

RESEARCH OF CONTACT PHENOMENA THAT OCCUR IN MILL ROLLS

ИССЛЕДОВАНИЕ КОНТАКТНЫХ ЯВЛЕНИИ В ПРОКАТНЫХ ВАЛКАХ

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Abstract: Available experimental data on the contact resistance of a rolling pair (solids of revolution made of quenched martensitic steels) are used to analyze processes that occur in the roll material. A refined failure mechanism is proposed. Recommendations are given to increase the contact resistance of mill rolls.

KEYWORDS: ROLLS, CONTACT RESISTANCE, DURABILITY

1. Introduction

The process of rolling, especially precise cold rolling, can be compared with cyclic contact loading characteristic of the interaction of solids of revolution or of a solid of revolution and a plane. However, rolling has certain peculiar features. In particular, the working surface fails under the action of a number of factors, such as mixed friction, metallic contact, surface roughness, impurities in lubricants and semifinished rolled products, and so on.

During operation, the working surfaces of a roll, especially those in a deformation zone, undergo repeated (cyclic) contact loads varying in time between two limiting values according to a certain law. GOST (State Standard) 2860-65 "Metals. Fatigue Test Methods" defines a *stress cycle* as a set of sequential values of variable stresses within one period of their change. The stresses in a cycle (Fig. 1) are expressed as:

$$\sigma = \sigma_m + \sigma_a f(t), \quad (1)$$

where σ_m is the average cycle stress, σ_a is the cycle amplitude, $f(t)$ is a continuous periodic function, and t is the time.

The $f(t)$ function is usually approximated by a sinusoid, since as a rule the shape of the cycle does not affect fatigue test results.

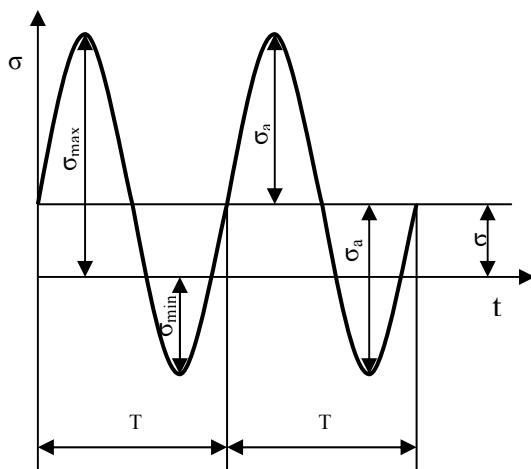


Fig. 1. Characteristics of a stress cycle

2. Preconditions and mans for resolving the problem

Contact fatigue tests are usually performed under conditions that are close to operating conditions. To determine the contact

fatigue, the number of cycles to failure must be no less than 5.0×10^7 cycles for metals with a Brinell hardness $HB < 400$ and no less than 10^8 for materials with an HB hardness > 400 . To construct a contact fatigue curve, one has to use no less than 12 identical samples, three of which must be at the limit of contact fatigue [1]. Usually, the number of operating cycles for a roll N does not exceed 10^5 cycles. However, this number can increase by an order of magnitude (to 10^6 cycles or even higher) for a modern rolling technology (especially precise rolling), optimum purified lubricants, the preparation of semifinished rolled products, and the optimization of the roughness parameters of the active surface of an instrument, i.e., for the effective conditioning of a production process and the use of high-alloy steel rolls. In this case, the operating conditions of a roll can be considered as ideal conditions, where the effect of stresses in deep. Contact fatigue test machines are divided into ball (ball-ball machines), roll (roll-roll machines), and combined machines. The following schemes of these machines exist: one-contact (two-roll), two-contact (three-roll), three-contact (four-roll), and so on.

It is well known that the study of residual stresses in the internal layers of quenched steels by X-ray diffraction methods is labor consuming and expensive. To minimize the cost and to simplify the determination of the residual stresses that appear in the near-surface layers of solids of revolution subjected to contact fatigue tests, researchers have established a linear relation between the residual stresses and hardness (Fig. 2).

