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THE EFFECT OF TECHNOLOGICAL PARAMETERS ON ADHESION STRENGTH IN THE PRODUCTION OF POLYMER COMPOSITE COATINGS FOR MECHANICAL ENGINEERING

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Abstract. This article examines the influence of technological parameters on the adhesion strength of polymer composite coatings used in mechanical engineering. The main properties of these coatings and the factors that ensure strong bonding with metal surfaces are analyzed. Particular attention is paid to the effects of surface preparation quality, temperature, curing time, and composite composition on coating performance. The proper selection of these parameters is essential for improving coating adhesion and reducing the risk of detachment. Furthermore, the possibilities of enhancing wear resistance and extending the service life of coatings through the optimization of technological processes are discussed. The findings of this article contribute to the improvement of technologies for producing effective polymer composite coatings to protect mechanical engineering components.

Keywords: mechanical engineering, polymer composite coating, adhesion strength, technological parameters, surface preparation, curing process, wear resistance.

Introduction.

In the mechanical engineering industry, protecting the surfaces of machines and mechanisms from environmental influences is essential for ensuring their reliable operation over an extended period. During operation, machine components may be damaged to varying degrees by factors such as friction, mechanical loading, moisture, temperature fluctuations, and corrosion. The use of polymer composite coatings is considered one of the promising approaches to preventing such damage. Composites consisting of a polymer matrix and various fillers make it possible to achieve the required material properties and adapt the coating to specific operating conditions. At the same time, coating performance depends not only on its composition but also on the strength of the bond formed between the coating and the metal substrate.

Adhesion strength refers to the resistance of the bond between a coating and its substrate to separation. When the bond between the coating and the metal surface is insufficient, external loads may cause the coating to detach or compromise the integrity of the protective layer. Therefore, improving adhesion is an important objective in the production and practical application of polymer composite coatings. In a review article published in 2023, Liu et al. examined surface preparation, surface roughness, wettability, and chemical conditions as factors affecting the strength of bonds in composite materials [1].

Technological parameters play a particularly important role in determining the adhesion properties of coatings. In particular, mechanical or chemical cleaning of the substrate surface, monitoring its condition, selecting the composite composition, controlling material application conditions, and managing the curing process may influence the final results. The effects of these

parameters vary depending on the type of polymer used, the properties of the metal substrate, and the coating production technology. Therefore, applying the same technological regime to all polymer composites is not advisable; appropriate conditions must be determined for each material system.

In recent years, increasing attention has also been paid to methods for improving coating adhesion by modifying polymer surface properties. A scientific review published by Primc and Mozetič in 2024 demonstrated that plasma treatment can alter the chemical composition, morphology, and wettability of polymer surfaces [2]. However, the authors emphasized that improved surface wettability does not always guarantee higher adhesion strength. This finding highlights the need to assess not only a single parameter but also the strength and durability of the bond when evaluating coating performance.

Research Methodology.

This article analyzes the influence of technological parameters on the adhesion strength of polymer composite coatings for mechanical engineering based on scientific studies conducted by researchers in this field. The analysis draws on information presented in scientific articles, academic literature, and international standards. The effects of surface preparation, polymer composite composition, temperature, and curing conditions on adhesion strength are examined by comparing the findings of previous studies. The collected information is systematized and evaluated using comparative analysis and generalization methods. Based on the analysis, scientific conclusions are formulated regarding the technological factors that play an important role in improving the adhesion strength of polymer composite coatings.

Analysis and results.

The adhesion strength of polymer composite coatings for mechanical engineering is closely related to the material composition, the condition of the substrate surface, and the conditions under which the coating is formed. Analyzing these factors makes it possible to understand the mechanisms responsible for strong bonding between the coating and the metal substrate and to evaluate the coating's stability during service. In scientific literature, adhesion is generally explained through mechanisms such as mechanical interlocking, interfacial physicochemical interactions, and, in certain cases, chemical bonding. In their review published in 2023, Liu et al. reported that surface treatment prior to bonding composite materials affects surface roughness, wettability, morphology, and bond strength [3].

Initial surface preparation is an important stage in ensuring strong bonding between a polymer composite coating and a metal substrate. If oil, dust, oxide layers, or other contaminants are present on the metal surface, direct contact between the coating material and the substrate may be restricted. As a result, weak areas may develop at certain points along the interface. Therefore, cleaning the metal surface and monitoring its condition before coating application should be regarded as essential components of the technological process.

