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(Review Article)

Study of structural changes in copper coating on the surface of structural steels working under repeated loads

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Abstract

This article discusses one of the important tasks of studying structural changes in copper coating on the surface of high-quality structural steels. Growing demands for increasing the efficiency of using structural materials and improving their performance properties, as well as more severe operating conditions of oilfield machinery and equipment, require the development of new calculation methods based on effective experimental methods for studying the stress state. One of such effective methods of studying the stress state is the method of galvanic copper plating, which allows determining the stress of parts in real conditions of their processing. The article, based on metallographic and electron microscopic studies, examines the mechanism of growth of copper-plated grains under the action of multiple alternating loads.

It has been established that as a result of the complex effect of stresses, volumetric stress states arise. As a result of multiple alternating loading of a steel sample, significant changes occur in the structure of the copper coating on the surface, which are controlled by the appearance of black and colored spots. It has been established that oxidations formed on the copper surface occur not under the influence of atmospheric air, but as a result of internal changes in the electrolytic copper layer under the influence of alternating loads. Grain growth on the copper coating under the influence of alternating loads to which the part is subjected begins at the interface between the copper coating and the base metal.

Keywords: Structural material; Copper plating; Stress; Cyclic loading; Strength; Microstructure; Lattice defect; Slip band.

1. Introduction

The expansion of the elastoplastic deformation zone occurs as a consequence of an increased number of individual contacts, resulting from the redistribution of stresses under the influence of normal load as well as combined tangential and radial stresses [1]. Under cyclic alternating loading, the joint action of radial and tangential stresses in the surface layer of the material leads to a triaxial stress state. Under such conditions, even high-strength materials demonstrate a certain degree of plasticity. The shear stresses in the surface layer comprise both internal resistance stresses and stresses that inhibit the movement of dislocations out of the surface layer [2].

In the manufacturing of machine components, it is essential to account for permissible defects, surface finish quality, variations in external forces, scale effects, stress concentrations, material tolerances, and other relevant factors. To address these aspects in design practices, comprehensive studies have been conducted worldwide, resulting in the preparation of review materials [3].

Recently, it was discovered that when surfaces are electroplated with a thin layer of copper, the copper crystals deposited around high-stress regions in components subjected to variable loads exhibit a change in color. Exploiting

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this phenomenon, the Japanese researcher Okubo was able to determine the stress concentration in such components [4]. Subsequent investigations extended this approach through both chemical and electrochemical copper coating techniques [5].

Currently, alongside various experimental methods for stress determination, the electroplated copper coating technique is also employed to investigate the stress state of machine components [6].

In numerous fields, including oil and gas equipment and installations, operating conditions are characterized by high complexity and variability, often involving intensive composite processes. Consequently, the development of surface coatings for machine components by different methods has gained particular importance in addressing these challenges. Experimental research based on effective methodologies contributes to enhanced durability and reliability of components, while simultaneously ensuring resistance to increasingly severe operating environments [7].

The aim of this study is to identify, using microscopic examination, recrystallization centers on the surface, depending on the amplitude of the changing load and the number of loading cycles, and to study the structural changes.

2. Material and methods

Electron microscopic examinations were conducted using electron and optical microscopes (PME OLYMPUS TOKYO and TESCAN VGA3). To obtain higher-contrast images and identify defects, the coating was etched with tungsten oxide.

Under laboratory conditions, fatigue strength tests were conducted on a KTC 405 testing machine with rotational bending (Fig. 1). Fatigue tests of samples and components were carried out for a maximum of 10×106 cycles [8].

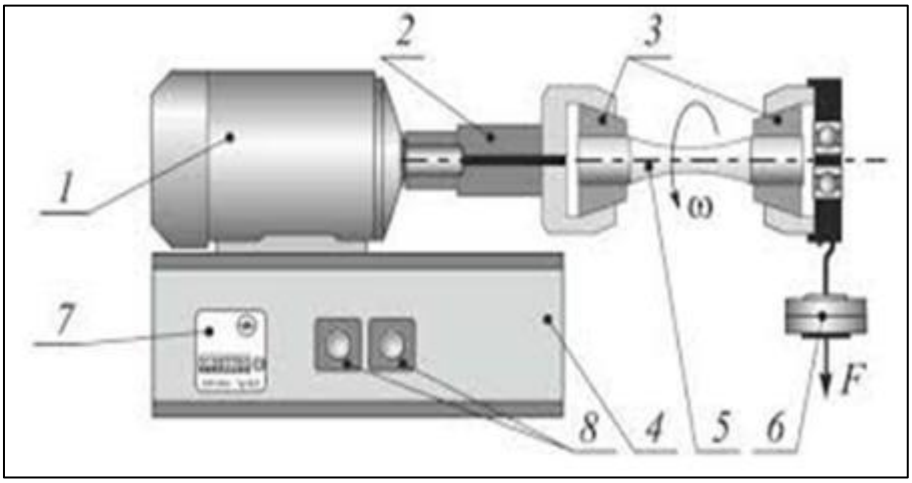

Figure 1 Schematic diagram of the testing machine: 1 – electric motor; 2 – spindle headstock; 3 – holders; 4 – cast-iron housing; 5 – test specimen; 6 – variable loads; 7 – cycle counter; 8 – control panel

