Effect of coating on steel mechanical properties

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Abstract. To ensure the required performance characteristics of metalware, various types of 3D and surface process treatment methods are used in the industry. In order to ensure the required durability of parts under a high-load operation, various protective coatings are widely used in practice. However, most of these have significant disadvantages, manifested, for example, in the complexity of the technological process, high porosity of the coating, low mechanical properties, which restrict the scope of their application. The paper presents the results of the analysis of existing production methods for applying metal coatings. Their advantages, disadvantages and influence on the performance characteristics of metal structures are provided herein. The most popular way to protect ferrous metals against atmospheric, soil and water corrosion is galvanizing. At the same time, regardless of their effect on the endurance of smooth samples, the endurance limit of the samples with stress concentrators increases. The corrosion resistance of steels is increased by many types of diffusion saturation (chrome plating, galvanizing, etc.); however, there are no data on the optimal values of the coating thickness. Limited theoretical and experimental data make it difficult to predict the physical and mechanical characteristics of coated metals and alloys. In addition, as a rule, there is no systematic comparative analysis of the negative impact of metal coating technologies on the environment quality in the literature.

1 Introduction

The contemporary mechanical engineering is impossible without increased requirements for structural materials, both in terms of geometric parameters and mechanical properties [1-4]. As a rule, the metallic materials used in mechanical engineering should provide a combination of strength, ductility and cyclic durability, taking into account the impact of aggressive environments on them, since the operational reliability of products made from steel structures is determined by the resistance of their materials to static, cyclic and corrosive destruction [5-8]. To ensure the required consumer properties of metallic products, various types of surface process treatment methods, both 3D and surface, are used in the industry [9-11]. In practice, a widely used method of ensuring the required durability of parts under a high-load operation is a protective coating [10-12]. Most of coatings have...
significant disadvantages, which are manifested in the complexity of technological process,
high porosity, unsatisfactory mechanical properties, etc. [13-15], limiting the application.

The paper evaluates the influence of the type and mode of coating on the mechanical properties of steels under static and alternating loading, taking into account the presence of aggressive media in the process of operation of metal materials.

2 Materials and analysis of coating methods used in production

In actual production conditions, metal coatings are applied in the following ways: electroplating – electrodeposition from aqueous electrolyte solution; hot coating – hot-dip coating in a molten metal bath; metallization – sputtering; thermal diffusion – powder coating at elevated temperature in a special chamber using a gas-phase reaction, ion-plasma, etc. It is possible to apply coatings with a thickness from several microns to several mm by electroplating; to obtain alloys that differ in their physical and chemical properties from alloys obtained by thermal method; to change the structure, physical, chemical, mechanical characteristics and other properties of coatings. Applying the method of thermal vacuum sputtering, it is possible to obtain coatings with zinc, cadmium, aluminum, chromium, nickel, etc. The essence of this method is that the coating metal is heated to a certain temperature, depending on its nature in a vacuum chamber, as a result of which it evaporates and precipitates onto the surface of the metal article. In this case, a fine-crystalline coating is formed on the surface. The simplicity of the process and the ability to process metal articles of almost any configuration makes diffusion saturation technologically accessible for many machine-building enterprises. This was an important prerequisite for the widespread use of such a coating in practice. For the efficient use of diffusion coatings, a deeper study of their effect on the mechanical properties of metals and alloys designed to work in conditions as close as possible to operational ones is required.

In industry, a method of saturation of metals with aluminum, beryllium, boron, vanadium, titanium, zinc, chromium and other elements is used to improve the surface properties of articles. In metallographic and X-ray diffraction studies of carbon, medium-alloy and stainless steels and iron with sixty variants of diffusion saturation, which, depending on the type, were performed by powder contact, gas non-contact, vacuum, electrolysis, liquid and galvanic thermal methods for various temperature and time modes, it was found that for some types of saturation, along with the main diffusion layer, there appears a zone of non-reactive diffusion (transition zone). The depth of this transition zone significantly exceeds the depth of the main diffusion layer. The change in the thickness of the diffusion layer at the bottom of the stress concentrator depends on the geometric parameters and the type of saturation. When carbon steels are saturated with carbide-forming elements (chromium, vanadium), the thickness of the carbide and transition zone at the bottom of the concentrator either does not change or even increases, and that of the decarbonized zone always decreases. The change in the thickness of the diffusion layer at the stress concentrator zone is explained by a change in the ratio of the adsorption area to the saturated volume. In this case, the direction of the main diffusion flows (the flow of the saturated element and the flow of carbon diffusing to the surface) plays an important role. The cleanliness of the workpiece surface is an important factor determining the change in the strength of pieces, especially in case of fatigue. It has been established that it is not recommended to prepolish the products the surface of which is intended for diffusion saturation, since the surface cleanliness class decreases after all types of saturation. Changes in the structure, chemical composition of the surface layers of products and the formation of new phases in these cause
residual stresses in these layers, with which many scientists associate changes in the physical and mechanical properties of metal and alloys [16]. Compressive stresses in the surface layers of carbon steel pieces occur as a result of coating the surface with chromium, aluminum, etc. The maximum value (1500 MPa or more) of residual stresses is reached as a result of chrome plating of medium and high-carbon steels. Residual stresses decrease with an increase in the thickness of the carbide and transition zone, due to both a decrease in temperature and an increase in saturation time.

