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Modification of Microstructure and Mechanical Parameters of Austenitic Steel AISI 316L under the Action of Low Friction

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Abstract: This work is devoted to the study of the tribological properties of AISI 316L austenitic steel and the effect of the relative velocity of rubbing bodies on the microstructure and mechanical properties. The specificity of the deformation is investigated in the mode of dry friction "metal/metal", namely, steel AISI 316L/steel St3sp, with a process duration of 15 h. The change in the microstructure of the samples as a result of friction and the determination of mechanical properties are carried out on the friction surface and on the cross-section of the samples. The mechanical parameters are studied by depth-sensitive indentation using a Berkovich indenter. It is shown that low friction with the relative velocity of rubbing bodies of about 30 rpm is capable of introducing noticeable microstructural and strength changes. Strength and relaxation properties (hardness, Young's modulus, plasticity index, and resistance index) increase in samples subjected to friction compared to the original undeformed sample. A change in the microscopic structure of the samples near the friction surface increases such material properties as microhardness (H) and Young's modulus (E). In particular, the microhardness increases from 1.72 GPa for the undeformed sample to 3.5 GPa for the sample subjected to friction for 15 h. Young's modulus increases from 107 GPa to 140 GPa, respectively. A comparison with the properties of samples deformed at the relative velocity of rubbing bodies of about 300 rpm shows a further increase in the microhardness and Young's modulus. Also noted is the sensitivity of the relaxation parameters to the friction process and the relative velocity of rubbing bodies. In particular, the relaxation parameters h_c and h_{res} decrease while $h_{e\text{-}p}$ increases.

Keywords: AISI 316L steel; relative velocity of rubbing bodies; microstructure and mechanical parameters

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1. Introduction

Various machines, machine tools, instruments, and equipment necessarily consist of many components permanently in contact with each other while subjected to friction stress of greater or lesser intensity. As a result, the components wear out, affecting the performance quality and the product's overall durability. For this reason, the study of various fundamental and applied aspects of the friction mechanism is very important, and a vast amount of the literature was devoted to these aspects [1–4]. In most cases, the regularities of deformation and the mechanism of the friction process are studied on materials and structures that are used in the creation of all kinds of moving parts and machines. In [2], the authors thoroughly analyzed three FCC materials (aluminum, copper, and austenitic steel) using nanosliding and scratching at various load levels. A clear influence of mechanical parameters on the mechanism of deformation and wear was noted. The threshold values for the transition of the wear mechanism from sliding to scratching and chipping increased with increasing hardness in the Al-Cu-steel series. Along with this, the resistance index H^3/E^2 indicated the magnitude of the contact pressures, upon reaching which a change in the wear mechanism occurred.

The degree of wear depends not only on the properties of the material subjected to friction, but also on operating conditions such as normal forces, relative velocities, and the length scales of textured surfaces. The higher the values of these parameters, the more wear products appear, and this transforms the friction mode from adhesive to abrasive. Wang et al. [3] showed that, under dry conditions, the smoothest surfaces do not show the least friction from the increase in adhesion forces, as might be expected. A surface with a slight microstructure reduces the coefficient of friction. In turn, macro-textured surfaces markedly increase the coefficient of friction from the abrasive effect of the surface. The effect of deformation treatment of the surface of 40KhNMA steel during sliding friction on an abrasive surface was studied in [4]. It was shown that deformation treatment promotes an increase in size and the presence of bulk defects in the crystal structure of steel. Deformation treatment should be used to increase the hardness and bulk strength of 40KhNMA steel. To do this, it is necessary to use hardening, which simultaneously increases the resistance to plastic deformation and the destruction of steel, estimated by increasing the rheological parameter.

During friction, there is a rigid contact between two bodies, accompanied by the rising of significant inhomogeneity in local stresses near the contact surfaces. As a result, inhomogeneous plastic deformation occurs in materials subjected to friction. Bowden and Leben [5] found that the friction force does not remain constant between two pieces of metal moving relative to each other. The process of friction is not continuous but occurs in large jerks. Under the action of a normal force, the contacting surfaces seem to "stick together" to each other, and it is necessary to apply a tangential force for their relative movement. As a result of gradually increasing tangential stress up to a certain maximum value, a sudden and very fast sliding occurs. The tangential stress drops to zero at this instant until the relative motion stops again. Then the tangential stress begins to increase again, and the process repeats over and over. However, the nature of this process is not the same for various combinations of rubbing materials. On the one hand, the friction process depends on the physical properties of the rubbing materials (such as the chemical bond of rubbing materials, hardness, elasticity, melting temperature, etc.). On the other hand, the friction force and the nature of friction depend on external factors, such as the magnitude of the normal load acting on the rubbing surface, the temperature at which friction occurs, the presence of lubricants, the relative velocity of rubbing bodies, etc.

