Analysis of factors affecting the strength of fixed bonds assembled using metal-polymer compositions

V E Zinoviev, P V Kharlamov, N V Zinoviev, R A Kornienko*
Rostov State Transport University, Rostov-on-Don, Russia

*e-mail: Kornienkoroman23@mail.ru

Abstract. The paper considers the relationship between the quality of the surface layer of the substrate and the strength of the fixed adhesive bonding of parts. A search was made for the dominant factors affecting the strength of fixed bonds. A block diagram of the mutual influence of the quality indicators of a fixed bond of parts using metal-polymer gap compensators is given. It has been proven that the quality of the surface layer of the substrate, in terms of aggregate and degree of importance of the factors, has the greatest dominant effect on the strength of a fixed bond assembled using metal-polymer composition.

1. Introduction
In the last 50 years, significant successes have been achieved in the theory and technology of the recovery of stationary compounds by polymer compositions, which is associated, in particular, with the creation of devices and methods that make it possible to carry out various tests, from the simplest to break and peel to complex non-destructive methods for determining the static and dynamic strength of compounds. However, despite the obvious progress in the field of the creation and use of sealing polymer compositions, an accurate explanation and understanding of the relationship between the quality of the surface layer of the substrate and the results of adhesion have not been achieved.

There are numerous theories of adhesion that explain the whole complex of adhesive phenomena in different ways [1-6]. There is currently no suitable mathematical or experimental apparatus for testing some of them. In most cases, these theories consider adhesion as the result of the interaction of molecules [1, 2], between which physical, chemical and intermolecular forces can act. To this should be added the interactions at the supramolecular level. Currently, the following adhesion theories are most used: molecular (adsorption), electrostatic, diffusion, rheological and chemical [1].

2. Mechanism of adhesion bonds formation in metal-polymer systems
In our opinion, the adhesion of polymer sealing compounds to the surface of the substrate (most often metal and plastic), as a rule, is caused, firstly, by micro-rheological processes occurring at the interface, and, secondly, diffusion. The micro-rheological mechanism of the formation of adhesive bonds is determined by the state of the surface of the substrates, their supramolecular structure, as well as the number of microdefects on their surface.

A number of authors [2, 5, 7] note that the mechanism of formation of adhesive bonds in metal-polymer systems is associated with the nature of bonds in the contact zone and their number. In turn, the nature of the bonds at the phase boundary (in the zone of formation of the adhesive contact) is determined by the structure of the adhesive and the substrate, which determines the corresponding nature.
of the interaction: chemical, intermolecular, electrostatic, etc. However, regardless of the nature of the bonds, their number is determined by the actual contact area of contacting surfaces. An increase in the number of bonds, due to an increase in the actual contact area, is accompanied by an increase in adhesive strength.

When studying the nature of the destruction of adhesive bonds, it was found [2, 5] that it never occurred along the interface, but is cohesive. However, this theory does not answer the main question: as a result of which there is a bond and how various forces (van der Waals, dipole-quadrupole forces, etc.) affect its strength.

However, it is necessary to distinguish between the forces causing adhesion and the bond strength itself. In order to understand the essence of the process of sealing the gap with a polymer layer in the fixed conjugation of parts, it is necessary to understand quite well the effect of intermolecular forces that affect adhesion and cohesion.

In our opinion, the surface quality of the substrate and the degree of wetting by the adhesive composition have the greatest impact on the quality of adhesion and the strength of the sealing layer. Moreover, there are a number of other factors that, when combined, can sufficiently affect the strength of the product and its operational properties, which also must be taken into account when choosing the assembly technology.

Existing adhesion theories do not provide a satisfactory answer to the question of the formation and properties of fixed joints of parts assembled using a sealing polymer layer. When considering the processes of adhesion of the polymer to the substrate, we will try to determine the dominant factors that determine the quality of adhesion.

The experiments performed show that a qualitatively assembled immovable joint, as a rule, does not collapse at the substrate-polymer interface; therefore, at break it is impossible to speak of a pure destruction of the molecular forces that cause adhesion. It has been established that before the destruction of the system, partial or complete deformation of the entire compacting polymer layer occurs [1, 2, 8]. On the basis of which we can conclude that the work that is spent on the destruction of a fixed compound is spent not only on overcoming molecular forces.

The publication was carried out as part of a grant from Russian Railways for the development of scientific and pedagogical schools in the field of railway transport.