Upon cyclic contact loading, forces tend to flatten bent surfaces. On the other hand, they induce stresses under the contact surfaces through these surfaces; the stresses can be calculated as the characteristic leveling stresses, whose maximum is located under the rolling-contact surface (Fig. 3). The data obtained in the 1960s–1980s when contact in a rolling-contact pair was modeled and studied by a polarization-optical method give a similar result. According to [2, 3], the maximum stress calculated from the hypothesis of an energyinduced change in the shape (Fig. 3) is

$$\sigma_v = 0.557 P_0 s \quad (2)$$

and it is located at a depth $z = 0.7b$ from the roll surface. It is assumed that, during superelastic deformation, plastic strains first appear in this place and then propagate further. The material fatigues. As for rolling, it is recommended that z be calculated by the formula (3).

$$z = 0.319 \epsilon_c (1 - \xi) \frac{P_p}{P_{\max}} \quad (3)$$

where P_{av} and P_{max} are the average and maximum contact pressures in GPa, respectively; l_c is the contact arc length (l_c is most often determined by Hitchcock's formula [4]); and ξ is the dimensionless coordinate of the maximum pressure ($\xi = 2V_{l.c.}/l_c$, $V_{l.c.}$ is the distance from the point of the maximum pressure to the line of centers). Usually, z is located at a depth $(0.2-0.3)l_c$.

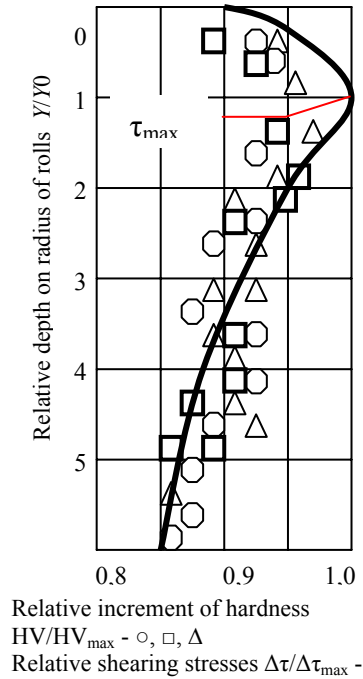


Fig. 2. Field of scatter of the hardness measured along the radius of a roll 190 mm in diameter made of 90X2MΦ steel with a Shore hardness of 95 after contact cyclic loading and the calculated tangential stresses. The points show a relative increment in HV , and the curve show the relative values of τ . Y/Y_0 is the relative depth along the roll radius

Experimental studies of the location of the maximum tangential stresses in the surface layers of solids of revolution and rolls support the theoretical dependences given above. When rolls are restored after an operating period, the wear working layer is replenished. The cutting depth is often specified by the physical wear of the working surface of a roll, and its defect layer (where microcracks form) is not removed. Other-wise, the rolling instrument can undergo premature failure.

The cyclic contact loading of a steel results in stress accumulation; submicrocrack formation; and the formation of microcracks, which cause failure in the form of spallation and cracks. These processes are characterized as *contact fatigue*. The mechanism of fatigue failure of metallic materials subjected to cyclic loading is taken to be described by the curve shown in Fig. 4 [5]. The upper region of the curve shows that, at superelastic cyclic loads, the time to failure decreases with increasing load. As the load decreases, there is a threshold below which a structure does not change and the material is not subjected to fatigue. Fatigue manifests itself in microplastic changes in a structure. In soft steels, fatigue occurs in four stages: in stage *A*, a structure deforms plastically, a relatively homogeneous deformation extends to a large volume of a part, and small discontinuities (so-called microcracks) form in the material. Stage *A* rapidly transforms into stage *B*. The microcrack density increases. Fatigue phenomena concentrate in small volumes at a microcrack tip. In stage *C*, one of the most stressed microracks develops and transforms into a macrocrack. In stage *D*, the process ends in fatigue failure. In quenched steels in stage *A*, only quasistatic or microplastic deformations occur. Microcracks form immediately

before failure, which means that the stage *A* extends for almost the whole service life [5].

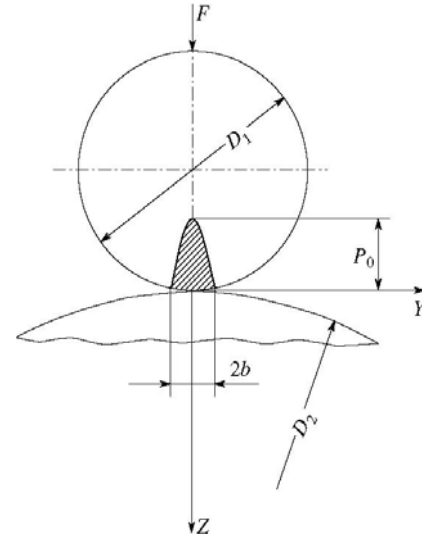


Fig. 3. Rolling pair with a contact arc and the Hertz contact-pressure profile: F is an applied load, P_0 is the Hertz contact pressure, b is the contact area half-width, and D_1 and D_2 are the cylinder diameters [5]

