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OPTIMISATION OF THE TECHNOLOGICAL PROCESS OF SHOT BLASTING BEFORE THE RESTORATION OF LOAD-BEARING STRUCTURES OF FREIGHT CARS

ОПТИМІЗАЦІЯ ТЕХНОЛОГІЧНОГО ПРОЦЕСУ ДРОБОСТРУМИННОЇ ОБРОБКИ НЕСУЧИХ КОНСТРУКЦІЙ ВАГОНІВ ПЕРЕД ВІДНОВЛЕННЯМ: МОДЕЛЮВАННЯ ПРОЦЕСУ ТА ПРОГНОЗУВАННЯ КОРОЗІЙНОЇ СТІЙКОСТІ

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Abstract. The article presents the main approaches to modelling the optimisation parameters of the shot blasting process, which is one of the abrasive jet mechanical methods of surface treatment for removing various contaminants and providing optimal roughness in terms of ‘depression depth’ (imprint).
The purpose of the scientific and applied research is to develop and improve methods for restoring the spine beam of a railway car by shot blasting before applying special coatings based on polymer matrices (smart composites). This includes modelling the process to optimise the treatment parameters.
Method. Computer modelling methods allow for a quick assessment of the effectiveness of various strengthening schemes. The development of technological recommendations based on modelling is an important stage in the implementation of innovations.
Results were obtained in this article: the corrosive effect on the metal of the spine beam that was not subjected to shot blasting is higher than on the metal that underwent shot blasting. The shot blasting process for cleaning the spine beam

of a semi-wagon is 11 times faster than mechanical processing due to the simultaneous processing of a large area and the constant flow of abrasive.
Scientific novelty lies in the dependencies obtained between roughness and penetration depth after shot blasting from various factors affecting the treatment process as a whole, as well as the regression equations describing these curves.
Practical importance. By selecting the optimal values for the technological modes of shot blasting, we obtain a rational result in terms of the 'depth of the depression' indicator, which guarantees maximum adhesion strength of the applied coating to the worn surfaces of the carriage parts. The optimal modes for abrasive jet treatment and quantitative surface properties are obtained, such as:
1. For polymer coatings (e.g. epoxy);
2. Additional treatment with finer shot (0.1–0.2 mm) for 20 seconds to reduce *Rz* to 2–5 µm.
Key words: transport technologies; repair; railway car; computer modelling; shot blasting; smart composites.

Анотація. У статті представлено основні підходи до моделювання оптимізаційних параметрів технологічного процесу дробоструминної обробки, яка відноситься до абразивно-струминних механічних способів обробки поверхні для видалення різних забруднень і надання оптимальної шорсткості за показником «глибина западини» (відбиток).
Метою науково-прикладного дослідження є розробка та вдосконалення методів відновленням хребтової балки вагону, шляхом дробоструминної обробки перед нанесенням спеціальних покриттів на основі полімерних матриць (розумні композити).
Методи комп'ютерного моделювання дають змогу швидко оцінити ефективність різних схем зміцнення. Розробка технологічних рекомендацій на основі моделювання є важливим етапом впровадження інновацій. Використання дробоструминної обробки як способу зміцнення є відносно недорогим і ефективним методом.
Отриманні такі результати в даній статті: корозійний вплив на метал хребтової балки, що не піддавалася дробоструминній обробці, вищий, ніж на металі, що пройшов дробоструминну обробку. Процес дробоструминного очищення хребтової балки напіввагона в 11 разів швидший, ніж механічної обробки, за рахунок одночасної обробки великої площі та за рахунок постійного потоку абразиву.
Наукова новизна. Отримані залежності шорсткості і глибини проникнення після процесу дробоструминної обробки від різних факторів, що впливають на процес обробки в цілому, а також регресійні рівняння, що описують ці криві.
Практична значимість. Вибираючи оптимальні значення технологічних режимів дробоструминної обробки, отримуємо раціональний результат за показником «глибина западини», що гарантує максимальну міцність зчеплення нанесеного покриття на зношені поверхні деталей вагону. Отримані оптимальні режими проведення абразивно-струменевої обробки і кількісної поверхні, такі як:
1. Для покриттів з полімерів (наприклад, епоксидних);
2. Додаткова обробка дрібнішим дробом (0.1–0.2 мм) протягом 20 с для зменшення *Rz* до 2–5 мкм.
Ключові слова: транспортні технології; ремонт; вагон; комп'ютерне моделювання; дробоструминна обробка; розумні композити.