An inadequate bond is a bond the destruction of which occurs in the boundary layer. A strong boundary layer can be obtained by completely eliminating the weak layer, which is achieved in various ways. In some methods, the weak layer is not completely eliminated, but only pressed into the surface of the substrate. The appearance of weak boundary layers is caused by the presence of adsorbed gases and liquids, particles of solid substances on the surface, etc. A weak layer may also occur if the sealant or its formulation is incorrectly selected (polymer base, solvent, their ratio, additives, etc.), violation of the curing regimen or application technology.

One of the reasons for the occurrence of inadequate layers is that the polymer composition does not wet the substrate well, as a result of which air bubbles are formed during application, which remain after the adhesive has cured. Such bubbles at the phase boundary are usually very difficult to detect. It is easy to determine them only in the case of transparent adhesives or transparent substrates, for example, with lateral (cross) lighting [1, 9]. In case of the restoration of cylindrical fixed joints, the detection of such inclusions is extremely difficult. In addition, there are materials that are practically non-wettable, for example, polytetrafluoroethylene, polyethylene, polypropylene, etc. Comparison of the peel strength of polytetrafluoroethylene-steel and polyethylene-steel joints obtained by deposition showed that the strength of the second system is much lower. At the same time, the breaking load of the polytetrafluoroethylene-steel adhesive bonding is close to the strength of polytetrafluoroethylene itself. Based on this, Bikerman believes that in the polytetrafluoroethylene-steel system, an inadequate (loose) layer occurs due to air ingress, and in the case of polyethylene, the material itself has a major influence on the speed and force of destruction.

The degree of wetting can be quantified by the wetting angle, which is called the contact angle. It is impossible to determine the exact value of the contact angle due to difficulties stipulated by the surface
properties, surface shape, and technological background of the substrate, therefore, an equilibrium contact angle is used. It is necessary to mention the wetting hysteresis - a phenomenon that is associated with the fact that a different volume of liquid can be on the same base of a drop, and, therefore, the contact angle will be different. The wetting hysteresis is manifested, as a rule, on an uneven surface, since on it the edge angle will be different than on perfectly smooth.

If there is no substance on the surface of the substrate that directly affects wetting, then the surface tension of the liquid polymer at the interface with the substrate affects the quality of the polymer layer. The relationship between the performance of adhesion and surface tension at the interface of the substrate-polymer system is expressed by the equation:

\[ W_A = \gamma_{S^0} + \gamma_{LV^0} - \gamma_{SL}, \]

where \( W_A \) is the performance of adhesion;
\( \gamma_{S^0} \) is equilibrium surface tension at the “solid surface-air” boundary;
\( \gamma_{LV^0} \) is equilibrium surface tension between liquid and air;
\( \gamma_{SL} \) is surface tension at the boundary between solid and liquid.

The surface of a solid substance very quickly adsorbs liquid vapor, solvent, moisture, which are very difficult to remove before application or during polymer application. Therefore, it is generally accepted that the adhesion performance upon wetting will be less (by a fraction of the consumed) adsorption energy, and relation (1) is transformed as follows:

\[ W_{A^x} = \gamma_{SV^0} + \gamma_{LV^0} - \gamma_{SL}, \]

where \( \gamma_{SV^0} \) is surface tension or free surface energy of a solid substance at the equilibrium boundary with vapors.

Having analyzed the above formulas and reasoning, we can conclude that wetting a metal with a liquid polymer in the bond directly affects the adhesion quality and strength of the cured bonding layer. The work that will need to be done to destroy the resulting bond is determined by the surface energy of the system and is expressed by the following expression:

\[ \Delta W = \gamma_2 + \gamma_3 - \gamma_{2,3}, \]

where \( \Delta W \) is the change in free surface energy per unit area that will occur when the compound breaks exactly along the substrate-polymer boundary;
\( \gamma_2 \) is polymer free surface energy (per surface unit);
\( \gamma_3 \) is free surface energy of the substrate (per unit surface);
\( \gamma_{2,3} \) is free surface energy of the polymer-substrate boundary.

According to Bickerman, bonds are inadequate in the case when weak adhesion bonds or an insufficient number thereof arise. It is known that a layer of adsorbed gas and moisture is rapidly formed on the surface of materials, which has good adhesion to the substrate, but is mechanically much weaker. This layer, together with by-products from the polymer, forms a weak zone, which determines the low strength of the sealing layer. Sometimes these layers are called transitional.

The above considerations show that these indicators must be taken into account when developing the technology for assembly work and when choosing the modes of curing of the sealing polymer layer. These parameters are easily predicted in the conditions of modern assembly production and are assigned depending on the parameters of the part, its shape and size.