Various methods can be used for surface preparation, including mechanical grinding, abrasive treatment, chemical cleaning, and other techniques. Mechanical treatment modifies the surface microtopography, creating conditions that may improve the mechanical interlocking of the coating with the substrate. However, increased surface roughness does not always indicate improved adhesion strength. Excessive surface irregularities, residual particles, or contaminants remaining after treatment may adversely affect bond quality. The studies reviewed by Liu et al. emphasize the importance of selecting surface preparation methods according to the properties of the material and taking the resulting surface condition into account [3].

The adhesion properties of coatings also depend on the nature of the polymer matrix and the composition of the composite. The polymer matrix serves as the primary binding phase, and its properties influence coating formation, deformation behavior, and interactions with the substrate. Fillers incorporated into the composite can modify its mechanical, thermal, and other operational properties. Nevertheless, an increase in filler content does not automatically lead to higher adhesion strength. Its effect depends on the type of filler, particle size, compatibility with the polymer, and uniformity of distribution throughout the composite. Therefore, when selecting a composite composition, it is necessary to evaluate not only coating hardness and wear resistance but also the strength of the bond formed with the metal substrate. If fillers are unevenly distributed within the polymer matrix or the structural integrity of the material is compromised, stress concentrations may develop within the coating. Under certain conditions, this may increase the risk of cracking or detachment from the substrate. Consequently, several properties must be considered simultaneously when determining an optimal composite composition.

One modern approach to improving adhesion strength involves modifying the physical and chemical properties of surfaces. In a scientific review published in Materials in 2024, Primc and Mozetič analyzed how plasma treatment can alter the chemical composition, morphology, and wettability of polymer surfaces [4]. Wettability affects the spreading of the coating material and its interaction with surface microstructures. These changes may improve contact between the coating and the substrate. However, the findings discussed in the review also reveal an important limitation: improved wettability does not necessarily result in a corresponding increase in adhesion strength. This may be attributed to the recovery of the surface toward its initial state over time, the formation of weak intermediate layers during treatment, and variations in plasma processing parameters. Therefore, the effectiveness of plasma treatment should be evaluated not only through contact angle measurements or wettability indicators but also through direct adhesion tests [4].

Temperature and curing time are important technological parameters that influence the final structure of polymer composite coatings. These parameters may affect polymer flow, wetting of the metal surface, and the progression of the curing process. At insufficient temperatures, the coating may not spread adequately across the surface, or the curing process may not proceed as required. Conversely, temperatures exceeding the appropriate range for a particular material may cause thermal degradation of the polymer or deterioration of coating properties. Therefore, temperature and curing time should not be assigned identical values for all polymers. Their selection must take into account the binder material, fillers, coating thickness, and production technology. Maintaining other conditions as consistent as possible is also important when comparing different technological regimes. Otherwise, it becomes difficult to determine which parameter is responsible for the observed changes in adhesion strength.

Selecting an appropriate testing method is essential for evaluating the adhesion strength of coatings. ASTM D4541-22 specifies a procedure for determining the pull-off strength of coatings on rigid substrates, including metal surfaces [5]. In this method, a force is applied perpendicular to the coating surface, and the force at which separation occurs is recorded. The test result may depend not only on the bond between the coating and the metal substrate but also on the cohesive strength of the coating and other components of the testing system. Therefore, the analysis should consider not only the final numerical value but also the location at which separation occurs. Furthermore, ISO 4624:2023 specifies three pull-off test methods for evaluating the adhesion of paints, varnishes, and related single- or multilayer coating systems [6]. This standard can be used to compare the adhesion properties of different coatings. However, direct comparison of results may be inappropriate if the testing method, equipment, substrate material, curing time, or environmental

conditions differ. Consequently, standardizing test conditions and expressing results in consistent units are essential when assessing the effects of technological parameters.

The reviewed scientific literature indicates that the adhesion strength of polymer composite coatings is determined not by a single technological parameter but by a combination of interrelated factors. Surface cleaning and preparation help improve the quality of contact between the coating and the substrate; the polymer and filler composition determines the material's structural integrity and mechanical properties; and temperature and curing conditions influence the final state of the coating. Modern techniques such as plasma treatment may provide additional opportunities for improving surface properties, although their effectiveness must be evaluated according to the treatment conditions and material type.

Thus, improving the production process for polymer composite coatings used in mechanical engineering requires an integrated approach to surface preparation, composite composition, and curing parameters. This approach supports the rational selection of technological regimes and the reliable evaluation of coating adhesion properties. Nevertheless, determining the most effective parameters for a specific polymer composite must be based on appropriate laboratory tests and repeated measurements.

Discussion.