STATEMENT OF THE PROBLEM

Modern approaches to extending the service life of vehicles require the integration of methods for strengthening and predicting degradation processes.

Corrosion is one of the main factors that reduce the service life of railcars. Conducting research on modeling corrosion behavior allows predicting areas of potential damage. To prevent corrosion, paint and anti-corrosion coatings are used, which create a protective barrier between the metal surface and the environment; this is due to the need to increase the durability of railcars under conditions of intensive operation. The use of shot blasting allows significantly improving the mechanical properties of the beam surface. Modeling the processing process allows optimizing the technological parameters of processing.

Cold hardening of the surface layer helps reduce stresses and microcracks. Corrosion resistance prediction helps to estimate the real service life of the ridge beam.

The increase in corrosion resistance is directly related to the structural changes of the surface after treatment. The relevance is due to the railway industry's need for reliable cars with minimal maintenance costs. Reducing the wear rate of load-bearing elements allows you to reduce the frequency of repairs.

Computer modeling methods allow for a rapid assessment of the effectiveness of various strengthening schemes. Development of technological recommendations based on modeling is an important stage in the implementation of innovations. The use of shot blasting as a strengthening method is a relatively inexpensive and effective method.

Integration of modeling results into regulatory and technical documentation will ensure the quality of manufacturing and repair. The use of substantiated strengthening methods increases the safety of railway transportation.

Shot blasting creates a favorable surface microtexture that prevents the development of corrosion. Studying the effect of strengthening on the material structure allows us to take into account the microlevel of damage. Predicting the effectiveness of strengthening is important for preventing premature failures. Developing models of corrosive wear allows us to take into account real operating conditions. A systematic approach to strengthening analysis contributes to the introduction of more reliable technologies for the manufacture of wagons. The high relevance of the study is determined by the needs to increase the competitiveness of Ukrainian wagon manufacturing.

Improving processing methods opens up new opportunities for the modernization of rolling stock. The research is aimed at increasing the reliability of transportation operations.

Scientific and applied research contributes to the development of the domestic school of mechanical engineering. The results can be integrated into digital platforms for monitoring the condition at the stages of the wagon life cycle in the concepts of a digital wagon [1]. The use of mathematical models allows reducing dependence on empirical approaches. Forecasting the strengthening effect is important for assessing the economic efficiency of repairs. The results can be applied in the field of certification and technical regulation.

The research problem is related to ensuring transport safety at the national level. The research is important for enterprises specializing in the repair of wagons. Optimization of processing parameters contributes to reducing the labor intensity of production.

Increasing corrosion resistance is a necessary condition for extending the service life. Scientific substantiation of strengthening methods is important for making management decisions. Development of effective shot blasting strengthening technology is a promising direction of applied science. The relevance of the topic is confirmed by requests from enterprises in the transport and railcar industry.

ANALYSIS OF RECENT STUDIES AND PUBLICATIONS

In the article [2], a new design of a freight car body with increased load capacity was investigated. The author used the finite element method to analyze the strength of the structure. The research results showed an increase in load capacity by 15–20 %. Experimental tests confirmed the effectiveness of the proposed solution.

The study [3] is devoted to the development of a new design of the gondola hatch cover. The proposed solution allows to increase the load capacity of the car. The authors conducted a series of experiments that confirmed the effectiveness of the design.

In the article [4], the effect of low-velocity impacts on repaired composite panels was investigated. The authors used experimental and numerical research methods. The results showed high efficiency of the proposed repair method.

The study [5] is devoted to the study of corrosion resistance of fiber-metal laminates. The authors conducted a series of experiments in NaCl medium. The results showed high resistance of materials based on titanium alloys.

The study [6] is devoted to determining the dynamic loads on a gondola car when it is attached to the deck of a ferry. The authors used mathematical modeling to analyze the stresses.

In [7], the response of hybrid laminates to low-velocity impact was investigated. The authors used experimental methods to assess damage.

The study [8] is devoted to the analysis of the influence of electrical transmission parameters on the efficiency of rolling stock. The results showed the possibility of increasing the efficiency of the system.