We believe that the factor determining the strength of the adhesive joint is the surface quality of the substrate. The study of the relationship between the polymer wettability of the substrate and the quality of the surface layer was often carried out from the point of view of chemical processes, and did not widely address the issues of surface preparation for assembly, which relates to the field of engineering.
technology. The available information is scattered and not generalized, comprehensive recommendations have not yet been developed, and optimal values of the surface layer quality indicators and their effect on wetting hysteresis have not been obtained.

When assessing surface quality, periodic changes along the surface and perpendicular to it can be noted. Along the surface, these can be geometric changes, anisotropy of physical and physico-mechanical properties (regions with different densities, crystal structures, stiffness, etc.), changes due to impurities and various external influences. Perpendicular to the surface, surface adsorbed and surface-oxidized or chemically modified layers appear, as well as changes in the composition, density, stiffness of the material, electrical conductivity, porosity.

Dependencies that allow controlling the technological process of compound formation when applying a polymer melt to a substrate containing microroughnesses are presented in the following form. The kinetics of leakage of the adhesive melt in the microroughness of the substrate surface determines the process of formation of the nominal contact area $S_n$:

$$S_n \approx \frac{P \cdot t}{\eta},$$

where $P$ is gluing pressure;
$t$ is pressure contact time $P$;
$\eta$ is effective viscosity of the polymer composition.

Each contact surface unit has $n_i$ units of bonds of a certain type (chemical, intermolecular, electrical, etc.). Each type of bond is characterized by its energy value $U_i$, which should be spent to break the connection. In accordance with this, the adhesive strength can be represented as:

$$A \approx K' \sqrt{\frac{P \cdot t}{\eta} \sum_{i}^{k} U_i \cdot n_i}.$$  \hspace{1cm} (2)

Coefficient $K'$ should include parameters reflecting the dependence of $A$ on the conditions for the destruction of gluing:

$$K' = k \cdot v \cdot e^{R \cdot T_p},$$

where $v$ is gluing destruction rate;
$T_p$ is temperature at which destruction takes place;
$U_p$ is energy spent on an elementary act of breaking bonds;
$k$ is coefficient taking into account the material of the parts to be joined.

The important factor affecting the adhesion strength is the gradient of mechanical properties normal to the surface of the substrate $\frac{\partial \Theta}{\partial z}$. It is obvious that the gradient of the mechanical properties of the third body will directly affect the coefficient of friction between the adhesive and the substrate, which, in turn, will affect the adhesive strength. According to the research of I.V. Kragelsky, deep tearing (destruction of bond) occurs when the threshold of external friction is violated due to the appearance of a negative gradient of mechanical properties along the depth of the friction surface or due to too large relative penetration. Such destruction is in the nature of tearing or puncturing the material not at the place of gluing, but inside one of the bodies.

Taking into account possible residual stresses in gluing $\sigma_{act}$, contributing to delamination of the sealing polymer layer and the conversion of formula 2, the quantitative dependence of the adhesive strength on technological factors in the case of micro-rheological formation mechanism can be represented as:
\[ A \equiv k \cdot v \sqrt{\frac{P \cdot t}{\eta}} \cdot \left( \sum_{i=1}^{n} U_i \cdot n_i \right) e^{\frac{U_i}{E}} - f(\sigma_{oct}) - \left( \frac{\partial \Theta}{\partial z} \right) . \]

It has been experimentally proved that surfaces machined to absolute smoothness, applied to each other and pressed by a load \( P \), can be torn off by a force \( F \), which is greater than \( P \), i.e. \( F/P > 1 \). If this operation is carried out in a "high vacuum", which will cause the desorption of weak layers, then \( F/P \approx 10^5 \). This refers to joining two solid materials without adhesive. Bonds using sealing polymer layers should be considered as a system consisting of five layers: substrate 1, transition (boundary) layer 1, polymer, transition layer 2, and substrate 2. A bond whose transition layers are so strong that destruction goes beyond them is considered to be correctly formed, solid bond. That is, the question again arises about the quality of the surface layer of the substrate and its preparation for assembly using a sealing polymer composition.