Improving the adhesion strength of polymer composite coatings in mechanical engineering requires material selection and manufacturing technology to be considered in an integrated manner. The scientific literature reviewed indicates that strong bonding between a coating and a metal surface is determined not only by the chemical composition of the polymer but also by the initial surface condition, the physical properties of the composite, and the conditions under which the coating is formed. Therefore, approaches aimed at improving adhesion strength should not be limited to optimizing individual technological operations but should encompass the entire manufacturing process.

One important issue to consider is the relationship between surface preparation and coating composition. Cleaning a metal surface can improve direct contact between the coating and the substrate; however, the effectiveness of this process depends on the final surface condition. For example, mechanical treatment modifies the surface microtopography, but abrasive particles or contaminants remaining after treatment may adversely affect bond quality. Therefore, the effectiveness of surface treatment should be evaluated not only by the type of operation performed but also by the condition of the surface obtained afterward. This approach highlights the importance of cleaning and inspection procedures in the coating production process.

Another important aspect is the influence of polymer composite composition on adhesion strength. The addition of fillers may improve coating hardness, thermal resistance, or wear resistance, but these changes do not necessarily indicate stronger bonding with the substrate. If the fillers are insufficiently compatible with the polymer matrix, defects may develop within the material or internal stresses may become unevenly distributed. Therefore, when selecting a coating composition, it is inappropriate to use a single mechanical property as the primary criterion. Instead, adhesion and operational properties should be evaluated together.

Technological temperature and curing conditions also require particular attention. During coating formation, these parameters influence the state of the polymer and its ability to cover the substrate surface. However, it cannot be concluded that increasing the temperature or extending the curing time will always produce positive results. The effects of these parameters vary depending on the polymer type, composite composition, and coating thickness. Consequently, the technological

regime should be selected according to the characteristics of the materials used and verified through appropriate testing.

The selection of an adhesion testing method also directly affects the reliability of the conclusions obtained. In pull-off testing, the measured value may depend not only on the bond between the coating and the substrate but also on the internal strength of the coating and the layer in which separation occurs. Therefore, interpreting the results should involve more than reporting a numerical value; the failure characteristics must also be considered. Comparing different technological regimes using the same testing method and, as far as possible, consistent conditions improves the validity of the conclusions.

It would be inappropriate to assume that a universal technological solution exists for improving the adhesion strength of all polymer composite coatings. Achieving optimal results requires coordinating surface preparation, composite composition, and curing conditions. Future practical work should focus on comparing the individual and combined effects of different parameters, measuring adhesion using standardized methods, and evaluating the long-term stability of coatings. Such an approach would support the scientifically justified selection of technological regimes for polymer composite coatings applied to mechanical engineering components.

Conclusion and recommendations.

The analysis of scientific studies and information presented in international standards indicates that achieving adequate adhesion strength in polymer composite coatings for mechanical engineering depends on the interaction of several technological factors. In particular, proper metal surface preparation, appropriate selection of the polymer composite composition, and optimization of coating application temperature and curing conditions are essential for achieving strong bonding. Furthermore, modern techniques such as plasma surface treatment can improve the surface properties of certain polymer materials; however, their effectiveness should be evaluated separately for each material system.

The analysis demonstrates that adhesion strength cannot be adequately assessed on the basis of a single technological parameter. The bond between the coating and the metal substrate, the internal integrity of the coating, and its operational properties must be considered together. In addition, the use of standardized testing methods and the assessment of failure characteristics can improve the reliability of adhesion measurements.

Based on these conclusions, the following recommendations are proposed:

1. Improving metal surface preparation: Before applying a coating, the substrate should be cleaned of contaminants, its surface condition should be assessed, and an appropriate treatment method should be selected according to the material properties.

2. Optimizing the polymer composite composition: Particular attention should be paid to the compatibility between the polymer matrix and fillers to improve adhesion and mechanical properties simultaneously.

3. Coordinating technological parameters: Temperature, curing time, and coating application conditions should be selected in accordance with the characteristics of the materials used.

4. Evaluating adhesion strength using standardized methods: The bond between the coating and the substrate should be assessed through appropriate tests, with results compared under consistent conditions and failure characteristics documented.

5. Assessing the long-term performance of coatings: In addition to adhesion strength, resistance to wear, corrosion, and temperature variations should also be evaluated.

In general, an integrated approach to improving polymer composite coating technologies creates opportunities to enhance the protective properties of machine components and extend their

service life. Before the proposed approaches are implemented in industrial practice, their effectiveness should be verified through appropriate laboratory tests, and optimal technological conditions should be established based on the results obtained.

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