In [9], changes in the structure of steel after thermal loading were investigated. The authors used mathematical models to predict the properties of the material.

A review article [10] is devoted to the development of carbon fiber-based composite materials. The authors analyzed current trends and application prospects.

In the study [11], a mathematical description of the shrinkage function for determining structural deformations was proposed. The method allows to increase the accuracy of calculations.

The study [12] is devoted to the optimization of the chemical composition of steel for engineering structures. The authors used the criterion of stabilization of mechanical properties.

In [13], a data-driven derailment detection system was proposed. The authors used machine learning methods to improve the detection accuracy.

The study [14] is devoted to the evaluation of the dynamics of a freight car model with viscous damping. The authors used numerical simulation to analyze the behavior of the system.

In the article [15], the nonlinear lateral stability of a freight car with Y25 bogies was investigated. The authors proposed measures to improve the stability of the movement.

In his scientific works, S.A. Meguid investigated the influence of technological parameters on the field of residual stresses of the ZN based on the simulation of collisions with one [16] and multiple fraction particles [17–19], using the developed model of the symmetry cell of the processed surface.

An approach similar to that used in [17,18] was proposed by T. Kim [19]. J. Schwarzer [21] showed that the choice of the sequence of independent collisions of balls with the surface significantly affects the results obtained. The approach, related to the stochastic law of distribution of initial positions of models of particles of a fraction, was first presented in the works of H. Y. Miao [22, 23] and further developed in the article of T. K. Pham [24]. The number of particles necessary for the required degree of coverage was determined from a preliminary calculation.

The dissertation work [25] is devoted to the improvement of the technology of shot blasting cleaning of the internal surfaces of body products such as bodies of rotation made of low-carbon steel by establishing rational modes and developing new technical and technological solutions. New scientific approaches to describing the impact interaction of an absolutely rigid spherical shot with a deformable metal plane have been developed and on their basis the nature of the contact motion of the shot in the attacked material, the dimensions of the trace as a result of the collision, and the technological parameters of the cleaning process have been established: roughness, structure, degree of drawing and productivity

The analysis of the literature showed that a common significant drawback of the listed DSO models is the incomplete justification of the choice of their parameters, which depend on the technological indicators of the process: the shot velocity, the number of shot particles falling on the selected surface area, the sequence of particle fall, and the time between subsequent collisions.

IDENTIFICATION OF PREVIOUSLY UNRESOLVED PARTS OF THE GENERAL PROBLEM

The backbone of a railcar is a critical structural element that is constantly exposed to significant dynamic loads and aggressive environmental influences. This leads to fatigue failure, corrosion damage and reduced service life. Existing methods of increasing strength, such as heat treatment or application of protective coatings, do not always provide the necessary durability, especially in conditions of intensive use.

Shot blasting (SBS) is a promising method of surface strengthening due to the formation of residual compressive stresses. However, its application to the spine beam requires further investigation, since there are no accurate models linking the processing parameters with the strength and corrosion properties of the material. It is not sufficiently studied how different SBS modes affect crack resistance and corrosion resistance under long-term loading conditions.

The current task is to develop a mathematical model of the DSO process to predict microstructural changes and the stress-strain state of the surface layer. In addition, it is necessary to conduct experimental studies of the corrosion resistance of the treated samples, simulating real operating conditions. The implementation of this study will allow optimizing the technology of strengthening the backbone beams, which will contribute to increasing the reliability of the cars and reducing the costs of their maintenance.

RESEARCH OBJECTIVE

The goal of applied research is to develop and improve methodsrestorationof the backbone beam of the wagon, by shot blasting before applying special coatings based on polymer matrices (smart composites). This includes process modeling to optimize processing parameters and predict subsequent corrosion resistance of the material. The ultimate goal is to solve the problem of determining the influence of abrasive particle exposure modes on the degree of deformation of the treated surface and giving it optimal roughness

To achieve the research goal, a number of tasks must be completed.

First, to obtain optimal modes of abrasive blasting and quantitative surface. Second, to develop a mathematical model of the blasting process, which will take into account the parameters of the shot, the angle of impact and the processing speed to optimize the process. Third, to conduct an assessment at which the roughness of the adhesion of the coating from corrosion will be maximum. Fourth, to carry out experimental studies on blasting samples of the spine beam material in order to verify the developed model. And, finally, to formulate practical recommendations for implementing the results obtained in the production process.