It has been established that the kinetics of the formation of the actual contact area is associated with the kinetics of the flow of the polymer melt into defects in the surface layer of the substrate, and also, creatively developing previously published works [5, 7], a method for calculating the true contact area based on the assessment of the defectiveness of the contacting surfaces was proposed. The total nominal contact area per unit area of the substrate can be calculated by the equation:

\[ S_n = 2n_1 \frac{h_i}{\cos \alpha} + 2n_2 \frac{h_i}{\cos \alpha} n_i \pi d^2 \sqrt{\frac{P \cdot t}{\eta}}, \quad (3) \]

where \( n_1 \) is the number of grooves (depressions) per unit surface of the substrate; \( h_i \) is maximum depth of inflow of the polymer composition in the micro-roughness of the surface of a part; \( n_2 \) is the number of other defects (in this case, cylindrical pores are considered) per unit surface of the groove; \( d \) is средний диаметр дефекта или поры в поверхностном слое субстрата; \( \alpha \) is half of the angle at the top of the groove section (depressions).

We slightly transform the presented formula to go to the generally accepted parameters of the surface roughness of the part. For example, the arithmetic mean deviation of the profile of parts within the base length is usually estimated by the following expression:

\[ R_a = \frac{1}{n} \sum_{i=1}^{n} |h_i|. \]

In our opinion, the effect of other surface defects, such as pores, on the joint area will be less significant and, therefore, can be neglected. In addition, the surface roughness obtained by us during the mechanical processing of the substrate can be predicted with a greater degree of probability, which means that more reliable results can be obtained in calculating the theoretical strength of the compound. Transforming formula 3, taking into account the above considerations, we obtain:

\[ S_n = 2nR_a \frac{P \cdot t}{\cos \alpha \sqrt{\eta}} . \]

Since the performance of adhesion, regardless of the nature of the bonds, is proportional to the true contact surface, we obtain the following expression:

\[ A = K \cdot E \left[ 2nR_a \frac{P \cdot t}{\cos \alpha \sqrt{\eta}} - \left( \frac{\partial \Theta}{\partial z} \right) \right] . \]

Where \( A \) is the adhesive strength; \( K \) is coefficient taking into account the nature of the stress distribution and the fluctuation mechanism of destruction; \( E \) is the energy of a single averaged adhesive bond multiplied by the number of adhesive bonds per unit of the true contact surface.

In the strength behavior of the adhesive bond, an important role is played by the character of the stress distribution in it, which is a function of the thickness and some other properties of the elements.
making up the bond. Therefore, the strength of the adhesive bond can also vary due to changes in the geometric or mechanical parameters of the surface layer. Although the nature of the processes that occur during surface treatment of substrates is different, all processing methods are aimed at increasing the surface energy of the substrate. Unfortunately, these factors are often neglected in explaining the behavior of the adhesive bond.

The assembly components of any modern technology have fixed bonds, which during operation should reliably and tightly fit to each other. These are shafts with disks, gears, rolling bearings rings pressed onto them, bearing shells pressed into the crankcases. Their immobility is ensured by friction between the pressed surfaces.

Under the influence of vibration and friction forces, the crystal lattice of pressed surface layers under cyclic tangential displacements becomes loose and collapses. The process of destruction is the abrasion of the surface without removing wear products. Detached metal particles oxidize rapidly. Oxides accumulate in contact, accelerating wear [1]. Methods of protecting mating from fretting corrosion should be aimed at preventing or drastically reducing the relative movement of contacting surfaces, corrosion-fatigue and related processes. Relative displacement occurs at the moment when the axial force from the external load exceeds the friction force in magnitude. In this case, it is necessary to reduce the axial load or increase the friction force.

It is possible to prevent relative displacement by transferring relative motion to the intermediate medium, for example, by applying a coating with a small elastic modulus to one or both contacting surfaces. Such material is polymers and, in particular, anaerobic materials, in which the elastic modulus is 200–500 times less than that of ferrous metals, and 70–160 times less than that of light alloys. For example, in anaerobic materials Anaterm-8K, Antherm-6K, the elastic moduli are 60 MPa and 40 MPa, respectively, while in steels they are 150,000–200,000 MPa, and for aluminum alloys - 70,000–71,000 MPa. At the same time, the application of polymeric materials on the surface of ferrous metal parts protects them well from the effects of corrosion processes. [2].

One of the main tasks on which the performance of the bonds depends on is the determining the optimal method of surface preparation, taking into account the operating conditions of the adhesive structure. In the absence of such an approach under real conditions, the strength of the bonds may turn out to be below the acceptable level, which leads to premature failure of the bonds. At the moment, there is no single theory covering the whole variety of different methods of surface preparation. However, there is a set of recommendations obtained empirically that are applicable to various specific polymer – substrate systems and can achieve the desired result.

