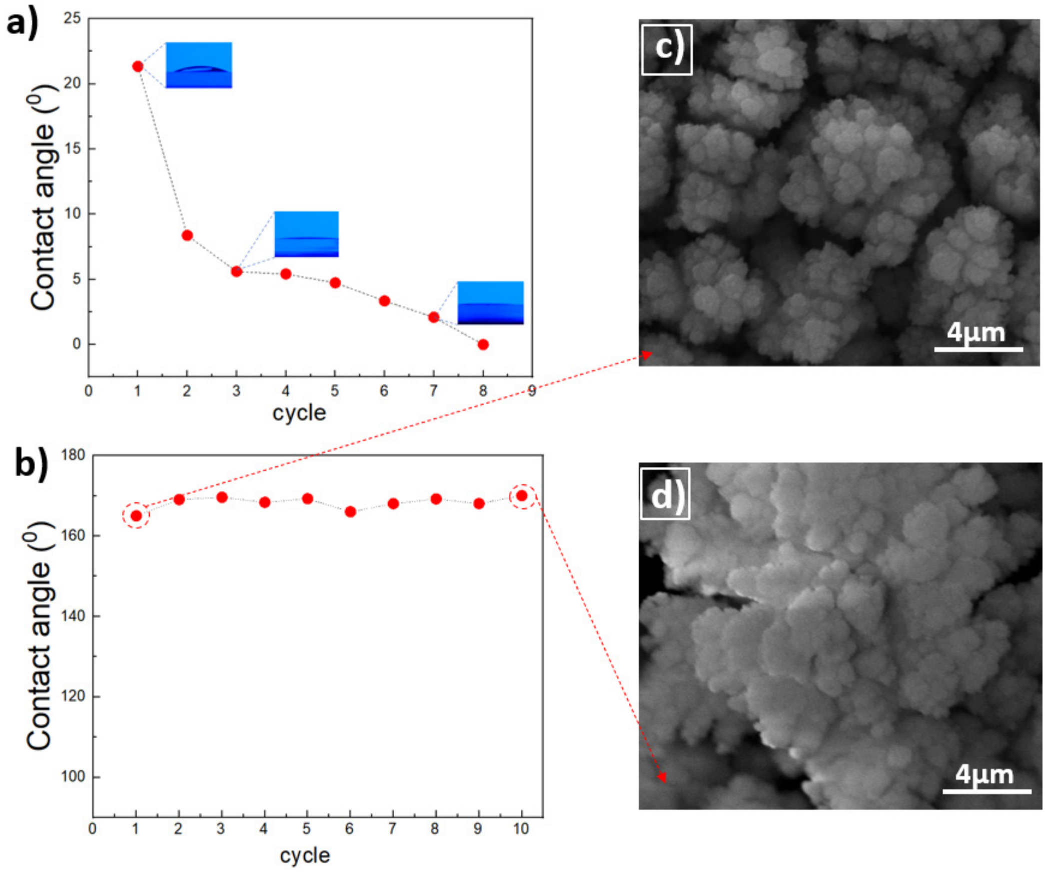

Figure 2 – Graphs of the dependence of the number of cycles for hydrophilic (a) and superhydrophobic (b) surfaces. SEM images of superhydrophobic coating after one (c) and ten (d) cycles.

In the study of the superhydrophobic properties of the coatings, the following parameters were used: a discharge power of 200 W, a pulse frequency of 1000 Hz, a primary argon flow rate of 40 cm³/s, a secondary gas flow rate (Ar + HMDSO) of 20 cm³/min, and exposure at room temperature. The effect of the number of deposition cycles on the contact angle was investigated. Varying the number of deposition cycles from 1 to 10 (Figure 2b) showed that the contact angle increased from 164.25° to 171.35° with an increasing number of cycles. Thus, a single deposition cycle is sufficient to form a superhydrophobic coating. To assess the characteristics of the coating formed as a result of the interaction of precursors on the surface of a glass sample with a plasma flow after one (Figure 2c) and ten (Figure 2d) cycles, the morphological properties were analyzed. The morphology of the synthesized coatings was examined using a scanning electron microscope (SEM). The obtained data showed that the formed particles have various shapes, including spherical ones.

The effectiveness of modifying the surface properties of synthetic fabrics using atmospheric-pressure plasma treatment technology was further investigated. Synthetic fabrics were used as substrates, onto which a superhydrophobic coating was subsequently applied. As a result of the treatment, the water contact angle of the surface reached 157.16° (Figure 3a), indicating a significant reduction in wettability and a transition of the material from a hydrophilic to a superhydrophobic state.