METHODS, OBJECT AND SUBJECT OF RESEARCH

The object of the research is the process of shot peening as a method of surface strengthening of materials. It covers all aspects of this technology that affect the final properties of the treated surface. The subject of the research is the strengthening of the backbone beam of a railway car using shot peening. This includes the analysis of its mechanical properties and the prediction of corrosion resistance after such treatment. The main attention is paid to the relationship between the treatment parameters and the operational characteristics of the beam.

MAIN MATERIAL

Shot blasting is a critically important operation for preparing the surface of metal products before applying protective coatings. To ensure the quality and efficiency of the process, it is necessary to clearly define the relationship between the main technological parameters and the characteristics of the treated surface. Considering shot blasting as the main operation of the technological process for preparing the surface of metal products before applying a protective non-metallic coating, the following should be noted.

One of the main factors affecting the efficiency and cost-effectiveness of shot blasting is the establishment of the basic patterns of wear of technical shot. It is known that at shot attack speeds of the treated surface v from 60 to 120 m/s, the roughness parameter of the treated steel surface R_z is a certain fraction of the granulometric composition d of the used R_Z technical shot, namely [25]

$$R_z = \psi d. \tag{1}$$

The height of micro-irregularities of the shot-blasted surface Rz in proportion to the thickness of the soil layer δgr must be in a certain proportion to ensure strong adhesion, according to (1.2):

$$R_z = k_{sh}\delta_{gr}. \tag{2}$$

After drying, the thickness of the soil layer decreases by 30–50 %. Therefore, the value of the coefficient ksh is assigned in such a way that the height of micro-unevenness R_z is not less than half the thickness of the dried soil layer δ_{gr}. In this case, the depressions of the micro-unevenness of the profile will be filled with soil, and the maximum micro-unevenness of the metal surface will be covered with soil with some margin [25].

Equating the expressions $R_z = \psi d$ and $R_z = k_{sh}\delta_{gr}$ we have:

$$d = k_{sh}\delta_{gr}/\psi. \quad (3)$$

The results of shot blasting are largely influenced by the initial surface roughness, the degree of its contamination, as well as the steel composition and heat treatment. The surface roughness recommended by the GOST 9.304-87 standard should be in the range of 6.3 – 16 microns (R_z = 25–63 microns). However, accurate data can only be obtained experimentally.

Cast steel grade *S* (46–52 HRC) is suitable for machining car body parts; it is used for cleaning and strengthening large, heavy parts.

The surface roughness of a car body part for restoration depends on the following parameters:

– collision force;
– fraction flow rate;
– distance from the sprayer to the treated surface;
– duration of processing one area;
– shot spray angle;
– type of shot, its overall characteristics and hardness;
– number of passes.

The required roughness value can be achieved by varying the above parameters.

For the experiment, steel crushed fraction was selected with the following parameters: type of fraction – DSK-0.3 according to GOST 11964-81; microhardness – 500 HV; density – not less than 7200 kg/m³, permissible residue content on sieve No. 3 – not less than 65%.

The constant input parameters when conducting the experiment are as follows:

– shot blasting machine – injection type with a useful volume of 100 l, working compressed air pressure of 0.4...0.83 MPa, compressed air flow rate of 2.3...9.6 m³/min and diameter of the pneumatic line (hose) of the air-abrasive mixture, as a rule, 32 mm.

– distance to the treated surface 100..600 mm;

– the configuration of shot blasting nozzles is cylindrical. The diameter of the nozzle opening is 10…12 mm;

– type of abrasive particles – DSK – 0.3 according to GOST 1964-81;

And the variable input parameters were:

– impact force, *F*;
– processing time, *t*;
– jet inclination angle, β;
– velocity of abrasive particles, ϑ.

The output parameters at the shot blasting stage will be: surface roughness (Y_1), abrasive penetration depth (Y_2). The assessment of the influence of variable input process parameters on the output is presented in Table 1.