It must be borne in mind that the physicochemical properties of the surface layer of the substrate almost always completely do not correspond to the properties of the material and its mass. On the surface due to various influences, both physical and chemical, its own story is imprinted, which is individual for each subject and cannot be reliably evaluated as a factor affecting the bonding strength. There is only one way out - to reach an unchanged mass of material with a known composition and properties. Hence the simplest preparation methods based on the cleaning action of solvents, abrasives, which allows you to remove both surface contaminants and an altered surface layer.

More sophisticated processing methods are aimed at increasing adhesion by creating a surface layer having higher adhesion than the starting material. The prepared surface can be kept suitable for use for a long time by applying a protective layer that is removed in the future. Otherwise, it is recommended to apply a layer of glue on the prepared substrate as quickly as possible. Roughening mechanically allows you to get a surface with which the adhesive has better adhesion by increasing the contact area, and accordingly increases the mechanical adhesion. However, it must be borne in mind that the height of the obtained roughness must be deliberately less than the thickness of the adhesive layer.

If it is necessary to achieve a particularly high bonding strength, surface preparation should be performed especially carefully using more laborious surface treatment techniques. So, for example, in the case of gluing aluminum that has been cleaned only with a solvent, a rapid drop in strength is possible under the influence of climatic conditions. But the same acid-etched aluminum, assembled using the same polymer compounds and placed under the same climatic conditions, allows maintaining high
strength of the fixed joint for many years. For the successful preparation of the surface of the part for subsequent assembly, it is necessary to more deeply analyze the basic quality indicators of the surface of the parts forming a fixed joint.

The surface quality of the substrate is determined by its geometric characteristics, physico-mechanical and physico-chemical properties of the surface layer [3, 4]. After machining and various types of action on the part, the surface layers of a solid have several layers interconnected with different forces. In the upper layers are molecules of adsorbed gas, water vapor and molecules of organic origin [3]. Depending on their concentration, they can form mono- or multi-molecular layers of homogeneous molecules randomly oriented relative to each other. Under this layer is a layer of molecules of organic origin, the molecular chains of which are parallel to the plane of the solid. This layer is bordered by a polycrystalline layer of polar molecules of organic origin. Further, layers of adsorbed gases and water vapors lie on the surface of the substrate, the layer of water vapor directly adjacent to the layer of oxides formed as a result of chemisorption of foreign molecules with the material of the surface layer of the substrate. The thickness of this layer is about 20–200 μm and depends on the medium in which the substrate was machined [3]. A strongly deformed riveted layer of substrate material is located under the oxide layer, which directly borders the main material.

3. Identification of dominant factors of contact surfaces quality and adhesion

Processing the surface layer of a part during manufacturing and other technological operations, no matter how perfect it may be, leads to a deviation of the surface profile from the ideal geometric shape specified by the drawing. Since the stationary conjugations of the “shaft-sleeve” and “body-ring” type were examined, in which the average diameter of the joint is comparable to or greater than the contact length, the following types of deviations, which can be divided into two groups according to related characteristics, are of interest. The first group includes barrel-shaped, concavity of cylindrical parts and surface taper. In the second group we combine non-circularity, ovality and cut.

When analyzing the first group, in relation to the aspects of the issue under study, one can draw the following conclusions. If the values of these errors are within normal limits, then they will not have a significant effect on the process of sealing the gap in the joint with a polymer composition. However, if their values (or the sum of the values) fall outside the tolerances, then a situation may arise in which part of the surface of the substrate will be excessively coated with the composition, while in some areas the surface will not be wetted at all or the composition will be applied in a minimal amount. Uneven distribution of the polymer layer over the surface of the substrate in the sealable gap will definitely cause a decrease in the strength of the joint and the system as a whole (Fig. 1) [3].

![Figure 1. The effect of the gap between the joined surfaces on the strength of the sealing layer of the polymer composition (YT-7)](image-url)
The surface errors combined by us in the second group will also affect the quality and the process of forming the sealing polymer joint. As in the case considered by us above, exceeding deviations of permissible values can significantly worsen the process of wettability of the substrate surface by the polymer. As a result, a denser polymer seam uneven in thickness is formed only in a plane perpendicular to the axial lines of the cylindrical parts of the bond. However, in this case, it is possible to improve the uniform distribution of the composition on the surface of the substrate by turning the shaft or ring (alternating the direction of rotation), which will somewhat neutralize the harmful effects of these factors.