One of the main methods of corrosion protection of steel products is galvanizing, since zinc provides electrochemical protection of metal in many conditions. The corrosion resistance of zinc coatings depends on the operating conditions. The corrosion rate of zinc is 1-2 microns/year in the atmosphere, 5-6 microns/year in the atmosphere of an industrial urban environment, and up to 50 microns/year in seawater. Corrosion of steel with a zinc coating of 5 microns thick in the atmosphere of an industrial area occurs on average on expiry of 12 months. Increasing the corrosion resistance of the zinc coating is achieved by creating protective films on its surface, as well as by alloying.

To increase the corrosion resistance of the surface of pieces after zinc coating, it is recommended to apply paint. Coating with 50% ZN+50% AI alloy, with a recommended thickness of 150 microns, does not provide good results in all atmospheres. The protective properties of the chemical nickel coating largely depend on the surface cleanliness and coating thickness. The surfaces of steel products before chemical nickel plating must be mechanically treated for surface cleanliness of class 7-8 and higher, and the coating thickness when working in a humid environment should be at least 20 microns.

The operating capacity of the structure at elevated temperatures is largely determined by the behavior of protective coatings at this temperature, the nature of the bonds between the coating metal and the base metal, oxidation of the coating, etc. The use of nickel and chrome coatings resistant to elevated temperatures has long been known. The main disadvantage of these coatings is that they reduce the steel fatigue limit, especially with large coating thickness. In case of small thickness, nickel and chromium, being a cathode coating, do not protect steel against corrosion.

In practice, nickel is used as protective metal coating, electrolytic or chemically precipitated coating is applied up to ≈ 400°C; chromium as an electrolytic or thermal diffusion coating—when operating up to 1000°C. The protective properties of nickel coatings with a thickness of 15 microns without additional heating are very low. After 1-2 days, spot corrosion of steel is detected, which increases as time goes on. Heating up at 400-500°C for 1-25 hours slightly increases the protective properties of nickel coatings.

Nickel coatings with a thickness of 15 microns are suitable for corrosion protection of products operating for a short time at 800°C. When coated with nickel (15 microns)–chromium (1 micron), heating at 400-600 °C practically does not affect their protective properties. Nickel-chrome coatings have higher protective properties in this temperature range than that of the nickel coatings (15 microns). At 500°C, nickel and chrome coatings have a very high heat resistance.

Coatings applied by chemical nickel plating have good heat resistance, but they greatly reduce the fatigue strength of steels (≈30%). To increase the resistance of carbon steels to gas corrosion, chrome plating is used, which is technologically easier to implement than other types of coatings. Diffusion saturation, depending on the type, method and mode of its implementation, affects the strength and ductility of steels in different ways. Sometimes the change in mechanical properties can reach 30% or more.

According to the nature of the effect on strength (tensile strength \( \sigma_{\mathrm{b}} \) and yield strength \( \sigma_{0,2} \)) and plasticity (percent elongation \( \delta \) and relative contraction \( \psi \)) characteristics, all types of diffusion saturation are divided into three main groups [17]:
The first group includes coatings consisting of solid carbide and a transition zone, under which a decarbonized zone of insignificant depth is located. Such coatings are formed as a result of saturation of carbon steels with chromium and other carbide-forming materials.

The decrease in mechanical properties with an increase in the thickness of the diffusion layer is parabolic in nature.

The second group includes coatings characterized by high hardness, under which there is a deep transition zone (1... 2 mm), resulting from the non-reactive diffusion of alloying elements to a considerable depth, as well as a result of the displacement of carbon from the surface of the workpiece when saturated with non-carbide-forming elements (boron, manganese, etc.). The increase in the strength and the reduction of plastic characteristics in this case reaches 30% and more.

The third group includes coatings with low and medium hardness, which are formed as a result of saturation with silicon, copper. Mechanical characteristics vary depending on the type, method and saturation mode, similar to changes in tensile strength and percent elongation. The influence of coatings on the change in mechanical properties increases with an increase in the thickness of the diffusion coating.

3 Experiment results

The paper studies the effect of a gas-phase nickel coating of different thickness—5, 10, 20, 50 and 100 microns at different substrate temperatures on the characteristics of static and fatigue failure of steel grades 40 and E10. The coating was applied [20] by thermal dissociation of nickel carbonyl vapors on a steel substrate heated to the decomposition temperature of carbonyl—130, 160, 180 and 200°C.

Using the example of E10 grade steel, it was found out that good adhesion to the substrate is observed at coating thickness being up to 30 microns (Fig. 1). At the same time, the coating itself is characterized by the absence of pores and is resistant to the effects of a corrosive environment.