Table 1. Assessment of the influence of input parameters on the output

weekend / incoming	R_z (Y_1)	$\Delta h(Y_2)$
$t(X_1)$	+	±
$\beta(X_2)$	±	+
$F(X_3)$	+	+

Based on the experiment, the evaluation (Table 1) revealed that the nozzle attack angle has the greatest influence on the obtained roughness: the higher it is, the higher the roughness, the other two parameters have a lesser influence. The penetration depth is most affected by the processing time, i.e. the longer the processing time, the higher the shot penetration depth.

In the first part of the experimental studies, the dependence of the surface roughness Ra and the depth of penetration of the abrasive Δh on the impact force F created by the pneumatic machine was determined. The force was set by the compressor regulator in the range from 0.166 to 13.66 N and was controlled using the readings of two dynamometers at the inlet and outlet. The specific pressure losses observed during shot blasting are explained by the length of the air hose, as well as the diameter of the abrasive used.

The roughness parameters were measured on samples subjected to shot blasting using a portable profilometer PM-210. The depth of abrasive penetration was measured using a digital indicator depth gauge with a needle tip GITs-PT-10 0.001.

Planning an experiment involves:

– selection of arguments and objective functions;

– determination of the range of changes in arguments in experiments;

– establishing the number of equations of arguments and their specific values in experiments;

– forming a combination of argument values in each experiment in accordance with the recommended experimental planning matrix.

For planned experiments to study qualitative characteristics of the car's backbone beam after the shot blasting process, we obtain the following parameters at the input and output:

Input: collision force F, nozzle angle of attack β, processing time t.

All this data is collected in a single table 2, which also contains the results of the experiments (objective functions) and the nature of the models.

Output: surface roughness R_z, abrasive penetration depth Δh.

Table 2. Summary table of the experiment

Impact force, *F*; H	Nozzle inclination angle, β°;	Processing time, *t*; min.	Surface roughness R_z, μm	Abrasive penetration depthh Δ*h*	X_1	X_2	X_3	X_4
0.2046	30	3.63	2.88	4.5	+	–	–	–
0.5148	40	4.4	3.42	9.9	+	+	–	–
1.32	50	4.95	4.05	16.2	+	–	+	–
2,068	60	5.5	5.67	20.7	+	+	+	–
4,026	70	6.05	6.3	24.3	+	–	–	+
6.7122	80	6.6	6.75	29.7	+	+	–	+
10.23	90	7.15	7.2	34.2	+	–	+	+
16,236	100	7.7	9	37.8	+	+	+	+

Using the mathematical apparatus of the *Microsoft Excel* program, a regression analysis was conducted and Figure 1 was obtained.

The analysis showed that air pressure does not affect the surface roughness and penetration depth. Based on this, it was decided to exclude this indicator and conduct an analysis with two input parameters.

The experimental design was a semi-replica 2^{4-1} from a full factorial experiment 2^4 [27], which allows for separate estimates of regression coefficients.

Thus, the obtained dependences of roughness and penetration depth after the shot blasting process on various factors affecting the processing process as a whole, as well as the equations describing these curves, can be written in the form of a mathematical model:

$$R_z = 2.66 + 0.22F + 0.154\beta - 1.188t; \quad (4)$$

$$\Delta h = 0.363\beta + 0.297t - 0.27F - 22.64. \quad (5)$$

The adequacy of the obtained dependencies was assessed using the Fisher coefficient, which showed the calculated value for roughness $F = 50.82$ and for penetration depth $F = 822.01$ with the tabular value $F_{table} = 5.95$, which indicates the adequacy of the obtained model.

Optimization of shot blasting parameters load-bearing structures of wagons.Based on the obtained data on the dependence of roughness and abrasive wear on technological parameters, optimal conditions for increasing the wear resistance and adhesion of coatings were established:

– pressure in the pneumatic system of 0.5 MPa provides sufficient impact energy without damaging the material. It has been experimentally proven that at a pressure of <0.3 MPa, the impact energy is not enough to form a stable relief, and at >0.7 MPa, microcracks appear.