The surface roughness of the substrate has a direct effect on the strength of the assembled bond and the sealing joint. On the one hand, an increase in roughness contributes to an increase in the real contact area of the adhesive with the substrate in the compound (Table 1, Fig. 2), and on the other hand, it prevents the uniform and complete wetting of the surface of the substrate with the polymer composition. In addition, in the depressions on the surface of the substrate, if they are excessively deep, hard-to-remove inclusions of oils, dirt and air bubbles accumulate, which also have a negative effect on the strength of the joint, reducing it by 30-40% (Fig. 3) [4].

| Contact area, cm² | Axial thrust, N·m | Specific axial thrust, MPa |
|-------------------|-------------------|---------------------------|
|                   | ΥГ-6              | ΥГ-9                       | ΥГ-6 | ΥГ-9 |
| 4,71              | 42               | 84                         | 8,9  | 17,9 |
| 18,84             | 96               | 148                        | 5,0  | 7,9  |
| 23,55             | 204              | 254                        | 8,6  | 10,8 |
| 37,68             | 218              | 428                        | 5,7  | 11,4 |
| 43,96             | 238              | 444                        | 5,3  | 10,1 |
| 50,24             | 248              | 450                        | 4,9  | 8,9  |
| 62,80             | 262              | 482                        | 4,1  | 7,6  |
| 94,20             | 345              | 588                        | 3,7  | 6,2  |

**Figure 2.** The dependence of the mechanical strength of the joint on the surface roughness: 1—material AN-6V (St. 45, clearance 0.25); 2 - material AN-6V (St. 45, clearance 0.25) [3]
Figure 3. The dependence of the moment of turning the connection parts relative to each other on the oil content on the surface of these parts

The waviness of the surface of the substrate is a periodic micro-deviation from the geometric shape of the part, which are practically equal in size to the elevation and depression, with a wave step significantly exceeding its height. Distinguish between longitudinal and transverse undulation.

Waviness arises as a result of feed unevenness during turning and grinding, forced vibrations of the “machine-tool-tool-component” system, etc. The wave height is more important, from our point of view, criterion, since the following parameters depend on the height:
- the actual length of the bearing surface;
- volume of profile voids;
- specific pressure.

It is known that in press fits, the smaller the wave height and its step along the surface of the substrate, the larger the actual contact area. When using sealing polymer and metal-polymer compositions, when transitional and sliding fits are used, the role of undulation in ensuring the immobility and operability of part connections is somewhat reduced. However, in the literature there is no evidence of a positive or negative effect of this type of substrate surface errors on the assembly quality of the fixed bonds using sealing compounds. It seems interesting to us to identify which types of waviness, the dimensions of the wave heights and their lengths significantly reduce the strength of the connection, or increase it.

To identify the dominant factors of the quality of contact surfaces and adhesion, affecting the strength of fixed bonds, we combine the above material and reasoning in the form of a block diagram (Fig. 4).

Obviously, the indicators presented in the diagram can be divided into groups by importance in terms of ensuring the quality of the bond. Moreover, it seems difficult to vary all the indicators in the conditions of assembly or repair production. Therefore, it is necessary to determine a number of factors, the change of which is possible under the conditions of production of components and assemblies of various machines and equipment, and their change will allow to achieve the best quality of fixed bonds. After analyzing the compiled block diagram, it was concluded that the surface quality of the substrate in terms of the number of influential bonds with other indicators turns out to be the most dominant indicator of the compound. Therefore, in order to achieve good assembly results, it is necessary to propose methods for preparing the surface of the part for the upcoming operation.

In addition to the chemical and mechanical methods of surface preparation mentioned above, physical methods exist, such as: flame treatment, ion bombardment in vacuum (corona discharge) and electric discharge treatment. These processing methods are especially relevant for inert plastics such as
polyethylene, polypropylene, polyethylene terephthalate, which simply cannot be effectively glued without such processing.

**Figure 4.** Factors and indicators affecting the quality of the fixed bond of parts using polymer sealing compounds

There are a number of reasons that cause a decrease in bond strength. The real chemical structure of the surface is quite complex, and information about its properties and the possibility of combining it with glue is often insufficient or completely absent. Therefore, to select the optimal surface treatment method, extensive experimental work should be carried out.

The essence of preparing the surface for gluing is to, using chemical, electrochemical, mechanical processes, the use of modifying additives, adhesive primers or other methods, change the nature of the surface of the substrate, make it more active when in contact with the adhesive to obtain the required strength. At the final choice of the surface preparation method, the design and technological features of the joint and the product as a whole, as well as the operating conditions, should be taken into account.