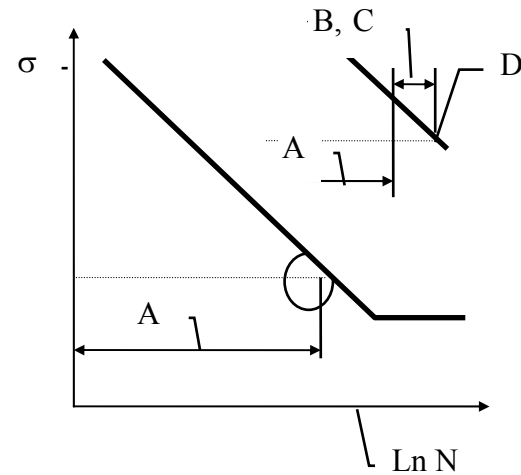


Fig. 4. Diagrams of contact resistance of rolls made of an quenched steel.

However, there are certain differences. First, the cyclic loading of quenched steels causes plastic deformation under the rolling surface at high pressures, which transform a martensitic structure into a relatively plastic state. As a result, the regions under high loads are subjected to an intense, relatively homogeneous deformation; at the beginning, this deformation does not cause microcrack formation. Moreover, it was found that, when rolls are loaded, cracks that induce the failure of a rolling element are almost exclusively initiated by nonmetallic inclusions [5], whose concentration can be decreased during steelmaking. This process strongly affects the lengths of fatigue stages *B*, *C*, and *D*. Processes in stage *A* depend mainly on the hardness, structure, and the macroscopic load.

The authors of [6, 7, 8, 9] propose to consider the failure mechanism during cyclic loading in more detail using the scheme in Fig. 5. Here, I is an incubation period; II is a loosening period, which is related to the appearance of discontinuities in the metal and to the nucleation and development of submicroscopic cracks;

III is a period for the development of critical microcracks; and IV is a period of failure or rupture. Based on the studies of the mechanism of crack formation, we may assume that the leading role in the formation of a fatigue failure zone is played by the boundaries of steel microstructure elements, along which high local deformations and stresses are accumulated. before failure, which means that the stage *A* extends for almost the whole service life.

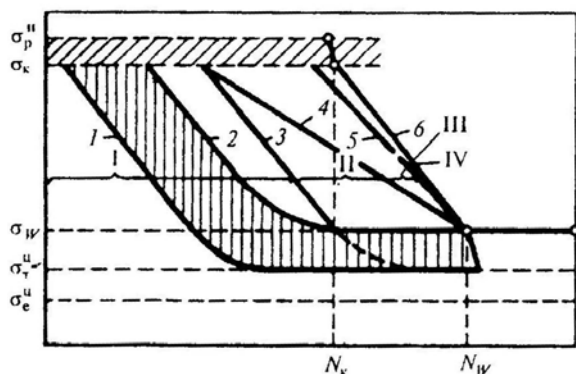


Fig. 5. Refined contact-resistance diagram: (1) the line of the beginning of a microscopic flow, (2) the line of the end of the microscopic flow, (3) the line of the beginning of formation of submicroscopic cracks, (4) the line of the beginning of formation of micro-scopic cracks (French's line), (5) the line of the beginning of catastrophic failure (rupture), and (6) the fatigue curve. σ_y is the cyclic yield strength, σ_e is the cyclic elastic limit, N_{cr} is the critical number of cycles, and N_w is the base number of cycles.

3. Conclusion

The key features of contact interaction in rolling pairs made of quenched martensitic steels (mainly, bearing and roll steels) have been analyzed. We proposed methods to estimate the depth of maximum stresses for the ordinary contact of a rolling pair and the contact in a deformation zone for rolling. This depth is 0.3–0.4 of the contact area width for the ordinary contact and 0.2–0.3 of the contact arc length in a deformation zone for rolling.

Based on the experimental results, we made some recommendations for increasing the contact resistance of the active surface layer of both conventional rolls (mainly for rolling-contact bearings) and mill rolls (especially rolls for precise cold rolling):

- to use processes that decrease the content of nonmetallic inclusions in the near-surface layers of the working surfaces of parts that undergo contact cyclic loading,
- to take into account changes in the actual dimensions of solids of revolution and to choose optimal conditions of mechanical treatment during the restoration of the wear surfaces of mill rolls.

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