The presence of such a large number of factors affecting the mechanism of friction and wear, naturally, was the reason for numerous studies. For example, the authors of [6] used friction stir treatment (FSP) to harden the surface of AISI 440C high-carbon martensitic stainless steel. An increase in hardness up to 779 HV1 and higher than that of the conditionally hardened sample was achieved. In another work [7], in order to obtain a hardening effect in AISI 316L stainless-steel sheets, friction treatment with stirring was carried out at a constant speed (63 mm/min) and relatively low rotation speeds (200 and 315 rpm). It was found that despite the decrease in plasticity by 50%, the maximum yield strength and ultimate tensile strength of the samples processed by friction with stirring increased by about 1.6 and 1.2 times compared to the original metal. Dogan et al. [8] studied the issue of friction and wear of stainless steel implanted with nitrogen and zirconium and coated with TiN. These implantations have been shown to improve the coefficient of friction, as well as the wear resistance of the stainless-steel surface.

The effect of silicon carbide in the range from 35–200 μm at various normal loads (P_{norm} = 50–110 N) on wear of steel 35NCD16 microstructure and abrasive grains was studied in [9]. It was shown that the coefficient of friction decreases with increasing normal load and/or decreasing abrasive particle size. At the same time, the wear rate increases with an increase in the normal load and/or abrasive particle size. It was found in [10] that severe abrasive wear occurs at low load, and the highest nanohardness, elastic properties, and creep resistance of SLMed IN718 superalloy is created directly under the wear surface. More detailed studies of various issues related to friction hardening were carried out by Rapoport and Rybakova [11,12], who established the formation of three microstructural levels (layers) near the contact surface.

The results above were confirmed in [13–15]. It was shown that during the friction of metal samples, the microstructure of a narrow surface layer differs significantly from that of the bulk since the material is subjected to ultrahigh internal stresses near the friction surface. These stresses are much higher than those in the bulk. In this case, a significant change in the material's behavior and the appearance of anomalous mass transfer phenomena naturally occur. It was also found that the length of the hardened surface layer depends both on the type of the deformable material (brass, copper, or steel) and on the friction method (hard dry friction, extrusion, impact, or indentation) [16,17].

From the reasons mentioned above that affect the specificity and degree of deformation during friction, it becomes obvious that the relative velocity of rubbing bodies also plays a significant role in all friction methods. This issue is studied insufficiently in the scientific literature and needs additional attention. In [17], the effect of friction on the micromechanical parameters of AISI 316L austenitic stainless steel was studied, taking into account the extensive use of this material in various sectors of the industry and, in particular, in medicine for manufacturing implants. In this work, the study of the specifics of deformation was carried out in two friction modes: 1—dry friction "metal/metal", namely, steel AISI 316L/steel St3sp, and 2—dry friction "metal/abrasive", steel AISI 316L/abrasive P2000, with different durations of the process (t = 1; 5 and 10 h). Friction processes were performed using a MoPao 160E grinding and polishing machine at a rotation speed of $v \approx 300$ rpm and a normal pressure of $P_{\text{norm}} \approx 400$ mN.

It was found that different modes of friction create plastic deformation in the test sample. The maximum modification of the microstructure was observed in a thin layer ($\leq$100 µm) directly adjacent to the friction surface, i.e., in the zone of severe plastic deformation. The degree of plastic deformation successively decreased with distance from the friction surface, and the sample acquired the original polycrystalline structure at a distance of $t \approx 600$–700 µm. Along with this, a change in the mechanical parameters, such as microhardness (H), Young's modulus (E), plasticity index (H/E), and resistance index (H^3/E^2), also occurred. The degree of their change depended on the experimental conditions. Taking into account that the friction conditions, in particular the relative velocity of rubbing bodies, affected the microstructure and plasticity parameters noticeably, the study was continued at a lower rotation speed but a longer process time.

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