Fig. 1. The dependence of the strength limits $\sigma$, yield strength $\sigma_{0.2}$ and $\sigma_{cracking}$ of E10 steel coating during static stretching on the thickness of the carbonyl nickel coating $\Delta$: I—the coating is cracked together with the substrate; II—the transition zone; III—peeling of the coating from the substrate.

Compiled by the authors.
increase in the thickness of the coating, the strength and plastic properties also practically do not change. The coating up to 30 microns has a good "adhesion" to the substrate, has no pores and is resistant to the effects of a corrosive environment. An increase in the thickness of the coating causes it to detach from the substrate when the steel is stretched. Due to the appearance of residual tensile stresses at the metal-coating boundary, the cyclic durability of steel grade 40 samples at loading frequencies of 180 and 3000 cycles/min decreases slightly with increasing coating thickness (Fig. 2).

![Fig. 2](image)

Fig. 2. The effect of the thickness of the carbonyl nickel coating $\Delta$ on the durability of $\lg N$ of steel grade 40 during cantilever bending with rotation frequencies of 3000 (1) and 180 cycles/min (2); the amplitude of the applied stress is 280 MPa.

4 Discussion

Stress state analysis shows that when saturated materials are stretched, even in the elastic area, due to the different physical properties of the layer and the core, there is a decrease in axial and an increase in annular compressive stresses, which, combined with the high brittleness of the layer, leads to its destruction by spalling. The plane of the layer cleavage is located at an angle of 45° to the direction of the annular stresses, which coincides with the plane of action of the maximum tangential stresses. The study of the kinetics of deformation and fracture during bending by a concentrated load of steel samples after diffusion saturation shows that during deformation of a composition in which the properties of the coating and the core are similar, for example, iron saturated with chromium (for the case of the formation of a solid solution of this element in $\alpha$-iron), the first signs of plastic metal flow in the form of sliding lines appear in favorably oriented base metal grains located directly under the diffusion layer. There is a localization of residual tensile stresses and increased dislocation density under the diffusion layer. In addition, alloying the surface layer of iron with saturating elements leads to a certain increase in the yield strength of the metal layer compared to the core metal. However, the destruction of the sample begins from the surface from the locations of various structural (pore inclusions) and process (notches, scratches) stress concentrators and is viscous in nature. If the steel contains a certain amount of carbon, then the destruction of chromium-coated steel is brittle and viscous. The presence of carbide inclusions along the grain boundaries of the diffusion layer causes its brittle destruction. A crack formed in the layer by a brittle mechanism develops only up to the boundary with the base metal, where the brittle mechanism is replaced by a viscous mechanism of destruction.

As regards the samples with a solid carbide coating, which occurs, for example, when medium- and high-carbon steels are coated with chromium, brittle fracture begins in the carbide layer, with cracks located both perpendicular and along the direction of action of tensile stresses. This is explained by the fact that the carbide layer consists of two zones of carbides $(\text{FeCr})_{23}\text{C}_{6}$ and $(\text{FeCr})_{7}\text{C}_{3}$, the physical and mechanical properties of which differ significantly. Cracks arising in the carbide layer, being effective stress concentrators, ...
predetermine the brittle destruction of the transition (pearlite) zone and only in the decarbonized zone the brittle destruction is replaced by a viscous one. The process of deformation and destruction of a composition consisting of a hard (martensitic) core and a soft (ferritic) coating proceeds in a different way, which is formed, for example, when applying the coating on the surface of stainless steels of the martensitic class. When the sample is bent in the tensile zone, cracks originate in the base metal along the boundaries of the diffusion layer and the substrate interface and develop inside the base metal mainly perpendicular to the action of tensile stresses. The destruction of the diffusion layer occurs when the core of the sample has almost completely lost its bearing capacity. Chromium coatings with a thickness of several microns change the mechanism of plastic deformation of siliceous iron: the sliding, characteristic of the deformation of siliceous iron at room temperature, is preceded by intense twinning, the contribution of which to the total elongation can reach 1/3 of the length.

5 Conclusions

The main methods of corrosion protection are galvanizing and cadmium plating. Nickel, chromium, and nickel-chromium are widely used as heat-resistant coatings. All types of diffusion saturation according to their effect on strength and plastic characteristics during static tests are divided into three main groups: a-reducing strength and plastic properties; b-increasing strength and reducing plastic properties; c-reducing strength and increasing plastic properties. At the same time, regardless of their effect on the endurance of smooth samples, the endurance limit of samples with stress concentrators increases. The corrosion resistance of steels is increased by many types of diffusion saturation (chrome plating, galvanizing, etc.) effects; however, there are no data on the optimal values of the coating thickness. Limited theoretical and experimental data make it difficult to predict the physical and mechanical properties of metals and alloys with coatings applied.

It has been established that the gas-phase nickel coating with a thickness of up to 30 microns has good "adhesion" to the substrate, has no pores and is resistant to the effects of a corrosive environment. At the same time, despite a slight decrease in mechanical properties, the gas-phase coating of steel products with nickel up to 30 microns thick can be considered appropriate due to its high chemical resistance and simplicity of the technological process.

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