The mechanical properties of materials operating under cyclic variable loading are determined from curves obtained during the testing of specimens made from these materials on specialized machines according to a standard program (Fig. 2). The curve ABC shown in the figure is referred to as the Wöhler curve. The stress value corresponding to point B is termed the endurance limit. As a result of the investigations [9], the following expressions were obtained:

$$\log\frac{N_2}{N_1} = m\log\frac{\sigma_1}{\sigma_2} \quad \text{və ya} \quad \log\frac{N_2}{N_1} = \log\left(\frac{\sigma_1}{\sigma_2}\right)^m$$

$$N_1\sigma_1^m = N_2\sigma_2^m = const$$

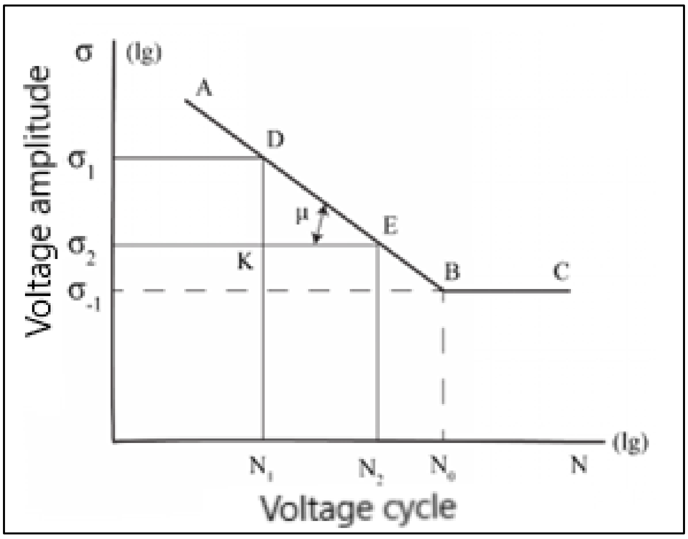

Figure 2 Graph of the dependence of stress amplitude on the number of loading cycles

3. Results and discussion

The primary criterion for determining stresses in machine components with electroplated copper coatings is the growth of copper grains deposited on the surface of the tested component. Under the influence of repeatedly varying loads, significant structural changes occur in the copper layer, accompanied by the appearance of dark spots on the surface (Fig. 3).

It was established that the formation of these spots on the copper coating surface does not result from mechanical changes in the state of the electrolytic copper layer, but rather from oxidation processes [10]. When exposed to a flow of calcium carbonate at 300 °C, no changes were observed. This indicates that the dark spots are formed due to oxidation of the surface layer of copper, and that the presence of the copper surface itself has no direct effect on their appearance.

Thus, it can be concluded that the formation of spots on the copper surface is the result of oxidation, which occurs not under the influence of atmospheric air but due to internal changes within the electrolytic copper layer under repeated loading. Indeed, when the copper-coated surface containing spots is subjected to chemical erosion, exposing the copper structure, significant structural modifications can be observed in the copper layer. These changes are attributed to grain growth under the action of cyclic loading [11]. Furthermore, with an increasing number of load cycles, grain growth can continue to very large sizes.

Figure 3 illustrates the structural transformation of the copper coating under repeated cyclic loading, beginning at the boundary between the copper layer and the base metal. The figure presents a longitudinal section of a copper-coated specimen after being subjected to an alternating stress of 220 MPa for $N = 5 \cdot 10^6$ cycles.

Microstructures were obtained from three regions of the specimen's working surface:

- Region I: $\sigma_a = 150$ MPa, $N = 5 \cdot 10^6$ cycles
- Region II: $\sigma_a = 200$ MPa, $N = 5 \cdot 10^6$ cycles
- Region III: $\sigma_a = 240$ MPa, $N = 5 \cdot 10^6$ cycles

To further investigate the mechanism of copper grain growth, electron-microscopic analyses were also conducted on copper samples after exposure to variable loads.

Since, in the current copper structure, the grains appear consolidated (Fig. 3), the recrystallization process would imply the existence of recrystallization centers, which act as nuclei for the formation of "non-standard" grains arising from such consolidation.