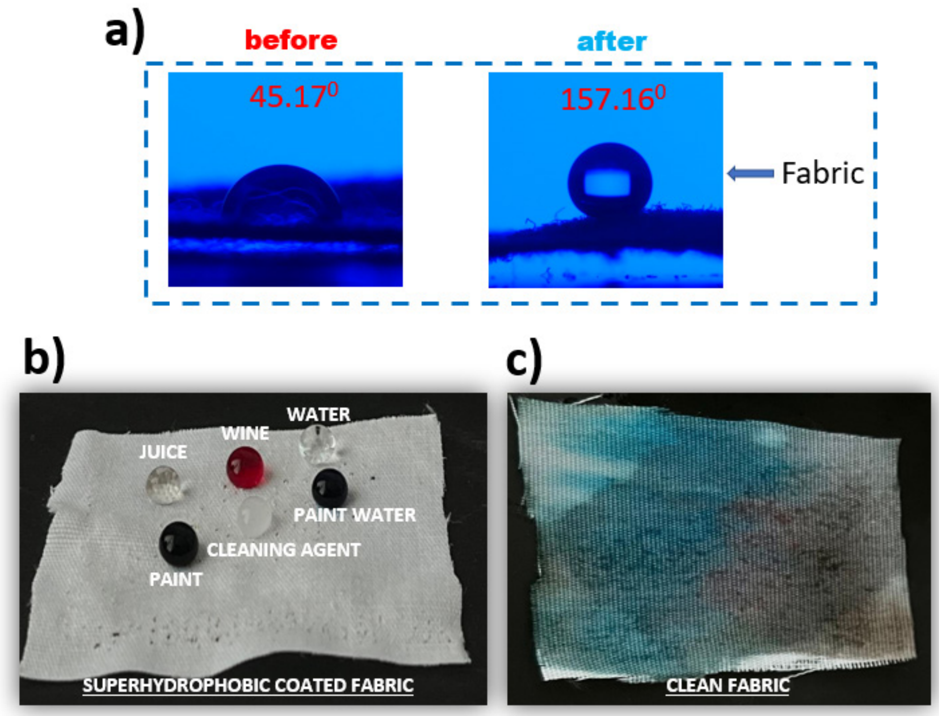

Figure 3 – Water contact angle on fabric coated with a superhydrophobic layer compared to plain clean fabric (a). Interaction of various types of liquids on fabric with a superhydrophobic coating (b) and clean fabric (c).

To evaluate the effectiveness of the obtained coating, experiments were conducted by applying various liquids to treated and untreated fabric samples. The tests demonstrated that the high contact angle promotes the formation of a superhydrophobic layer, preventing surface wetting (Figure 3b). In contrast, on untreated fabrics, liquid substances easily penetrated the material's structure, leaving stains that hindered reuse and led to significant cleaning costs (Figure 3c).

Thus, the obtained results demonstrate the high efficiency of atmospheric-pressure plasma treatment for creating superhydrophobic coatings on textile materials. This technology has potential applications in various fields, including the production of water-repellent clothing, protective coatings for textiles, and medical and industrial textiles requiring resistance to contamination and moisture.

4. Conclusion

This study investigates the formation of hydrophilic and superhydrophobic coatings using radio-frequency (RF) plasma discharge at atmospheric pressure. The wettability of modified surfaces was analyzed, and the durability of the obtained coatings under various conditions was evaluated. The results showed that increasing the number of plasma treatment cycles enhances hydrophilic properties by removing organic contaminants and activating the surface, thereby promoting the formation of polar functional groups. Conversely, the deposition of low-surface-energy compounds led to the formation of superhydrophobic coatings, with contact angles reaching 171.35° after multiple deposition cycles.

The study also examined the effectiveness of plasma treatment for modifying synthetic textile surfaces, achieving a significant reduction in wettability, with a water contact angle of 157.16°. The treated materials demonstrated strong resistance to liquid penetration, preventing staining and enabling self-cleaning. Comparative tests confirmed that untreated fabrics readily absorb liquids, whereas plasma-modified textiles effectively repel them.

These findings highlight the potential of atmospheric-pressure plasma treatment as an efficient and environmentally friendly method for controlling surface wettability without the use of hazardous chemicals. The ability to precisely tailor hydrophilic and hydrophobic properties through plasma treatment opens new opportunities for various industrial applications, including waterproof textiles, protective coatings for packaging materials, biomedical coatings, and filtration systems. Further research is needed to optimize treatment parameters to enhance coating durability and to evaluate large-scale implementation strategies for industrial applications.

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