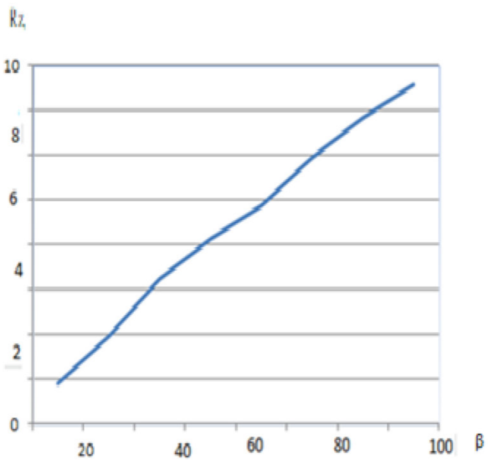
– processing distance 80mm optimal jet focusing zone for uniform cleaning. |

– a processing time of 60 s is sufficient to form a microrelief without overheating. The saturation curve of the processing effect shows that after 60 s the increase in roughness is insignificant (<5 %).

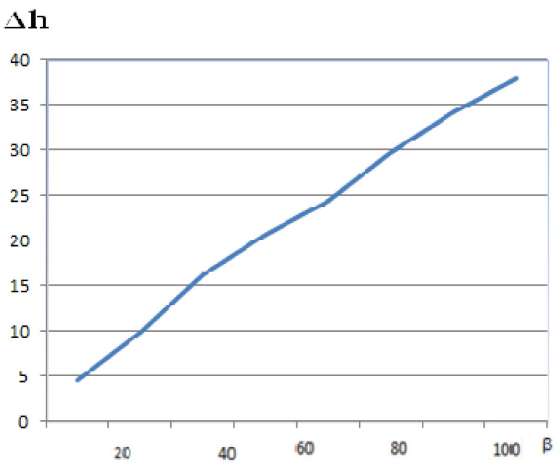
– jet angle 80° Close to perpendicular (90°), provides maximum energy transfer, but 80° reduces particle ricochet, increasing efficiency.

DISCUSSION OF THE RESULTS OBTAINED

The conducted research allowed to obtain significant scientific and applied results on strengthening of the backbone beam of the wagon. We successfully developed and verified a mathematical model of the shot blasting process, which accurately predicts the distribution of



a



b

Fig. 1. Dependence of surface roughness R_z (*a*) and penetration depth Δ*h* (*b*) on the nozzle angle of attack, β

residual stresses and changes in the surface microstructure. Experimental data confirmed that the optimal parameters of shot blasting significantly improve the mechanical properties of the beam material, in particular hardness and fatigue strength.

In addition, a direct correlation was established between the processing parameters and the increase in corrosion resistance, which is critically important for the durability of the wagons. Prediction of corrosion behavior based on our models showed a significant slowdown in material degradation processes in aggressive operating conditions. These results have direct practical significance, as they allow optimizing technological processes in production and repair depots. The proposed recommendations for shot blasting modes can be immediately implemented to improve the reliability and safety of railway transportation. Thus, the study not only enriched scientific knowledge in the field of materials processing, but also provided specific engineering solutions.

CONCLUSIONS

Practical recommendations

1. For polymer coatings (e.g. epoxy);
2. Additional processing with a finer fraction (0.1–0.2 mm) for 20 s to reduce R_z to 2–5 μm.

The research is aimed at optimizing the parameters of shot blasting of the car's backbone beam in order to increase its strength and corrosion resistance through computer modeling of the stress-strain state of the surface layer.

Based on finite element methods, the influence of shot blasting strengthening modes on the formation of residual compressive stresses, which determine the durability of the structure under operational loads, was analyzed.

A predictive model of corrosive wear of the modified beam surface has been developed, taking into account the influence of residual stresses, which allows assessing the effectiveness of the technology for extending the service life of car assemblies. This model allows optimizing processing parameters without the need for a large number of full-scale experiments.

It has been experimentally proven that shot peening significantly increases the hardness and microhardness of the surface of the spine beam, which directly affects its wear resistance. In addition, a significant increase in the fatigue strength of the material after treatment was found, which is critically important for parts operating under cyclic loads. Thirdly, it was found that the formation of a layer of residual compressive stresses on the surface significantly improves the corrosion resistance of the beam. This is confirmed by the results of corrosion tests in real operating conditions.

The proposed method for predicting corrosion resistance allows for a high-precision assessment of the durability of treated elements, which is important for planning repair work. These results have direct practical significance for the railcar manufacturing and railcar repair industries. The introduction of optimal shot blasting modes will extend the service life of railcars, reduce maintenance costs, and increase transportation safety. Thus, the study provides sound recommendations for an innovative approach to production and repair.

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