Thus, the choice of solvent type and degreasing method depends on the type of suspected surface contamination. After the degreasing process, regardless of where the part goes for gluing or for further processing, it is important to determine its effectiveness, the degree of surface cleanliness. In practice, it is determined by testing the continuity of the water film. This method allows you to give a relative assessment of changes in surface tension and determine the possibility of further technological operations.
In preparation for gluing metals, the following features exist. The freshly processed surface of metals with rare exceptions: gold, platinum, titanium and high-quality stainless steels is highly active, it is especially easily coated with an oxide film and is able to absorb airborne contaminants, dust and moisture. Therefore, we again recommend gluing as soon as possible after finishing the surface.

Metal surfaces are almost always contaminated with oils. Hence, a degreasing operation is mandatory, which can be done with water vapor, wiping the surface with a cloth dampened with a solvent (until traces of pollution no longer appear on a clean cloth). Treatment in solvent vapor is very effective. Degreasing should be thorough, in all cases it will not be superfluous to rinse the surface with a fresh portion of a clean solvent. Sometimes they are limited only degreasing. But when applying more complex methods of surface preparation, degreasing is in any case an obligatory first stage of processing. It is easy to check the effectiveness of degreasing by applying water to the treated metal. In the absence of oils or fats, a water film forms, flowing evenly, without droplets and tears.

After degreasing in any way, cleaning agents or detergent solutions should be used to remove dirt and other inorganic residues. Strong alkaline non-inhibited solutions are used for ferrous metals, titanium and some copper alloys. For aluminum and its alloys, when surface etching is to be avoided, inhibited solutions must be used. As inhibited alkaline solutions, synthetic detergent solutions can be used. Alkaline cleaning is usually accompanied by chemical or mechanical treatment, since alkali-treated surfaces are incompatible with most structural adhesives. Before bonding, the surface should be drained with hot air.

Mechanical, abrasive treatment is used when the metal surface bears a noticeable layer of corrosion or scale (steel, cast iron). Oxides are rapidly formed on aluminum and its alloys, in contrast to the inert metals mentioned above. Mechanical methods include those based on the abrasive effect of wire brushes, glass and sandpaper, shot blasting, which can remove unnecessary surface layer. While abrasive treatment roughens the surface and increases the contact area between the adhesive and the substrate, it should be noted that after this treatment the tendency for moisture or solvents to penetrate into the adhesive joint increases. This method may be completely unsuitable for parts that have undergone precise machining, where the final dimensions are strictly specified.

When treating surfaces by dry abrasive blasting, good results can only be achieved by using grains with good cutting edges, i.e. using materials with high hardness, such as aluminum, silica sand or carborundum. Round glass or metal balls can cause a metal surface to ripen and are therefore unsuitable. The nature and size of the grains are the important factor in shot blasting and sandblasting. For most metals and alloys, the grain size of the abrasive and the processing methodology were empirically determined. In addition, the grains of abrasives themselves should not carry pollutants that can nullify all the work. A final rinse with a solvent removes abrasive residues, the presence of which on the adhesive-substrate section will weaken adhesion. If it is possible to use blown moistened abrasives, you need to know that this method is preferable, since it has a wider range of abrasive materials that can be used. If water is used as a humidifier, the use is limited only to non-corrosive metals or corrosion inhibitors must be added to water.

Chemical and electrochemical methods of surface treatment, when compared with mechanical ones, are more effective, cheaper and give good reproducibility of the results. Besides the fact that they have a cleaning effect, these types of processing often provide the formation of a chemical layer on the surface, contributing to the long-term preservation of the strength of the adhesive bond. The process called etching involves immersing the substrate in solutions of acids or alkalis (from dilute to strong) at various temperatures. Acids or alkalis destroy the surface layer of oxides faster than the base metal. If necessary, inhibitors must be added to the acid solution, which increase the difference in the dissolution rate of the metal and oxide. This is especially important for thick layers of scale, if for any reason the use of abrasive treatment is unacceptable.

After removing thick layers of oxides from the surface by etching, then the metal should be treated in weaker solutions, for example, in an “acid-dichromate” bath, which leads to the formation of a thin oxide film with the necessary structure, firmly bound to the main metal layer. The final rinsing and
rinsing should be carried out in clean water, meaning the distilled water, which was stored under
conditions excluding the ingress of foreign impurities, and unsaturated with atmospheric oxygen.