Accordingly, the process of heterogeneous grain growth under cyclic stress can be explained by the emergence of a certain number of surface defects in the coating after repeated loading, the quantity of which depends both on the amplitude of the alternating stress and the magnitude of the cyclic loads applied.

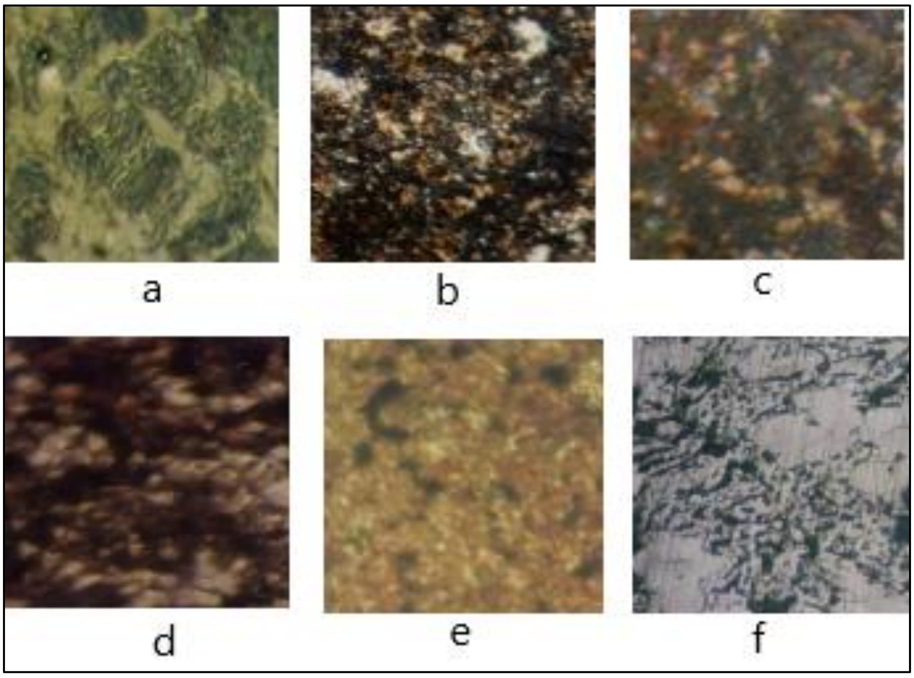

Figure 3 Structural changes on the surface of the copper coating: a – Steel 40, ×400; b – spots on the copper coating, ×200; c – grain growth, ×200; d – longitudinal section (σ_a = 220 MPa, N = $5 \cdot 10^6$ cycles); e – thin continuous slip band, ×200; f – electron-microscopic image in Region III, ×4000

Clusters of such defects can serve as nucleation centers. The objective of the electron-microscopic investigations was to detect recrystallization centers that depend on the amplitude of alternating stress and the number of loading cycles.

A detailed examination of Region I under the electron microscope (σ_a = 150 MPa, N = $5 \cdot 10^6$ cycles) did not reveal the expected changes in the copper structure. It should be noted, however, that optical microscopy studies showed no copper grain growth under alternating stresses below 160 MPa. Apparently, at these stress amplitudes, plastic deformation of localized microregions, associated with the formation of thin stable slip bands, does not lead to changes in the structure of surrounding grains.

In the electron-microscopic study of Region II (σ_a = 200 MPa, N = $5 \cdot 10^6$ cycles), noticeable structural changes in copper were observed. These changes can be explained by the formation of crystal lattice defects and the development of thin stable slip bands on the metal surface. In Region II, a clear arrangement of defects within the copper single crystal can be seen along directions emanating from the center of the single crystal, indicating a common origin of these defects.

In Region III (σ_a = 240 MPa, N = $5 \cdot 10^6$ cycles), the formation of surface defects was the most pronounced. Figure 3 shows clusters of point defects obtained at various electron microscope magnifications.

4. Conclusion

It has been established that after repeated exposure to alternating stresses, copper grain growth in the surface layer of the copper coating begins at the interface between the base metal and the copper coating. Based on the microstructures obtained from three regions of the specimen's working surface, structural changes in the copper coating under low, medium, and high stress levels—after an identical number of cycles—were determined, along with the types of crystal lattice defects. In summary, the results indicate that the mechanism of copper grain growth under repeated alternating loading can be attributed to the formation of crystal lattice defects on the metal surface.

Compliance with ethical standards

Acknowledgment

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Disclosure of conflict of interest

The authors declare that they have no competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent statements

All study participants were informed about the goals and conditions of the work, as well as about the increased attention to written information.

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