4. Conclusion
Analyzing the data and reasoning, as well as relying on the experience of other works [1–4], we can
draw a number of conclusions:
- Achieving sufficient adhesion strength and operational reliability of the metal-polymer bond is
possible provided that the maximum contact surface and active interaction of the adhesive and substrate
at the interface are realized;
- the viscosity of the polymer composition should be at the time of application such that the filling
time of the capillaries and cavities on the surface of the substrate is sufficiently small in comparison
with the rise time of the adhesive viscosity during curing;
- good wetting of the substrate surface can be achieved if the contact angle tends to zero;
- surface wetting hysteresis is significantly affected by surface quality, the presence of contaminants
and the viscosity of the polymer composition;
- the main indicators of the surface quality have a number of optimal values at which the maximum
bonding area is achieved, but there is no reaction to wetting the surface of the polymer with a polymer;
- it is necessary to solve the issue of competent and technological removal of air and foreign
inclusions from the polymer sealing layer;
- it seems interesting from the point of view of the mathematical apparatus to relate surface quality
indicators, wetting hysteresis values and strength of the assembled bond.
- as a rule, the list of sealing polymer compositions produced by the chemical industry is limited and
stable. Changing the basic physical and mechanical characteristics of the composition under production
conditions is not possible. The development of new compositions by manufacturers on order will
inevitably cause a rise in the cost of production;
- changing the material of the substrate and the scale factor of the connection (the dimensions of the
main parts that make up the connection) is also not advisable, since it is impossible without coordination
with the developers of the project and will require a lot of time and effort;
- the wettabiity of the substrate surface with a polymer composition and the actual contact area
directly depends on the quality of the surface layer of the substrate, the viscosity of the polymer
composition and the pressure in the bond;
- the surface quality of the substrate in terms of the number of influential bonds with other indicators
is the most dominant indicator of the connection;
- the main indicators of the quality of the surface layer of the substrate, taking into account the large
number of mechanical and other types of surface preparation, can easily vary;
- a change in the technology for the production or repair of fixed bonds can be carried out in mass
production without significant costs and higher production costs..

Researches are conducted within realization of a grant of JSC "Russian Railways" on development
of scientific and pedagogical schools in the field of railway transport.

References
[1] Boyko N.I. Resource-Saving Technologies for Vehicle Repair with Metal-Polymer
Compositions: Monograph / N.I. Boyko, V.E.Zinoviev. M. : Marshrut, 2003. 250.
[2] Vasiliev A.S. Technological Fundamentals of Machine Quality Management / A.S. Vasiliev [et.
al.]. – M. : Mashinostroenie, 2003. 256.
[3] Suslov, A.G. Scientific Foundations of Engineering Technology / A.G. Suslov, A.M. Dalskiy. M.
Mashinostroenie, 2002. 684.
[4] Kartashov E.M. Structural and Static Kinetics of Polymer Failure / E.M. Kartashov, B. Tsyo, V.V.
Shevelev. M.: Khimiya, 2002. 736.
[5] Berlin A.A., Basin V.E. Polymer Adhesion Basics. M.: Khimiya, 1974. 391.
[6] Kovacic L. Bonding of Metals and Plastics. M.: Khimiya, 1985. 240.
[7] Van Krevelen D.V. Properties and Chemical Structure of Polymers. M.: Khimiya, 1976. 416.
[8] Kagan D.F., Gul V.E., Samarina L.D. Multilayer and Combined Film Materials. M.: Khimiya, 1989. 288.
[9] Lipatov Y.S. Physicochemical Fundamentals of Polymer Filling. M.: Khimiya, 1991. 260.
[10] Gul V.E., Kuleznev V.N. Structure and Mechanical Properties of Polymers. M.: Vyshaya Shkola, 1979. 352.
[11] Bartenev G.M. Strength and Fracture Mechanism of Polymers. M.: Khimiya, 1984. 280.
[12] New Methods for The Study of Polymers. Collection of Articles Edited by Lipatov Y.S. – Kiev: Naukova Dumka, 1975. 200.
[13] Zinoviev V.E. Research of the Static Strength of Fixed Bonds Assembled Using Polymer Anaerobic Compounds / Zinoviev V.E., Khachkinayan A.E., Zinoviev N.V.// Izvestiya VolgSTU, January (No. 223) 2019 No. 1. 12-16.
[14] Zinoviev V.E. The Effect of Microcracks, Latent Defects and Residual Stresses of the Polymer Adhesive Layer On Its Destruction / Zinoviev V.E., Kharlamov P.V // Fundamentalnye Issledovaniya, 2015, No. 12. 37-42.